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Age-aware Solder Performance Models: Level 2 Milestone Completion

Elizabeth A. Holm, Michael K. Neilsen, Paul T. Vianco, and Matthew Neidigk

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Age-aware Solder Performance Models: Level 2 Milestone Completion

Elizabeth A. Holm[1], Michael K. Neilsen[2], Paul T. Vianco[3], and Matthew Neidigk[2]
[1]Computational Materials Science and Engineering;
[2]Component Science and Mechanics;
[3]Multiscale Metallurgical Science and Technology
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185 U.S.A.

Abstract

Legislated requirements and industry standards are replacing eutectic lead-tin (Pb-Sn) solders with lead-free (Pb-free) solders in future component designs and in replacements and retrofits. Since Pb-free solders have not yet seen service for long periods, their long-term behavior is poorly characterized. Because understanding the reliability of Pb-free solders is critical to supporting the next generation of circuit board designs, it is imperative that we develop, validate and exercise a solder lifetime model that can capture the thermomechanical response of Pb-free solder joints in stockpile components. To this end, an ASC Level 2 milestone was identified for fiscal year 2010: **Milestone 3605: Utilize experimentally validated constitutive model for lead-free solder to simulate aging and reliability of solder joints in stockpile components.** This report documents the completion of this milestone, including evidence that the milestone completion criteria were met and a summary of the milestone Program Review.

Acknowledgements

Computational model development was supported by the Advanced Simulation and Computing (ASC) Physics and Engineering Models (P&EM) program and by the U.S. Navy and Lockheed Martin via a Defense Technical Objectives project. Validation and application efforts were supported in part by the Enhanced Surveillance Campaign, the DoD/DoE/MOU, and the C6 campaign, as well as leveraged efforts with Lockheed Martin, the U.S. Army, and the Joint Group on Pollution Prevention. 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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1. Executive Summary

Eutectic lead-tin (Pb-Sn) solder is the only solder alloy used in circuit board applications in the enduring stockpile. Because it operates at a high homologous temperature under thermomechanical fatigue conditions, Pb-Sn solder evolves during service and, in some cases, cracks and fails. In fact, almost half of electronics failures in stockpile components are attributed to solder joint fracture.

Since solder joints represent a challenge for weapons designers and stockpile stewards, Sandia has supported a variety of efforts to characterize and model their behavior. A longstanding project in the Advanced Simulation and Computing (ASC) program has developed a predictive design and analysis model, the Solder Interconnect Predictor (SIP), for Pb-Sn solder aging. SIP has been widely validated and has been applied to a variety of stockpile components. The desktop version of this model is the TurboSIP ©, which is widely used by Sandia, the U.S. Navy, Lockheed Martin, and other customers.

Because of concerns over environmental lead, legislated requirements and industry standards are replacing Pb-Sn solders with lead-free (Pb-free) solders in future component designs and in replacements and retrofits. These solders are typically low melting point alloys of tin, silver and copper, termed SAC solders. Pb-free solders are less than a decade in widespread application. Since they have not yet seen service for long periods, their long-term behavior is poorly characterized. Understanding the reliability of Pb-free solders is critical to supporting the next generation of circuit board designs. Thus it is imperative that we develop, validate and exercise a solder lifetime model that can capture the thermomechanical response of Pb-free solder joints in stockpile components. To this end, an ASC Level 2 milestone was identified for fiscal year 2010:

Milestone 3605: Utilize experimentally validated constitutive model for lead-free solder to simulate aging and reliability of solder joints in stockpile components.

For this milestone, we validated and exercised our new, continuum constitutive model to capture thermomechanical (temperature dependent creep/plasticity) response of lead-free solder joints in stockpile components. The lead-free solder aging model developed in this program is Sandia's first for these important materials.

The identified completion criteria for this milestone were: (1) Reproduce Pb-free solder fatigue behavior as observed in experiments on ring-and-plug samples and/or model circuit board solder joints. (2) Utilize the Pb-free solder model to predict solder joint lifetime in an identified stockpile component currently under development.

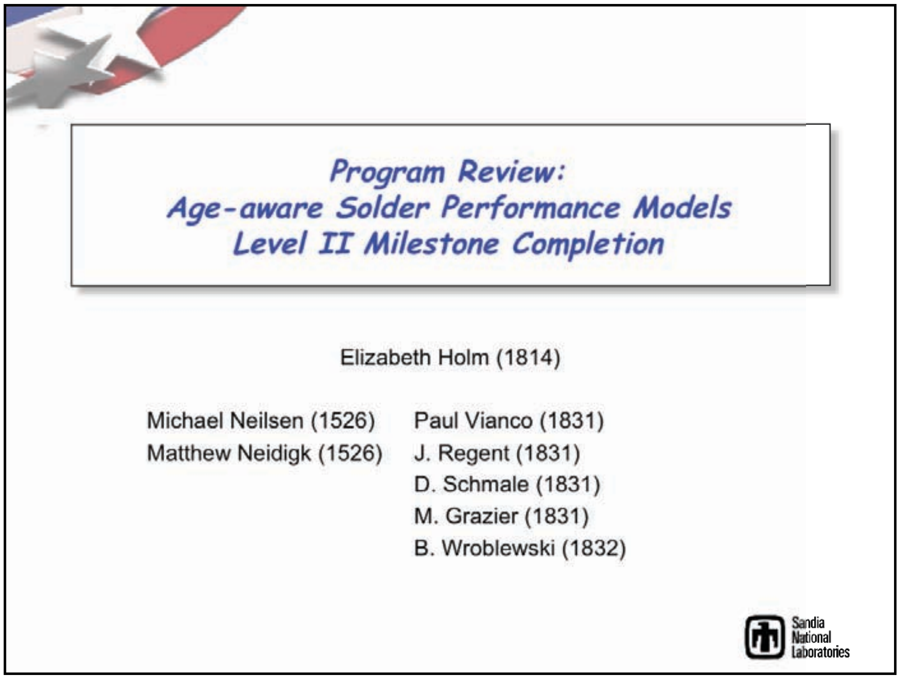
This report documents the completion of this milestone. The body of the report consists of a set of annotated slides presenting an introduction to solder joint failure; the computational approach to predicting solder joint lifetime; the success of this approach for Pb-Sn solders; and the extension and application of this method to Pb-free solders. The slides conclude by providing evidence that the milestone completion criteria were met.

These slides were presented to ASC management and the weapons customer at a Program Review, which took place at Sandia New Mexico on August 25, 2010. Attendees included Elizabeth Holm (Principal Investigator), R. Allen Roach (ASC Physics and Engineering Models Project Manager), Joel Lash (ASC Physics and Engineering Models Program Element Manager), and Pierrette Gorman (Electronic Neutron Generator Design Customer). Documentation of this review is contained in Appendix A.

As shown in the presentation materials, the SIP package was extended to incorporate Pb-free solder alloys. The Pb-free SIP code was applied to model mechanical response in compression and ring-and-plug tests, as well as in the Joint Group on Pollution Prevention test vehicle circuit board. The results were validated against experimental data with excellent agreement, meeting completion criterion (1). The validated Pb-free SIP model was subsequently applied to support the selection of a Pb-free solder alloy for the Electronic Neutron Generator (ELNG), which will be the first use of Pb-free solder in a stockpile component. The Pb-free SIP model was instrumental in making the design decision for Pb-free solder, and its utilization meets completion criterion (2). Further details on the model and validation experiments can be found in the papers listed in Appendix B.

With the completion of this Level 2 milestone, Sandia adds a predictive capability for Pb-free solder aging and reliability to the suite of solder design and evaluation codes developed under ASC. This milestone enables designers to utilize new, required materials – Pb-free solders – with confidence in their performance and reliability in new, replacement, or retrofit circuit boards.

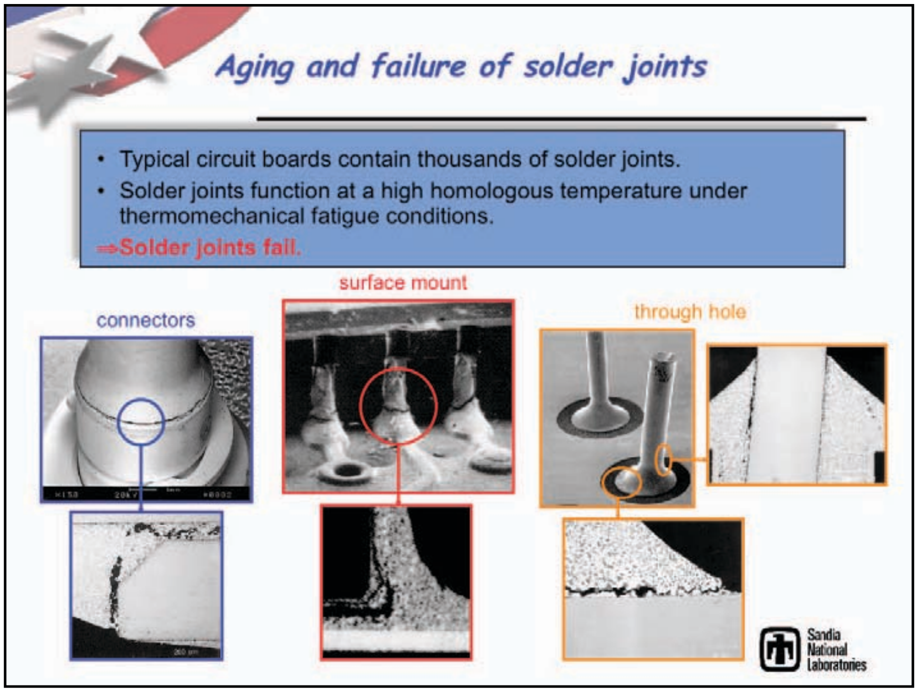
2. Annotated Program Review Slides



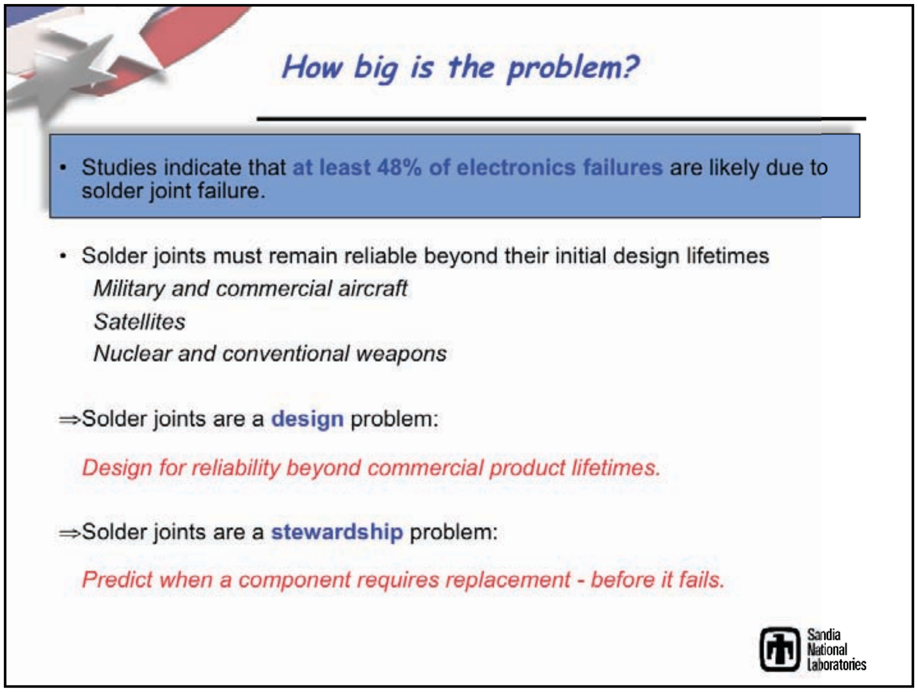
Holm is the project Principal Investigator.

Neilsen and Neidigk performed the modeling and simulation in support of the Level 2 Milestone.

Vianco, Regent, Schmale, Grazier, and Wroblewski performed the validation experiments.



Photos are from a variety of solder joints studied at Sandia.

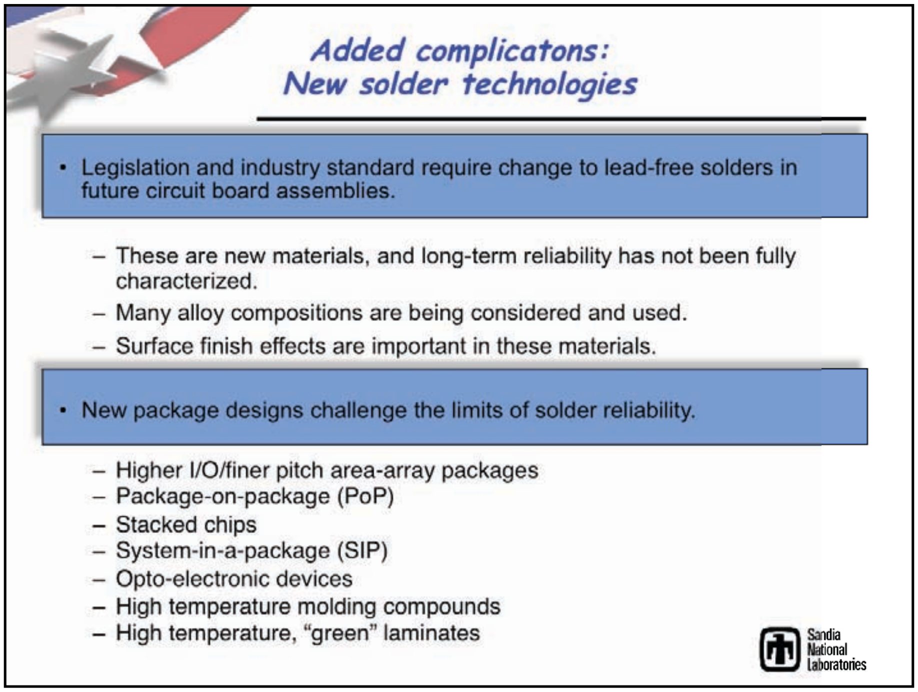


The statistic that 48% of electronics failures comes from post-mortem analysis of stockpile components at Sandia.

Specifically, In 80% of weapons electronics failures, a component is pulled and replaced. In 60% of these cases, the component tests normal.

When the component tests normal, the conclusion is that it was the solder joints connecting the component to the board that have failed.

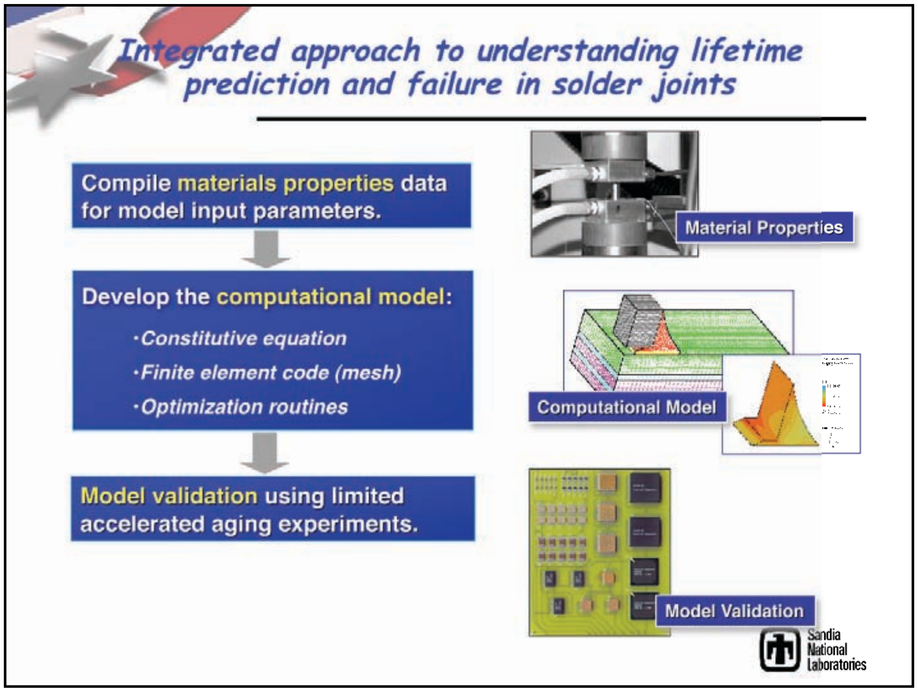
However, the act of pulling the component off destroys the solder joints, so the failure is not observed directly.



Government applications, including Sandia’s NW components, have an exemption from the Pb-free requirement.

However, manufacturers are moving towards all Pb-free shops, as the vast majority of their business is now Pb-free.

Thus, Sandia is under pressure to go Pb-free even though it is not legislated.


Integrated approach to understanding lifetime prediction and failure in solder joints
Compile materials properties data for model input parameters.
Develop the computational model:
·Constitutive equation
·Finite element code (mesh)
·Optimization routines
Model validation using limited accelerated aging experiments.
Material Properties
Computational Model
Model Validation
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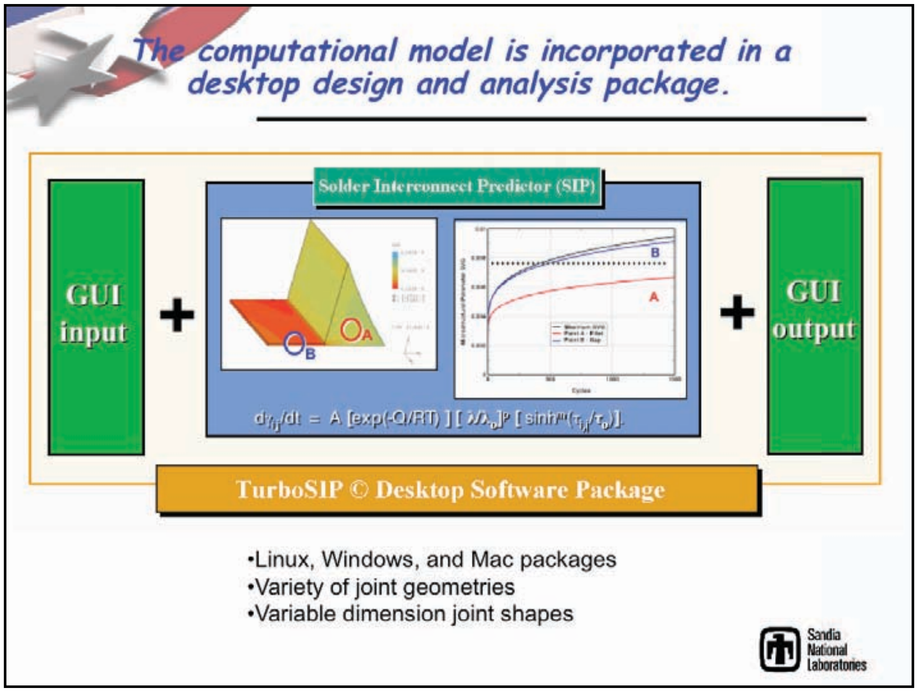
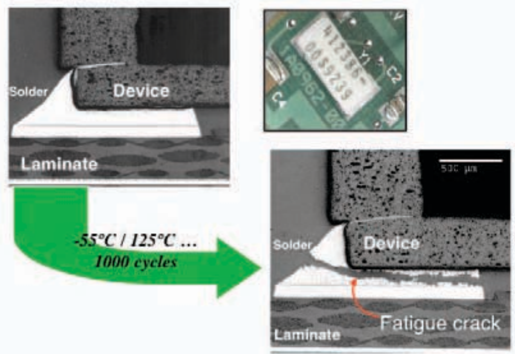


TurboSIP is the desktop package that models individual solder joints.

SIP is the solder model that is implemented in both TurboSIP (for single solder joints) and SIERRA (for larger scale calculations, including whole circuit boards).

Validation and application of SIP for eutectic Pb-Sn solders

- Pb-Sn solder predominates in the current and anticipated stockpile.
- SIP has been widely applied to stockpile components.



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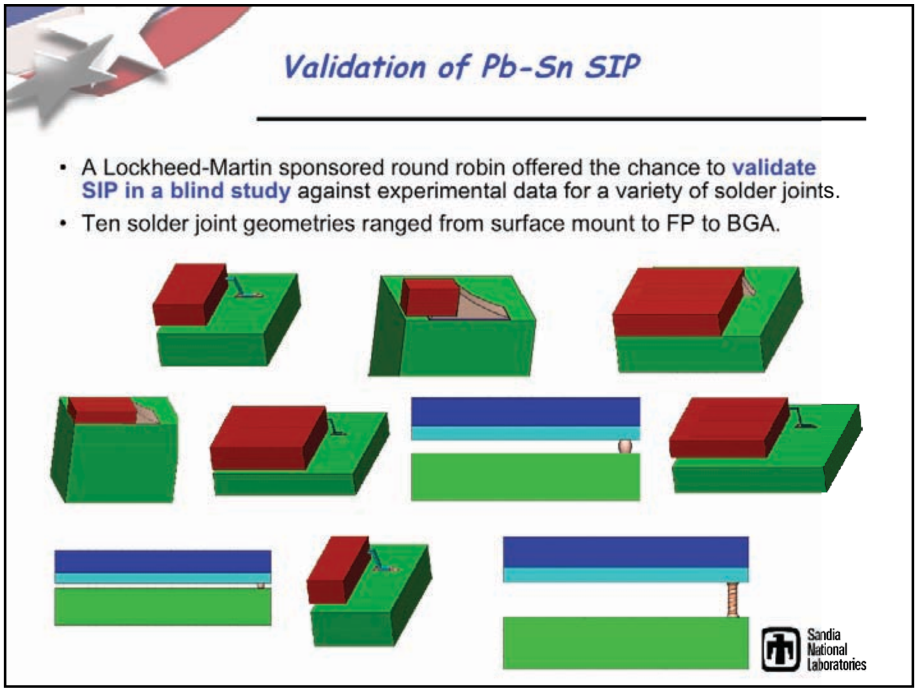
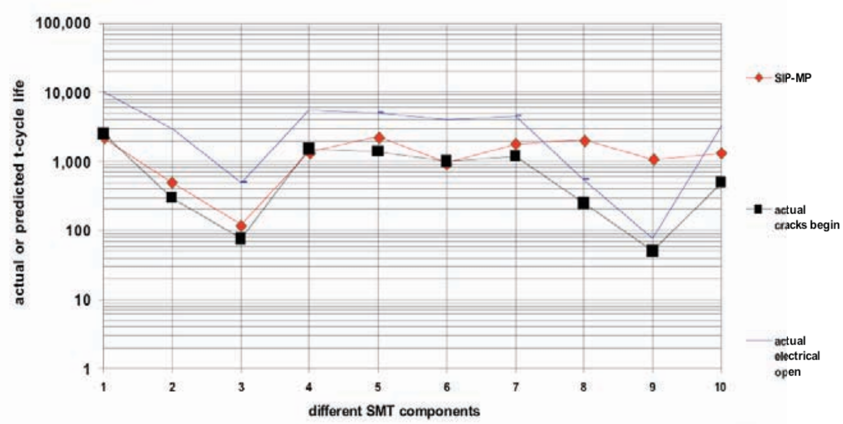
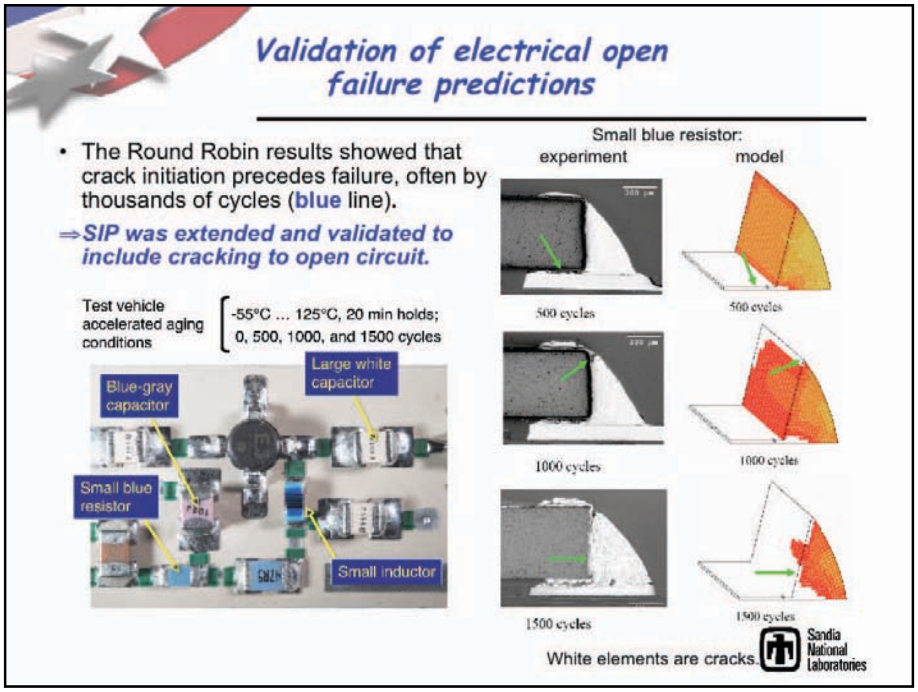


The ten solder joint geometries are shown in no particular order.

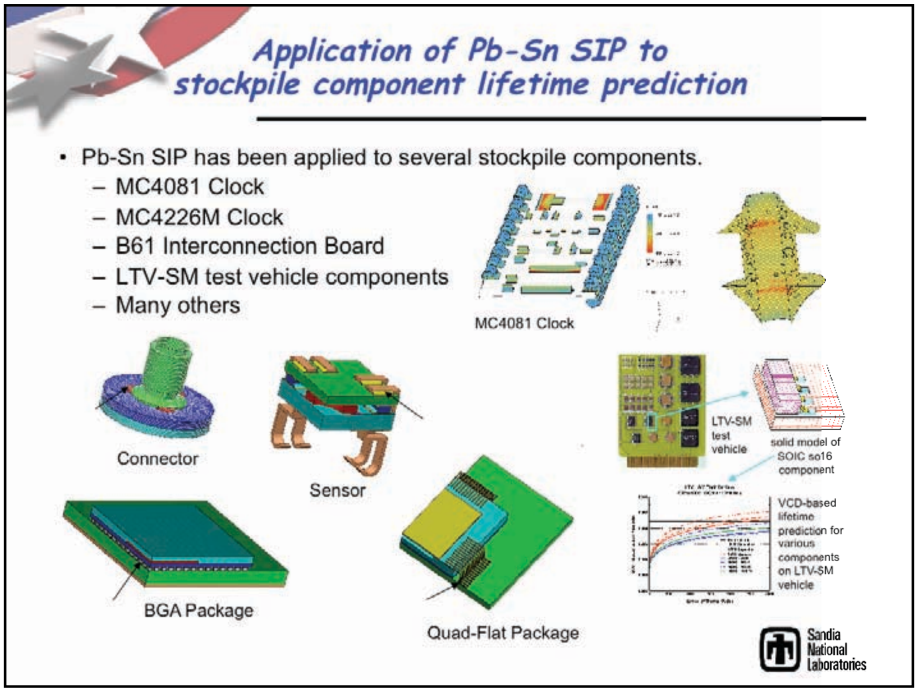
Validation of crack initiation predictions

- SIP crack initiation predictions (**red** line) agreed very well with experiment (**black** line) for most joint types.
- Components 8 and 9 demonstrated mesh refinement issues that have been addressed.





The crack model uses very soft, elastic elements to represent the crack.


Application of Pb-Sn SIP to stockpile component lifetime prediction
• Pb-Sn SIP has been applied to several stockpile components.
– MC4081 Clock
– MC4226M Clock
– B61 Interconnection Board
– LTV-SM test vehicle components
– Many others
MC4081 Clock
Connector
Sensor
LTV-SM test vehicle
solid model of SOIC so16 component
VCD-based lifetime prediction for various components on LTV-SM vehicle
BGA Package
Quad-Flat Package
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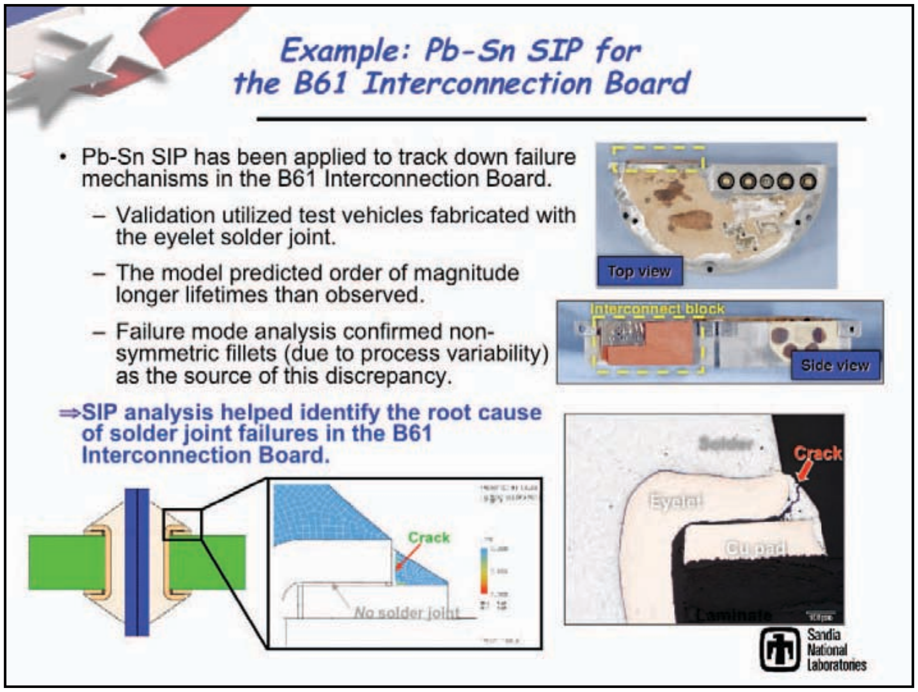


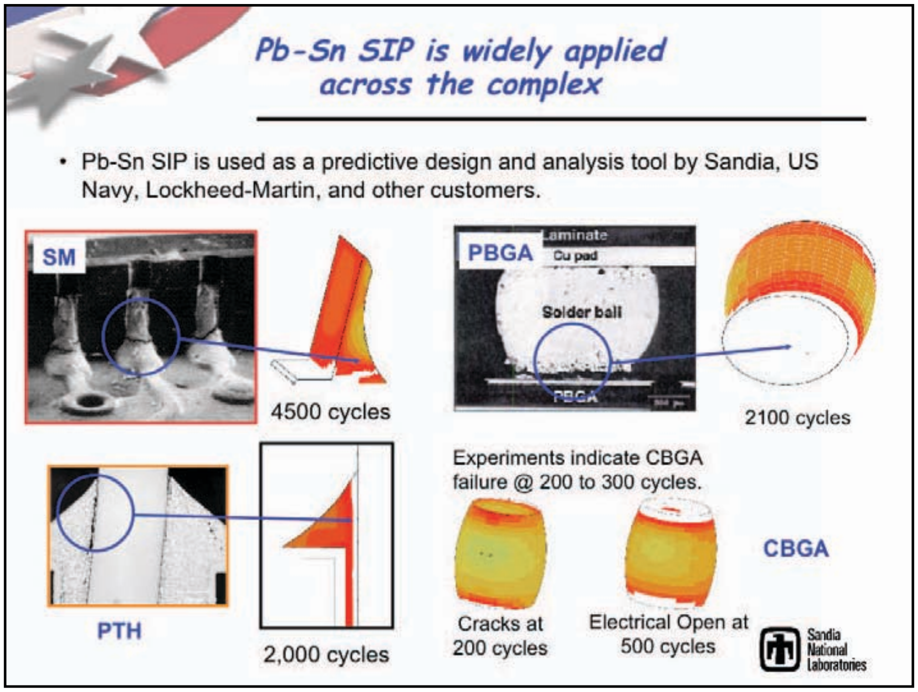
A pseudo-quantitative validation of these predictions was developed, using test vehicles fabricated with the eyelet solder joint, which were then subjected to thermal cycling and thermal shock environments

.•The model predicted longer lifetimes than observed in the available thermal shock test vehicles.

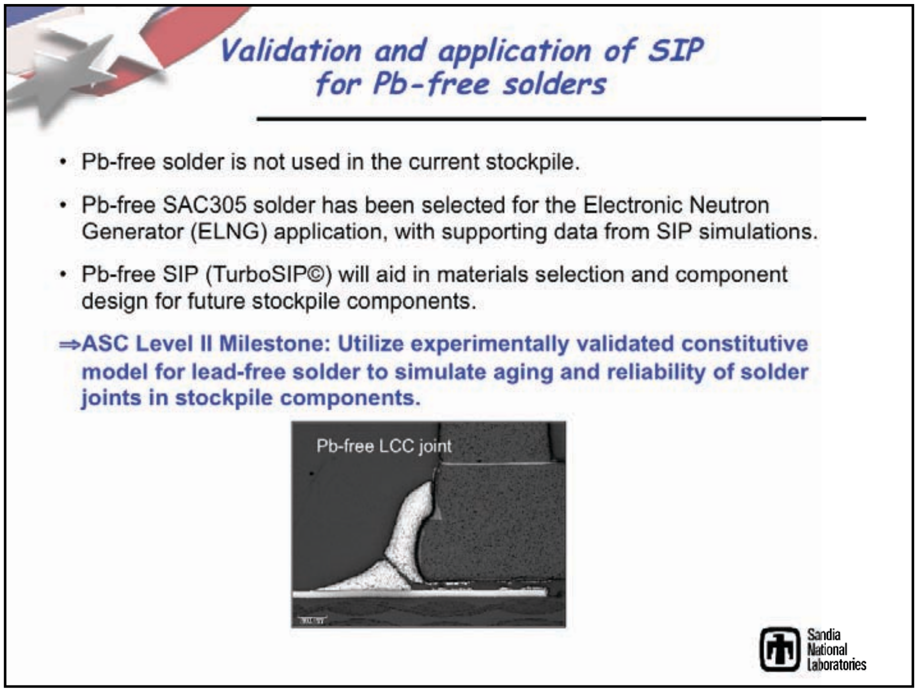
•The discrepancy was an order of magnitude; factors of 2x to 3x were anticipated from historical results.

•Failure mode analysis and those test vehicles confirmed non-symmetric fillets as the source.

Although the test vehicle data could not provide a deterministic validation of the model predictions, the validation “bound” those predictions so that a root-cause was identified for the failure.

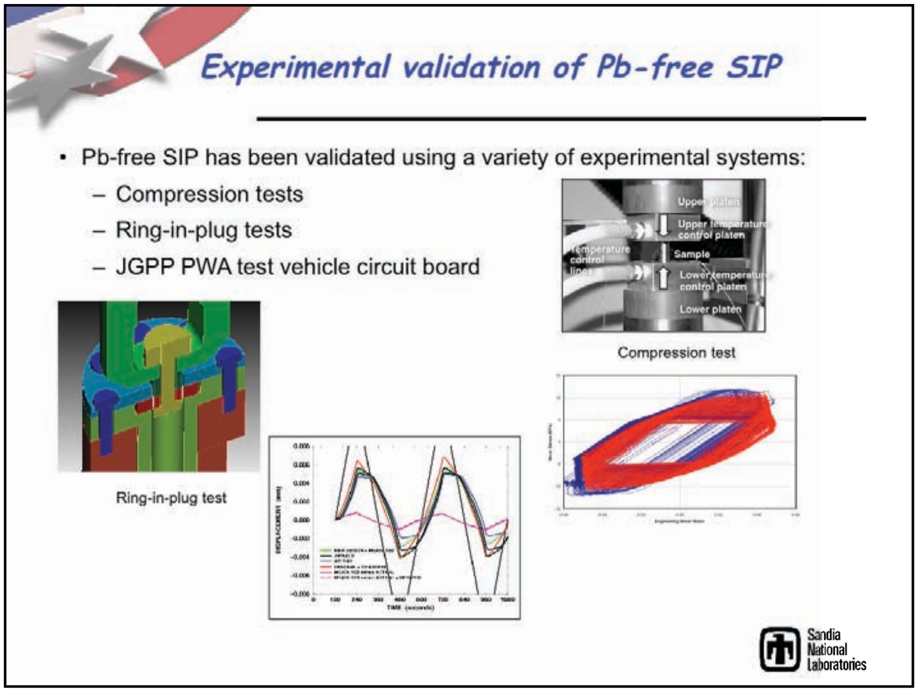


The pictures show applications of SIP for Sandia and other customers. The agreement between SIP predictions of crack location and actual observations validates the model.



SAC305 = 96.5Sn-3.0Ag-0.5Cu

The ELNG will be the first application of Pb-free solder in the stockpile. Selection of Pb-free solder was supported by SIP simulations.



In the compression test, the blue data is the model; the red is the experiment. Individual cycles agree well both at early and late times.

In the RIP test, the green curve is the measured displacement and the blue is the actual (i.e. from the FEM model).

Example: JGPP PWA test vehicle validation of Pb-free SIP

- The Joint Group on Pollution Prevention (JG-PP) Pb-free Solder Project is a partnership between DoD, NASA and OEMs, created to examine the reliability of solder joints when exposed to harsh environments representative of NASA and DoD operational conditions.
- SNL participation in the JG-PP consortium provides PWA test vehicle data for validation of the model over a range of component geometries.
  - Example: BGA225 component
    - Model and experiment agree on crack location.
    - SIP predicts crack initiation and open circuit failure at comparable cycles to experimental observations (within ±35%).
    - In this component, simulations and experiments confirm that Pb-free solder has a longer lifetime than Pb-Sn solder.
  - Other components have been tested with similar results.

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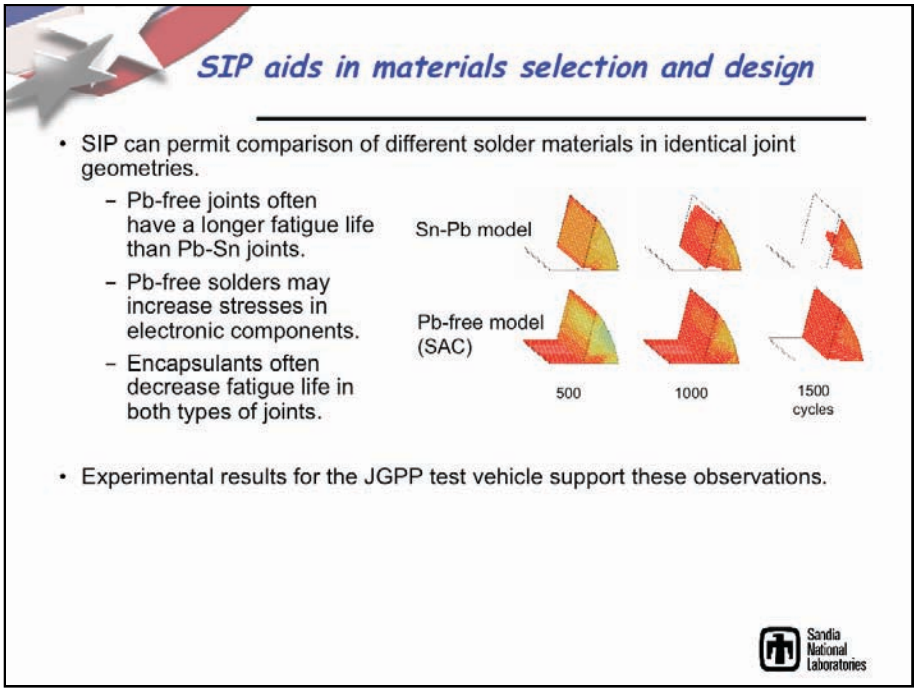
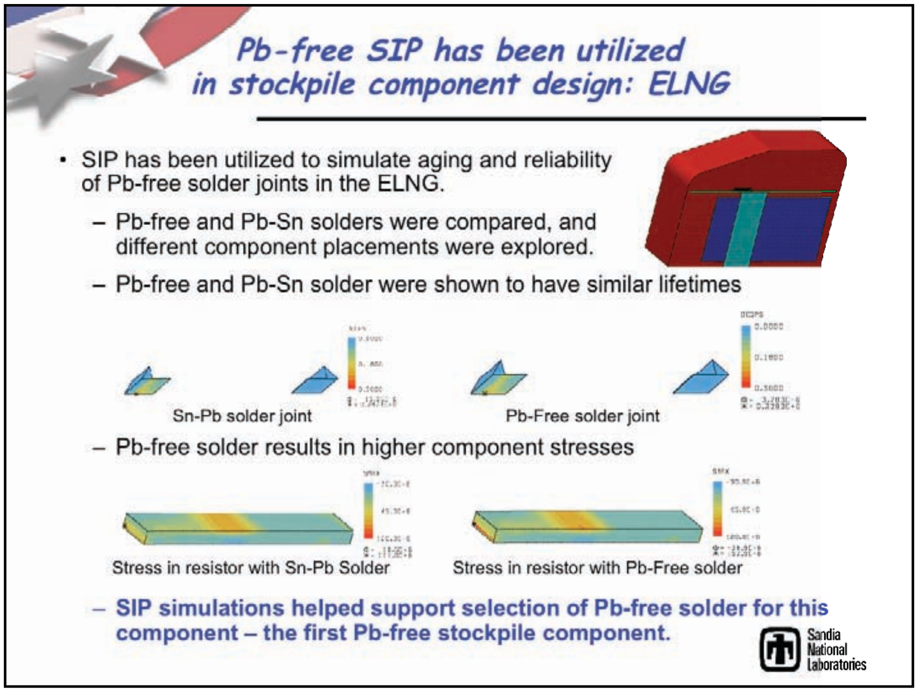


The pictures show identical solder joints under identical conditions, except that the top joint is Pb-Sn, and the bottom one is Pb-Free solder.

White elements are cracks. It is apparent that the Pb-Sn joint cracks and fails sooner than the Pb-free joint.



The upper set of results show the solder joint itself.

The color scheme gives the DEQPS (change in equivalent plastic strain), which is a measure of the damage per thermal cycle for the solder joint.

Because the DEQPS is about the same for Sn-Pb and Pb-free joints, the lifetime is similar as well.

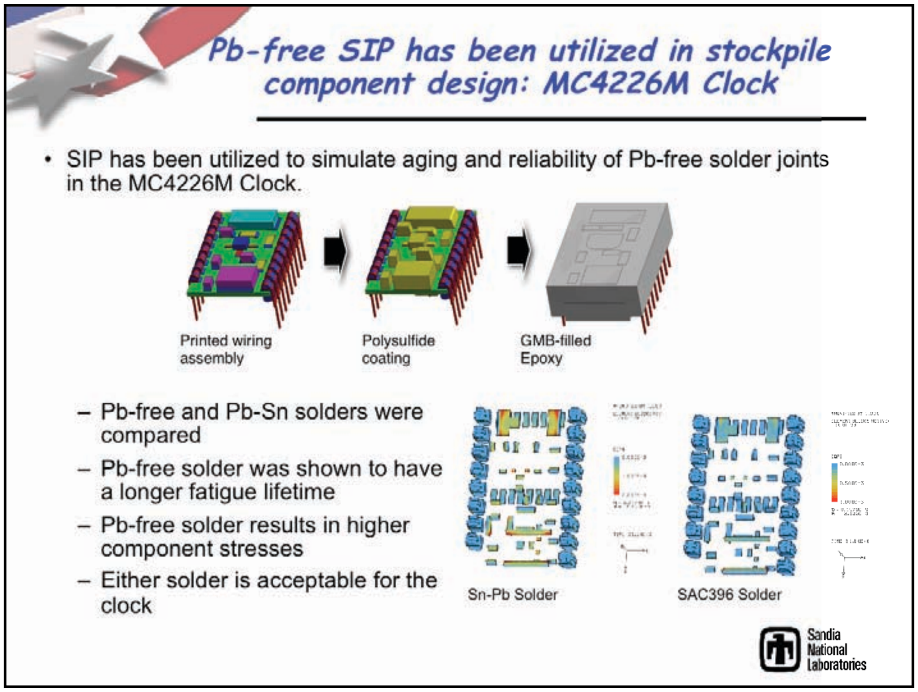
The lower set of figures is for the component, a ceramic resistor.

The color scheme gives the maximum stress.

The Pb-free system (on right) has a higher stress concentration in the resistor at the location of the solder joint.

However, all stresses are within design tolerance.

The Pb-free solder here is SAC396 (Sn-3.9Ag-0.6Cu)

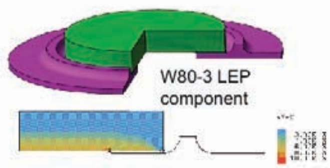


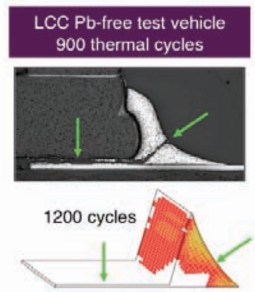
Note that these full circuit board simulations were performed using SIP in a full, FEM based implementation on ASC HP computers.

The FEM engine used was SIERRA, and the simulation used 878,066 elements run on 160 processors of an ASC-TLCC machine.

Pb-free SIP is being applied across the complex

- Pb-free SIP is being exercised as a predictive design and analysis tool by customers at Sandia, Lockheed-Martin, and the US Army.





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Advantages of the SIP approach:

- Supports the design process
- Provides design flexibility
- Decreases experimental trials
- Identifies potential failures early
- Prioritizes retrofit/replacement efforts
- Improves design for reliability
- Permits lifetime prediction
- Certifies lifetime extension

….Decreases cost, risk, and uncertainty.

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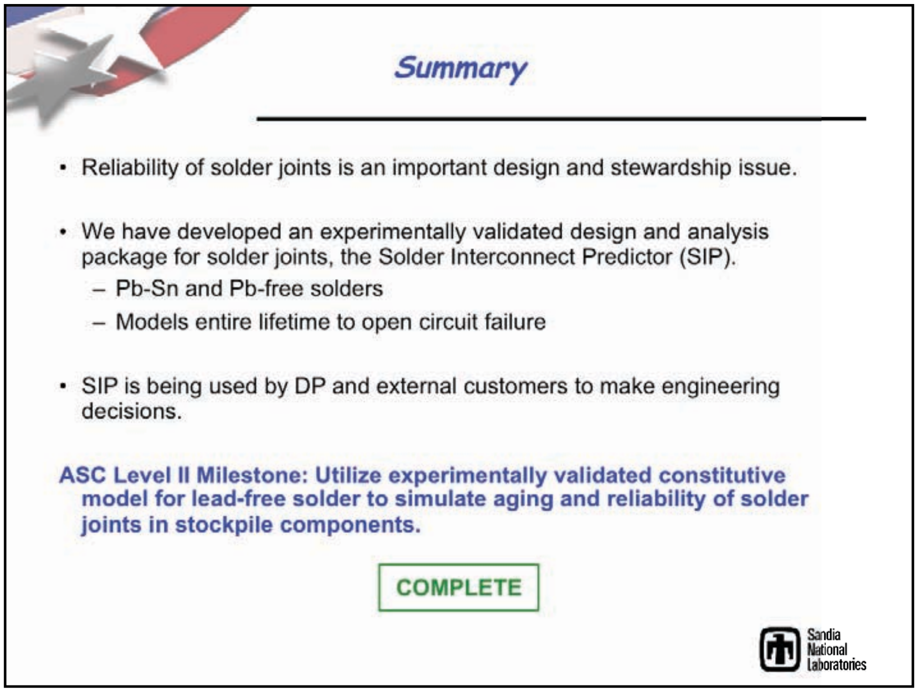
Summary
• Reliability of solder joints is an important design and stewardship issue.
• We have developed an experimentally validated design and analysis package for solder joints, the Solder Interconnect Predictor (SIP).
– Pb-Sn and Pb-free solders
– Models entire lifetime to open circuit failure
• SIP is being used by DP and external customers to make engineering decisions.
ASC Level II Milestone: Utilize experimentally validated constitutive model for lead-free solder to simulate aging and reliability of solder joints in stockpile components.
COMPLETE
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Appendix A. Documentation of Program Review

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date: September 10, 2010

to: Julia Phillips, 1200, ASC Program Director

from: Joel Lash, 1510, ASC P&EM Program Element Manager

subject: Completion of ASC FY10 Level 2 Milestone 3605

This memo documents the Program Review for ASC FY10 Level 2 Milestone 3605: Utilize experimentally validated constitutive model for lead-free solder to simulate aging and reliability of solder joints in stockpile components.

The one-hour Program Review took place at Sandia New Mexico on August 25, 2010. Attendees included Elizabeth Holm (Principal Investigator), R. Allen Roach (ASC Physics and Engineering Models Project Manager), Joel Lash (ASC Physics and Engineering Models Program Element Manager), and Pierrette Gorman (Electronic Neutron Generator Design Customer).

During the review, Dr. Holm presented background and evidence of completion of the Level 2 Milestone. Attendees asked questions and provided feedback. At the conclusion of the meeting, it was agreed that the milestone completion criteria had been met.

Customer feedback was quite positive, including confirmation that the lead-free constitutive model had been instrumental in the materials selection process for the Electronic Neutron Generator.

ASC Program feedback was also supportive, indicating that this milestone is an excellent example of the ASC model.

Based on the Review and feedback, it is our conclusion that Milestone 3605 has been successfully completed.

Concurrence Signatures:

Joel Lash, 1510 R. Allen Roach, 1814 Pierrette Gorman, 2732

[Original, signed copy is on file at ASC Program Office.]

Appendix B. Selected Bibliography of Supporting Papers

For further information on the solder joint model and validation, see the following papers:

A.F. Fossum, P.T. Vianco, M.K. Neilsen, D.M. Pierce, ‘A Practical Viscoplastic Damage Model for Lead Free Solder,’ *J. Electron. Packag.*, Vol. 128, pp. 71-81, March 2006.

D.M. Pierce, S.D. Sheppard, A.F. Fossum, P.T. Vianco, and M.K. Neilsen, ‘Development of the Damage State Variable for a Unified Creep Plasticity Damage Constitutive Model of the 95.5Sn-3.9Ag-0.6Cu Lead-Free Solder,’ *J. Electron. Packag.*, Vol. 130:011002, March 2008.

D.M. Pierce, S.D. Sheppard, P.T. Vianco, J.A. Regent, J.M. Grazier, 'Validation of a General Fatigue Life Prediction Methodology for Sn-Ag-Cu Lead-Free Solder Alloy Interconnects,’ *J. Electron. Packag.,* Vol. 130:011003, March 2008.

D.M. Pierce, S.D. Sheppard, and P.T. Vianco, 'A General Methodology to Predict Fatigue Life in Lead-Free Solder Alloy Interconnects,' *J. Electron. Packag.*, Vol. 131:011008, March 2009.

D.F. Susan, A. C. Kilgo, M.K. Neilsen, and P. T. Vianco, ‘Accelerated aging and thermal-mechanical fatigue modeling of Cu-plated through holes with partial solder filling,’ *Intl. J. Materials and Structural Integrity*, Vol. 2, pp. 138 – 163, 2008.

D.F. Susan, A.C. Kilgo, P.T. Vianco, and M.K. Neilsen, 'Thermal Fatigue and Failure Analysis of Cu-Plated Through Hole Solder Joints,' *Microscopy and Microanalysis*, Vol. 15, pp. 26-27, 2009.

M. Neilsen, P. Vianco, A. Kilgo, E. Holm, “A Capability to Model Crack Initiation and Growth in Solder Joints,” *Proc. IPACK2009*, IPACK2009-89230 (ASME Press, San Francisco, CA, 2009).

E. A. Holm, M. K. Neilsen, P. T. Vianco, A. C. Kilgo, “Modeling the Aging and Reliability of Solder Joints,” *Advances in Materials Science*, D. Kusnezov and O. Shubin (eds.) (DOE OSTI, Washington, DC, 2009, ISBN 978-1-61584-923-9) pp. I-10 – I-14.

P. T. Vianco, J. M. Grazier, J. A. Rejent, A.C. Kilgo, F. Verdi, and C. Meola, ‘Temperature cycling of Pb-free and mixed solder interconnections used on a package-on-package test vehicle,’ *Proc. Surface Mount Tech. Assoc.* (Surface Mount Technology Association, Edina MN, 2010).

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