A WORKSHOP FOR PLANNING THE EFFICIENT TRANSFER OF RECENT CERAMIC ARMOR/ANTIARMOR MODELING RESULTS TO THE ARMOR DESIGN COMMUNITY: SUMMARY AND DRAFT PLAN

FINAL TECHNICAL REPORT

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MAY 1999

U.S. ARMY RESEARCH OFFICE

CONTRACT NO. DAAG55-98-K-0004

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Development and Engineering Center

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
May 1999

3. REPORT TYPE AND DATES COVERED
Final Report August 1998 - June 1999

4. TITLE AND SUBTITLE
A Workshop for Planning the Efficient Transfer of Recent Ceramic Armor/Antiarmor Modeling Results to the Armor Design Community: Summary and Draft Plan

5. FUNDING NUMBERS
DAAG55-98-K-0004

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SRI International
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Menlo Park, CA 94025-3493

8. PERFORMING ORGANIZATION REPORT NUMBER
2501

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 38773.1-MS-CF

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

In the mid-1980s DARPA began sponsoring several programs to develop ceramic armor for heavy armor applications, supported by DARPA- and ARO-funded technology base initiatives in modeling, experiments, and materials science. These various programs resulted in significant advances. Most of those programs have now ended, and, unfortunately, the results of most of the modeling efforts have not yet been transferred to practical armor/anti-armor designers. Thus, there is danger that the efforts of the past dozen years or so and ARO's and DARPA's investment will be wasted unless an effort is made to explicitly plan and execute a technology transfer. Under the sponsorship of the U. S. Army Research Office, SRI International organized a workshop with the purpose of planning for the efficient transfer of recent mesomechanical ceramic armor modeling results to the armor/antiarmor design community. This report gives the background that led to the workshop, a summary of the meeting, and a description of the resulting technology transfer plan. The plan includes suggestions for its sponsorship, management, a rough-order-of-magnitude cost, and a schedule.

14. SUBJECT TERMS
Ceramic armor, technology transfer, modeling, micromechanical model, mesomechanical model, continuing model, engineering model

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Sta. 239-18
298-102

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

CLASSIFIED BY :

N/A

DECLASSIFY ON : N/A

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

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INTRODUCTION

Under the sponsorship of the U.S. Army Research Office, SRI International organized a workshop to plan for the efficient transfer of recent mesomechanical ceramic armor modeling results to the armor/antiarmor design community. The Institute for Advanced Technology in Austin, Texas, provided the venue and conference services. This report gives the background that led to the workshop, a summary of the meeting, and a description of the resulting technology transfer plan. The plan includes suggestions for its management, a rough-order-of-magnitude cost, and a schedule.

BACKGROUND

The development of ceramic armor began in earnest during the Vietnam conflict, when the need arose for lightweight armor for helicopters. The work of Wilkins is the most important research from this era. His work was supported mainly by DARPA. After the Vietnam conflict, interest waned until the mid 1980s, when DARPA began sponsoring several programs to develop ceramic armor for heavy armor applications, supported by DARPA- and ARO-funded technology base initiatives in modeling, experiments, and materials science. These various programs resulted in significant advances in the technology base. Most of those programs have now ended. Unfortunately, the results of most of the modeling efforts have not yet been transferred to practical armor/antiarmor designers. Thus, there is danger that the efforts of the past dozen years or so and ARO's and DARPA's investment will be wasted unless an effort is made to explicitly plan and carry out a technology transfer.

Furthermore, present military hardware planning and acquisition requires ever more rapid turnaround at ever decreasing cost. Thus, armor design needs to be done accurately yet more quickly and cheaply. The old approach to armor design, based almost entirely on build-and-shoot, has become too expensive and too slow to be used to reach an optimum design in the new, compressed development cycles that are demanded. The only way this kind of design can be done is by incorporating modeling and simulations. However, modeling and simulations will never completely supplant build-and-shoot because the latter approach offers concrete proof of the validity of a design. Hence, a hybrid of build-and-shoot and simulations will likely emerge as the best approach.

Fortunately, the needs for speedier design at lower cost have developed in parallel with the ability to do increasingly detailed simulations at lower computational cost. However, simulations are only as good as the models supporting them. We identify four types of models suitable for modeling ceramic armor: (1) microphysical models, (2) mesomechanical models, (3) continuum models, and (4) engineering models.

In microphysical models, individual material particles and their boundaries are all discretized in exquisite detail. Current versions of these models are accurate, but even with today's computing power, microphysical models are impractical for use in armor design, war gaming, antiarmor selection, and so forth.

In mesomechanical models, the microphysical processes are included but they are averaged over a relevant volume element (RVE), so that fewer computing resources are required. Due to the averaging process, the mesomechanical models are necessarily less accurate in capturing microscopic details of ceramic behavior.

In continuum hydrocode models, behavior is further averaged so that micromechanical and mesomechanical details are reflected in, say, an analytical description of a yield surface and an internal state variable that reflects damage. Continuum models are less able to capture details but require fewer resources than mesomechanical models. Nevertheless, continuum models are becoming efficient to use for design, but are not efficient for war gaming and similar activities.

Engineering models are used solely for penetration predictions and are typically analytical and nearly "back-of-the-envelope." These models are efficient enough to use in armor and antiarmor design, war gaming, weapon selection, and interpolation of live-fire testing and evaluation results. We now have access to a few good, efficient engineering models, but the connection between the model parameters and penetration physics and material properties is weak and poorly understood. Thus, the engineering models cannot be used with high confidence to optimize material properties and other design parameters.

The primary technical approach of the proposed technology transfer plan is to link the parameters in the current, efficient engineering models to continuum, mesomechanical, and micromechanical models. Establishing this linkage will enable the armor/antiarmor designer to better vary material properties and other physics-based design parameters to achieve optimum results. In addition, war gamers, antiarmor planners, and live-fire testers will have greater confidence in their results.

WORKSHOP SUMMARY

Fourteen persons representing a wide but necessarily incomplete cross section of the ceramic armor community attended the two-day workshop. Table 1 lists the attendees with their affiliations and areas of modeling expertise.

TABLE 1. ARO MESOMECHANICS WORKSHOP PARTICIPANTS

Name	Affiliation	Expertise*
Dr. Charles E. Anderson, Jr.	SwRI	Continuum models
Dr. John Bailey	ARO	Sponsor
Dr. Stephan Bless	IAT	End user/experimentalist
Dr. Lalit Chhabildas	SNLA	Micromechanics
Dr. Donald R. Curran	SRI (Retired)	Mesomechanics
Dr. Sunil Dwivedi	Purdue	Micromechanics
Dr. David Grove	BRL	Mesomechanics
Dr. Richard W. Klopp	SRI	Organizer/experimentalist
Dr. Werner Riedel	EMI—Freiburg	Continuum models
Dr. Sikhanda Satapathy	IAT	Engineering models
Dr. S. Robert Skaggs	Consultant	End user
Dr. David Stepp	ARO	Sponsor
Dr. Douglas Templeton	TARDEC	End user
Dr. James D. Walker	SwRI	Engineering models

*Each participant has several areas of expertise. The expertise in the table is the one most closely associated with the workshop presentation.

Dr. Richard Klopp began the workshop by welcoming the attendees and outlining the agenda and goals. Dr. John Bailey from the U.S. Army Research Office then gave ARO's perspective on the purpose for the meeting. Dr. Bailey also introduced Dr. David Stepp, who is planning to take over some of Dr. Bailey's responsibilities at ARO.

Dr. Bailey explained that ceramic armor research funding is in a state of flux and unclear. ARO is to be combined with the Army Research Laboratory (ARL), and ARL's 6.1 funds are to be managed by the new ARO/ARL. Because of the reorganization, ceramic armor research management is also in a state of flux. Dr. Bailey welcomed the opportunity for summarizing existing efforts that the workshop provided. He hoped that the plan envisioned as the outcome of the workshop could result in a Broad Agency Announcement for its implementation.

End Users Perspective

After the introductory remarks, Dr. Douglas Templeton, Dr. Robert Skaggs, and Dr. Stephan Bless provided us with end-users' perspectives on the modeling of ceramic armor. The main points were that (1) computational models exist and are used in design, but they are weakly validated, (2) the cost of build-and-shoot versus a hybrid of build-and-shoot combined with simulations needs to be established, and (3) the emphasis should be on small caliber threats.

Dr. Templeton related that high-level Army officers are demanding ever more rapid implementation of new armor/antiarmor ideas, to the exclusion of ideas that take longer that 24 months to implement. "Virtual Prototyping," i.e., testing armor design prototypes on the computer, is a growing trend. Templeton's desire is to have a virtual prototyping "black box" that would be built around validated models that have been verified against realistic scenarios and correct material properties. In spite of the trend toward virtual prototyping, armor design remains somewhat of a "black art." Templeton praised Dr. Tim Holmquist's efforts to build a database of ceramic material properties results and suggested that ARO could help close gaps where data are lacking or of questionable validity.

Dr. Templeton stated that ceramics are currently of primary interest for protecting against small caliber threats and against the wash of debris that results from "active protection" (e.g., reactive armor) components of an armor system. Some of the small caliber threats are on the order of L/D = 10. Designers currently predict the behavior of ceramics against these threats by using empirical models based on experimental databases.

Dr. Robert Skaggs described how armor designers work. First, they rely on a wealth of experience to estimate design parameter values. Next, they rely on empirically based engineering models to narrow the values. At this point, most designers build prototypes from whatever stock is on hand and shoot them. A very few other designers perform detailed hydrocode simulations, using a continuum model. Skaggs stated that we need to perform a cost/benefit analysis to see whether the build-and-shoot approach is cost effective compared with a hybrid of build-and-shoot and computational simulations. Although a majority of the workshop participants favor the hybrid approach, some in the design community are skeptical of the accuracy of simulations and therefore rely completely on build-and-shoot. Skaggs stated that there is a barrier that we must cross to convince the build-and-shoot style of designers that modeling is worthwhile. Clearly, build-and-shoot conflicts with the "virtual prototyping" approach that Templeton described.

Dr. Stephan Bless reinforced Dr. Templeton's statement that the technology transfer plan should emphasize armor against small arms. According to Bless, small arms are becoming more effective, making current small arms armor obsolete. Bless said that many questions remain unanswered in the small arms ceramic armor area, such as why thick tiles are inefficient and how best to make layers of thin tiles work.

Mr. Werner Riedel offered that, from the end user's standpoint, whatever armor design models emerge from the technology transfer plan, the models must be made accessible to all users by incorporating a user-friendly interface.

Status of Micromechanical Models

Dr. Sunil Dwivedi and Dr. Lalit Chhabildas presented developments in micromechanical modeling of ceramics and concretes. In these micromechanical models, individual material particles are discretized with a finite element mesh, boundaries between the particles are allowed to separate, and contacts between the particles are tracked. Given that each particle contains tens to thousands of elements and there may be thousands of particles, the computing resources needed to process all the elements and keep track of the interactions between the particles is enormous. These models currently are impractical for armor design. However, since these models promise great accuracy and close ties to the underlying material physics, they will be useful for understanding the underlying physics and the connection between the parameters of simpler mesomechanical, continuum, and engineering models.

Dr. Sunil Dwivedi introduced recent Purdue work on micromechanical modeling.[1] This work was prompted by the Purdue multiplane mesomechanical model's lack of a mechanism to model discrete fragmentation. The new micromechanical model is based on the finite element discretization of candidate fragments and the application of cohesion and contact laws between the fragments. The fragments themselves are modeled with the mesomechanical model. Fracture paths are not specified *a priori*, but the minimum fragment size is predetermined by the discretization, and transfragment fracture is disallowed. Dwivedi showed results of simulations of ceramic rod impact tests that predicted fragments. These simulations were necessarily large due to the significant computing resources required. Many of the results required more than a week of CPU time on a workstation.

Dr. Lalit Chhabildas summarized Dr. Marlin Kipp's (SNLA) micromechanical modeling of concrete.[2] Kipp homogenized the cement paste-fine aggregate mixture and then discretized the mixture and the coarse aggregates. He allowed for separation (cracking) throughout. Despite homogenizing the fine aggregate-cement paste mixture, Kipp's plate impact simulations had around ten million elements. Agreement between Kipp's simulations and experimental results was good.

Status of Mesomechanical Models

Dr. Dwivedi's model is partially micromechanical and partially mesomechanical, because the fragments themselves are modeled using the mesomechanical multiplane model. Similarly, Dr. Kipp's model treats the cement paste-fine aggregate mixture by meso- or continuum mechanics. Drs. Curran and Grove presented models that were more directly mesomechanical. Dr. Donald Curran described the FRAGBED mesomechanical model, and Dr. David Grove described the Rajendran-Grove (RG) model.

The FRAGBED model[3] is based on an analogy between fragment motion and dislocation plasticity. By focusing on the holes between the fragments and tracking the size and motion of the holes, the FRAGBED model predicts flow, comminution, and the effects of porosity. Dr. Curran showed the results of two-dimensional axisymmetric penetration simulations of Dr. Bless's long rod penetrations into AD-995 alumina that showed good agreement with the measurements, at least in terms of steady-state penetration velocity. Curran noted that FRAGBED is currently lacking a good way to model the initial fragment bed formation. He noted that the RG model is a good candidate for this task. Curran also noted that FRAGBED has been run against only a narrow selection of experimental data.

Dr. David Grove gave an overview of the RG model.[4] The RG model assumes an initial flaw distribution and tracks the growth of the flaws as a measure of the material damage. Once the material is fully damaged, continued flow is treated by a continuum cap model. Thus, the RG model shares features of mesomechanical models and continuum models. The RG model parameters are obtained by fitting to plate impact and penetration data.

Status of Continuum Models

Continuum hydrocode models are better developed and more widely used than either the micromechanical models or the mesomechanical models. We did not hear a presentation on the most popular continuum model for ceramics, the Johnson-Holmquist model version 2 (JH2).[5] That model has a damage parameter that gradually lowers the yield surface in shear strength versus compressive mean stress space. As is typical of continuum models, the connection between the softening parameters and the actual physical processes in the material is tenuous.

Dr. Charles Anderson presented an overview of SwRI's porting of Wilkins' model for penetration of ceramic tiles from HEMP to CTH.[6] This tensile failure ceramics model is applicable to thin tiles. Anderson reported that the model does a good job at predicting dwell time because it can slow damage development. However, the model is probably not well suited for predicting spall and deep penetration.

Mr. Werner Riedel described an effort to link a continuum model and a mesomechanical model for concrete.[7] By first looking at the simpler case of wave propagation in elastic composites, Mr. Riedel was able to demonstrate how one links the actual particle size distribution to a characteristic length and thence a relevant volume element (RVE) cell size at the continuum level. He also noted how the actual particle size distribution is related to various "rules-of-mixtures" on the continuum level. Riedel described how to introduce nonlinear equation-of-state (EOS) behavior to obtain a Hugoniot mixture law for the continuum that is based on the actual particle size distribution. This method could be used to account for porosity by assigning a null EOS to the pores. Riedel showed how one might use this method to derive the average Hugoniot from the components' properties. One would then understand how changes in individual properties would be expected to change the overall response.

Status of Engineering Models

The engineering models are used solely for penetration predictions and are usually implemented analytically, so they are very fast. They are useful for rapidly evaluating armor designs, assessing armor vulnerability, and antiarmor lethality. With the right parameter values, they can provide very accurate predictions of penetration depth. They could be useful in situations such as war games, weapons selection, and live-fire test and evaluation interpolations where the speed of the engineering models is essential.

Dr. James Walker presented two engineering models.[8] One is suited for deep penetration by long rods and the other for penetration of thin plates. The penetration model of Walker and Anderson for metals produces results that are in good agreement with experimental data and hydrocode calculations. The primary material property needed by the model is the characteristic flow stress of the target metal. This flow stress is typically the flow stress from a uniaxial compression test for somewhere between 20% and 50% strain. Given this material property, the penetration model for metal penetrators impacting metal targets gives answers that are typically within 10% (or better) of experimental values.

The ceramic penetration model of Walker and Anderson for thick ceramic targets uses three material parameters to characterize the target response of the failed ceramic. The first is a low pressure strength, the second the slope of the strength versus pressure line (the Drucker-Prager or Mohr- Coulomb surface), and then a high pressure maximum strength. These numbers define the response regions in the target. The analytic ceramic penetration model has been verified by CTH calculations that use the same failed material response as input. This implies that the Walker-Anderson model correctly captures the important features of the flow fields in the ceramic and the penetrator.

For light or thin ceramic armor, the Walker and Anderson model uses an additional parameter to model the ceramic failure process: the ceramic failure time. This failure time is not a material property, since it depends on impact geometry. Currently this number is calculated for different tile thicknesses using hydrocodes and then interpolated to other tile thicknesses for optimization studies. All the mechanics of ceramic failure are lumped into the failure time. There is a need for understanding which material properties determine this parameter and whether a simple expression relating the properties to the parameter can be found.

In summary, to understand the parameters in the Walker and Anderson penetration model, we need to know the following from the more fundamental material response models:

1. The mechanics of ceramic failure. This failure is currently modeled with a fracture time that depends both on the material properties driving failure and on the geometry of the impact.

2. The failed ceramic response. This response is currently modeled as a bilinear function of the pressure, parameterized by two material properties.

Addressing both these issues entails

1. Finding an expression for or a clear consistent way to determine the fracture time or finding a more detailed and accurate (yet simple) failure model that could be directly used in the analytic engineering models.
2. Finding better material constants for the current constitutive model or better constitutive models that are simple enough to be incorporated into the analytic model framework for the flow field in the ceramic and penetrator.

This work would lead directly to better engineering models. Such models can be verified directly against mesomechanical and continuum hydrocode calculations performed with exactly the same constitutive models. Then such models can be validated against experimental data to determine the accuracy and usefulness for the intended armor application. In this sense, the engineering models can be "certified" for an armor designer. In other words, a high degree of confidence can be provided to the armor designer that the penetration values or perforation/no perforation decision will be within a certain confidence level of being correct.

Dr. Sikhanda Satapathy described an analytical solution for cavity expansion in ceramics that he developed with Dr. Stephan Bless.[9] The model includes elastic, cracked, and comminuted regions around the spherical or cylindrical cavity. The model is more general than other analytical cavity models to date. The model is used to predict the pressure necessary to expand the cavity, and this pressure is used in turn to find the material resistance parameter in a Tate model of penetration. Satapathy's model indicates that the tensile strength of the ceramic and the compressive strength of the intact ceramic have little influence on the pressure for cavity expansion. The model also indicates that either the slope of the pressure/shear frictional response of the comminuted ceramic or the maximum shear strength of the comminuted ceramic are controlling material response depending on their relative magnitudes. The Satapathy and Bless model provides important clues revealing the linkage between continuum model parameters and penetration behavior. The model is of course sensitive to the accuracy of the analogy between cavity expansion and penetration, but the success of the Walker-Anderson model, which uses the cavity expansion analogy to estimate the extent of the flow field, suggests that this analogy is good.

Technology Transfer Planning

Once the presentations on the status of modeling were complete, we began considering how to link the parameters among the different types of models and transfer the models to end users in the armor/antiarmor design community. We outlined the basic framework of the technology transfer program and discussed formation of a steering committee, funding issues, model "certification," and construction of databases of "standard" materials against which to compare the models. The draft plan is given in the Appendix.

The plan includes the formation of a steering committee that acts independently of the interests of individual modelers. The primary purpose of the steering committee is to set the technical approach to be followed by the members of the modeling and experimental community who write proposals as part of the technology transfer effort. The steering committee will also allow dynamic redirection of the plan in response to new needs in the user community, new models, and new experimental data. The steering committee will ensure that the technology transfer remains on schedule and that the output of the effort is useful to the community.

The workshop attendees noted that funding in the area of ceramic armor modeling has decreased to levels that inhibit transfer of modeling results to the user community. They felt, however, that the end user community, once convinced of the value of the models and with cooperation between users in various services and industry, may be willing to fund the plan.

Dr. Stephan Bless mentioned that to "certify" models might be a good way to add value to the effort to link parameters between the models and to calibrate and validate the models against "standard" data. Certified models would be valuable to end users because the accuracy of the models and their ranges of validity would be well documented and would have been judged by the steering committee, independent of the model developer.

We discussed several problems related to the databases of "standard" materials for comparing the models. One problem is that some models depend on parameters that may not be practical to measure. For example, the FRAGBED model contains parameters relating applied loads to stresses on an individual fragment. We must infer these stresses from indirect measurements. Thus, we concluded that a database of standard materials must be based on real, measurable material properties, but must also contain material properties that are simply best estimates obtained from micromechanical modeling, for example.

Another problem with developing standard materials is that installing the same model with the same parameter values into two different hydrocodes may result in two different answers because of different numerical procedures and associated accuracies. One way to avoid this dilemma is to look at how changes in parameter values relate to changes in, say, penetration depth predicted by each model, rather than looking at absolute penetration depth. An alternative, or perhaps a concurrent, approach is one in which several models are implemented within the same numerical test bed (i.e., hydrocode) and then applied to the same set of problems. Rajendran and Grove have demonstrated the value of this approach.

Action Items

Action items resulting from the meeting were (1) for SRI to set up an e-mail discussion group for the plan, (2) for attendees to submit slides or summaries of their presentations to SRI for inclusion in the workshop report, (3) for SRI to write a report summarizing the workshop and presenting the draft plan, and (4) to iterate on the report and plan via e-mail so that it can be presented to ARO and to the end user community for implementation.

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A PLAN FOR THE EFFICIENT TRANSFER OF RECENT CERAMIC ARMOR/ANTIARMOR MODELING TECHNOLOGY TO ARMOR DESIGN

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Donald R. Curran, Sunil Dwivedi, David Grove, Werner Riedel, Sikhanda Satapathy,
S. Robert Skaggs, Douglas Templeton, and James D. Walker

Recent developments in the modeling of ceramic armor promise to increase the speed and reduce the cost of armor design. However, those developments have not reached the end user armor design community. We have designed the following plan to accomplish the technology transfer. The plan is focused on obtaining, in a short time, versions of existing engineering models and continuum hydrocode models that are "certified" to be accurate when compared with a standard set of experimental data. The plan also ensures that the models meet the needs of end users. To keep the plan on track and to redirect the effort as necessary as the transfer progresses, we suggest that a steering committee be formed. We propose that there be little or no new model development work under this plan. We present a draft of the plan in the following.

MANAGING AGENCY

The Army Research Office (ARO) has sponsored much of the development of the models that are the focus of the technology transfer. We suggest that ARO manage the technology transfer effort and oversee the steering committee. However, because ARO's mission is basic science and the technology transfer that we envision is not basic science, we suggest that ARO funds should not be used for the transfer. Instead, ARO should solicit sponsorship from entities that will use the transferred technology. Thus, the program managers and the program sponsors would be different entities.

STEERING COMMITTEE

The steering committee will define the technical approach for implementing the plan and ensure that the approach is followed. The committee will also redirect the approach in response to changes in user needs and model developments. The committee will have at least one representative from the "customer" community, that is, the military Services. In addition, the committee members should be well versed in ceramic armor modeling so that they can knowledgeably coordinate the work by the organizations doing the technology transfer. The committee members will avoid conflicts of interest and the appearance of conflicts of interest insofar as possible. The managing agency should provide guidance on this issue. One possibility is that steering committee members associated with organizations doing the technology transfer should be nonvoting members. The steering committee should have about five members to ensure reasonably broad representation without being unwieldy.

A possible method for forming the steering committee is to use the same method that agencies like the Army Research Office use to form proposal review committees. This method would permit the managing agency to form the committee at its own discretion and avoid a broad formal solicitation.

PLAN OUTLINE

The major tasks in the technology transfer effort are to (1) form the steering committee, (2) ready the models for validation against standard data, (3) develop the database of standard data, (4) iteratively adjust the models until they agree with the standard data and each other, (5) develop user interfaces for the engineering models, (6) certify the models by the steering committee, and (7) document and deliver the results to the Services.

We suggest that the steering committee be five persons chosen by ad hoc agreement between the end user community, the program sponsors, the program managers, and the modeling community. In case of disagreements over who should be on the committee, the program sponsors will make the final decision.

Figure 1 shows the relationships between the micromechanical, mesomechanical, continuum, and engineering models and the standard databases they can be compared against. Note that the micromechanical models cannot currently be used to simulate penetrations. Therefore, there is no direct link between the engineering models and the micromechanical models. Mesomechanical and continuum models are necessary to complete the link. Similarly, there is no way to use the engineering models to simulate anything but penetration experiments. Thus, the other types of models must be used to link the engineering models to experimental data for other, simpler kinds of experiments.

Both the simple lab experiments database and the penetrations database include "pseudo" data. In the case of the simple lab experiments, the pseudo data contains parameters that are impractical to measure and are instead simply best estimates obtained from micromechanical modeling, for example. In the case of penetrations, the pseudo data might be results of highly detailed simulations using mesomechanical or even micromechanical material models.

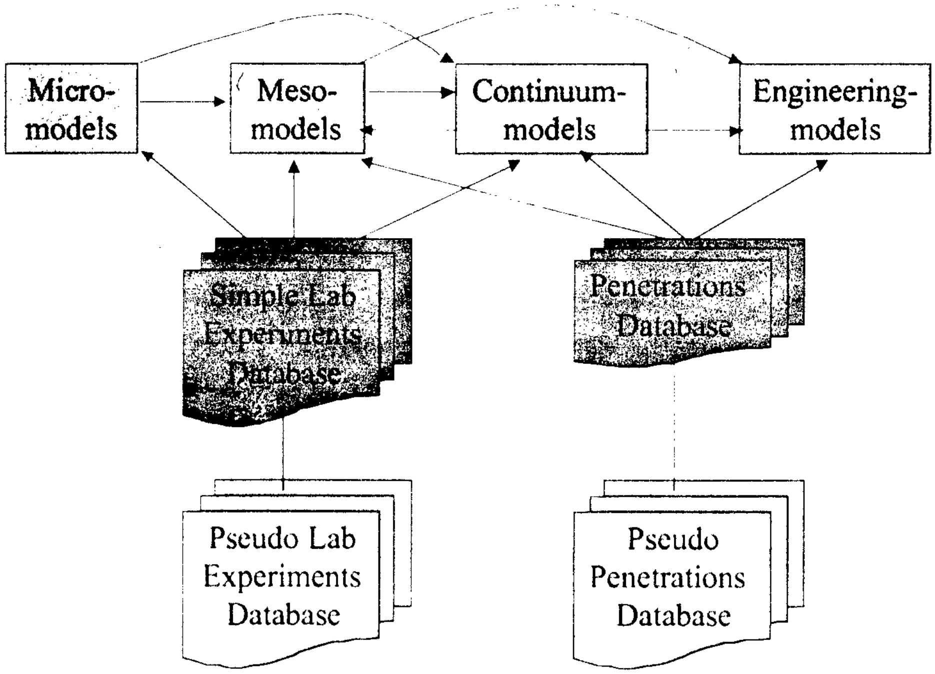

Figure 1. Linkage between the models and databases.

SCHEDULE

We envision that, with careful direction from the steering committee and with focused effort from the modeling community, the six tasks of the technology transfer can be accomplished within 24 months, assuming that reasonable funding is available from the outset.

A significant uncertainty in meeting this schedule is whether the database of standard data can be constructed rapidly enough. Thus, the early part of the technology transfer effort should focus on this task. Once a database of standard data is available for comparing the models, exercising the models against it and varying model parameters to identify trends in ceramic response with material physics should proceed rapidly. We note that TARDEC has just published a ceramic armor material database* that would make an excellent foundation upon which to build the standard database.

Figure 2 shows the schedule for the technology transfer effort. Formation of the steering committee would require 1 month. The committee will meet regularly face-to-face and via e-mail for the duration of the program. The committee will host quarterly program review meetings. At these meetings, program participants will present progress and plans, the steering committee will meet in private to discuss progress and set goals for the next quarter, and then the steering committee will present the goals to the program participants. Development of the database of standard data will require 8 months and will begin as soon as the steering committee is formed and is able to select the contractors who will do the work. In parallel with database formation, the modeling community can ready their models for validation against the data. We estimate that this effort will also require 6-8 months. Once the models are ready, modelers can vary parameters to determine the linkage between models at different levels and the linkage between parameters and the physics. Modelers can also determine parameters that give best agreement with the standard data. These efforts will require 12-15 months. User interface development will require a relatively small effort spread over 15 months, and final certification of the models by the steering committee will require 3 months. Documentation and delivery to the Services will require the final 6 months of the program.

MILESTONES

To ensure that the technology transfer is on track, the steering committee should measure progress against a set of milestones. The program sponsors, program mangers, and the steering committee should define the milestones, but possible milestones are

(1) Formation and funding of the steering committee

(2) Selection of engineering models and continuum models eligible for certification

(3) Selection and funding of micromechanical, mesomechanical, continuum, and engineering modelers to perform the technology transfer

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*T. J. Holmquist, A. M. Rajendran, D. W. Templeton, and K. D. Bishnoi, "A Ceramic Material Database," TARDEC Technical Report, U.S. Army Tank Automotive Research, Development and Engineering Center, Warren, MI (January 1999).

(4) Selection of laboratory test and ballistic test data for the standard database and designation of values for parameters that cannot be measured

(5) Micromechanical, mesomechanical, and continuum modelers match results of simulations of laboratory test data and thereby relate continuum parameters to basic micromechanical parameters

(6) Mesomechanical, continuum, and engineering modelers match results of simulations of ballistic test data and thereby relate micromechanical parameters to engineering model parameters via mesomechanical and continuum parameters

(7) The steering committee evaluates which continuum and engineering models do best against the standard data and thereby merit certification

(8) With input from the contractors, the steering committee documents the certification process and summarizes all results in a final report for delivery to the end users.

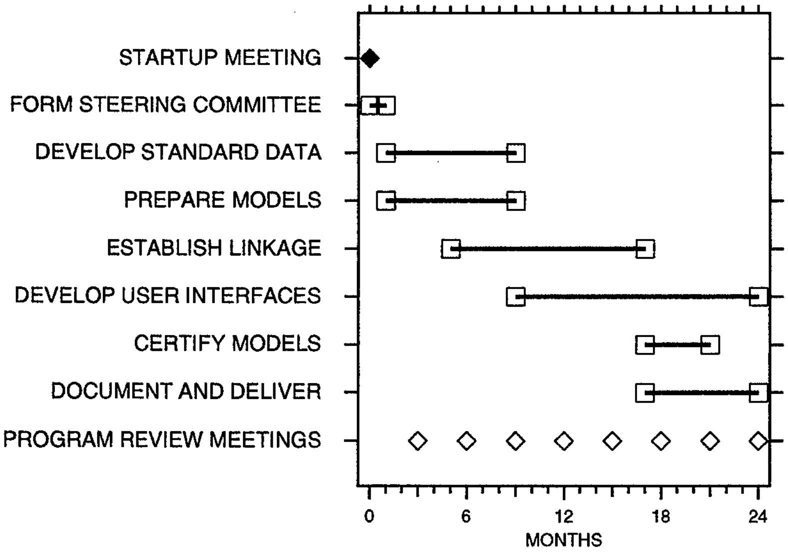

Figure 2. Program schedule.

COST

Because this is a multiple-contractor effort, we estimated the cost per contractor and then multiplied by the number of contractors to obtain totals. The steering committee will involve 5 contractors, developing the standard databases will require 2-4 contractors, and linking the models will require about 10 contractors, since there appear to be about 10 contractors with eligible models.

The cost of the steering committee in work-weeks will be equal to the number of persons on the committee (5) times the number of weeks per year that the committee will work times the number of years in the program (2). We estimate that the steering committee will need to work 5-7 days per quarter, or roughly 4 weeks per year per committee member. Thus, the cost of the steering committee will be 20 work-weeks per year for a total of 40 work-weeks for the program, or roughly $200,000. The steering committee can perform some of its work via the Internet, thereby reducing travel expenses and reporting costs. The costs of the program participants attending the program review meetings will be about 10 persons times 2 weeks per year, or 20 work-weeks per year for a total of 40 for the program, or roughly another $200,000.

The cost to develop a database of standard data will depend on whether new experiments need to be run or whether existing data are sufficient. In either case, the experimental data will need to be supplemented by material properties that are simply fixed or are determined using detailed microphysical modeling. Without experiments, the cost will be approximately 3 work-months per contractor. Two or three contractors would incur this cost. With a few experiments, such as 1/10-scale reverse-ballistics long-rod penetrations with flash x-ray instrumentation, the cost will increase because an additional contractor may be needed. The total cost to develop the database is estimated to be 0.5 to 1 work-year or $125,000 to $250,000.

The cost of bringing the models to a point where they can be compared with the standard database will be something like 2 work-months per contractor. Once the models are ready for application, an additional 1 work-year will be required to iteratively vary parameters until parameter linkage to microphysics is understood and good agreement with the standard data is achieved. Contractors will need an additional 6 work-months to polish user interfaces. Thus, the total cost per contractor for this segment of the work is estimated to be 1.7 work-years or about $420,000. There appear to be about 10 contractors with eligible models, so the total cost is estimated to be $4.2 million.

Finally, each of the 5 steering committee members will require approximately 1.2 work-months ($25,000) to review the performance of the models, certify them, and present the results of the program, for a total of 6 work-months or $125,000.

In summary, the steering committee members are estimated to need $65,000 per member, the database builders are estimated to need $63,000 per contractor, and the modelers are estimated to need $440,000 per contractor. The grand total estimated cost is $5 million.