Engineering Systems for Extreme Environments

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Many of the systems designed at APL must function in extreme environments that require the systems engineer to perform risk assessment and propose risk mitigation strategies early in the concept development phase. This article describes the types of environments that can be classified as extreme and presents several examples of testing and evaluation (T&E) and modeling and simulation (M&S) as risk mitigation strategies. The selected examples in this article show that for extreme environments, gaining the understanding necessary to design reliable systems and then demonstrating that the design is reliable require significant investment in time, money, and resources.

INTRODUCTION

When Ray Bradbury wrote the science fiction novel *The Martian Chronicles*, he didn't complicate the story line by noting that the daily temperature on Mars can vary from −197°F to +86°F. Nor did he mention that the main component of the atmosphere of Mars is carbon dioxide (CO_2). During the Martian winter the poles are in continual darkness and the surface gets so cold that as much as 25% of the atmospheric CO_2 condenses at the polar caps into solid CO_2 (dry ice). Mars is the essence of an extreme environment—arid, rocky, and cold; the Red Planet offers few amenities. Designing a system that must operate on Mars, with its volcanoes, crazy weather patterns, and cold temperatures, represents a clear example of designing for an extreme operational environment.

There are conditions on our own planet, however, that also can be classified as extreme. A concise attempt at defining extreme environments for systems engineering purposes might include environments where there is little *a priori* knowledge about how the system will function under these extreme conditions. Extreme environments in general can typically be categorized as involving abnormally high or excessive exposure to cold, heat, pressure, vacuum, voltage, corrosive chemicals, particle and electromagnetic radiation, vibration, shock, moisture, contamination, or dust, or extreme fluctuations in operating temperature range. These situations are made more extreme when, upon deployment, the system is no longer available for maintenance or repair. An extreme operational environment may also include systems that are time critical, such as a missile sitting in a torpedo tube that must work when called upon. For systems engineers, these extreme conditions do not simply expand the requirements of the system; they also expand the project's scope to include efforts to gain a clear understanding of the environment and its interaction with all of the subsystem components, subsystem interfaces, and materials involved. Readily available test and physical property data for system components and materials are usually limited to more typical environmental conditions, making reliability estimates difficult. In addition, testing equipment and procedures for evaluating the components and materials in extreme environments may be limited or unavailable. Operating in extreme environments places critical constraints on systems engineering efforts to meet critical schedules, achieve reasonable cost objectives, meet system reliability requirements, and manage risk.

Examples of systems engineered at APL to operate in extreme environments include the following:

- **Implantable insulin pump:** APL originally designed and manufactured the first prototype implantable insulin pump in the early 1980s, when implanting electronics into the body represented an extreme environment. Little was known at that time about how various materials and electronic systems would perform in a potentially corrosive environment that is designed to attack foreign bodies. Infections, rejection, inflammation, malfunction, thrombosis (blood clotting), and rampant endothelial production still plague implantable devices today. The damage and traumas often associated with removing faulty devices such as stents and pacemakers do not always allow for easy maintenance.
- **Deep ocean sensing systems:** In support of undersea technology development and national security, APL has deployed many electronic systems on the ocean floor that are subject to corrosive saltwater and extreme pressures. Many of these systems are encapsulated (protected) with the clear expectation that saltwater will eventually penetrate the enclosures.
- **Electronics in rail gun projectiles:** Electronics placed in projectiles to transmit performance data experience accelerations not achievable with most commercial testing systems. The eventual vaporization of the projectile upon impact disallows a postmortem on the electronics for reliability analysis.
- **Interplanetary space missions close to the Sun:** Missions that fly close to our Sun can require heroic measures to shield electronic systems from thermal radiation and electromagnetic interference.
- **Body armor—helmets and bullet-resistant vests:** Improving survivability in a blast and projectile environment also places constraints on systems engineers. Although it is straightforward to evaluate the relative performance of protective vests and to determine whether the bullet or shrapnel penetrated the vest, it is much more difficult to ascertain the effects of the projectile or the blast impact on the soldier who must wear the vest in combat.
- **Microelectromechanical systems (MEMS):** MEMS are built on the scale of micrometers, where bulk physical properties are not valid and viscous forces predominate. Because of scale, MEMS devices are extremely fragile and, like most semiconductor devices, they cannot be repaired. The performance of these devices is also extremely sensitive to the manufacturing processes used to build them.

This article uses examples to illustrate the importance of both testing and simulation for mitigating system risk, assuring system performance, and improving system reliability for operation in extreme environments. The "physics-of-failure" approach to engineering systems is also discussed with regard to its importance in assessing the reliability of systems that must operate in harsh conditions.

STRATEGIES FOR ASSESSING AND MANAGING RISK

Risk is a risky proposition—too much risk in a program is not good, but too little risk could mean no program at all. Risk usually has a payoff, and sponsors are typically unwilling to fund programs without a significant payoff. In fact, APL's prime objective of providing critical contributions to critical challenges invites work that has significant elements of risk. Obviously, real innovation comes with some risk in addition to brains and hard work. Assessing and managing risk is key. For programs operating in extreme environments, identifying and being prepared to address risk at the earliest stages of concept development is imperative. Initial risk assessment exercises may involve identifying weak links in a system vulnerable to the rigors of a harsh environment. These weak links might be identified in brainstorming sessions, in design reviews, or by using checklists made available to the systems engineer that are based on prior systems. Strategies for both risk assessment and managing risk often include a number of complementary approaches, including environmental awareness, system design, testing and evaluation (T&E), and modeling and simulation (M&S).

System Design as a Risk Mitigation Strategy

Improving system design by adding additional components to protect against harsh environmental conditions is a common risk mitigation strategy. Adding components that compensate for the environment is typically not free, and such additions are subject to the usual design constraints of cost, dimensions, schedule, and resource availability. Spacecraft command and control systems typically have redundancy built into them as a hedge against unforeseen or random failures. Spacecraft electronics are often protected from the cold of deep space through the use of thermal blankets and onboard heaters. Both of these solutions come with an increase in power and weight. The increases in power and weight can often result in a reduction in the mission's scope.

Accelerated Testing

Typical factors that can accelerate the decline in the function of a device are temperature, voltage, mechanical load, thermal cycling, humidity, and vibration. Degradation mechanisms include fatigue, creep, cracking, wear, radiation, and corrosion/oxidation. Accelerated testing can be conducted on materials and components as well as at the system or subsystem level. The purpose of such testing is to estimate the useful life of critical components and subsystems. The assumption is that the failure mechanisms during tests using high or accelerated loading rates are similar to those from testing longer at normal rates. The problem with this assumption is that it is often untrue, and it may be even less true for extreme temperature or stress limits. For example, solder joint cracking, a common failure in electronic assemblies, may exhibit one failure mode (fatigue) when cycling between −55°C and room temperature and another failure mode (creep) when cycling between room temperature and +125°C. Also, the cycle frequency can be an important factor in determining the number of cycles to failure. Cycling at higher frequencies often increases the number of cycles to failure. In practice, it is desirable to maintain short dwell times for accelerating the testing; however, dwell time may become a significant degradation mechanism at higher temperatures because of creep. For testing soldered joints, extended dwell times and low-frequency testing are usually required, even at the expense of longer test durations. Despite some of these shortcomings, with some caveats, accelerated testing can be a useful strategy if the accelerated life tests are conducted properly and the proper conclusions are drawn from them.

Material Characterization

Selecting materials for use in extreme environments can be a determining factor in whether the system will operate as designed over its required service life. Material considerations that are important when designing for extreme environmental conditions include elastic modulus, coefficient of thermal expansion (CTE), yield strength, resistance to creep and fatigue, and thermal conductivity; all of these properties are dependent on temperature. Also important are the glass transition temperature (T_g) and decomposition temperature for plastics and the ductility and electronegativity (corrosion/oxidation potential) for metals. Having access to material data over a broad temperature range, or having access to the testing equipment necessary to measure these physical properties, can improve the reliability of a system by facilitating the judicious choice of component materials and the proper design of interfaces. For example, wide temperature excursions may require that materials joined by solder have relatively compatible CTEs. Flexible epoxies may be a better choice than rigid ones for bonding materials with differing CTEs, such as aluminum heat sinks to printed wiring boards. Material characterization also can provide data needed for M&S purposes. Thorough material characterization is essential to improving component and subsystem reliability, particularly for extreme environments.

M&S as a Risk Assessment and Risk Mitigation Strategy

When the system development schedule is compressed and the environment is sufficiently extreme, accelerated testing may not be an option, and M&S is almost a requirement, particularly for assessing and mitigating system risk. A wide variety of M&S methods are used in systems analysis. This article is concerned primarily with the effect of the environment on the survivability of the system, rather than an effort to simulate the system's function for target detection, acquisition, tracking, etc. Various simulation strategies are available, depending upon the availability of accurate physical models and physical property data. With the ever-increasing computational capacity of modern computers, numerical simulations using finite element-based multiphysics models (physics involving coupled field variables such as electric, magnetic, strain, etc.) are becoming quite common. Analytical models are preferable when available but are usually quite limited in scope and applicability, particularly for extreme environments, mostly because physical constants are highly variable with respect to temperature or some other field variable. When models are accurate but model parameters vary because of inherent randomness, Monte Carlo simulation is a useful simulation technique. Sensitivity analysis is often required to evaluate system performance when manufacturing processes are difficult to control.

The Physics-of-Failure Method

The physics-of-failure method[1] is a science-based approach that uses modeling and simulation to design in reliability. This approach models the root causes of failure, such as fatigue, fracture, wear, radiation, or corrosion. Computer-aided design (CAD) tools have been developed to address various failure mechanisms. An example of a failure mechanism is the fatigue cracking of solder joints used in electronic assemblies. The goals of the physics-of-failure approach include reducing the testing burden, improving the understanding of useful life, increasing fielded reliability, and decreasing operations and support costs. The physics-of-failure approach involves the following:

- Identifying potential failure mechanisms (chemical, electrical, physical, mechanical, structural, or thermal processes leading to failure), failure sites, and failure modes.
- Identifying the appropriate failure models and their input parameters, including those associated with material characteristics, damage properties, manufacturing flaws and defects, and environmental and operating loads.
- Determining the variability for each design parameter when possible.
- Computing the effective reliability function (e.g., Weibull function). Note that a significant amount of testing is typically required for computing such a reliability function, and in many cases a simpler "go–no-go" test may be preferred. However, many existing reliability functions for electronic systems are available in the literature.
- Accepting the design, if the estimated time-dependent reliability function meets or exceeds the required value over the required time period.

The most common simulation techniques for physics-of-failure modeling in electronic systems include finite element calculation of temperature, stresses/strains, random shock, vibration, buckling, thermal stress, creep, fatigue, mass transport, and electrochemical reaction rates. Statistical methods using Monte Carlo simulations and Arrhenius-based models are also commonly used.

RISK MITIGATION PLANNING

System Design

Establishing alternative system design options represents one method of risk reduction planning. This exercise is usually done early, as various design strategies are considered before selection of what may be considered the most attractive solution, i.e., the solution having the lowest scope and budget while avoiding substantial impact on the objectives of the program. A fallback position or "plan B" is usually pursued in high-risk situations, but there is typically a cost associated with pursuing multiple paths or options. In many extreme environments such as deep space, failure is so costly that it may be prudent to entertain multiple design options. These design options will likely require additional T&E or M&S to prove their reliability. The system design plan must incorporate all of these fallback options so that their impact can be accurately reflected in the cost proposal.

One pitfall to be aware of when designing the system is to watch for a critical element on which the entire design may depend. If this element poses some risk, the fallback position would necessitate an entire redesign. For example, quite often in electronic packaging of spacecraft electronics, the choice of a connector will determine the arrangement of boards in a chassis, the size of the boards, and even the chassis configuration itself. If the connector proves to be unreliable and there is no equivalent fallback connector, the entire chassis and the electronic subassemblies would have to be redesigned and possibly remanufactured. Such design dependencies or "linchpins" should be avoided if possible to reduce system risk.

Modeling and Simulation

As with testing, M&S-based risk reduction requires systematic planning. Often it is assumed that system, subsystem, and reliability engineers have all the tools and data necessary for the simulations. When designing for extreme environments, situations arise where the data simply are not available (e.g., body organ physical properties). For extreme environments, anisotropic and nonlinear material properties are the norm, requiring iterative numerical techniques that can consume vast amounts of computer time and resources.

The systems engineer should develop a checklist of questions to consider before choosing to rely on M&S to validate the system design. These questions might include the following:

- Are the simulation models required to validate system reliability readily available?
- Are the necessary analyst resources available when required?
- Are material properties available for simulation? If not, is the testing required to obtain them within the scope of the cost proposal?
- Are adequate computer resources (workstations, blade servers, mainframes, etc.) available to execute the models?
- Are the numerical tools in place to simulate complex models?
- Is the purchase of necessary simulation tools or services within the scope of the cost proposal?
- Are well-established analytical models applicable to the extreme environment?
- Can the simulation results be validated?

If the answer to one or more of these questions is "no," then the best approach may be to validate the design through testing. This decision needs to be made before the cost proposal is submitted.

Because it is difficult to model and simulate a system operating in a complex environment, it is sometimes necessary to combine M&S with testing. In this case, a good model or simulation should guide testing and also help interpret test results.

Testing and Evaluation

All sufficiently complex systems require a T&E plan. These plans are often formulated late in the concept development phase. For systems that must operate in extreme environments, the T&E plans will likely be more extensive and may result in a significant portion of the system development costs. As a result, the tests need to be well thought out and specified concurrently with concept development activities so that they are clearly detailed in the cost proposal.

The T&E process usually begins with a T&E master plan that describes the goals of the plan and lists features of the system that will be included in the test as well as features that will not be included. This is followed by a list of the testing methodologies to be employed and a detailed description of the purpose of each test and associated testing procedure. It is important to structure the test in such a way that the results are unambiguous and satisfy the primary reasons for conducting the test. Data evaluation techniques (performance, regression, etc.) for subsystem, component, and interface testing should be clearly defined in this portion of the testing plan. Details of the testing plan may include fabrication of test articles, procurement of special testing equipment or testing services, or any other items that must be addressed before testing. Also for purposes of cost control, an exit criterion should be established for each test item, i.e., a definition of when enough data have been collected to meet system requirements. The plan should also include resource requirements such as test engineers, software and hardware necessary for testing, and special tools and procedures. Finally, scheduling tests and resources is essential to ensure that test results are available well before the integration or delivery phases.

It is important to emphasize the link between T&E and M&S. We stated previously that M&S results should guide testing, but the reverse is also true: good test data should be used to refine models and simulations. This is often an iterative process requiring several M&S and T&E cycles to refine system models.

MARS SCIENCE LABORATORY ROVER ACTUATOR ELECTRONICS

An example of the application of an early risk mitigation strategy for an extreme environment can be found in the Jet Propulsion Laboratory (JPL) Mars Science Laboratory (MSL) program. This space mission to Mars features a rover vehicle that will assess whether Mars ever was, or is still today, an environment able to support life. The rover is illustrated in Fig. 1. It was designed with a heated compartment to protect its computer and most of the electronics from the extreme Martian temperatures. The rover has an arm that maneuvers several instruments close to the Martian soil. The electronics used for actuation of the motors on the arm and the wheels are chip-on-board assemblies (i.e., printed wiring boards with "unpackaged" integrated circuits); they are located far from the heated body and must operate at temperatures ranging from −127°C to +30°C, the maximum daily temperature variation on Mars.

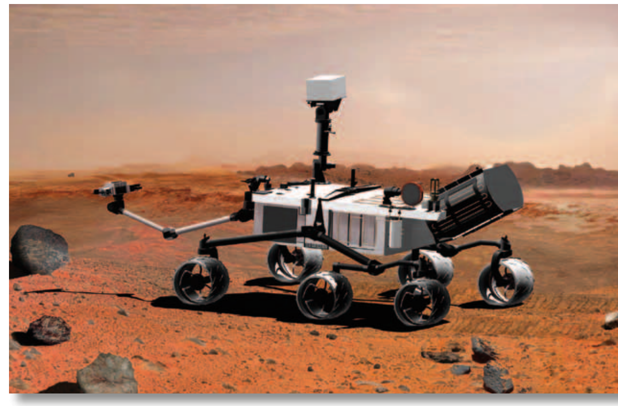


Figure 1. The MSL rover. (Source: NASA/JPL-Caltech.)

One of JPL's main reliability concerns involved the unpackaged actuator electronics. JPL systems engineers realized that the materials (glob-top encapsulants) protecting the integrated circuit devices and bond wires from handling during the pre-launch phase of the mission may be susceptible to failure due to the extreme temperature variations on the Martian surface. JPL program managers sought the assistance of APL because of its wide experience in material characterization and environmental testing. APL's desire to use a physics-of-failure approach to addressing the extreme environment on Mars led to a further collaboration with the University of Maryland's Center for Advanced Life Cycle Engineering (CALCE). APL assisted JPL in determining suitable materials and packaging strategies and provided critical material characterization, accelerated testing, and finite element thermomechanical simulation services. CALCE developed generic analytical models for reliability simulations. Table 1 is a sample checklist for evaluating potential failure sites by using the physics-of-failure methodology.

Testing and Simulation Plan

Three primary objectives were outlined in APL's testing and simulation plan for the Mars Rover actuator electronics:

1. Design and manufacture representative test coupons for thermal cycling over the extended temperature range. Perform an initial test with various substrate materials, glob tops, and encapsulants. From the initial sample, identify the best combination of substrate, die adhesive, and glob top. Follow this up with a thermal cycling test with additional samples to ascertain the reliability of the chosen system.
2. Perform a material characterization study to evaluate the Young's modulus, T_g, CTE, and the yield

strength as a function of the anticipated temperature range.

3. Develop analytical and finite element models (FEMs) to simulate the mechanical reliability of the actuator electronics in the Martian environment.

Temperature Cycling Testing Plan

Before designing the temperature cycling testing plan, all potential failure sites were identified using the physics-of-failure methodology. Care was taken to make sure that the test would properly stress all of the critical failure points:

- Substrate fracture
- Substrate bond pad lifting
- Wire breakage, wire thinning, and ball shear
- Adhesive failure at the die/substrate interface
- Encapsulation cracking

The goal of this plan was to determine whether representative test coupons made using a matrix of material configurations would yield one or more combinations that could withstand the Martian environment for the duration of the mission. The temperature range was extended somewhat (from −127°C to +80°C) to accelerate failures. Wire bond, substrate, and die integrity were monitored *in situ* using specially designed test coupons. Test specimens that failed before test completion were removed and inspected using X-ray tomography. An endpoint was set for the test, after which the surviving units were X-ray inspected for signs of excessive wear.

The test initiation phase began with the construction of extended-range temperature cycling chambers that could handle the extreme temperatures encountered during the proposed test. Also, test coupons mimicking the chip-on-board assemblies used in the actuator electronics were constructed using numerous combinations of substrates, die-attach adhesives, and glob-top encapsulants. A silicon test die and various test substrates were fabricated in APL's microelectronics facility. Test substrates are illustrated in Fig. 2. The silicon test die included a daisy-chained bond pad arrangement and fine aluminum meander lines on the silicon to mimic either wire bond breakage or stress-related fracture of

Table 1. Sample checklist for a physics-of-failure approach to identifying potential risk in system components.

Failure Mechanisms	Physical and Environmental Factors	Root Causes of Failure: Performance	Fatigue	Wear	Corrosion	Fracture
Chemical	Particle radiation					
	Outgassing					
	Moisture					
	Salt spray					
	Chemical environment					
	Mold and mildew					
	Intermetallic formation				X	
Physical	Material properties					
Structural	Manufacturing defects					
	Dimensions					
Electrical (includes electrostatic, magnetostatic, and electromagnetic effects)	Static electric field (i.e., ESD)					
	Static magnetic field					
	Electromagnetic radiation (EMI)					
	Corona					
	Electro-migration					
	Eddy current heating					
	Joule heating					
Mechanical	Vibration					
	Acceleration					
	Static loading					
	Dynamic loading					
	Impact					
	Handling					X
Thermal	Temperature range	X	X			
	Temperature loads					
	Material phase change					

Subsystem: Mars actuator electronics; **component:** glob-top encapsulated integrated circuits; **failure site:** wire bonds.

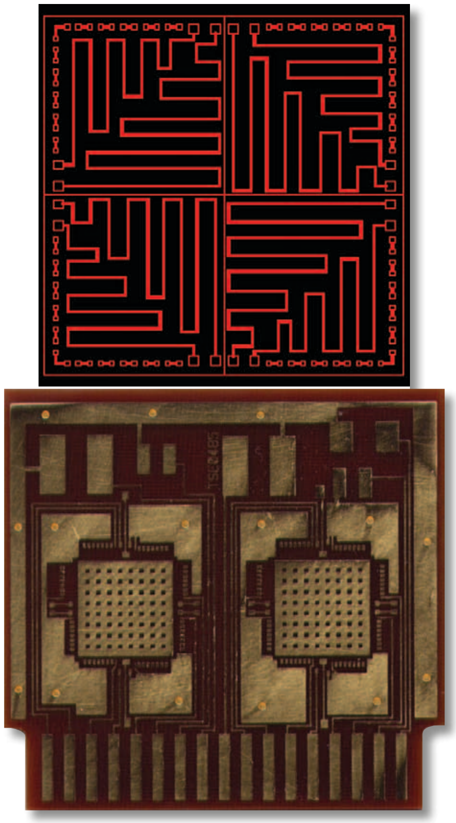


Figure 2. Test coupons for evaluation of glob-top materials: a silicon test die with meander lines and daisy chains (upper) and a polyimide printed wiring board test coupon for two silicon chips (lower).

the silicon during cyclic temperature loading. Four substrate types were used to interconnect two of the silicon test coupons: alumina (99% Al_2O_3), thick film (96% Al_2O_3), low-temperature cofired ceramic (LTCC), and a polyimide printed wiring board. Five die adhesive materials and three glob-top materials were evaluated.

The three failure modes observed after testing are shown in Fig. 3. All failures were either wire failures or substrate pad lifting failures. No case showed any indication of silicon fracture or delamination of the silicon at the substrate interface. Test results are shown in Table 2.[2] The shaded cells indicate that no wire bond or pad lifting failure occurred. Based on the testing, the combination of the polyimide substrate, the 84-1 die attach adhesive, and the 4402 glob top was selected.

As a part of the original plan, additional test coupons were constructed and subjected to a life test that was performed for a period of more than one calendar year with a daily temperature cycle between −125°C and +80°C without a failure. Performing an environmental test without using an acceleration factor is a bit unorthodox, but the lack of sufficient existing reliability data over this extended temperature range and the cost associated with failure made the duration of this test a prudent measure.

Material Characterization

APL, with its affiliation with The Johns Hopkins University and access to a wide array of material characterization tools and expertise, is uniquely suited to address the extreme environments on the Martian surface. The goal of the Mars Rover material characterization study was to measure the CTE, Young's modulus, and yield strength as a function of temperature for a variety of materials. Four testing methods were used for these tests:

1. The dynamic mechanical analysis technique (DMA) determines the complex modulus E^* from oscillatory measurements of load and displacement and is given by the equation

$$E^* = |E^*|e^{i\delta} = E' + iE'',\ \tan\delta = \frac{E''}{E'}\ , \qquad (1)$$

where E' is the Young's modulus, E'' is the loss modulus (unrecoverable viscous effects), and δ is the phase lag between applied strain and resultant stress and is a measure of damping. The glass transition temperature T_g is the peak in the tan δ curve. The DMA testing method is particularly well suited to flexible materials such as silicone glob-top encapsulants and the flexible conductive die attach adhesives.

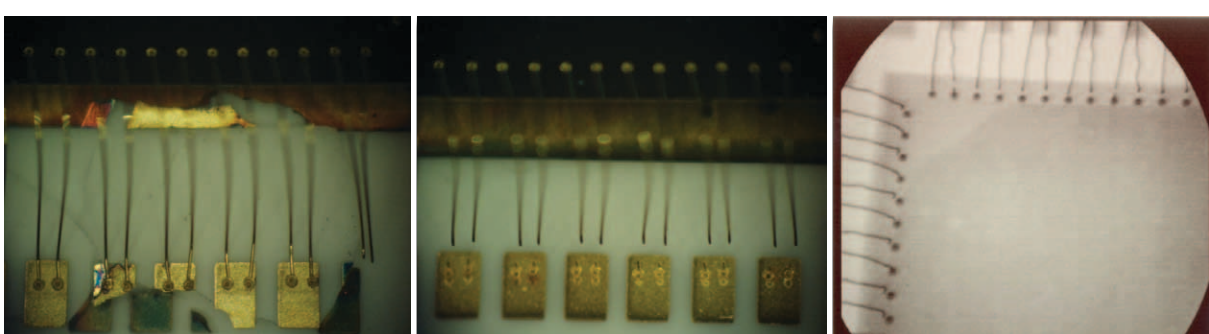


Figure 3. Wire-bond failure modes for temperature-cycled test coupons: pad lifting on a 99% alumina substrate (left), wire breakage at wedge bonds (center), and wire breakage near the ball bond (right).

Table 2. Results of initial thermal cycling test for Mars Lander actuator test coupons.

Die-Attach Adhesive	Glob-Top Encapsulant Failures (%)															
	None (Control)				Hysol 4402				Hysol 4450				Hipec Q1-4939			
	Polyimide	LTCC	99% Al_2O_3	96% Al_2O_3	Polyimide	LTCC	99% Al_2O_3	96% Al_2O_3	Polyimide	LTCC	99% Al_2O_3	96% Al_2O_3	Polyimide	LTCC	99% Al_2O_3	96% Al_2O_3
84-1	0	0	25	25	0	0	100	100	0	25	100	100	0	0	25	25
ZVR 6000.2	25	0	0	25	25	0	100	100	50	25	100	100	0	50	0	25
TC-601.1	0	25	25	0	0	0	75	100	0	0	100	100	0	25	0	25
967-1	25	0	25	25	0	0	50	100	0	0	100	100	25	100	50	50
AI 8414	0	0	0	0	0	0	100	75	25	50	100	100	0	75	25	25

Shaded boxes represent samples that exhibited no failures after completion of the test.

2. The uniaxial tensile testing apparatus is used for obtaining yield strength for the rigid epoxies and encapsulants.
3. The interferometric strain/displacement gage (ISDG) method developed by Dr. William Sharpe at The Johns Hopkins University (Fox et al.[2]) was assembled at APL for measuring millimeter- and micrometer-scale materials in cases where bulk properties are not valid.
4. A flat-plate dilatometer was used to measure the CTE of candidate materials as a function of temperature.

Sample test data from the MSL material characterization study are given in Fig. 4.

MSL Rover Actuator Electronics M&S

Optimized Wire Bond Analytical Model

In keeping with the physics-of-failure approach, analytical models are preferred to numerical ones when appropriate, and these solutions often can be employed for an entire class of situations. Numerous physics-of-failure analytical models have been developed in recent years to address the common failure mechanisms of electronic interconnections.

It is well known that a structural system in equilibrium with specified geometry, loads, and support conditions will deform in such a manner as to naturally minimize its strain energy. Here we attempted to optimize the shape of a wire bond by minimizing its strain energy. We used the principle that the lower the initial strain energy, the more likely it is that the wire bond can sustain deformations without a loss in structural integrity. The approach taken here was to develop an optimized wire bond shape that was the least susceptible to strains caused by deflections in the glob-top material.

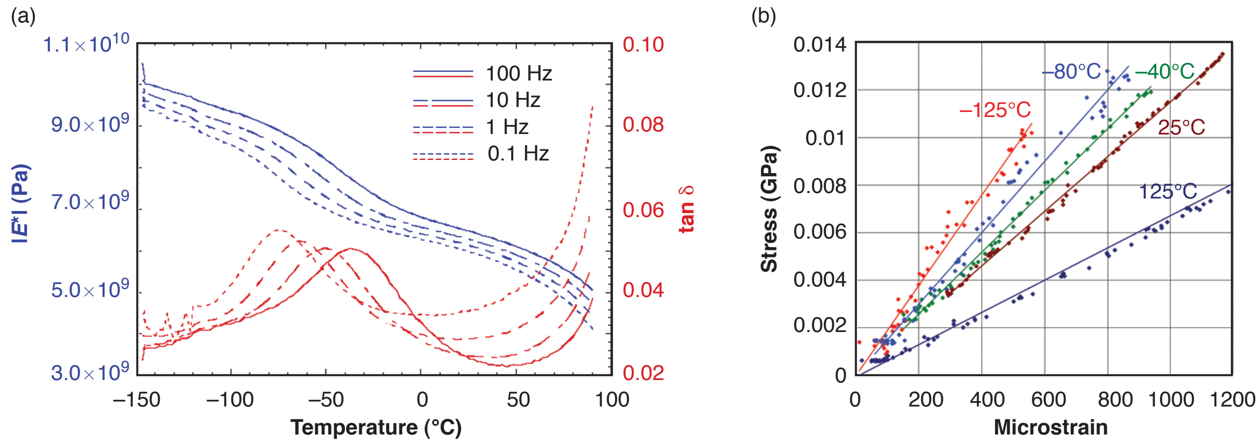
The wire bond was represented by two cubic splines and then the strain energy minimized using a strain-energy minimization method.[3] The model was parameterized to represent the continuity and boundary conditions at the wire ends; it is illustrated in Fig. 5. The two curves are represented by x and y as a function of the dimensionless spline variables u $[x = 0, x = d]$ for curve 1 and the interval v $[x = d, x = D]$ for curve 2. From Fig. 5, the two cubic spline curves are given by[4]

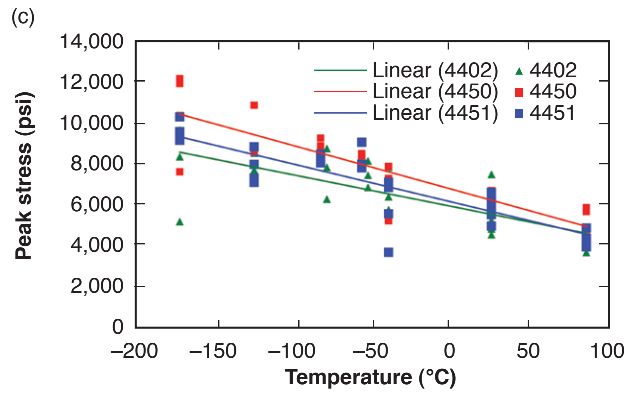
Curve 1:

$$y_1(u) = uh - uh(1-u)^2 - (d\theta - h)u^2(1-u)$$
$$x_1(u) = ud$$

Curve 2:

$$y_2(v) = (1-v)h + vH + [(D-d)\theta - (H-h)]v(1-v)^2$$
$$x_2(v) = (1-v)d + vD + (D-d)v^2(1-v) ,$$





(d)

Sample	CTE below T_g (µm/m per °C)	CTE above T_g (µm/m per °C)	T_g (°C)
A	16.4	78.4	166
B	11.7	78.4	167
C	90.0	512.7	–117
D	84.7	134.9	140
E	55.8	156.6	161

Figure 4. Samples of material characterization data for flexible glob-top encapsulants. (a) DMA complex modulus data. (b) ISDG stress–strain data (Young's modulus). (c) Yield strength data. (d) CTE data.

where (d,h) is the point where the two cubic splines meet, θ is the slope at (d,h), D is the span of the wire bond, and H is the height difference (or chip height) between the wedge bond and the ball bond.

The potential energy of the system can be expressed as the sum of the bending energy in both splines.

$$\Pi = \frac{EI}{2}\int_0^d \kappa_1(x_1)^2\,dx_1 + \frac{EI}{2}\int_d^D \kappa_2(x_2)^2\,dx_2\,, \quad (2)$$

where κ_1 and κ_2 are the curvatures of the two splines; E is the Young's modulus, and I is the moment of inertia of the wire cross-section. The curvature of each spline is given by the equation

$$\kappa = \frac{y''}{(1+y'^2)^{\frac{3}{2}}}\,. \quad (3)$$

By minimizing the potential energy with respect to both adjustable parameters d and h,

$$\frac{\delta\Pi}{\delta d} = 0 \text{ and } \frac{\delta\Pi}{\delta h} = 0\,,$$

two nonlinear equations are obtained from which the optimal values d and h can be obtained. Figure 6 is a plot of the optimal loop height versus wire span. The optimal wire bond design was used for the long-duration test coupons.

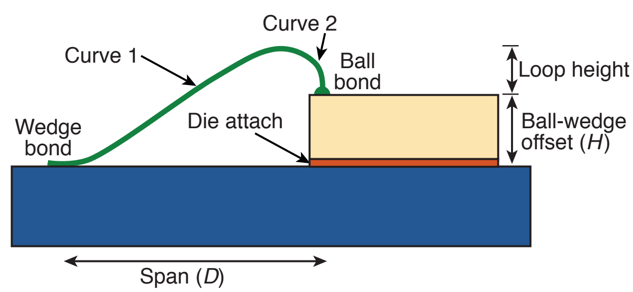


Figure 5. Two-cubic-spline model of a bond wire.

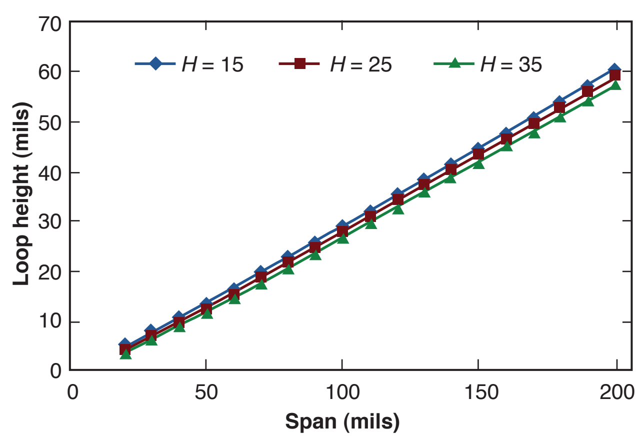


Figure 6. Optimum loop height versus wire span for different chip heights.[4]

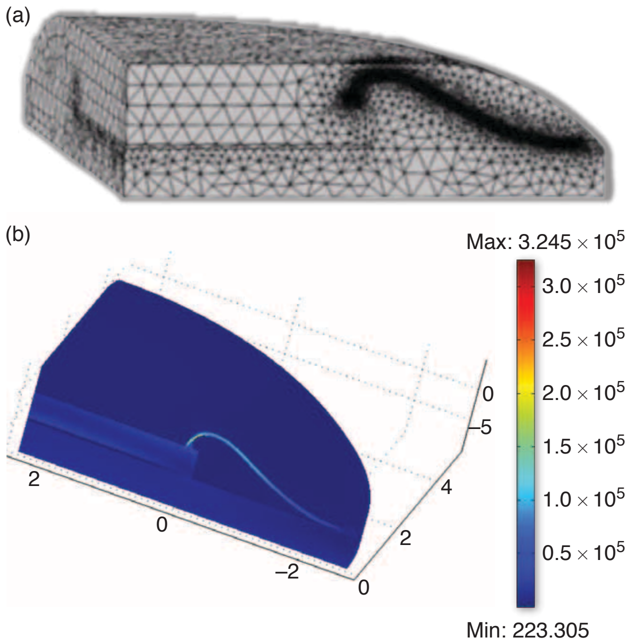


Figure 7. FEM of encapsulated wire bond (a) and von Mises stress contour plot (b).

FEM Simulations of Glob-Topped Integrated Circuit

Although it was once true that use of finite element or boundary element methods to parametrically represent physical models was impractical, increased computer power, improved solids modeling capability, and adaptive-meshing techniques have significantly reduced the time required for parametric modeling. Finite element and boundary element techniques also facilitate the use of nonlinear, time-dependent, and temperature-dependent analysis methods.

An example of an FEM used to analyze an encapsulated 2-mil gold wire bond for the Mars Rover actuator electronics is shown in Fig. 7. The nonlinear FEM was a one-quarter symmetric model and simulated the stresses resulting from a wire-bonded chip cooled from the cure temperature (150°C) down to −125°C. A coupled thermo-mechanical finite element analysis with temperature-dependent material properties was used. The analysis confirmed that the glob-top encapsulant chosen for the actuator electronics would not produce an overstressed condition in the assembly, confirming the results of the thermal cycling tests. As a consequence of the good correlation between the T&E and M&S results produced on this program, long periods of expensive testing can be replaced with relatively inexpensive short-duration simulations for future Martian missions.

TESTING AND SIMULATION IN A PROJECTILE AND BLAST ENVIRONMENT

Human Surrogate Torso for T&E of Body Armor

Another example of system design for extreme environments involves the development of body armor to protect soldiers, particularly those fighting limited-scale police actions. APL's Human Surrogate Torso Project [funded by Defense Advanced Research Projects Agency (DARPA)] is an effort to develop an instrumented T&E platform for evaluating the effectiveness of various body armors in protecting against blast and projectile impacts and for providing critical feedback to M&S efforts to predict these effects in a wider range of scenarios. The T&E and M&S plan for the program is shown schematically in Fig. 8.

The long-term objective is to assess techniques that aid in predicting human injury due to nonpenetrating ballistic impact and blast. This includes computational and experimental model development, high-rate tissue testing, and correlation of physiological injury with mechanical or engineering parameters. Nonpenetrating ballistic impact and blast were studied with a focus

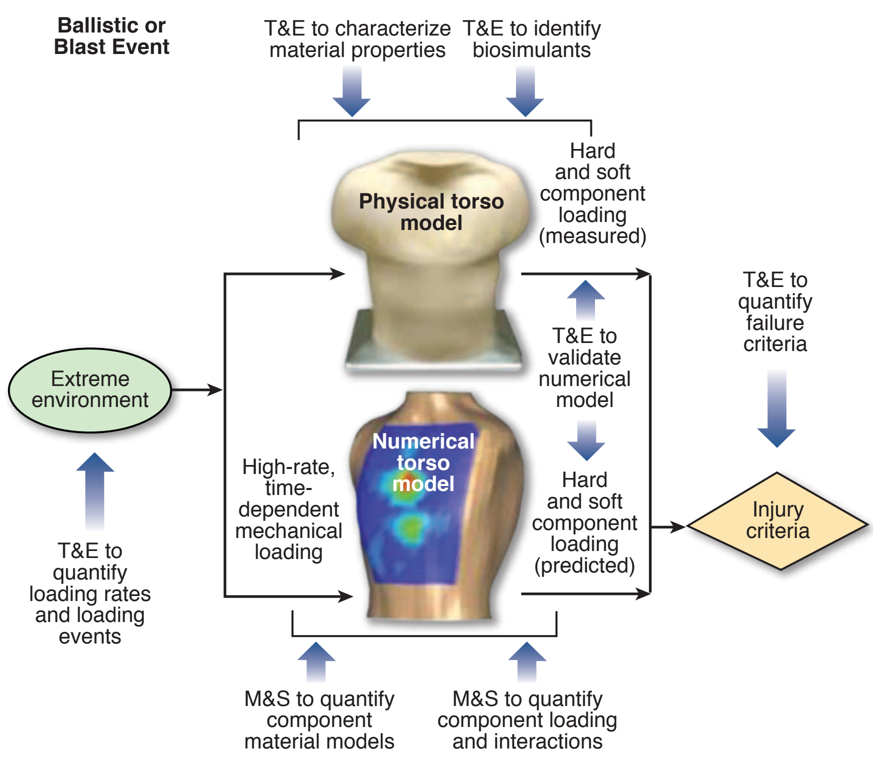


Figure 8. Schematic of T&E and M&S for the DARPA Human Surrogate Torso Project.

on the torso because of the frequency of impact in that region and the potential for damage to vital organs. Nonpenetrating events may occur when either the projectiles themselves are "nonpenetrating" (less lethal) munitions that hit an individual, or when an individual is outfitted with an armor vest that defeats the ballistic round or shrapnel during impact. Both scenarios can lead to significant injury, including behind-armor blunt trauma (BABT). The battlefield represents an extreme environment. Evaluating body armor systems in the real environment requires the examination after the fact of hundreds of persons injured or killed. The human torso model gives designers a T&E vehicle for new and future body armor designs. We hope that correlations with simulation data from finite element studies will provide an M&S approach to evaluating future body armor systems.

Experimental Surrogates—Physical Torso Model

As in the case of the Mars Rover actuator electronics, a test article was needed for the T&E of body armor systems. For nonpenetrating ballistic impact studies, APL developed a physical human surrogate torso model of a 50th-percentile human male including the skeleton, heart, lungs, liver, stomach, and intestines, which is shown in Fig. 9 along with a picture of the computer solid model. The simulated bones were fabricated to have the tensile and fracture properties of human cancellous bone,[5] and the organs were formulated of silicone gel. Microspheres were added to the silicone gel to represent the lungs. A gas-filled mass was added to the intestines with variable states of pressurization to represent this portion of the human torso. Piezoresistive pressure sensors were placed in the heart, liver, stomach, and intestines, and an accelerometer was mounted to the back of the sternum. The human surrogate torso model was tested under nonpenetrating ballistic impact and blast conditions. The results were later compared to an FEM of an identical-scale torso model.

Figure 9. Computer solid model (left) and actual human surrogate torso model (right).

Material Characterization

To create a detailed, accurate FEM of the human torso, the material properties must be properly characterized; in this case, the relevant viscoelastic properties need to be determined for soft tissues. Similarly, the development of a surrogate experimental human torso required the use of biosimulants (molded soft-plastic organs, etc.) with properties similar to those of human tissue. However, the properties needed to be determined in the relevant strain-rate range seen for tissue during a ballistic impact or blast event: between 10^1 s^{-1} and 10^3 s^{-1}. Characterization of materials at these high strain rates required testing equipment different from the standard techniques used in the MSL study described above.

Higher-rate testing has been performed using modifications to a split-Hopkinson bar[6,7] testing technique. The modifications allow the use of a compression cell for measuring bulk modulus and a double-lap shear fixture for measuring the dynamic shear modulus of human tissue and other soft polymers under high-strain-rate conditions.[8] The shear modulus for human heart, lungs, liver, and stomach were measured using this modified split-Hopkinson bar technique at strain rates from 200 s^{-1} to 2300 s^{-1} (see Ref. 9). Characteristic shear stress–strain data used to estimate the shear modulus in the material FEM is given in Fig. 10. Much of the variation in the data in Fig. 10 results from the variability in human tissue samples, sample orientation during testing (all human tissue is anisotropic), and less-than-optimal loading while testing. Future tissue testing is expected to address some of the variability in test data.

Dynamic Simulation of Blast and Projectile Impact

M&S of Human Torso

Human surrogate and simulation models can be exercised repeatedly with reproducible results and can be used to study a variety of impact conditions. This section concentrates principally on dynamic time-dependent computational models, specifically FEM of the human torso.

A number of torso models have been developed for investigation into the thoracic response to ballistic impact. Considerable variation between the initial FEM results and the instrumented physical torso model test data was attributed to anatomy, material property representations, meshing, the contact algorithms in the FEM, and the time and frequency response in the instrumentation.

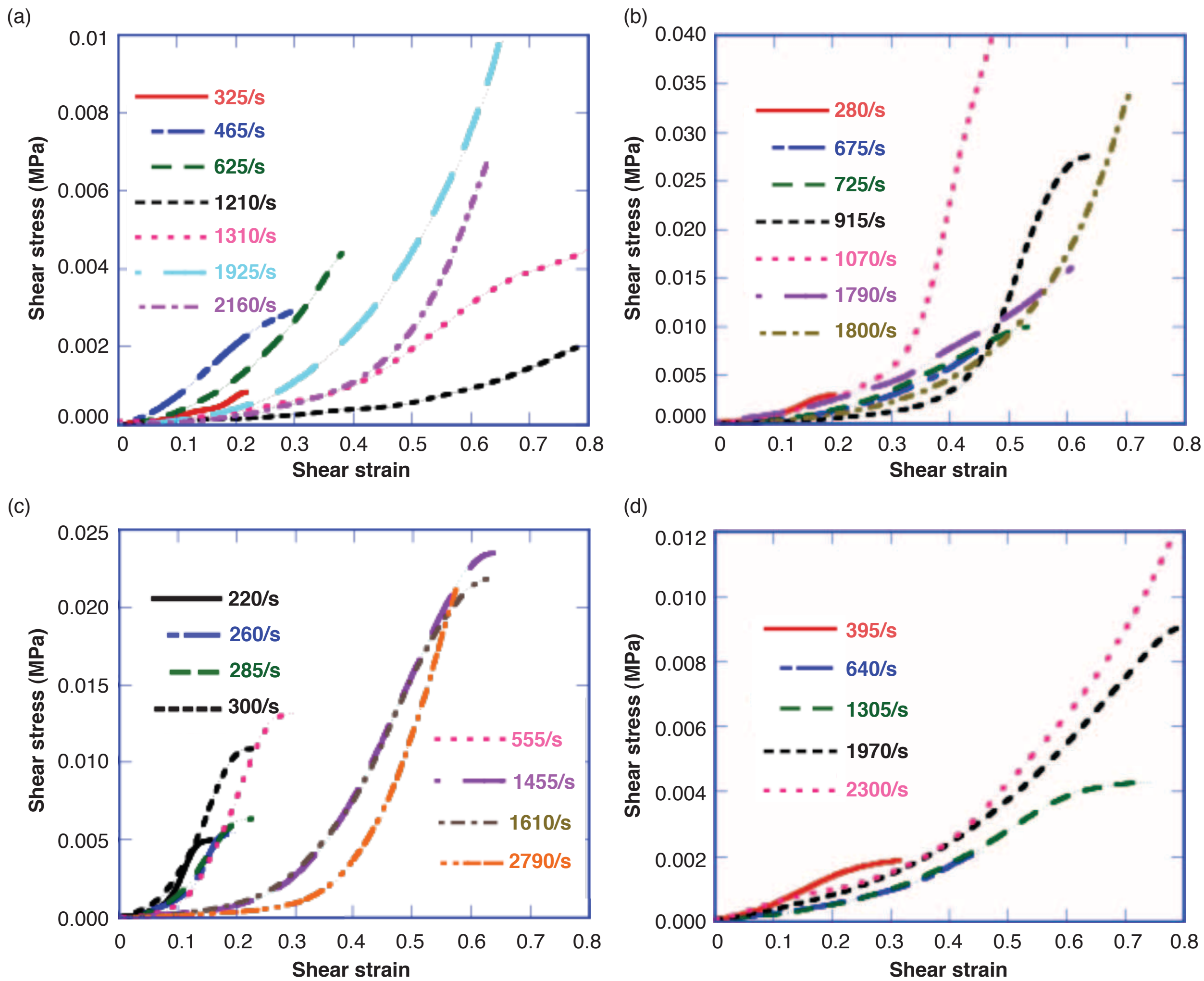


Figure 10. Shear stress–strain results from testing with a modified compression cell technique. (a) Stomach. (b) Liver. (c) Heart. (d) Lung.

As software became more capable and higher-speed computer resources became more available, an FEM of a human torso that included the skeleton (ribs, sternum, cartilage, and vertebral column) and internal organs (heart, lungs, liver, and stomach) was created for ballistic impact and blast simulation. This model is illustrated in Fig. 11. The bony structure was assumed to be linearly elastic, while all organs were treated as nonlinear viscoelastic. The simulation model consists of approximately 110,000–150,000 elements and more than 300,000 nodes. Figure 12 compares the FEM data with the human surrogate torso model data.

The correlation is reasonably good for initial impact response between the instrumented torso and the FEM except for the heart data. The heart is located behind the sternum and therefore does not see the full force of the impact. The pressure wave disperses after impact with the sternum, and the pressure sensor in the heart shows a much reduced value. Because the pressure sensors are unidirectional, any offset in the sensor direction records a much different pressure than what the computational model records. Therefore, the poorer agreement of the results for the heart than for other soft tissue is to be expected. The 15–20% difference in peak pressures between the FEM and the experiment in impact over the liver or stomach sensors, which are located directly behind the impact point, is typical for all tests. Note that because this is the first such human torso model, improvements in system design can be expected from future versions.

Reasonable correlation of the FEM data with the test data validates the M&S approach and offers much promise in providing an alternative method for evaluating the effectiveness of body armor. In addition, the M&S approach allows the system designer to vary the stressors from bullets to blasts and the armor from vests to vehicles.

SUMMARY

Systems engineering guidelines were presented for designing systems that must operate in extreme environ-

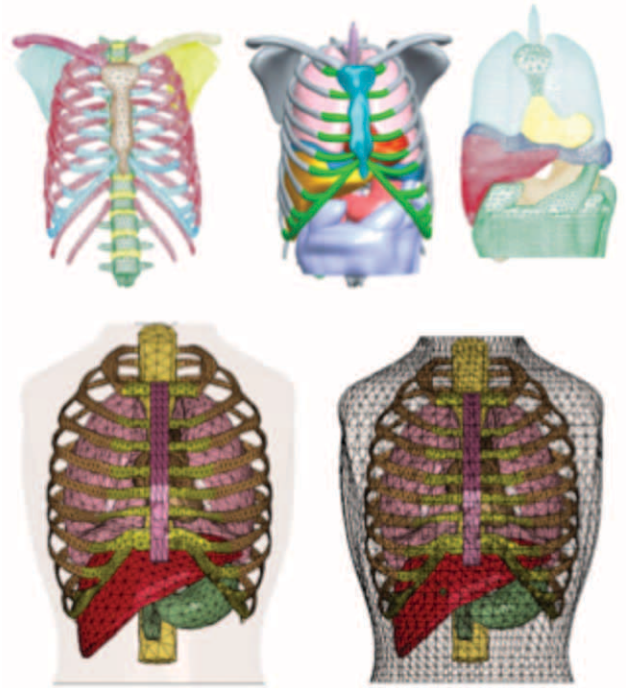


Figure 11. FEM of a human torso with vertebral column, ribs, sternum, cartilage, heart, lungs, liver, stomach, muscle, and skin.

ments. These guidelines include addressing potential system design flaws by using a physics-of-failure methodology for risk assessment and by using both M&S and T&S as approaches for risk mitigation. The two examples described in this article emphasize the importance of risk assessment and the degree of planning and effort required for risk mitigation when designing for extreme environments.

Risk assessment is required early in the concept development phase to allow ample time for risk mitigation activities such as T&S and M&S. The physics-of-failure approach offers a structured approach both to risk assessment and to interface and failure site management. Early and comprehensive planning is required for risk mitigation, not only to assure that the cost of these activities is captured in the cost proposal, but also to ensure that the right conclusions regarding reliability are obtained and all M&S and T&E are completed before the system integration phase. The examples discussed in this article emphasize the amount of effort involved in gaining an understanding of how the system will function in an extreme environment.

APL has long been a leader in M&S and T&E. In recent years, APL has invested heavily in both

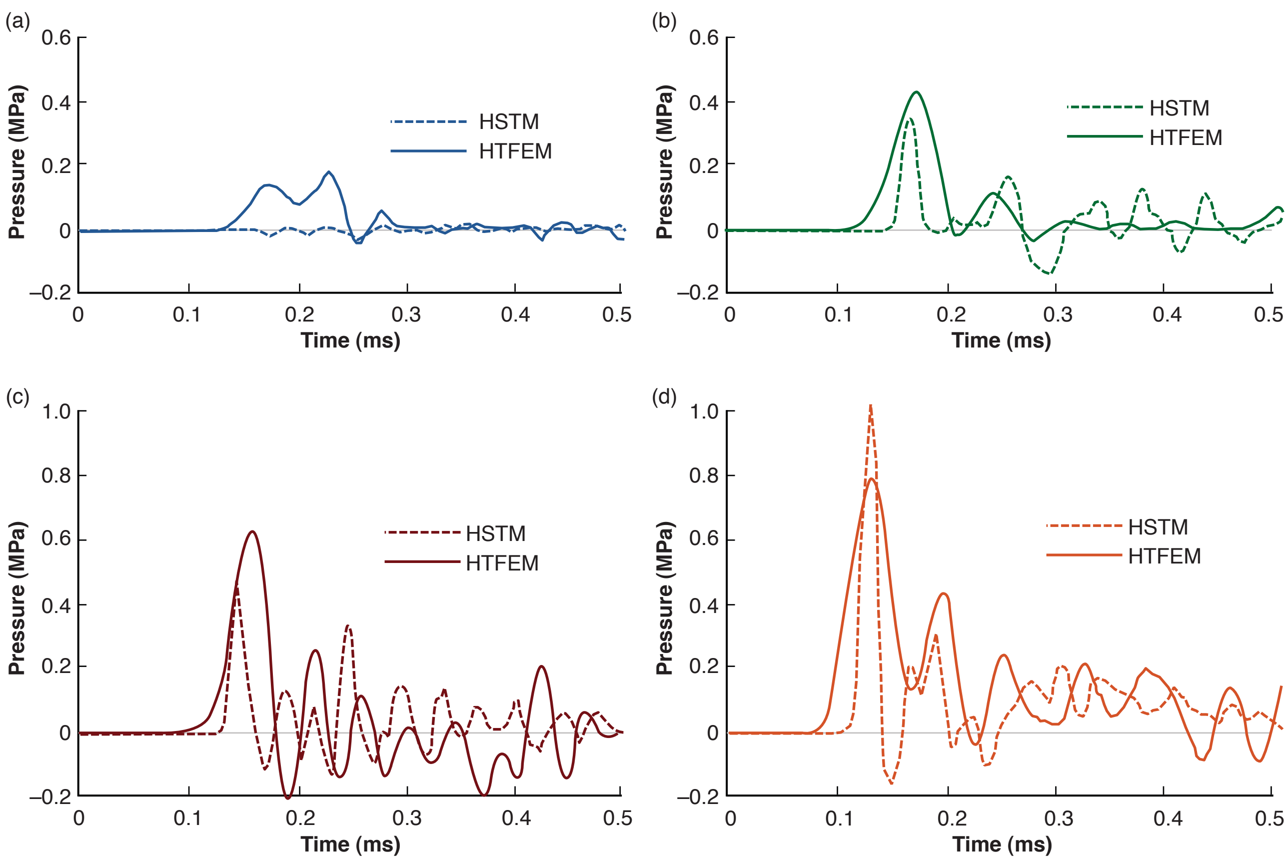


Figure 12. Comparison of FEM results with measured organ pressure for a ballistic impact (9-mm bullet) over the right central liver. The first peak is the most important data point with respect to internal injuries. (a) Heart. (b) Stomach. (c) Right liver. (d) Left liver. HSTM, human surrogate torso model; HTFEM, human torso FEM.

equipment and expertise relating to material characterization and accelerated life testing. More recent investments have been made to develop a core capability that specializes in addressing a wide variety of complex M&S activities pertaining to system reliability. Expertise in T&E methods, material characterization, and advanced M&S techniques can provide systems engineers with the resources necessary to make important design decisions early in the design phase while providing the means to mitigate risk for those systems that must operate in extreme environments.

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