Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No. 1065

Packaging Certification Thermal Testing at Sandia

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Abstract
The approach to radioactive material (RAM) package thermal certification at Sandia National Laboratories is presented in here. The paper shows how programmatic risks associated with under- or over-testing high value prototype packages are virtually eliminated through the use of test facilities with well-controlled boundary conditions. Evolution of this capability at Sandia and details of the resulting facilities are presented. Advantages of utilizing high-fidelity simulations as part of the test design process and the utilization of modern diagnostics and facilities are also discussed.

Introduction
Designing RAM packaging for the safe transport of hazardous materials that will qualify when tested to the hypothetical accident thermal conditions specified in 10CFR71 or IAEA TS-R-1 requires full understanding of the accident fire environment, the packaging response to the environment, and the thermo/chemical/mechanical coupling that occurs between the two. To meet this need, Sandia designed a Thermal Test Complex (TTC) (Figure 1) to serve as an international resource for development and validation of applicable high fidelity full physics models as well serving as the packaging hardware qualification facility.

The TTC is the culmination of over 40 years of experience in full scale fire testing and high fidelity computational thermal simulation. Ongoing experimental fire research, validated modelling tools, and phenomenological model development activities form the basis of an integrated capability that is brought to bear on the design and qualification of RAM packages at Sandia.

In what follows, a brief history of package thermal testing is presented with the intent of bringing out issues associated with testing full scale test items in outdoor fires. Details of the TTC are then reviewed to show there is considerable advantage to moving testing indoors. This is followed by a short discussion of available diagnostics, and how together with recent advances in modelling and simulation, programmatic risks of producing over and under tests are essentially eliminated by their use.

Figure 1. A large quiescent burn room (FLAME), a cross-wind burn tunnel (XTF), a radiant heat fire simulator (RHTC), and a high temperature thermal environment lab (ATEL), comprise the Thermal Test Complex.

Evolution of Certification Fire Testing

Historical Issues

RAM package testing has been underway at Sandia since the 1970's. Transport containers for over the road, on-site, air, and rail have all been tested at the outdoor facility. Exploratory and design evaluation testing was also conducted for other hazardous systems such as munitions. Testing has been, and still is, performed according to requirements set forth by the pertinent regulatory body such as the NRC, IAEA, DOT, and/or DOD [1,2,3,4]. The requirements vary in the details, but in general require the unit under test to be fully engulfed in flames for a required time interval. Thermocouples located on or near the package are required to record temperature levels. Often, the location of the packages in the setup and the size of the fuel source are specified in an attempt to ensure that the packages are engulfed in flame during the entire test. This rarely occurs in outdoor testing as the packages, flames, and wind all interact in a coupled manner that produces random, large-scale, time-varying flow features. This coupling is somewhat allayed by following the requirements, but ultimately conformance is a post-test qualitative assessment of video records and thermocouple traces. The programmatic risk from non-conformance to these requirements lies in having to repeat the test – with a longer burn, a larger fire, and/or better wind conditions. In any event, the result is increased cost and time delays for the shipping container certification effort.

Early Mitigation Schemes

It has long been recognized that the main issue with outdoor testing is the presence of wind. Early on, wind shielded facilities were designed and used for specific testing programs. Figure 2 shows some examples of the types of enclosures that were developed. These facilities, although useful for the specific test programs, proved to have limited flexibility when sizes of packages changed. Both over- and under-testing became a problem when attempting to use these facilities with large-size packages.

Figure 2. Left, the SWISH, a water-cooled wall enclosed pool fire facility for a 1 x 1 m pool. Center, the LAARC insulated wall enclosure for a 3 m dia pool fire with passive air control. Left, the SMERF, a water-cooled wall enclosure for a 3m x 3m pool with active air control.

Outdoor pool fires proved to be more flexible when fitted with wind fences (Figure 3). These testing fixtures consisted of a steel tub surrounded by chain link fencing. Metal slats were inserted into the fencing screen to reduce the wind velocity at the pool by a factor of three.

Figure 3. The 6 m x 6 m outdoor pool with 6 m high wind fences. The fences are located at a distance from the pool edge.

These facilities were useful in producing engulfing fires in low wind conditions. However, the fire characteristics were not repeatable and, furthermore, it was not possible to extract meaningful time and spatial temperature averages from the point measurements made on and around the unit under test.

Advent of High Fidelity Computational Simulations

With the advent of high performance computing and high fidelity multi-physics computer simulations, fire specialists at Sandia were no longer limited by restrictive correlations developed from sparsely instrumented experiments to design and interpret fire scenarios of interest. Advances in computer hardware and computational tools led fire scientists at Sandia to develop a combined experimental/computational approach to design tests and interpret results. Fire scientists began to view computational results as being a partial truth, fully exposed, and the experimental results as being a complete truth, partially exposed. The two were connected via data-to-simulation comparisons made in light of experimental and computational uncertainties.

Pre-experimental simulations were run to direct development of test setups and instrumentation locations. These simulations included estimates of uncertainty, sensitivity of proposed measurements, and the impact of uncontrolled boundary conditions. After the test, post-test simulations were re-run that captured changes in the setup and boundary conditions during the testing. Direct comparisons between data and simulation results were made in light of both experimental and computational uncertainty. Point measurements made in the experiment were then tied to time and spatial averages for demonstrating that the fire environment met requirements and for aiding in interpreting the package response.

It soon became evident that the quality of the computational simulation depended on the ability to specify the boundary conditions. This led to the return of fire testing to indoors in a new thermal test complex, where boundaries could be set by the presence of temperature-controlled walls and the location and strength of air sources. Simulation was key in the design of the present day indoor fire facilities. The desire to control boundary conditions has led to systems that allow jet fuel, methanol, and other liquid fuels as well as hydrogen, methane, and other gas fuels to be used as part of the testing. The facility has served as an international resource for development and validation of applicable high-fidelity, full physics fire models. Because of this, fires in the facility are highly repeatable and well understood.

The Thermal Test Complex

Available Indoor Test Cells

Quiescent-wind fire experiments for fire environment characterization are performed in the 20 m diameter by 12 m high Fire Laboratory for Accreditation of Models and Experiment (FLAME) test cell that has water-cooled walls and well controlled/characterized airflow equipment. Laser diagnostics are used in the cell to observe the air/fuel mixing and burning process. Calorimeters are simultaneously employed to gather heat flux from the fire to full size target objects. Systems to allow jet fuel, methanol, and other liquid fuels as well as hydrogen, methane, and other gas fuels are a part of the design. The conditions in the cell allow for performing the qualification fires for packages that would fit in a 3 m diameter pool fire as can be seen in Figure 4.

Figure 4. A set of 30-gallon shipping drums in a 3 m diameter fire in the FLAME facility. The visible and IR views clearly demonstrate full engulfment of the test items.

The boundary conditions in FLAME are well understood which enables high quality computational modeling for determining test setup details. Figure 5, shows a prediction calculation compared with data. The prediction was used to select the pool size to ensure full engulfment.

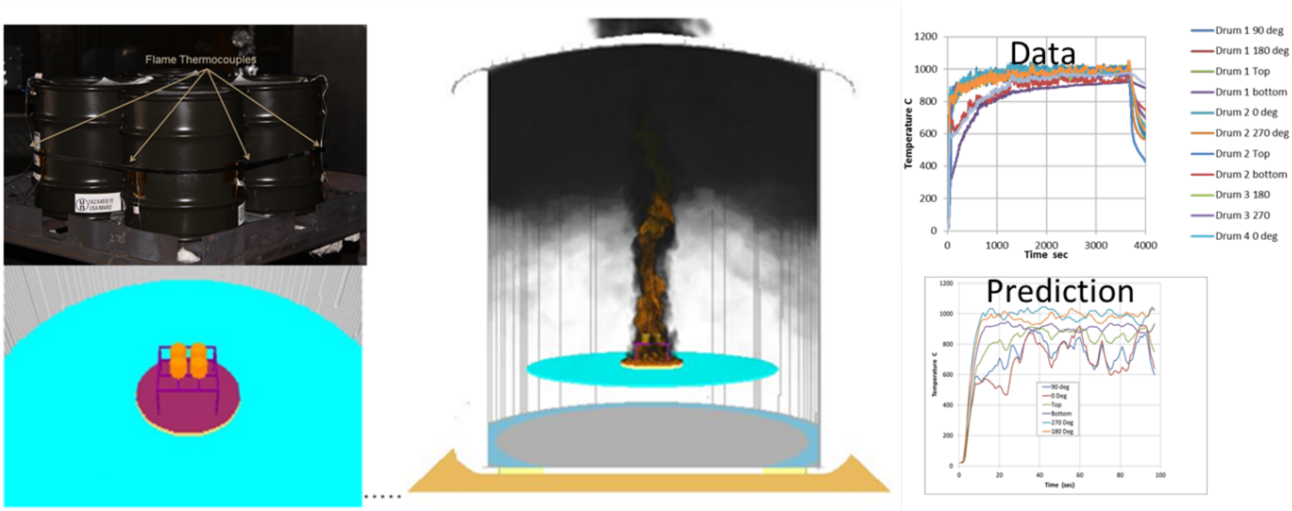

Figure 5. A 12-million element mesh used to simulate the 30-gallon drum test. The simulation was performed for 60 seconds of real time over 3 days of computational time on 36 processors.

Full scale packages can also be exposed to fire level heat fluxes in a stand-alone 5.2 MW Radiant Heat Test Cell. Feedback controlled radiant heat lamp arrays can apply full fire heat loads on a package with a surface area up to 15m^2 in approximately 1 minute. The process is fully controlled and highly repeatable.

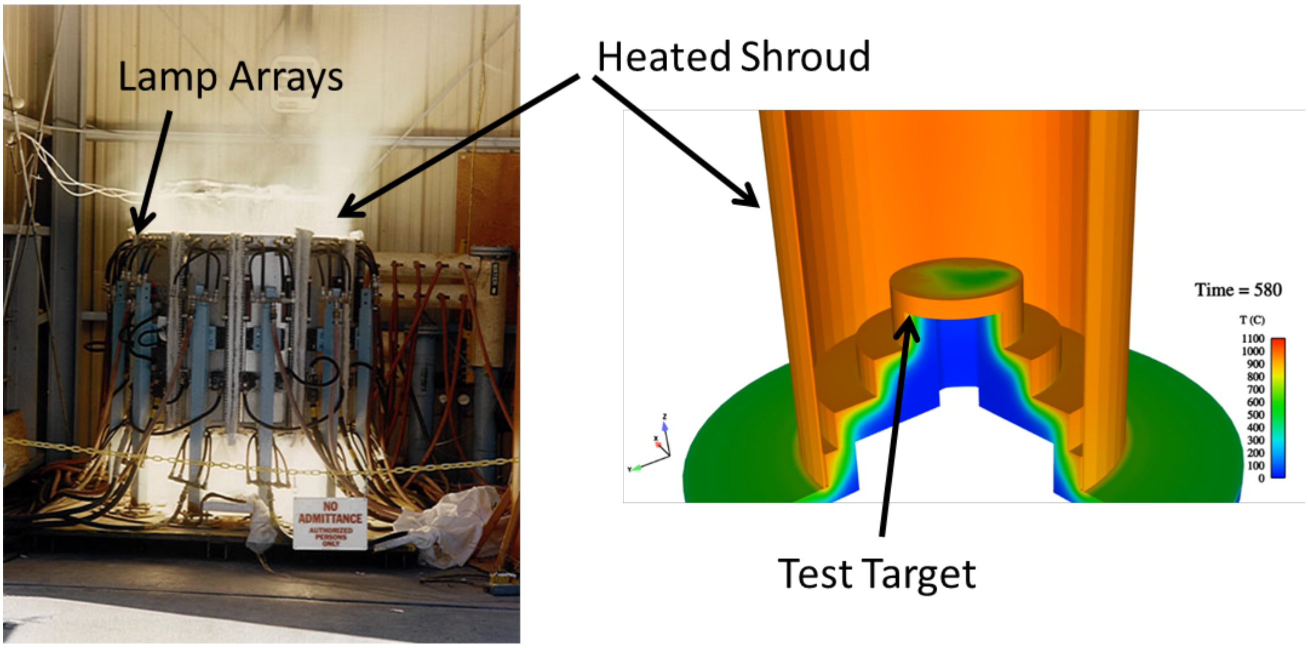

Figure 6. The Radiant Heat circular array. The setup is amenable to modelling which allows pre-test simulations for test design and post-test simulations for data interpretation.

A Cross Flow Fire Test Facility, or XTF, is a 7.6 m x 7.6 m x 25 m long facility that is an indoor "fire wind tunnel" for testing objects with hazardous components (including explosives) at wind speeds up to 10 m/s. Laser diagnostics and real time x-ray are available. Built with 0.8 m reinforced concrete walls and special refractory concrete, the XTF also has radiant heat test capabilities.

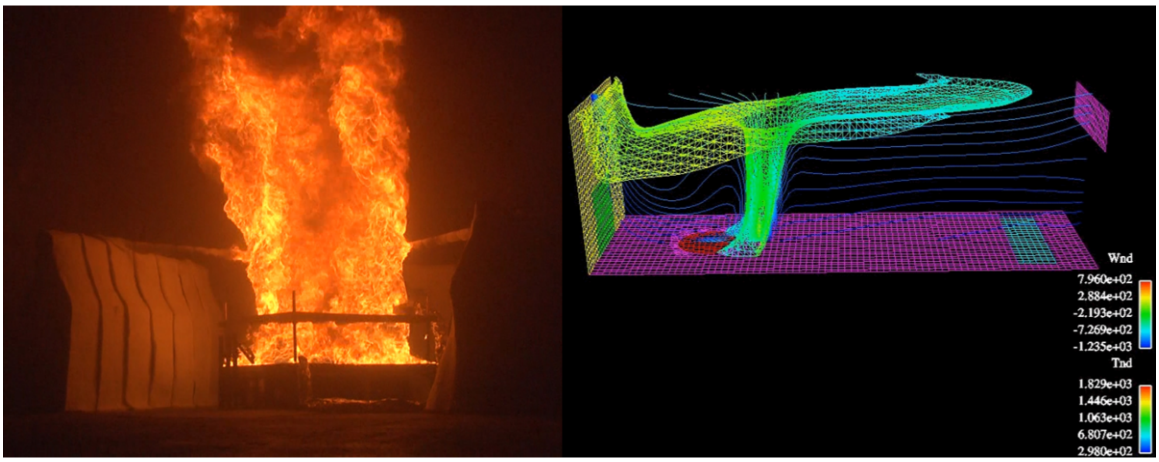

Figure 7. The cross flow in the XTF facility allows for flame stabilization configurations.

Available Outdoor Test Facilities

Large test items still require testing outdoors due to size limitations of the indoor facilities. Sandia took advantage of advanced modeling capabilities for the redesign of wind mitigation devices. Figure 8 shows the setup where the wind fence is brought in to the edge of the pool and is only as high as the test item in the center. Remotely controlled modulating air dampers around the base of the fire are active during the fire and close off the upwind side of the pool. This action serves to stabilize the fire and maintain the test item fully engulfed. The placement and sizing of the dampers are based on a computational study.

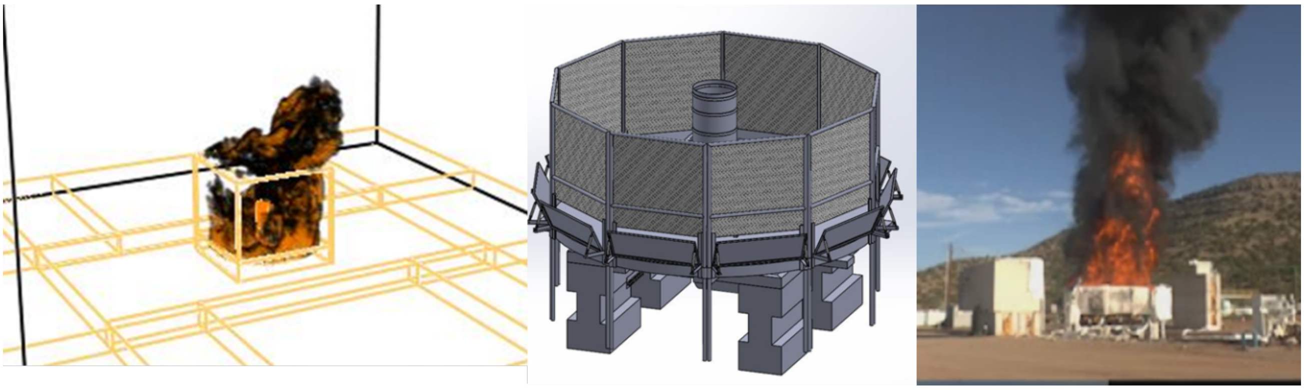

Figure 8. Close-in wind fences for outdoor fires. On the left, the design is based on a computational simulation of an outdoor pool fire with 1.7 million element mesh in a 30m x 30m x 22 m domain. Sixty seconds of simulation time took 3 days on a single processor. Center, the physical setup allowed for modulating wind driven flow underneath the fence as determined from the computational study. Left, the system successfully engulfed the package for a full hour in a variety of wind conditions.

Standards Development

The staff at the Thermal Test Complex actively engages in ASTM Standards development. At the present time, the staff is involved with E3057-16, “Standard Test Method for Measuring Heat Flux Using Directional Flame Thermometers (DFTs) with Advanced Data Analysis Techniques” and with the E2230-13, “Standard Practice for Thermal Qualification of Type B Packages for Radioactive Materials”.

The E3057 standard addresses an alternative to typical gauges such as Schmidt-Boelter and Gardon gauges. The DFTs are of simple construction and perform well in sooty fire environments. Data from DFTs can be analyzed post-test using first principles to extract an incident heat flux history on the gauge surface. As the standard develops, more advanced data reduction will allow real time heat flux determination from the gauges.

The E2230 standard is intended to guide thermal testing efforts for Type B RAM packages. A part of the standard is based on experience at Sandia in this area. The standard is updated as the wider testing community accepts new practices.

NQA-1 Program

Sandia is fully engaged with the NQA-1 quality assurance program [5]. As part of the activity, Sandia has made a large investment in data acquisition. The Mobile Instrumentation Data Acquisition System (MIDAS) is used to support all phases of package certification testing. MIDAS (Figure 9) was developed and documented in accordance with a stringent quality assurance program to ensure accurate and reliable response data.

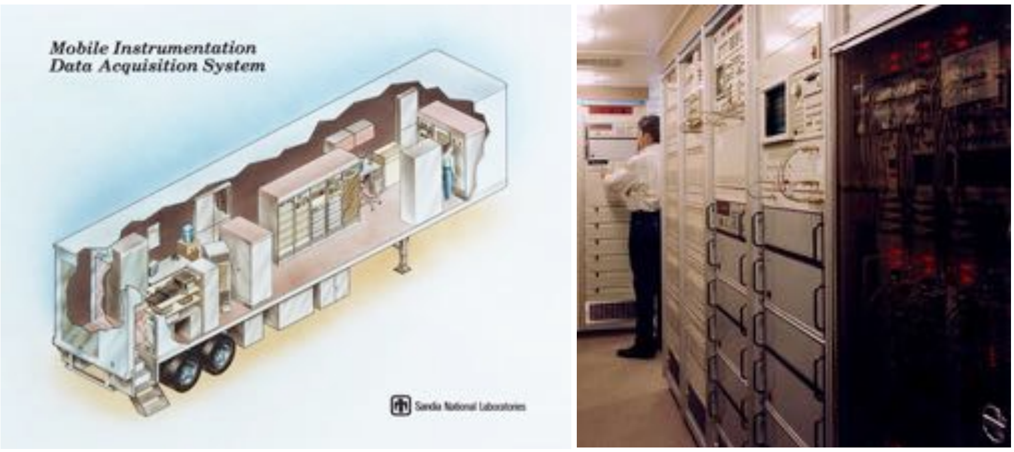

Figure 9. The MIDAS is fully mobile and supports package testing at worldwide sites. This unique self-contained mobile system is capable of acquiring and processing up to 168 channels of piezoresistive or voltage based transient structural data. In addition, up to 100 channels of temperature data can be collected and processed.

Conclusions

Many unique testing facilities exist at SNL that can be used to perform a broad range of verification and certification tests on radioactive material packages or component sections. Both regulatory and extra-regulatory test environments can be simulated. In the thermal arena, these SNL facilities provide an experience base that has been established during nearly four decades of development and certification testing of radioactive material packages.

The most recent improvement has been with directly incorporating computational simulation into the testing activities for design of the setups and interpretation of the results. This has been made possible by the close attention to controlling the boundary conditions. Control of the boundary has been accomplished by moving testing indoors whenever possible. The use of models also allows the use of virtual instrumentation which allows the extension of experimental point measurements to time and spatial averages via the model. All of this leads to lower programmatic risk associated with the test and a good defensible case to present to the regulators for package certification.

Acknowledgments

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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