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Title: Testbeds to Reduce Uncertainties in Simulations and Tests (TRUST)

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Testbeds to Reduce Uncertainties in Simulations and Tests (TRUST)

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Summary

Testbeds to Reduce Uncertainties in Simulations and Tests (TRUST)—formerly Benchmark Extensible Tractable Testbed Engineering Resource (LA-UR-16-23828)—are experiments, with accompanying models and simulations, that support engineering capability development by helping to identify weaknesses and address needs. Weapon systems, subassemblies, and components are often complex and difficult to test and analyze, resulting in low confidence and high uncertainties in experimental and simulated results. The complexities make it difficult to distinguish between inherent uncertainties and errors due to insufficient capabilities. TRUST will first use simplified geometries and materials such that testing, data collection, modeling and simulation can be accomplished with high confidence and low uncertainty. Modifications and combinations of simple and well characterized TRUST can then be used to increase complexity in order to reproduce relevant mechanics and identify weaknesses. The ultimate goal is to help improve capabilities and increase confidence by building TRUST. This document presents the motivation, concept, benefits and examples for TRUST.

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1 Motivation

The Los Alamos National Laboratory (LANL) Engineering Technology and Design (E) division's Advanced Engineering and Analysis, and Weapons Test Engineering groups are tasked with simulating and testing weapon assemblies, and components. The intention of conducting such tests and simulations is to characterize relevant test articles with high confidence through a range of mechanical and thermal environments. Any lack of confidence, or increased uncertainty, related to such work negatively impacts the groups' abilities to make the assessments and predictions that are critical to the mission of the laboratory.

Modeling and simulation work conducted by the Advanced Engineering and Analysis group is often complicated due to uncertainties in modeled geometries, poorly characterized mechanical and thermal loads, uncertainties in mechanical and thermal interface properties, and materials with unknown pedigree and loading history. The various uncertainties must then be combined in order to conduct simulations. Experimental work conducted by the Weapons Test Engineering group is often difficult due to the complexity of instrumenting assemblies and components, the need to reliably collect data through taxing mechanical and thermal environments, and the efforts needed to post-process and interpret large amounts of data collected from complex test bodies.

With so many sources of uncertainty it is difficult to test, collect data, and simulate with high confidence. Such uncertain conditions make it difficult to identify needs, improve testing and modeling deficiencies, and validate testing and modeling efforts. The premise of Testbeds to Reduce Uncertainties in Simulations and Tests (TRUST) is to eliminate or significantly reduce as many of the extraneous uncertainties as possible in order to identify, and eventually minimize, sources of error directly associated with the measuring and analysis techniques. The expected result will be improved capabilities and techniques, and higher confidence in analyses and tests.

2 Concept

Collections of TRUST, with corresponding experiments and analyses, are specifically designed to identify uncertainties and errors in experimental and computational techniques. The testbeds are intended to be very simple in comparison to weapon systems and their related subassemblies and components, which typically involve combinations of complicated materials, geometries, and interactions. TRUST will be simple enough to facilitate testing and modeling, yet still reproduce relevant mechanics.

Initially, complicated material behaviors and complex geometries will be discarded. Materials will have well known properties and constitutive models. Components will have well characterized and simple geometries such as circular disks, rings, or hollow cylinders. The initial goal is to have components and assemblies that can be tested and analyzed with relative ease. Furthermore, test and analysis engineers will have control over materials, geometries, boundary conditions and loading, and instrumentation such that the resulting tests and analyses are of utmost value to their needs.

The test bodies may start with single parts made with well characterized materials and geometries. The single parts can then be combined to make assemblies of well characterized parts such that deficiencies in testing, modeling and analyses can be attributed to weaknesses in those areas. Modularity of the individual components will allow for the building and modification of test bodies into more complicated but still well characterized systems. Complexity of the geometries, materials, and interfaces may be increased, and using well characterized components will facilitate characterization of the systems.

Building and maintaining TRUST is intended to be a continuing effort. Existing testbeds can always be used to maintain capabilities or investigate new test and analysis tools. New and different testbeds can always be developed to explore different test and analysis needs. The efforts made with TRUST can be documented and maintained such that future engineers may learn from, reproduce, and build on past efforts.

2.1 Summary of TRUST Characteristics

The desired characteristics are summarized here for emphasis.

1. *Representative*. TRUST must be representative of the mechanics that could be exhibited by weapon assemblies, subassemblies, and components.
2. *Well Characterized*. Before tests or analyses are performed on any TRUST assembly, the components of the assembly must be well characterized in terms of materials, geometries, and interface behaviors.
3. *Modular*. The test bodies must be designed to be modular, such that features can be added or components swapped in order to increase complexity.
4. *Well Defined*. Test and analysis engineers have full control over the materials, geometries, loading conditions, and procedures used in TRUST experiments so that efforts and results directly support their needs.

3 Benefits to Engineering Capability Development

TRUST is envisioned to directly support the testing and analysis groups, but can also have uses outside their division and even outside the laboratory.

3.1 Benefits of TRUST

How can TRUST be used within the Engineering Technology and Design division?

- TRUST can be treated like weapon systems by running them through typical mechanical and thermal environments, and modeling and simulating their responses in order to validate the results. Doing so gives test and analysis engineers the opportunity to exercise relevant capabilities that are critical to the divisions.
- Models of the testbeds can be managed like Engineering Analysis Baseline Models (EABMs) [2] by storing, maintaining, and documenting the tests and analyses such that any engineer can access, comprehend, and reproduce the experimental and simulated

data analyses. The efforts made towards storing, maintaining, and documenting models of TRUST can serve as examples to support the the same efforts for the EABMs.

- Modeling and simulation efforts of the testbeds can be used to investigate, develop, and exercise the complex tools and processes required for generating and using EABMs.
- Analysis engineers can efficiently gain experience with the tools used to develop and simulate EABMs by making similar efforts with TRUST. Doing so would also help analysts adopt EABM tools and processes to non-EABM efforts.
- The modeling and simulation of the well characterized test bodies with statistically characterized inputs can support the development of techniques for quantifying margins and uncertainties of numerical simulations.
- The test bodies, their simulations, and their well characterized inputs can be used to facilitate fully populating the experimental and numerical statistics needed for verification and validation of the techniques used for quantifying margins and uncertainties.
- The test bodies and their simulations can be used as trainers for test and analysis engineers, including unclassified versions to train new-hires. Engineers can gain experience by working with a relatively easy problem for which they can compare their data and solutions to existing results that are known to be correct.
- Well characterized test bodies can be developed in order to exercise and validate interface models for friction, adhesion, and heat transfer.
- The test and analysis results for the test bodies can be validated by comparisons to analytic solutions, when available.
- Material constitutive models for complex materials such as foams, rubbers, and high explosives can be developed and validate using simple geometries and well characterized test bodies.
- Components with complex geometries and well characterized materials can be developed, tested, and modeled in order to validate that the material constitutive models can reproduce realistic and representative responses.
- Software upgrades, or potential replacements, for the tools used for modeling and simulation can be exercised and evaluated using simple TRUST test bodies.
- Software packages used by other laboratories can be used to reproduce test body models and simulations in order to benchmark results and maintain extended capabilities.
- New sensors and instrumentation techniques can be developed, tested, and validated by comparing their results to existing data from TRUST test bodies.
- Experiments and simulations of the test bodies can be used to effectively demonstrate capabilities to other groups and give customers a better understanding of the levels of effort required to conduct those experiments and simulations with high confidence.

How can TRUST be used outside of the Engineering Technology and Design division, and outside LANL?

- TRUST can be used as projects in the National Security Education Center, Engineering

Institute's Los Alamos Dynamic Summer School so that engineers can gain experience mentoring students, while students get exposed to the experimental and simulation work that is critical to the lab.

- The testbeds can be used for collaborative efforts with universities that share interests in mechanical testing and numerical simulation in order to build relationships with faculty and students. Funding can be provided to university faculty and students for capstone projects, and the relationships can help attract students to the laboratory.
- The testbeds can be shared with other LANL testing and engineering divisions, and other laboratories, in order to compare testing and analysis capabilities.

3.2 Further Discussion of Some Benefits

This section presents further discussion of some of the benefits listed in the Section 3.1. The items being elaborated are quoted at the beginning of each discussion.

3.2.1 Testing, Modeling, and Simulation of Weapon Systems

> TRUST can be treated like weapon systems by running them through typical mechanical and thermal environments, and modeling and simulating their responses in order to validate the results. Doing so gives test and analysis engineers the opportunity to exercise relevant capabilities that are critical to the divisions.

Tests conducted on weapon system assemblies, etc., typically require large budgets to account for the levels of effort involved with test planning, procurement of costly and potentially scarce test articles, facility scheduling, logistics of test article handling and storage, and test execution. Similarly, simulations of weapon system assemblies, etc., typically require large budgets to support the levels of effort related to development and execution of large and complicated simulation models. Such budget requirements make these tests and simulations unsuitable for exercising and developing capabilities, and that is especially true when considering the iteration and repeat efforts that are typical of development cycles. Often times experimental and analysis capabilities are developed immediately before or during testing and simulation of the desired test body, which is inefficient because it takes time and effort away from investigating the actual test.

TRUST would be relatively easy to store and handle, and their related experiments and simulations would be relatively easy to conduct. This would facilitate more frequent testing and analysis at lower costs and levels of effort. Testing and analysis capabilities would be regularly developed and exercised so that engineers and equipment would be better prepared for tests and simulations of actual systems, and the testing and analysis engineers could focus new efforts on being proactive instead of reactive.

3.2.2 Engineering Analysis Baseline Models

> Models of the testbeds can be managed like Engineering Analysis Baseline Models (EABMs) [2] by storing, maintaining, and documenting the tests and

> analyses such that any engineer can access, comprehend, and reproduce the experimental and simulated data analyses. The efforts made towards storing, maintaining, and documenting models of TRUST can serve as examples to support the the same efforts for the EABMs.

and

> Modeling and simulation efforts of the testbeds can be used to investigate, develop, and exercise the complex tools and processes required for generating and using EABMs.

and

> Analysis engineers can efficiently gain experience with the tools used to develop and simulate EABMs by making similar efforts with TRUST. Doing so would also help analysts adopt EABM tools and processes to non-EABM efforts.

EABMs are weapon models that serve as the foundations of most modeling and simulation efforts carried out by the Advanced Engineering and Analysis group. There exist EABM requirements [2] on development, maintenance, management, storage, and documentation that were developed with the intentions that EABMs are produced such that any analyst can efficiently learn about them and use them. Such requirements demand consistent levels of effort that are difficult to maintain when the EABM developer(s) are simultaneously using their models to answer questions.

TRUST can be used to more efficiently develop and implement the modeling, meshing, simulation, post-processing, documentation, storage, and maintenance tools that are needed by the EABM developers to satisfy the requirements. Facilitating the development of the tools separate from the EABMs would give the EABM owners established methods for satisfying the requirements, while allowing the EABM owners and developers to focus their efforts on increasing EABM capabilities. Having matured EABMs will then give users all the benefits that are intended by the requirements.

3.2.3 Quantification of Margins and Uncertainties[1]

> The modeling and simulation of the well characterized test bodies with statistically characterized inputs can support the development of techniques for quantifying margins and uncertainties of numerical simulations.

and

> The test bodies, their simulations, and their well characterized inputs can be used to facilitate fully populating the experimental and numerical statistics needed for verification and validation of the techniques used for quantifying margins and uncertainties.

[1]This section was contributed by T. B. Tippetts.

For at least the past decade, decision-makers and analysts at all levels of the nuclear weapons complex have recognized Quantification of Margins and Uncertainties (QMU) as essential for assessment activities. The Engineering QMU (EQMU) project is an effort started in 2016 to apply QMU techniques in the Advanced Engineering and Analysis group.

EQMU uses a more enriched type of information than that required by a single-run analysis. The need for this information reveals two types of gaps in validation data currently available. The TRUST project is necessary to fill in these gaps. In so doing, TRUST will provide immediately applicable information to real weapon systems.

Quantifying margins requires bridging the gap in threshold information. Margin is essentially the distance between 1) a system's predicted operating condition and 2) the threshold that bounds a failure condition. Proper threshold characterization is therefore essential to margin estimation. This in turn requires validation data for physical processes in the vicinity of failure.

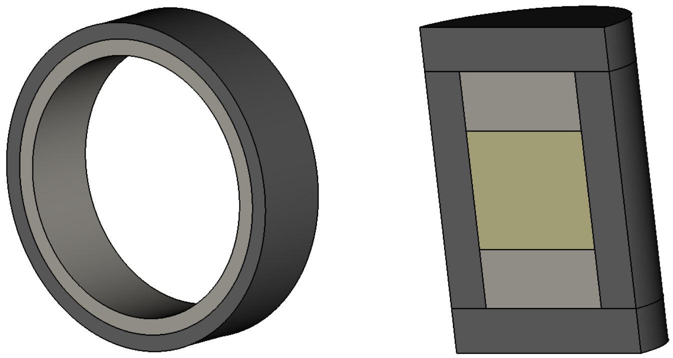
Processes such as material degradation, contact interactions, and nonlinear boundary conditions are often quite different at these physical extremities than under nominal operating conditions. Many failure processes such as fracture, yield, fretting friction, fatigue, etc., might not occur at all under nominal conditions.

Other validation tests are often designed to keep the test article within the nominal range for which the system was designed to operate, rather than to approach failure. This is especially true for large-scale system tests. Nominal-range validation tests help improve model prediction in the parameter space where the system spends its normal operation, but they do not support prediction of failure thresholds or margin. Test articles designed for TRUST could approach material failure conditions safely and without exceeding equipment capabilities. This would meet an essential need for margin prediction for EQMU analyses.

Quantifying uncertainty requires bridging gap in complexity. A second gap in currently available validation data occurs in terms of scale and complexity. At one extreme, data are available for very simple, single-coupon material tests. These tests are limited in the type and regime of physical phenomena that they can excite, especially in terms of interaction effects and highly confined boundary conditions. At the other extreme are data from large-scale, full-system or complex subsystem tests. These tests excite relevant physics, but their high level of complexity makes it difficult to distinguish and quantify individual contributions to uncertainty.

TRUST fills this gap by using a small number of components to create the relevant interactions and non-trivial boundary conditions. Overall uncertainty is controlled by using only components that are well-characterized, with the possible exception of a single part whose uncertainty is to be reduced.

Recent development of a Bayesian model updating capability in the EQMU project now allows an analyst to fit a model from an integral effects test as easily as a from a single coupon test. The TRUST project would provide an ideal form of data to use this new capability to characterize dependencies between uncertain parameters in our models.



(a) (b)

Figure 1: Sketches showing conceptual versions of (a) the concentric rings, and (b) a cross-section of the stacked disks. The images shown here are idealizations that may need slight modifications to facilitate instrumentation and testing.

4 Examples

This section presents examples of potential TRUST applications. Each example presents a description of the conceptual geometry, including how that geometry represents relevant mechanics, and a discussion of how the geometry would be instrumented, tested and analyzed.

The examples in this section exercise certain capabilities required of test and analysis engineers.

- Collect data such as acceleration, displacement, strain, load or temperature.
- Accurately characterize component geometries using inspection tools.
- Characterize mechanical and thermal responses of individual components.
- Successfully model geometries, material constitutive models, mechanical and thermal properties across component interfaces, mechanical and thermal tests.
- Successfully analyze experimental and simulated test data.

4.1 Concentric Rings[2]

This TRUST application uses two concentric rings, shown in Figure 1(a), to evaluate the ability to simulate and measure thermal and mechanical strains resulting from parts made of materials with mismatched coefficients of thermal expansion (CTE). The primary challenge when attempting to measure the strain of such a system is that the output of the strain gages will vary with temperature. The primary challenge when modeling it is that the thermal resistance between the two metals may be a function of the pressure between the interfaces and the surface condition of the parts. This test will provide a measure of current capabilities when dealing with these challenges and will likely lead to improvements in techniques.

The two concentric rings must be fabricated of well-characterized materials with different CTEs; for example, aluminum and stainless steel. The thermal and mechanical material

[2]This section was contributed by P. E. Schembri, M. A. Buechler, and A. A. Siranosian.

properties of these materials are well known, especially if the mechanical response remains elastic, though tests might have to be conducted to verify that the properties were not affected by fabrication processes. The thermal interface properties are relatively well known due to recent tests and results discussed in [1]. The geometry of the rings needs to be inspected, and tolerances need to be determined such that knowledge of temperature provides knowledge of stress in the rings within a reasonably low uncertainty. Furthermore, in order for the interface thermal resistance to be estimated, the roughnesses of the ring mating surfaces need to be measured and possibly controlled.

The two rings would be assembled, and the mechanical and thermal strains measured through several thermal cycles. Cycling the temperature slowly enough that the two rings maintain uniform and equal temperatures eliminates dependence on the interface thermal resistance. Then, modifying the test to yield non-uniform temperatures would introduce thermal interface resistance dependence. This could be done either by cycling the temperature quickly or by providing nonuniform heating, while maintaining well controlled boundary conditions that can be simulated.

Assuming the CTEs and elastic properties of the materials are known, an analytical solution should be available for the uniform-temperature test. This may not be possible for the nonuniform temperature test. Once test and simulation are complete then differences between simulation, test, and analytical solution should be investigated and experimental and numerical methods improved until there is agreement and/or understanding of why the results should not agree with the analytical solution.

4.2 Stacked Disks[3]

The test body shown in Figure 1(b) represents an axially preloaded assembly that consists of three disks stacked inside a closed container, where the container is composed of a hollow cylinder with caps at both ends. It is intended to exercise the experimental capabilities related to collecting load, strain and temperature data from an assembly; and to evaluate the simulation capabilities related to mechanical interface modeling for friction, thermal interface modeling for heat transfer and material constitutive models.

The geometries of all components need to be well characterized. The materials for all the components also need to be well characterized, and they are initially intended to exhibit only linear elastic responses through a relatively large range of stresses. Furthermore, the middle disk is chosen to be compliant relative to the other parts in the test body and it will be designed such that it compresses during assembly to provide a preload in the test body. The outer disks are included in order to produce symmetric and easily characterizable boundary conditions on the center disk.

In its most simple form this testbed should be easy to exercise and analyze. Instrumentation would include sensors for load, displacement and strain. There could be challenges in the instrumentation depending on where data will be collected, e.g. if sensors are placed within the container. Challenges for the analysis would be the characterization of the friction and heat transfer between pairs of contacting surfaces, and modeling of the end caps and their means of attachment to the cylinder.

[3]This section was contributed by A. A. Siranosian.

During assembly the container would be open on one end and the disks would be loaded, then the remaining cap would be placed on the open end and the disks would be compressed by the closing cap. Data collected during assembly would include the load applied to the cap on the open end and the displacement of the cap relative to the container body. The assembled test body could be mechanically loaded or thermally conditioned while loads, strains and temperatures were recorded.

Experimental and simulated characterization of the simple form of the testbed and its components will exercise basic capabilities. Once the simple form of the test body is fully characterized then it can be used as a validation testbed for more complex materials and/or middle disk geometries. The material for the middle disk could be replaced with foams, polymers or polymer composites and the geometry could be changed such that the disk exhibits a more complicated response.

5 Conclusion

Testbeds to Reduce Uncertainties in Simulations and Tests (TRUST) are envisioned as experiments and analyses that are specifically designed to identify uncertainties and errors in experimental and computational techniques. Addressing those weaknesses will result in measurably increased confidence, and decreased uncertainty, in future weapon-related experiments and simulations to support assessments and predictions. TRUST offers numerous benefits in support of experiment and simulation capability development, with the potential for immediate and long-term gains.

References

[1] A. T. Nelson, "Measurement of contact conductance of 304L stainless steel and 6061-T6 aluminum interfaces through multilayer laser flash analysis," LANL, LA-UR-15-29092, 2015.

[2] A. A. Siranosian, "Engineering analysis baseline model requirements," LANL, LA-UR-19-20418, 2019.