Evaluation, Selection and Qualification of Replacement Reworkable Underfill Materials

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Abstract
A study was performed to investigate, evaluate and qualify new reworkable underfill materials to be used primarily with ball grid arrays (BGAs), Leadless SMT devices, QFNs, connectors and passive devices to improve reliability. The supplier of the sole source, currently used underfill, has indicated they may discontinue its manufacture in the near future. The current underfill material is used on numerous circuit card assemblies (CCAs) at several sites and across multiple programs/business areas. In addition, it is used by several of our contract CCA suppliers. The study objectives include evaluation of material properties for down select, dispensability and rework evaluation for further down select, accelerated life testing for final selection and qualification; and process development to implement into production and at our CCA suppliers. The paper will describe the approach used, material property test results and general findings relative to process characteristics and rework ability.

Introduction
This paper summarizes the approach and process development activities conducted to survey, identify, select, evaluate, test and qualify a reworkable underfill material as a replacement for qualified underfill material used in production that may be discontinued in the near future. The main objective of this effort was to identify one or more underfill materials that could be used as an alternate to the current, qualified underfill material in existing and future CCA designs. A secondary objective was to be able to incorporate the selected alternative underfill material(s) into CCA designs with minimum manufacturing process and/or equipment changes. In this way, the assemblies that were qualified for use with the current underfill would be subjected to minimal additional testing and re-qualification. In addition, the replacement underfill material(s) should preserve and enhance the solder joint integrity of the BGAs, LGAs, BTCs, leadless devices, and similar packages to the same degree the current underfill material does. Also, it was desirable for the material properties (storage conditions, shelf-life, pot life, cost, etc.), the application process and the rework method of the alternate material(s) to be similar or better/easier than for the current qualified underfill. All these attributes would either minimize the re-qualification of legacy product designs and/or ease the implementation of these alternate underfill materials.

The underfill materials are widely used in the electronics manufacturing industry to protect solder joints and improve product reliability. Surface mount area array packages (BGAs, CGAs, LGAs, CSPs, and similar leadless SMT devices) are generally the types of packages that require the use of underfill materials to improve solder joint reliability. The coefficient of thermal expansion (CTE) differences between the surface mount component package body (and/or die) and the PWB surface padscan cause the solder joints to fracture. This happens when units containing these types of devices are exposed to the temperature and mechanical stresses present at the environmental conditions in which these units operate. The continuous operation under these conditions causes solder joints to fatigue and fail. In order to reduce mechanical stresses that cause solder joint fatigue and prevent failures, underfill materials are used to encapsulate the solder joints. Application of underfills is typically accomplished by dispensing the material along one or more sides of the component with an automated dispenser and relying on capillary forces to draw the material under the component body. As the underfill flows under the device, it fills the gap between the component package and the PWB to encapsulate and protect the solder joints. Once the material is applied and cured, it helps dissipate the stresses created by the CTE differences and reduce solder joint fatigue and failure risks. The following figure illustrates the stresses caused by CTE mismatch on the solder joints of a BGA device.

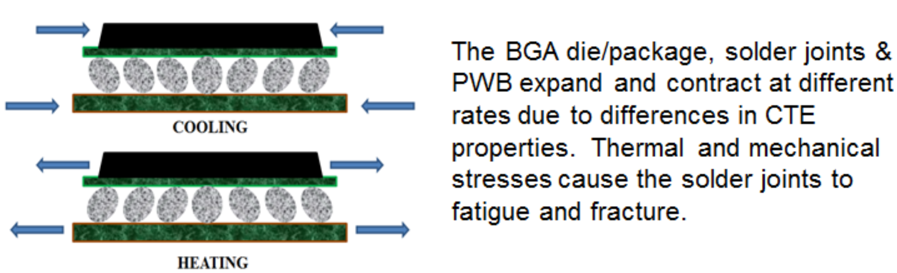

Figure 1- Stresses on a BGA package caused by coefficient of thermal expansion (CTE) mismatches.

Initial Screening and Down Selection Process for Replacement Underfill Candidates

A research activity was conducted to identify potential replacement candidates for the reworkable underfill used in production. Multiple adhesive manufacturers were surveyed and a number of potential products were selected as candidates for review. A total of ten (10) different underfill materials from six (6) manufacturers were selected for initial consideration. The technical data sheets (TDSs) of these candidates were assessed and the material properties compared against the current underfill. After this initial assessment, a group of potential eight (8) candidates from four (4) manufacturers were identified for further review. Besides technical/business considerations such as minimum buys, location of the fluid manufacturers, distributors and material packaging size, the material pot life, the recommended curing schedules and the application methods (jetting vs. positive displacement pump dispensing) were among the properties considered for the down selection process.

Samples were obtained and as-received (rheology, viscosity and pot life) and cured physical properties (CTE, modulus and Tg) were measured and compared to the current underfill. We leveraged our relationship with an industry consortium partner and discussed their experience and recommendations regarding several potential candidate materials. In addition to the material properties, other factors relevant to the underfill dispensing process were evaluated and additional screening tests were performed. The combination of the industry survey, physical property testing and consortium partner recommendations, were used to reduce the group of potential replacement underfill materials to four (4) leading candidates in order to continue the process and rework evaluation. Select physical properties from the manufacturers' TDSs for the four (4) leading candidates and the current underfill material are listed in Table 1 below.

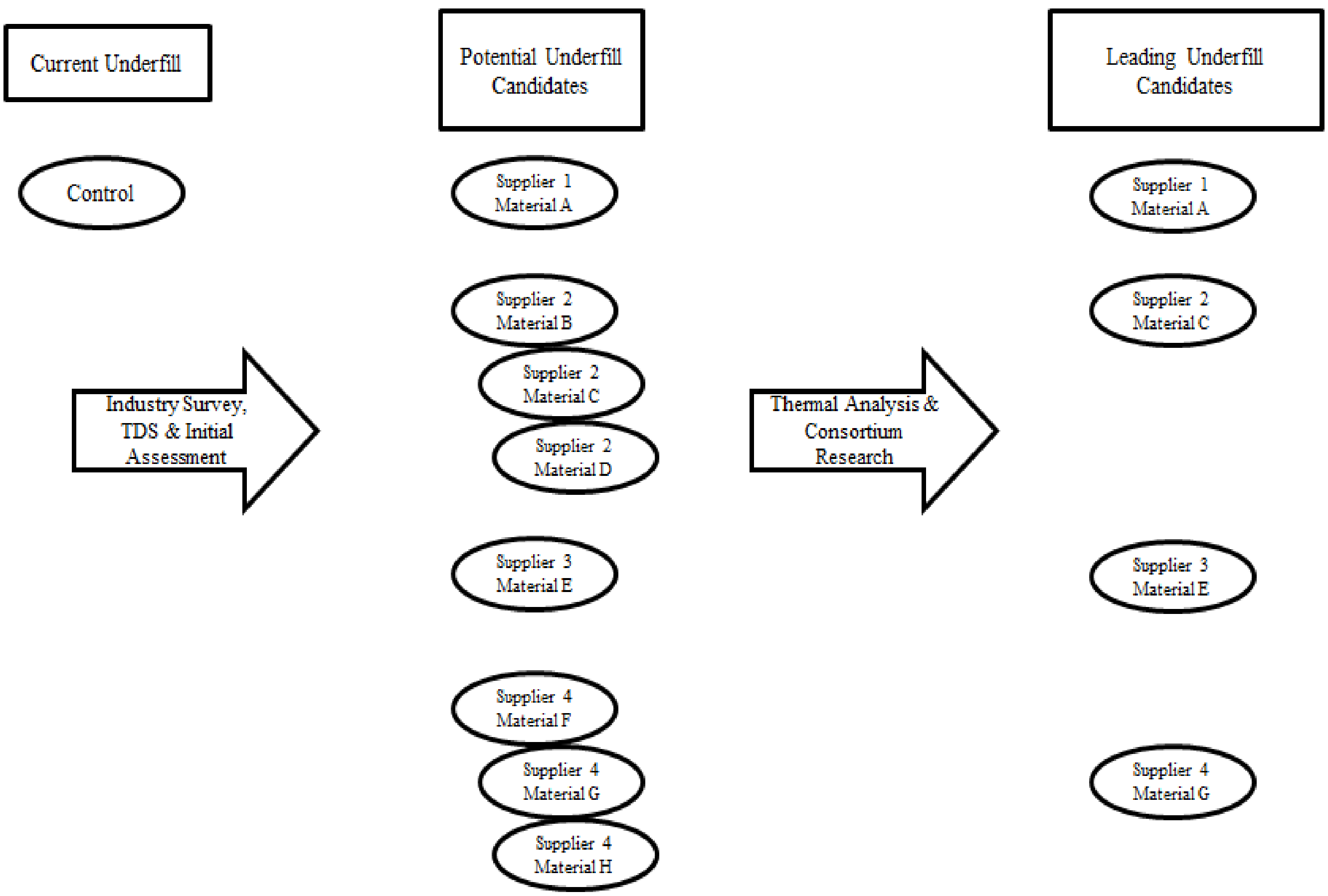

Figure 2 – Down selection process of the underfill candidates for BGA Process Development and Rework.

Table 1 - Material Properties of Control and Candidate Underfill Materials

		Material				
Physical Property	Units	Control	A	C	E	G
Tg (Vendor) by TMA	°C	70	102	100	105	80
CTE Below Tg (Vendor)	ppm/°C	40	55	38	60	31
CTE Above Tg (Vendor)	ppm/°C	145	171		180	122
Modulus (Vendor) @ 25°C	Gpa	1.4	2.99	8.6	4	3.0 (Shear)
Pot Life	Hours	30	72	36	24	36
Viscosity	cps or Pa*s	300-2000	394	1800-1900	700	1800

Test Board Development and Methodology Plan

Once the leading candidates were identified, a test board containing four (4) unique BGA device types was designed and fabricated for use during process development and accelerated life testing (ALT). Thetest board was a single-sided PWB, with approximate dimensions of 8" x 10" and a thickness of 0.07". It was constructed usinga high Tg epoxy/glass laminate with an ENIG (Electroless Nickel-Immersion Gold) surface finish. The solder joints on the boardwere daisy chained to allow for continuous monitoring using an event detector. The test board was also used as a rework development tool.

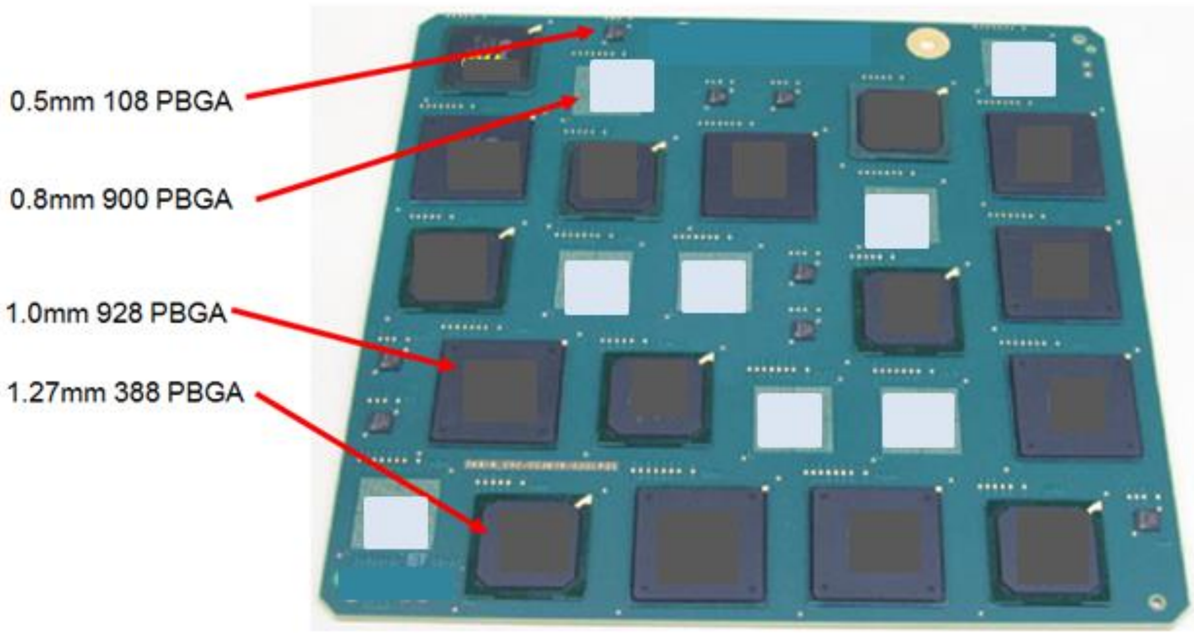

Figure 3 – Test article CCA

The BGA device types selected for inclusion on the test board included a variety of different sizes, I/O counts, pitches and configurations. The selection was based on BGA types used on current CCA designs and encompassed the range of devices that are underfilled in production with the current underfill material. Also, the selected BGAs were consistent with previous accelerated life test (ALT) results, so that the data from the ALT of the alternate underfill materials could be compared with the current qualified material. The following table provides the details of the BGAs devices included in the test board design.

Table 2 - BGA devices

BGA #	I/O Count	Solder Ball Pitch	Package Size	Array Style
A-1	108	0.5 mm	7x7 mm	Perimeter
B-1	900	0.8 mm	27x27 mm	Full
C-1	928	1.0 mm	40x40 mm	Perimeter
D-1	388	1.27 mm	35x35 mm	Perimeter

Procurement of Underfill Candidates and Process Development

The leading candidate underfill materials were procured in order to perform detailed BGA underfill process and rework development. Lead time, cost and other factors were assessed during the procurement phase. For example, some of the materials were only available in larger volume syringes and would require re-packaging by a third-party into our preferred syringe size. This would cause additional cost, lead time, handling and risk. Several candidates were dropped from further evaluation due to having excessively long lead times. Once procurement of the potential replacement materials was in process, the next step was to define the dispensing parameters for the new underfills.

The objective was to use the same dispensing method (equipment and process) and maintain as much consistency with the current underfill processing as possible. With this in mind, a programmable dispenser equipped with a positive displacement valve was used to dispense all the underfill materials. In order to determine the preliminary dispensing parameters, the technical data sheets and the physical characteristics of the candidate underfills were compared to the current underfill material. The goal was to incorporate these new underfills into the dispensing operation with minimal process changes. This was achieved by matching the flowrate (FR) range used for the current underfill material. This approach allowed the use of the current valve settings (needle size/type, acceleration and reverse speed) and established the valve forward speed as the only variable. The forward valve speed was adjusted for each one of the underfill candidates until the desired flowrate (FR) range was obtained. Multiple iterations were performed to validate the results and confirm the flowrate measurements were within the desired range, therefore the main dispensing parameters for each candidate underfill were established.

With the main dispense settings defined, the underfill process development continued using the four (4) selected BGA packages. A custom fixture was used to determine the parameters for an initial dispense recipe, which included the total underfill volume, the number of passes, delays between passes and needle offsets. An initial dispense recipe was developed for each BGA package and candidate underfill combination. BGAs soldered onto a test board were underfilled using these recipes and cured. The cured specimens were submitted for cross sectioning and acoustic microscopy. Several iterations were completed and the cross-sectioned specimens were evaluated against the applicable BGA underfill criteria in order to select the final dispense recipe for each BGA-underfill combination. The figure below shows an underfilled BGA device that has been cross-sectioned and the corresponding acoustic microscopy image.

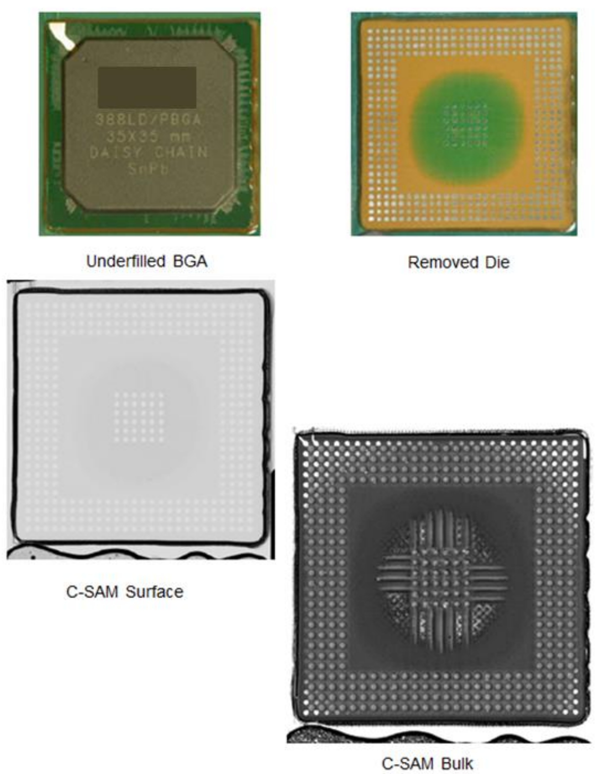

Figure 4 – Example of Underfilled BGA, Cross-section and Acoustic Microscopy Images

The BGA underfill recipes for processing the test articles includes the following parameters: dispense valve type, reverse speed, acceleration, needle gauge, device offsets, dispense mode, substrate temperature and curing temperature. These parameters are fixed for the underfill dispensing process. The remaining parameters are unique for each fluid/BGA package combination and provided in the following format.

Table 3 - BGA Underfill recipe format

Parameter	Value
Underfill	A
Valve Forward Speed	(#)%
Total Underfill Volume Dispensed	(#) mg
Number of Passes	#
Volume per Pass	(#) mg per pass
Delay between Passes	Seconds

Once the underfill recipes for all the BGA devices and underfill candidates were completed, the project effort continued with an evaluation of the rework ability of each candidate underfill. A hot air BGA rework system was used to remove and replace the underfilled BGAs. The assemblies were baked-out and thermally profiled per the applicable procedures. The following figures show the basic steps to remove and replace a BGA and the typical setup of the hot air rework machine.

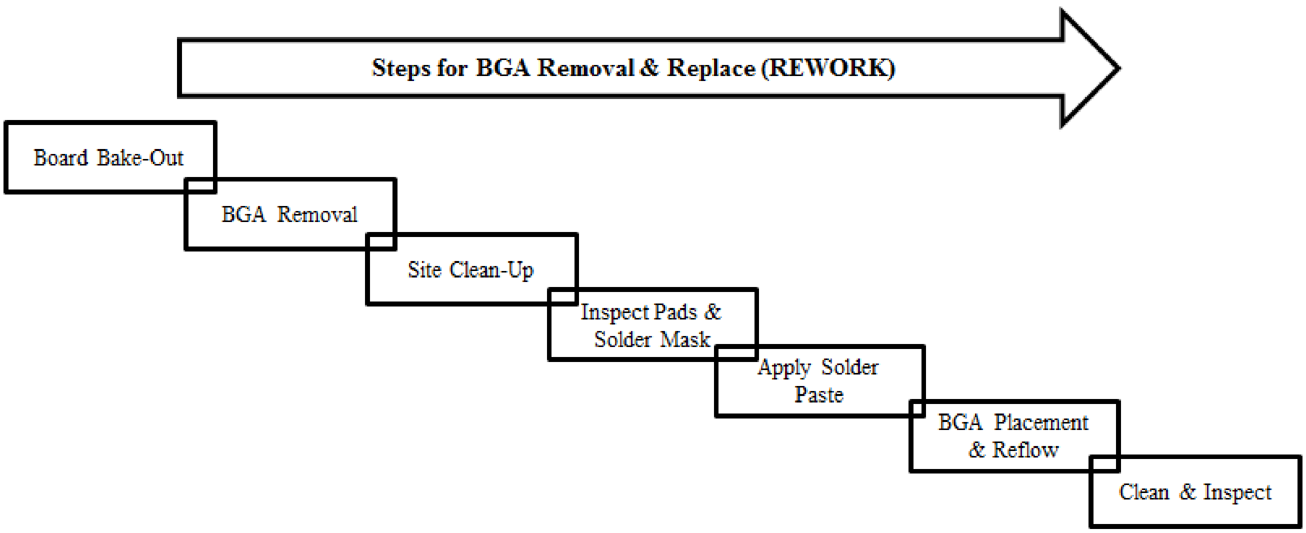

Figure 5 – Underfilled BGA Removal and Replacement Process

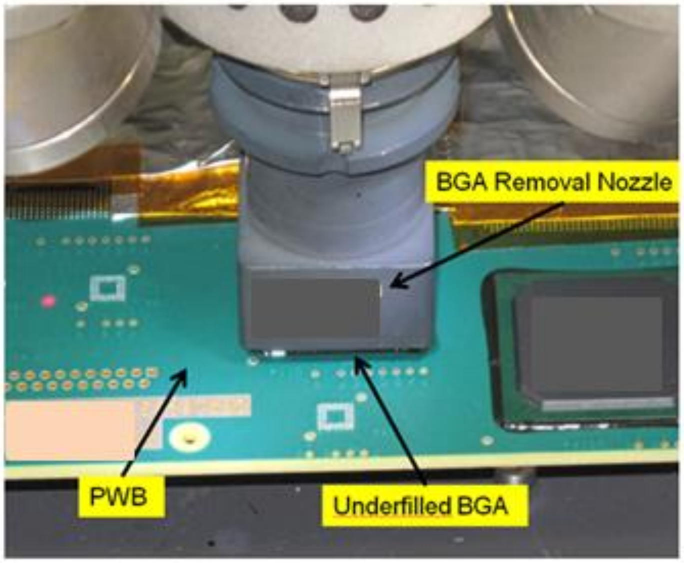

Figure 6– Typical Setup for an Underfilled BGA Removal using a Hot Air Rework Machine

After performing removal and replacement of the underfilled BGAs, the rework ability of each candidate underfill material was qualitatively evaluated. The following table lists some of the factors considered.

Table 4 – Characteristics used to evaluate the results of the underfilled BGA Rework

	FACTORS				
Underfill Material	Adhesion of underfill material to the BGA package or PWB surface	Ease or difficulty of BGA removal	Amount of PWB and/or solder mask damage	Amount and effort to remvove any reside underfill material that remained after BGA removal	Environmental concerns (generation of dust, particulates, smoke, fumes, ETC.) during the BGA removal and/or site clean up
A	1	3	3	3	3
C	1	3	3	3	3
E	1	1	2	1	2
G	1	1	2	1	5
Factor Rating :	**1** = Best Performance	**5** = Worst Performance			

Based on the process development and reworkability results, the list of candidate materials was reduced to two (2) final candidates, materials E and G, which would be subjected to Accelerated Life Testing (ALT). The down selection process is described in the following figure.

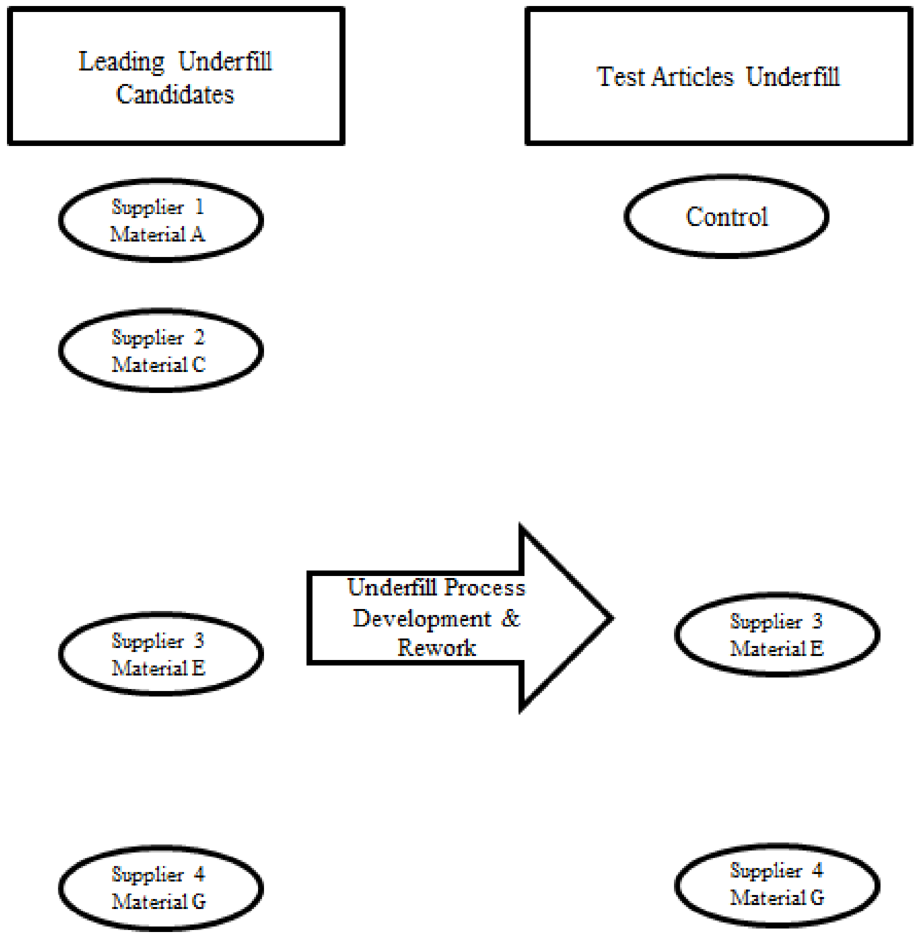

Figure 7–Down selection process of the leading underfill candidates for Accelerated Life Testing

Accelerated Life Testing (ALT) for Reliability Comparison

After starting with an initial list of ten (10) candidate underfill materials, our process and rework evaluations yielded two (2) final underfill candidates that would go into accelerated life testing (ALT), material E from supplier3and material G from supplier 4. A test matrix was developed to qualify these underfill materials via temperature cycling and included the current approved underfill material as a control. This matrix included multiple CCAs with BGAs devices that were underfilled and reworked at two (2) different manufacturing sites. The ALT testing is scheduled to be completed in Q42016, and then failure analysis and data analysis will be performed to determine if either of the two (2) final candidate underfill materials could be used as an alternate to the current qualified underfill material.

Summary

This effort helped to identify and down select reworkable underfill materials to replace a current underfill that may be discontinued. Although we do not have final results, the preliminary results obtained from the accelerated life testing (ALT) on test articles underfilled with suppliers 3 and 4 materials are promising. The project methodology to survey available underfill materials from the different adhesive manufacturers, to validate the material properties and to incorporate these new materials into a qualified BGA underfill dispensing process, was fully developed and validated during this effort. The evaluation process included, not only a compatibility assessment of these new materials against the current underfill material, but the design and fabrication of a test board for a performance comparison. The approach used for process and rework development, to down select these reworkable underfill candidates can be used to evaluate similar materials and processes. The lessons learned are many and they provide a common perspective to approach replacement material evaluations for qualified products that may be subjected to the constraints of diminishing material sources (DMS).

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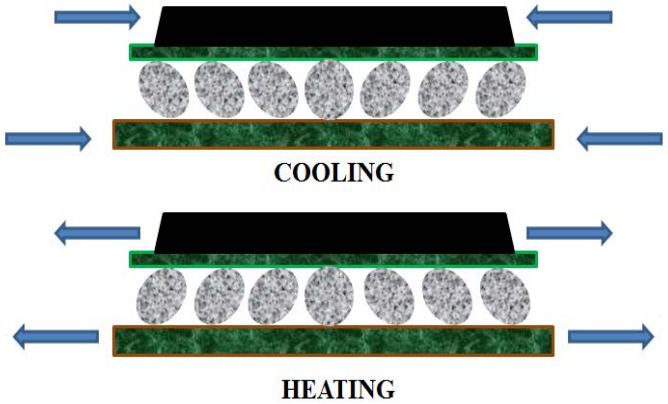
Agenda

- What is an underfill and Why we use it?
- Objective / Motivation of this Investigation
- Underfill Candidates Initial Evaluation (Trade Study & Thermal Analysis)
- Test Article Development & Methodology Plan
- Underfill Candidates (Procurement & Process Development)
- BGA Underfill Process Development
- BGA Underfill Rework Development
- Accelerated Life Testing Candidates
- Summary (Final Selection & Path Forward)

What is an Underfill and Why we use it?

- An underfill is an encapsulant adhesive that helps to reduce stresses on solder joints caused by the CTE mismatches. The underfill dissipates the stresses (mechanical/thermal) at the package (die) / PWB pad interfaces reducing solder joint fatigue and the potential for cracks (failures).



The BGA die/package, solder joints & PWB expand and contract at different rates due to differences in CTE properties. Thermal and mechanical stresses cause the solder joints to fatigue and fracture.

- There are two (2) types of underfill, Reworkable and Non-Reworkable. They are applied (dispensed) under the devices to encapsulate the solder joints and fill the gap between the component package and the PWB pad.

Solder joint encapsulation extends the life of the components/devices exposed to harsh environmental conditions

Motivation / Objective of this Investigation

- Anticipated DMS (sole source) – Current underfill material manufacturer suggested the possibility to discontinuing production in near term. Lifetime buy was not an option due to material shelf life.
  - Current underfill material has been qualified for > 10 years for multiple programs and CCA designs.
- Research, evaluate and qualify new reworkable underfill materials used with Ball Grid Array (BGA), Chip Scale Packages (CSPs), Quad Flatpack No-Leads (QFN), BGA Connectors and other SMT devices.
- Provide an alternative material for internal and contract manufacturers use.
  - Implementation of new underfill material(s) into production should require minimum process and/or equipment changes. Qualified processes and suppliers should not be subjected to additional testing.
- The replacement material should preserve and enhance the solder joints integrity of leadless devices (hidden joints) same as the current underfill. Re-QUALIFICATION would not be required

Similar Dispense & Rework properties; Easy process implementation;
Validates reliability studies with comparable performance

Underfill Candidates—Initial Investigation

- Initial approach was to identify potential replacement candidates.
  - Conducted an industry survey and supplier reviews
    - Surveyed a total of six (6) companies
  - A total of ten underfill materials were identified and eight (8) were evaluated.
    - Leveraged participation in a Consortium
    - Fluid manufacturing/distributor location, curing schedules and application method among considered factors
- Reviewed Technical Data Sheets (TDS) and material properties.
  - Ordered samples to measure key material properties: Tg, CTE, Modulus, pot life, curing characteristics, storage conditions, shelf life, etc.
- Performed thermal analysis and compared to with current underfill material.

Underfill Candidates—Initial Investigation

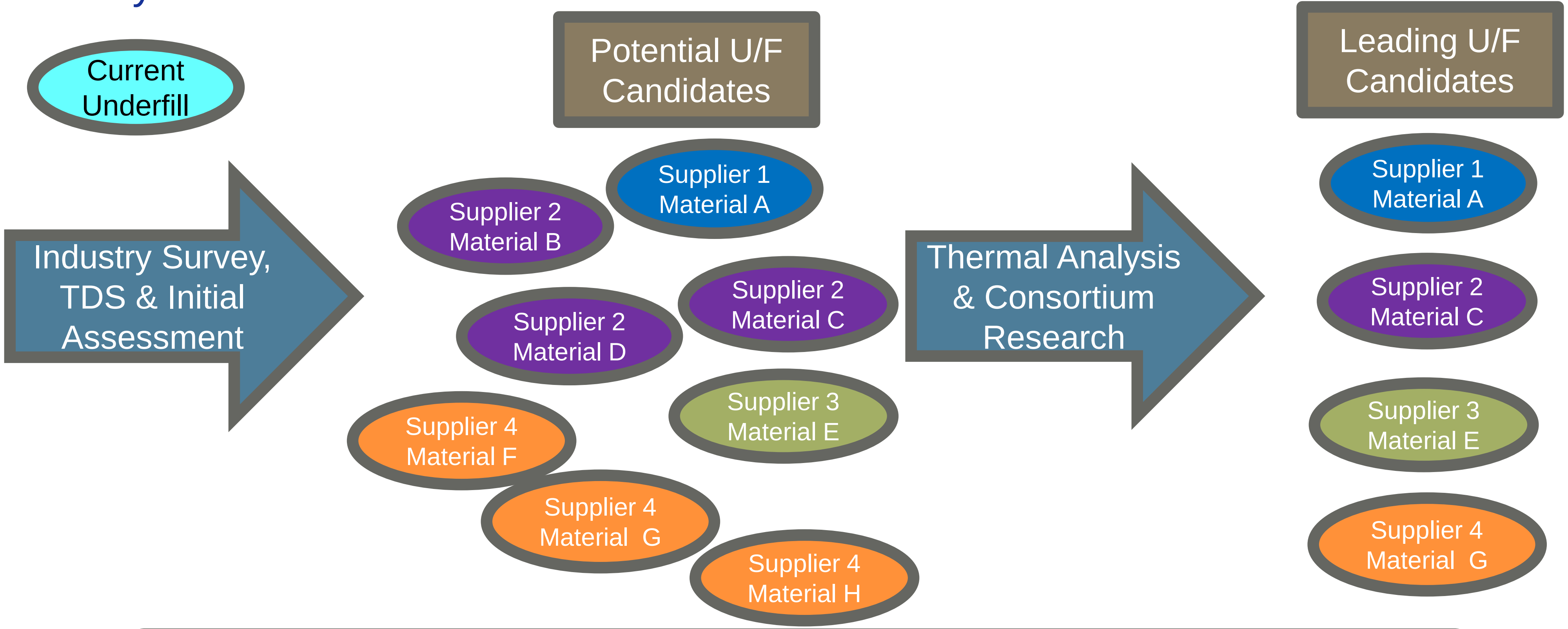
- Material properties of the Control and Candidate Underfill Materials
  - *Viscosity within Range (compatible to dispensing method)*
  - *Longer Pot Life (similar to the current process)*
  - *Comparable CTE (similar behavior – reliability)*

		Material				
Physical Property	**Units**	**Control**	**A**	**C**	**E**	**G**
Tg (Vendor) by TMA	°C	70	102	100	105	80
CTE Below Tg (Vendor)	ppm/°C	40	55	38	60	31
CTE Above Tg (Vendor)	ppm/°C	145	171		180	122
Modulus (Vendor) @ 25°C	Gpa	1.4	2.99	8.6	4	3.0 (Shear)
Pot Life	Hours	30	72	36	24	36
Viscosity	cps or Pa*s	300-2000	394	1800-1900	700	1800

Most important properties: Viscosity (Dispensing); Pot life (Processing); CTE (Reliability)

Underfill Candidates—Initial Investigation

- Down selected potential candidates using trade study, material properties comparison, thermal analysis and Consortium research results



Down selected potential candidates: Trade study, Material properties comparison, Thermal analysis and Consortium research

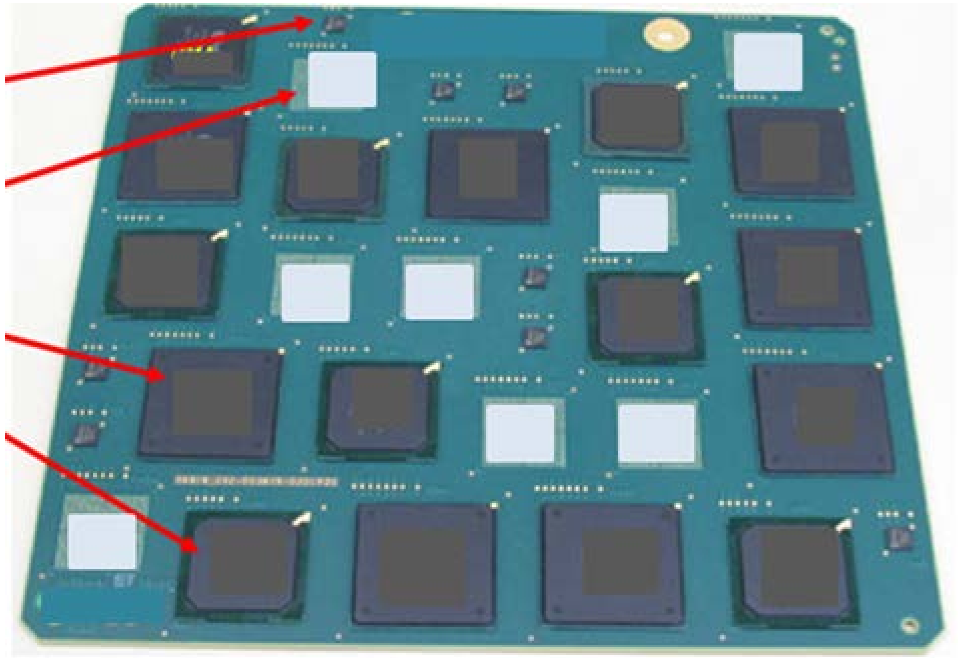
Test Article Development & Methodology Plan

- A plan was developed to order the required parts for underfill process development and for the reliability testing.
- The BGAs were selected and purchased
  - 4 unique BGA Packages (see Table below)
  - Range of BGA sizes and Ball pitches encompass the range of devices that are underfilled in production and can be compared to previous accelerated life test results.

BGA #	I/O Count	Solder Ball Pitch	Package Size	Array Style
A-1	108	0.5 mm	7x7 mm	Perimeter
B-1	900	0.8 mm	27x27 mm	Full
C-1	928	1.0 mm	40x40 mm	Perimeter
D-1	388	1.27 mm	35x35 mm	Perimeter

Test Article Development & Methodology Plan

- Test article (PWB) was designed and fabricated. Included multiple BGA footprints configurations.
  - Single-Sided PWB, High Tg Epoxy/Glass Laminate with Electro-less Nickel-Immersion Gold (ENIG) surface finish, LPI Solder mask
  - Daisy chain design to permit continuous monitoring of solder interconnects.
  - Eight (8) placements of each unique BGA package
- Development of underfill parameters for these parts support testing on a variety of devices similar to the ones that are currently qualified for production.



Test Article Development & Methodology Plan

- Developed a test matrix to evaluate different BGAs, underfill and rework combinations.
  - One manufacturing site assembled the test articles
  - Underfill and Rework Development done at two (2) manufacturing sites
    - Underfill Recipe Conversion & Application (similar dispensing machine, parameters)
    - Removal & Replace with different rework methods
    - Different footprint condition for parts replacement and re-underfill
  - Accelerated Life Testing (Temperature cycling) for Reliability
    - Underfilled devices (BGA Assembly – Underfill Application and Test)
    - Rework/Underfilled devices (BGA Assembly – Underfill Application – Rework – Re-Underfill and Test)
    - To compare results and select the best candidate(s). Same or better performance than the current underfill material in order to meet products / programs reliability requirements.

Developed Methodology Plan; Designed/FAB test article; Selected BGA packages: Assembled development article to compare performance results and continue down selection process

Underfill Candidates (Procurement & Process Development)

- The four (4) candidates were selected for further underfill process and rework development based on the initial investigation results (viscosity, pot life, CTE, thermal analysis and Consortium research information)
- Lead time, cost and other issues identified during the procurement phase.
  - The underfill from Supplier 1 (Material A) was dropped from further evaluation due to lead time constraints
- Easy implementation into production was essential, so candidate selection was driven by ability to implement into current application process with minimum process/equipment changes
  - Determined Application Method (Equipment & Process)
  - Selected key parameter to convert fluids dispensing (Flow Rate)
  - Maintain current process parameters (Needle size, process temperature and curing temperature)

Cost, lead time and consistency to current underfill dispensing process were essential factors

BGA Underfill Process Development

- Process development was performed using an Programmable Dispenser equipped with a positive displacement pump.
- Physical characteristics of the leading candidate materials were assessed & compared to the current underfill material.
- Goal was to dispense the candidate underfills at the same flow rate (FR) range as the current underfill material. The same (FR) range will
  - Reduce process setup changes
  - Similar process parameters for all candidates
  - Minimize changes to qualified underfill recipes
- Each candidate was submitted to multiple machine setups & flow rate measurements. Machine & dispense valve settings were adjusted to obtain the desired flowrate.
- It was found that making adjustments to the valve speed without changing other process parameters the desired flow rate can be achieved. (Process changes were minimal)

Use of the same Auto Dispenser; similar setup parameters except for the valve speed. Established flowrate range consistent to the current underfill

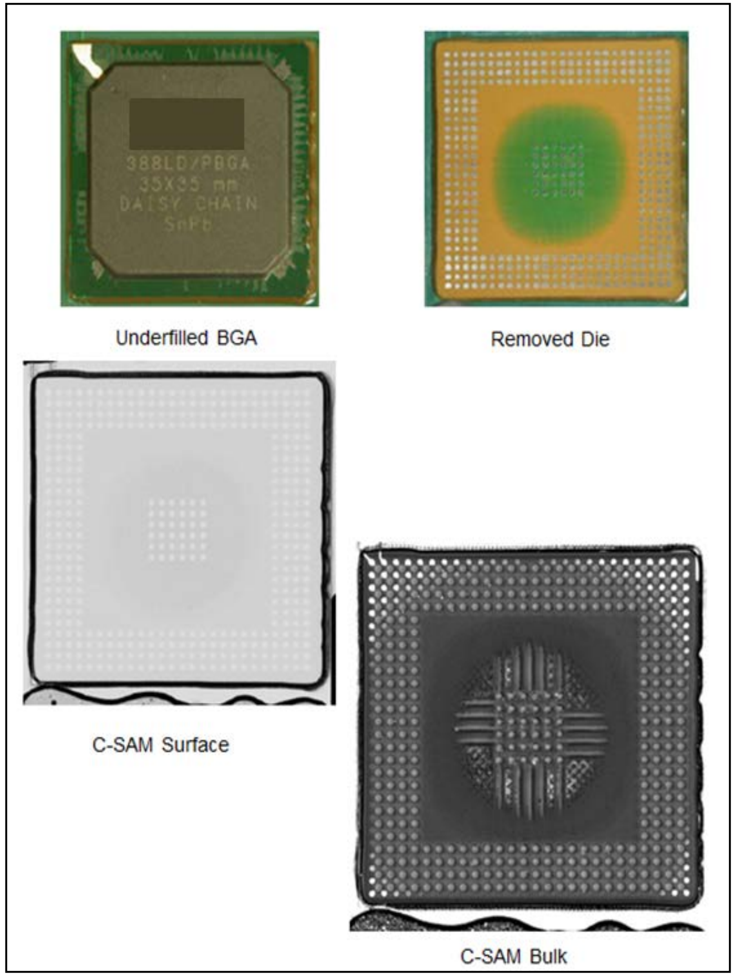
BGA Underfill Process Development

- Custom Fixture used for Underfill Recipe Development
  - Secured BGA devices in a fixed position
  - Provided the ability to assess underfill fluid wetting characteristics and flow in real time
  - Permitted reuse of BGAs/components
    - Components could be removed, cleaned and reused for additional dispensing trials/iterations
  - Allowed the evaluation of flow characteristics, direction and the speed of material wetting
  - Used to establish the initial recipe parameters such as total volume, number of passes and time delays

Custom tool used to establish initial underfill recipe. Dispensing parameters such as total volume and delays were obtained. Reuse parts.

BGA Underfill Process Development

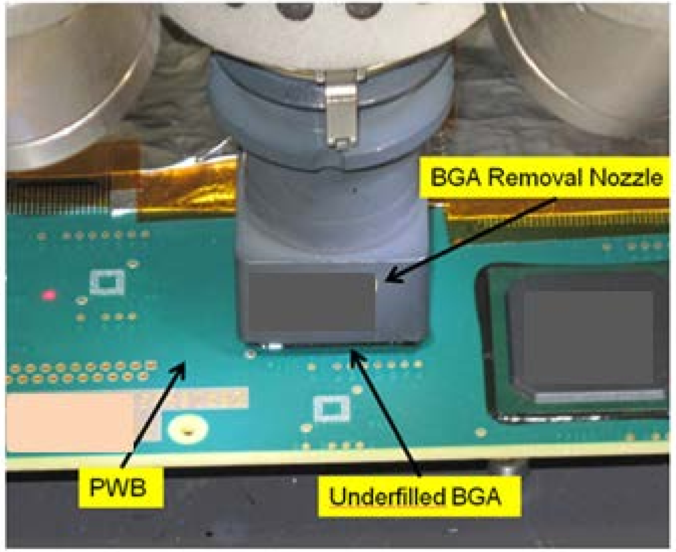
- Cross Sections & C-SAM Used for Underfill Recipe Qualification
  - The BGA package is removed and the underfill material exposed
  - Voiding was assessed per the applicable criteria (Internal and industry)
  - Multiple iterations were performed to confirm and validate results
  - Dispense Recipe (for each underfill candidate & device combination) selected for Test Article use
    - Dispense parameters
    - Volume per pass (dispense mode)
    - # of passes and time delays



Recipe Qualification & Criteria. The underfill voiding content and overall results used to continue rework development and the down selection process

BGA Underfill Rework Development

- BGA Removal & Replace (Hot Air Rework Machine)
  - *Board Bake-out*
  - *BGA Removal*
  - *Site Clean-up*
  - *Inspect Pads & Solder Mask*
  - *Apply Solder Paste*
  - *BGA Placement & Reflow*
  - *Inspection and Cleaning*
- Rework was evaluated for adhesion to components, easy of removal, PWB damage, processing and environmental issues



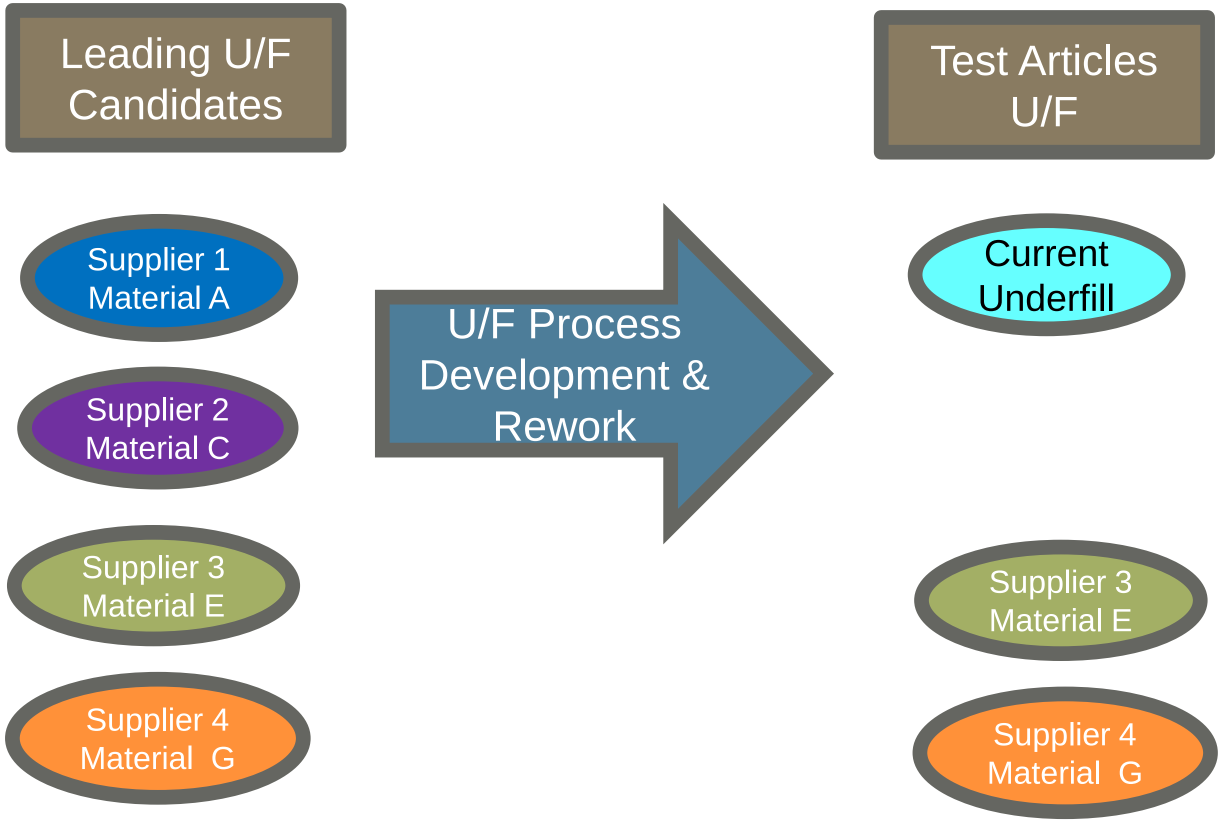
Developed rework process. Removal and placement sequence similar to BGA devices underfilled with the current material. Assessed rework results.

Reworkability of Candidate Underfill Materials

Candidate	Adhesion to BGA or PWB	Ease of BGA Removal	Level of PWB & Solder Mask Damage	Effort to Remove Remaining U/F Residues	Generation of Dust, Fumes, Smoke, etc. during Rework	Total Score
A	1	3	3	3	3	13
C	1	3	3	3	3	13
E	1	1	2	1	2	7
G	1	1	2	1	5	10

Scoring: 1 = Best/Preferred; 5 = Worst/Least Preferred

Accelerated Life Testing Candidates



Down selected underfill candidates for Test. Developed matrix. Temperature Cycling on multiple BGA configurations from two manufacturing sites.

Summary (Final Selection & Path Forward)

- Perform Accelerated Life Testing to compare reliability data between current underfill material (Control) and potential candidates (Performance Comparison). The ALT results are promising.
  - Metallurgical cross sectional analysis to confirm failure mode(s)
- Assessed and compared overall factors (thermal analysis, material properties, procurement considerations, cost, dispensing, rework methods and reliability) to qualify alternate materials as replacements of the current underfill.
- The methodology to survey underfill materials, test their properties and introduce them to a qualified BGA Underfill dispensing process was developed and validated during this effort.
  - Collaboration to develop test articles and plan to assess materials performance
  - An approach that ease the transition of these materials to qualified production without the need to re-test or to re-qualify products internally or at suppliers.
- Lessons Learned provide a common perspective to approach similar DMS (diminishing material sources) opportunities

Performance Comparison. Identified alternates and Lessons Learned to ease transition of these materials into production. Methodology approach for similar DMS

Thank you!

Q & A