Underfilling Micro-BGAs

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Abstract

Micro-BGAs and chip scale packages have been developed as an alternative to direct flip chip attachment for high-density electronics. The larger solder sphere diameter and higher standoff of CSPs and micro-BGAs improve thermal cycle reliability while the larger pitch relaxes wiring congestion on the printed wiring board [1]. Micro-BGAs and CSPs also allow rework to replace defective devices. Thermal cycle reliability has been shown to meet many consumer application requirements. However, micro-BGAs and CSPs have difficulty meeting mechanical shock and substrate flexing tests for portable electronics applications.

The micro-BGA used in the study is a 10mm package with the die wire bonded. The package substrate is BT and the solder sphere diameter is 0.56mm. Two types of underfill were examined. The first was a fast flow, snap cure underfill. This material rapidly flows under the package and can be cured in five minutes at 165°C using an in-line convection oven. The second underfill was a thermally reworkable underfill for those applications requiring device removal and replacement. The paper discusses the assembly and rework process. In addition, liquid-to-liquid thermal shock data will be presented along with mechanical shock/flexing test results.

Introduction

In the continuing push to increase functional densities for portable electronics, semiconductor packages are being reduced in size or eliminated. With the exception of 3-dimensional packaging, flip chip provides the ultimate in size reduction. However, a number of factors have limited the widespread use of flip chip technology. These factors include testability, standardization, die-shrink, PWB routability, rework and the underfilling process. Chipscale packages and microBGAs have been developed to address these issues. The larger solder sphere diameter and higher standoff of CSPs and micro-BGAs improve thermal cycle reliability while the larger pitch relaxes wiring congestion on the printed wiring board [1]. Micro-BGAs and CSPs also allow rework to replace defective devices. Thermal cycle reliability has been shown to meet many consumer application requirements. However, micro-BGAs and CSPs have difficulty meeting mechanical shock and substrate flexing tests for portable electronics applications. Underfills are being used to improve the mechanical reliability of area array packages [2]. Underfilling adds process steps to the assembly process and potentially limits reworkability.

In this paper the manufacturing process with underfill is explored along with the process for reworking with a thermally reworkable underfill. Liquid-to-liquid thermal shock, drop tests and flexing tests were used to characterize the reliability of the test vehicle.

Test Vehicle Design and Assembly

The microBGA selected for this project was a 108 I/O, 0.8mm pitch, 10mm x 10mm package from Abpac. A cross-section of the device is shown in Figure 1. The die is 4mm x 4mm and is wire bonded to the BT substrate. The solder spheres are arranged in a 3-row perimeter configuration. The solder spheres are outside the area of the die, although the die is near the inner row of solder spheres. This design is expected to perform well in thermal shock or cycling. A larger die would place more stress on the solder joints.

The printed wiring board was designed to hold 5 of the 108 I/O microBGAs and 5 of a

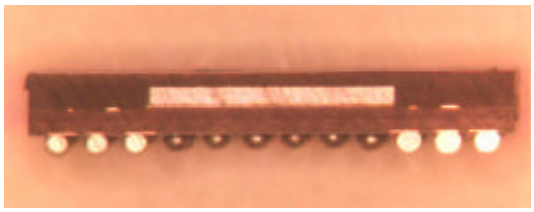


Figure 1. Cross-Section of MicroBGA

smaller 48 I/O microBGA. The smaller microBGA was not used in this test. The board was a four layer design. The two internal layers were a checker board pattern with 50% copper coverage to simulate a typical four layer design. The two outer layers were designed with the required interconnect pattern. The design would allow assembly and testing of microBGAs on both sides of the PWB. Only one side was assembled for this test. The PWB was 2.96" x 7.2" x 0.039" thick. The PWB was fabricated with FR4-06 laminate and the surface finish was electroless nickel/immersion gold. 'Black pad' is an issue with electroless nickel/immersion gold, particularly with area array packages [3]. The authors are familiar with the problem, but no evidence of failures related to 'black pads' were observed with these boards.

No-clean eutectic solder paste was stencil printed using an MPM AP automatic printer and a 0.005" thick chem-etch stencil. The solder paste print was inspected prior to assembly. The microBGAs were placed from waffle packs using a Siemens F5 pick and place system and reflowed in a Heller Industries 1700 reflow oven. After reflow, the parts were inspected and electrically tested.

Two underfill materials were used in this study: Loctite 3566 and 3567. Loctite 3566 is an unfilled, fast flow, snap cure underfill. Maximum underfill speed is achieved by not including fillers in the formulation. The coefficient of thermal expansion (CTE) is 50ppm/^{o}C below the T_g (135°C by DSC) and 170ppm/^{o}C above the T_g. With a cure schedule of 5 minutes at 165°C, this material was developed for maximum through-put in underfilling CSPs and microBGAs. It is not reworkable.

Loctite 3567 is a thermally reworkable underfill. The filler content is 30%. The CTE is 65ppm/^{o}C below the T_g (94°C by TMA) and 190ppm/^{o}C above the T_g. The cure schedule is 15 minutes at 165°C.

A Cam/Alot 3700 fluid dispense system with the volumetric measurement system was used to underfill the microBGAs. The boards were heated to 85°C for dispense to increase the underfill flow rate. After underfilling, the parts underfilled with 3566 were cured using a conveyer oven with a 5-minute, 165°C profile. The 3567 underfilled parts were cured in a box oven for 15 minutes at 165°C.

MicroBGA Removal

Loctite 3567 is designed to breakdown when heated to solder reflow (rework) temperature. This breakdown of the thermoset network is a result of the incorporation of a patented monomer which has a special linkage designed to break apart upon heating. The breakdown of the network reduces the adhesion allowing easy removal of the microBGA. The underfill is also now ready for easy removal from the network breakdown.

The microBGAs were removed using a Flomaster Rework Station, with hot air nozzles positioned above and below the site. The air above the microBGA was set to 220°C (machine measurement) and the air below was set to 175°C. After 10-25 seconds, the microBGA was removed from the board using tweezers and a twisting motion. The site after microBGA removal is shown in Figure 2. Most of the underfill materials remains on the board and must be removed prior to assembly of the new microBGA.

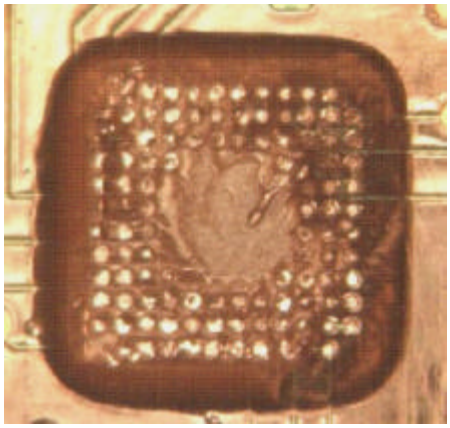


Figure 2. MicroBGA Site after Removal

Mechanical brushing is used to clean the die site. For this work, a hand held Dremel tool was used with a flat-end horsehair brush. While cleaning, the brush must apply a minimal amount of pressure on the board, and move slowly across the site to allow removal of all residual adhesive. It is easiest to concentrate first

on the fillet, which has the greatest amount of adhesive, then move to the center of the die site once the fillet has been cleaned.

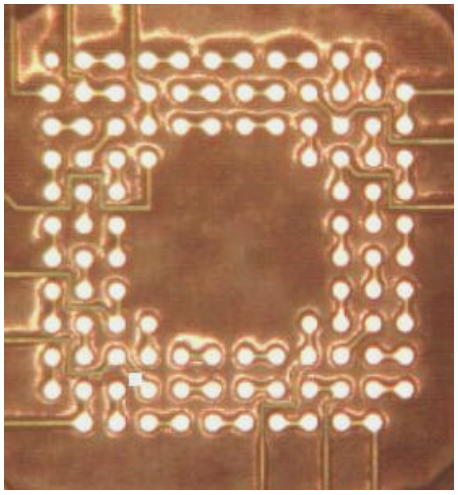


Figure 3. MicroBGA Site Cleaned and Ready for Assembly.

Under high magnification, no residue or damage was seen. The goal is to clean just long enough to remove all adhesive (Figure 3). There is some abrasion of the solder mask that results in a matte appearance. Excess brushing increases the chances of board damage. Harder solder masks are preferred, as they are less prone to damage. The site can be cleaned with isopropyl alcohol to remove any debris.

A custom cleaning machine has been designed by Loctite and fabricated (Figures 4 and 5). The machine provides x, y and z control.

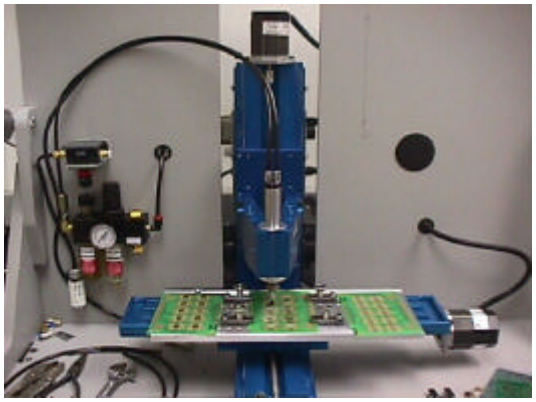


Figure 4. Site Preparation Station

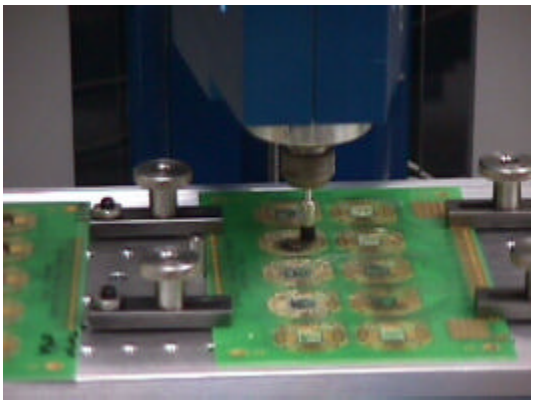
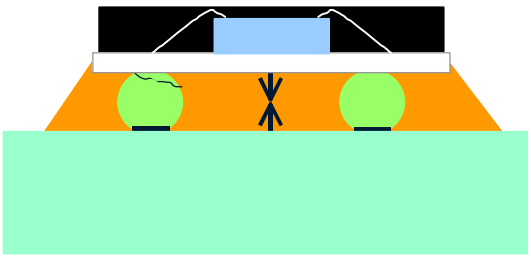


Figure 5. Close-up of Site Cleaning

In this work, all five microBGAs were removed from an assembled and underfilled board. After microBGA removal and site preparation, the boards were reassembled and underfilled with Loctite 3567 using the procedure previously described for new board assembly.

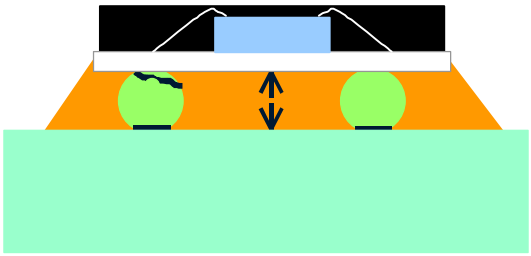
Thermal Shock Testing

Four boards (20 microBGAs) from each group (non-underfilled, underfilled with 3566, underfilled with 3567 and underfilled with 3567 and reworked) were tested in liquid-to-liquid thermal shock. The cycle was from -40°C to +125°C with 5 minutes at each extreme and a 1-minute transition time. In-situ monitor is required for accurate thermal shock or thermal cycle testing of underfilled microBGAs. The authors have observed failures (high resistance/open circuits) with daisy chain flip chip and microBGAs in the hot bath hundreds of cycles before the failure is observed at room temperature or at the cold extreme. This can be explained using the illustration in Figure 6. From finite element modeling, the maximum stress on the solder joint occurs at the low temperature extreme of the cycle since the ‘stress-free” temperature should be near the cure temperature of the underfill. However, at the cold temperature extreme the contraction of the underfill will hold the cracked solder joint together maintaining electrical continuity (the CTE of the solder is lower than that of the underfill).



Room Temperature

(a)



High Temperature

(b)

Figure 6. Illustration of the Need for In-situ Monitoring.

Upon heating to the high temperature extreme, the expansion of the underfill will open the crack and a failure can be measured. Thus, periodic measurements for continuity at room temperature will not discover high temperature intermittent opens and will over estimate the reliability of the connections.

The results of the thermal shock test are plotted in Figure 7. The test was terminated at 3000 cycles. No failures were observed after 3000 thermal shock cycles in the 3567 not-reworked group.

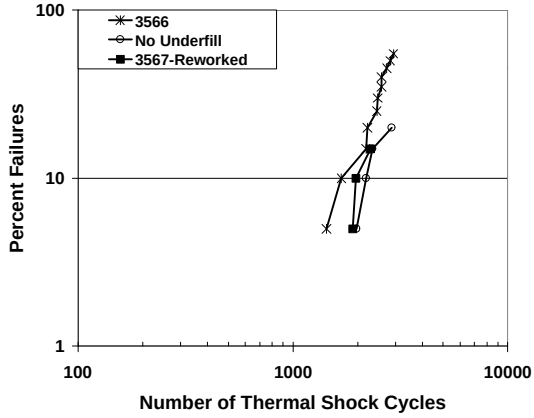


Figure 7. Plot of –40°C to 125°C Liquid-to-Liquid Thermal Shock Test Results.

All groups exceed the typical 1000 cycles required for most portable electronics applications. With the exception of two early failures with the 3566, the failure rates are similar for non-underfilled and underfilled parts. This is somewhat unexpected. Cross-sections of underfilled parts revealed voids at the base of the solder joints (Figure 8). These can be attributed to flux residue (Figure 9). Voids near flip chip solder balls can result in extrusion of solder into the void during thermal cycling and early failure. Extrusion of solder into a void and a crack in the underfill (3566) after 3000 thermal shock cycles is shown in Figure 10. Low residue solder pastes would be recommended for use with microBGAs that are to be underfilled.

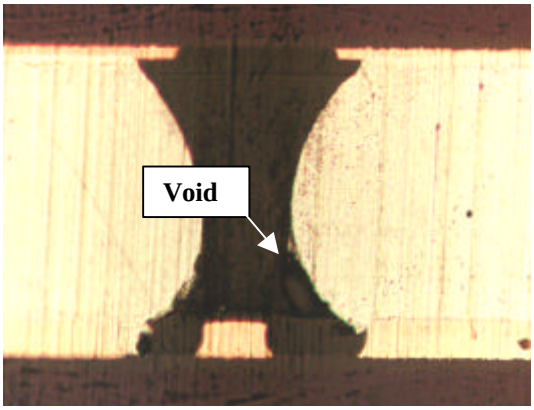


Figure 8. Example of Void in Underfill at the Base of the Solder Joint.

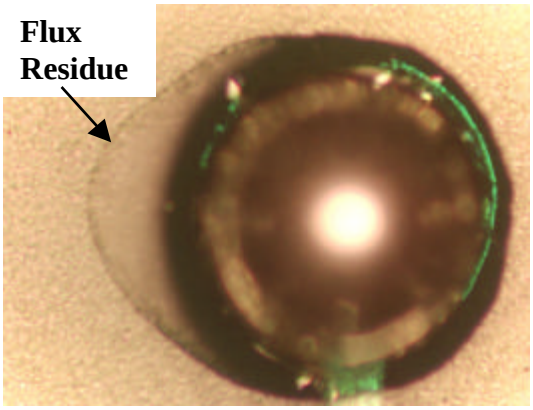


Figure 9. Close-up Photograph of Reflowed Solder Paste and Flux Residue.

Drop Test

Four boards (20 microBGAs) were drop tested for each test group. The boards were dropped through a rigid plastic tube. The tube

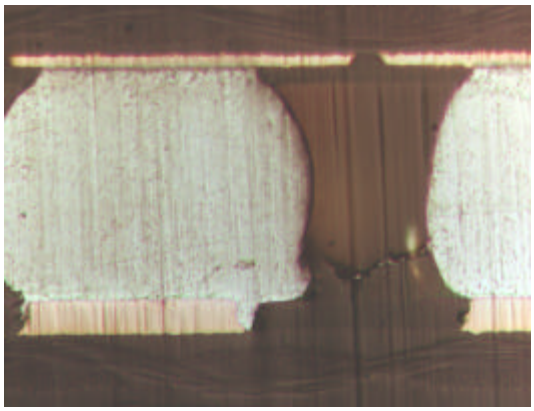


Figure 10. Cross-Section of MicroBGA Underfilled with 3566 after 3000 Thermal Shock Cycles.

was slightly larger in diameter than the board width to ensure the narrow edge of the board would impact perpendicular to the steel plate. The drop height was 6 feet. Each board was dropped 10 times. The board was dropped on alternate ends with each drop. After each drop, the resistance of each microBGA daisy chain was recorded. A 10% increase in resistance was considered a failure. The results are plotted in Figure 11.

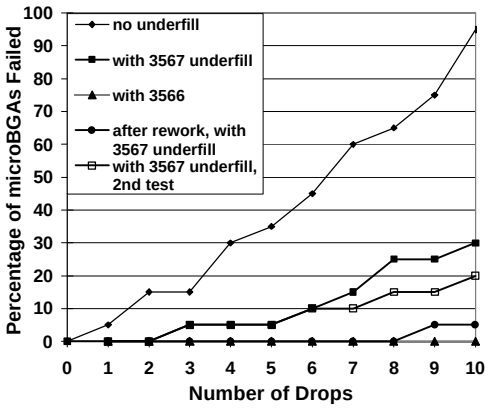


Figure 11. Results of Drop Test.

As expected the underfill significantly improved the drop test results. The reworked 3567 samples performed better than the unreworked 3567 samples. The test was repeated for the case of unreworked 3567 and the results (also plotted) are nearly the same. Figures 12 - 14 show the underfill fillet for samples that did and did not fail during the 10 drops. Cracking of the fillet is evident in the failed specimen. It is believed that the slight abrasion of the solder mask during the rework process improved the underfill-to-solder mask adhesion, improving the drop test results. Further improvement in the drop test performance of unreworked 3567 may

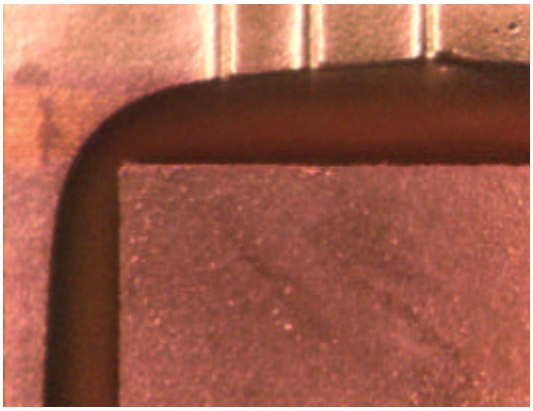


Figure 12. Fillet of MicroBGA that Did Not Fail Drop Test.

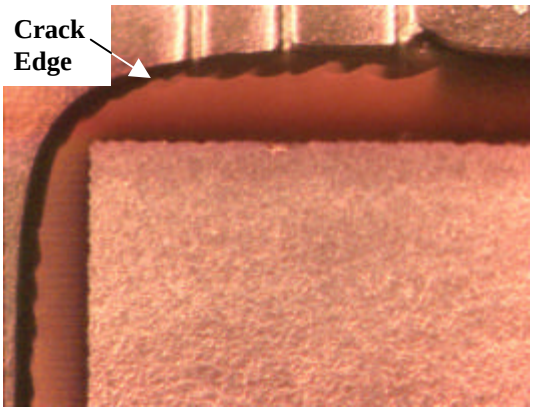


Figure 13. Fillet of MicroBGA that Did Fail during the Drop Test. The lighter area in the fillet is cracked. The resulting gap leads to the shade variation.

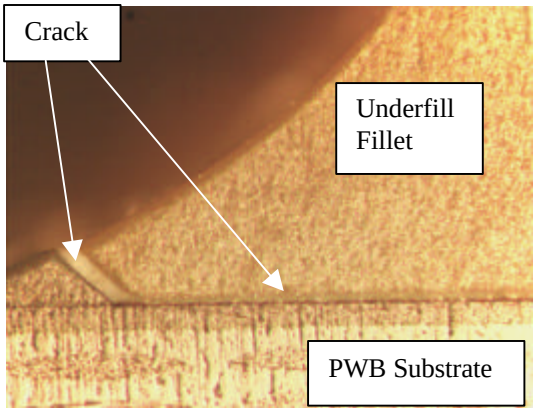


Figure 14. Cross Section of Failed MicroBGA. The runs through the fillet and along the substrate-underfill interface.

be obtained by evaluating various solder mask materials. No failures were observed with the 3566 underfill.

Flex Testing

The experimental test facility is configured as shown in the schematic diagram in Figure 15 and the photograph shown in Figure 16. The test board is simply supported at two locations by music wire tensioned in aluminum frames. Plexiglas clamps are attached to each end of the test board. They provide an extended surface for the contacting of the flexing forces that are applied to the board. A 1/4 *hp* electric motor with a torque and speed controller is used to rotate two eccentric disks around a common shaft. The disks have holes drilled at 0.5 in., 0.75 in., and 1.0 in. for insertion of the rotor shaft. This configuration allows for variation in the displacement level applied to the clamp pieces (which in turn applies forces to the test board). The disks are positioned on the shaft so that they are each equidistant from one end of the test board, so that equal forces are applied at each end. This results in the section of test board between the two simple supports being subjected to a uniform moment. All microBGAs on the test board will then (theoretically) experience the same stress level. However, local effects arising from the applied forces and from the supporting wires results in some non-uniformity of stress distribution in the vicinity of the supports. In order to minimize the impact of such effects, the testing only considers the three center chips and disregards data from the two chips closest to the supports. A data acquisition board is used to continuously monitor the resistance of the microBGA daisy chains.

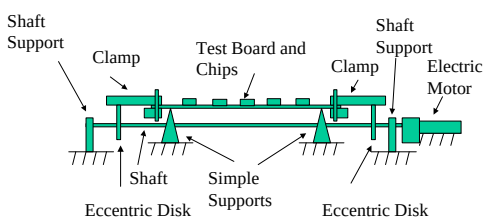


Figure 15. Schematic Diagram of Flex Testing Facility

To establish the radius of curvature for the cyclic flex testing, the ultimate static flex limit of a non-underfilled test sample was determined. Failure was observed at a bend radius of 8.76 inches. For cyclic testing the eccentric disks were set to produce a radius of curvature of 17.5 inches.

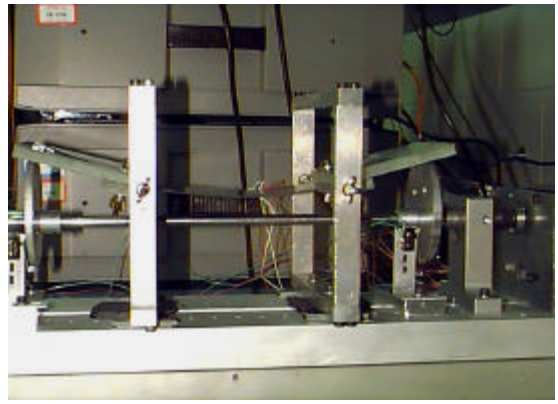


Figure 16. Photograph of Flex Testing Facility

The results from initial flex testing are presented in Table 1. Two boards (6 microBGAs) were tested for each sample type. There was little variation in the cycles to failure for the non-underfilled microBGAs indicating uniform bending for the three center microBGAs. None of the underfilled parts failed after 1250 flex cycles.

Table 1. Flex Testing Results

Sample	Average Number of Flex Cycles to Failure	Standard Deviation (cycles)
no underfill	113	8
3567 underfill	No Failures *	-
reworked, 3567 underfill	No Failures *	-
3566 underfill	No Failures *	-

* = No failures after 1250 flex cycles.

Summary

Mechanical shock and flexing requirements are the primary reason industry is considering underfills for microBGAs and CSPs. This work has demonstrated significantly improved mechanical performance with both a reworkable and a non-reworkable underfill. Reworkability is a requirement for many manufacturers. The rework process described in this paper did not degrade mechanical performance.

The microBGAs were tested in thermal shock from –40°C to 125°C. All samples exceeded 1000 cycles without failure. Use of underfill did not significantly alter the thermal shock performance. Voids at the base of the solder joint due to flux residue from the no-clean

solder paste are thought to have limited the performance of the underfilled microBGAs. Low residue solder pastes are being evaluated to increase thermal shock performance for harsh environment applications.

References

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Acknowledgements

The authors would like express thanks to Speedline MPM, Siemens Energy & Automation, Heller Industries and Speedline/CAMALOT for equipment used in this work.

This work was sponsored in part by the Center for Space Power and Advanced Electronics at Auburn University – a NASA and Industrial Partner funded Center.