Solutions for Low Cost, Near Hermetic Air Cavity Packages

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Abstract

This paper will detail the design and manufacturing elements of near hermetic air cavity packages produced by injection molding of low moisture liquid crystal polymer (LCP). The process uses a proprietary sealing methodology to take maximum advantage of the properties of the LCP. The material properties and advantages will be presented. The very low moisture absorption properties of the packages produced provides excellent environmental protection for various semiconductor applications, including RF, sensors and photonics amongst others. The focus of this paper will be on RF Power applications and in particular cellular basestations. The LCP material has a low microwave loss tangent which, when combined with low resistivity conductors and thermal bases, produce packages with outstanding microwave performance. Microwave matching structures are built into these packages that transform very low transistor input and output impedances to design friendly intermediate impedances. This feature minimizes board level discrete components and reduces assembly sensitivity. The technology offers cost advantages over many alternatives, with higher performance and faster time to market. Representative packages illustrating these features will be shown and the process and equipment developed for these packages detailed.

Key words

air cavity plastic, B-stage epoxy, sidewall, matrix lid

I. Introduction

This paper describes the design and manufacturing processes for injection molded near hermetic air cavity plastic packages. RJR Technologies' (RJR) air cavity plastic (ACP) are molded with a liquid crystal polymer (LCP) material around an unpopulated leadframe. This is known as a premolded package. A semiconductor die is mounted into the package cavity, connected to the leads and finally sealed with a lid with preapplied B-stage Epoxy. A typical ACP package is illustrated in figure 1 and a cross section in figure 2. The die and wirebonds are in a cavity rather than being embedded in an thermoset plastic as in transfer molded packages. Traditional transfer molded packages are made by completely filling a mold using a thermosetting plastic which encapsulates a leadframe with a mounted die. This plastic completely surrounds and embeds the die and wirebonds compromising device performance. For decades, the semiconductor industry used ceramic packages to provide the benefits of an air cavity enclosure. In the last few years, RJR's ACP has effectively obsoleted the use of ceramic packages in the RF Power market by providing customers with higher electrical and thermal performance at reduced costs and faster time to market. This is not only true for this market but any electronic application that requires the use of an air cavity package.

Figure 1 – ACP Package

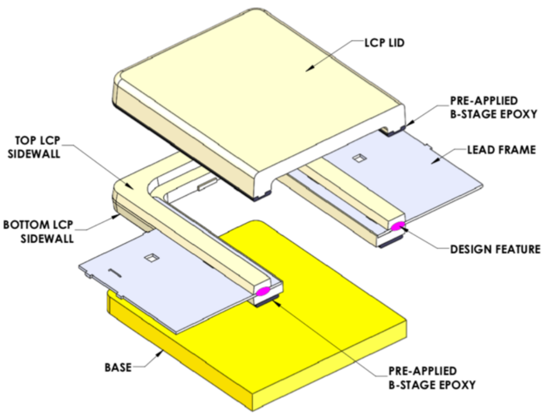
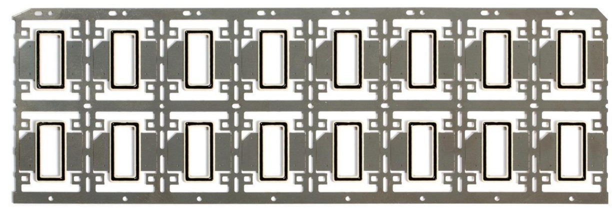


Figure 2 – ACP Package Cross Section

II. Air Cavity LCP Plastic Package for Macro Cell

In the Macro Cell space, GaN Power Amplifiers (PA) are ramping to high volume production in 5G networks. The use of an LCP ACP sidewall and lid coupled with a copper thermal base vs a CPC base (Cu/Mo70Cu/Cu, a laminate of copper and coppermolybdenum) as is used in ceramic packages provides higher RF performance due to the lower dielectric constant of the LCP and higher thermal performance (30% improvement) of the copper thermal base as well as lower costs than ceramic packages. In addition, the sidewall is glued to the thermal base (by the use of a B-stage preapplied epoxy to the sidewall) rather than brazed, which reduces the stress and distortions of the base. This in turn allows the use of thinner matching capacitors, reducing RF losses both at the gate and the drain. The result is higher gain and efficiency compared to ceramic packages. Likewise, the air cavity plastic package delivers improved and consistent performance compared to an overmold solution. RJR provides: package sidewall with preapplied epoxy to attach the thermal base to the sidewall and lid with preapplied epoxy, that attaches to the sidewall to make a sealed package. Both the sidewall and lid are molded using LCP. The sidewall, lid and base are attached using RJR's proprietary epoxies and sealing systems to make up the completed package solution. Depending on the type of die attach process, RJR packages can be supplied as a 2-piece package (base/sidewall with lid) for silver sintering or a 3-piece package (base, sidewall and lid) for eutectic die attach. [1] In the latter, the die is first mounted on the base, then attached to the sidewall, then wire bonded and sealed with the lid. [2]

The sidewalls are manufactured using a common leadframe size of 183.4mm x 65mm across all ACP family sizes. This allows reuse of manufacturing equipment at RJR and enables the use of the ACP strips as the carrier in the customer's assembly process rather than individual headers, reducing handling time and allowing more variation in lead shape and length while simplifying logistics. Depending on the customer's assembly requirements the sidewall can be delivered singulated or in the strip they are molded in as shown below.



A Strip of ACP Transistors

RJR couples advances in polymer materials that are ideal for the construction and life cycles of electronic packages, with semiconductor package technology know-how, and mature injection molding to bring ACP to the market. The details of the injection molding process and methodology are described in "Injection Molded Surface Mount 32 Pin vision package Competes with Ceramics". [3] The advantages of RJR air cavity packages come from a combination of materials, design, manufacturing processes and dedicated equipment. All come together in what is termed "The Total Package Solution".

The materials used to make RJR packages are fundamental to the electrical and environmental performance advantages of ACP. The 4 basic components are: 1) HTP 1280, an LCP thermoplastic molding material; 2) custom formulated sealing epoxies that make a near hermetic cavity package; 3) metal leadframe; and 4) a thermal base.

Liquid Crystal Polymer (LCP)

HTP 1280 Liquid Crystal polymer is a high performance thermoplastic molding material with many intrinsic advantages. The properties of HTP 1280 are summarized in the below table.

Table I

Physical properties	Value	Unit	Test Standard
Density	**1670**	kg/m³	ISO 1183
Molding shrinkage, parallel (flow)	**0.3**	%	ISO 294-4, 2577
Molding shrinkage, transverse normal	**0.6**	%	ISO 294-4, 2577
Water absorption, 23°C-sat	**0.041**	%	Sim. to ISO 62
Humidity absorption, 23°C/50%RH	**0.011**	%	ISO 62
Mechanical properties	**Value**	**Unit**	**Test Standard**
Tensile modulus	**16000**	MPa	ISO 527-1, -2
Tensile stress at break, 5mm/min	**145**	MPa	ISO 527-1, -2
Tensile strain at break, 5mm/min	**1**	%	ISO 527-1, -2
Flexural modulus, 23°C	**16000**	MPa	ISO 178
Flexural strength, 23°C	**230**	MPa	ISO 178
Charpy notched impact strength, 23°C	**11**	kJ/m²	ISO 179/1eA
Izod impact notched, 23°C	**7**	kJ/m²	ISO 180/1A
Compressive modulus	**16000**	MPa	ISO 604
Compressive stress at 1% strain	**134**	MPa	ISO 604
Rockwell hardness (M-Scale)	**96**	M-Scale	ISO 2039-2
Thermal properties	**Value**	**Unit**	**Test Standard**
Melting temperature, 10°C/min	**280**	°C	ISO 11357-1/-3
DTUL at 1.8 MPa	**270**	°C	ISO 75-1, -2
Coeff. of linear therm expansion, parallel	**0.11**	E-4/°C	ISO 11359-2
Coeff. of linear therm expansion, normal	**0.21**	E-4/°C	ISO 11359-2
Flammability @1.6mm nom. thickn.	**V-0**	class	UL 94
thickness tested (1.6)	**1.5**	mm	UL 94
Flammability at thickness h	**V-0**	class	UL 94
thickness tested (h)	**0.40**	mm	UL 94
UL recognition (h)	**UL**	-	UL 94
Electrical properties	**Value**	**Unit**	**Test Standard**
Dielectric constant (Dk), 100Hz	**4.2**	-	IEC 60250
Dielectric constant (Dk), 1MHz	**3.7**	-	IEC 60250
Dissipation factor, 100Hz	**200**	E-4	IEC 60250
Dissipation factor, 1MHz	**50**	E-4	IEC 60250
Volume resistivity, 23°C	**1E12**	Ohm*m	IEC 62631-3-1
Surface resistivity, 23°C	**1E15**	Ohm	IEC 62631-3-2
Electric strength, 23°C (AC)	**25**	kV/mm	IEC 60243-1
Comparative tracking index	**PLC 3**	-	UL 746
Arc resistance	**165**	s	Internal
Arc resistance	**165**	s	Internal

The crystalline domains in the LCP material result in a polymer with very low water vapor transmission and moisture absorption characteristics. The low moisture transmission rate means that packages made with LCP are more nearly hermetic than any other type of plastic package. This is shown in the comparison to other polymers in figure 3. This water vapor permeability rate of LCP shows that it is similar to glass!

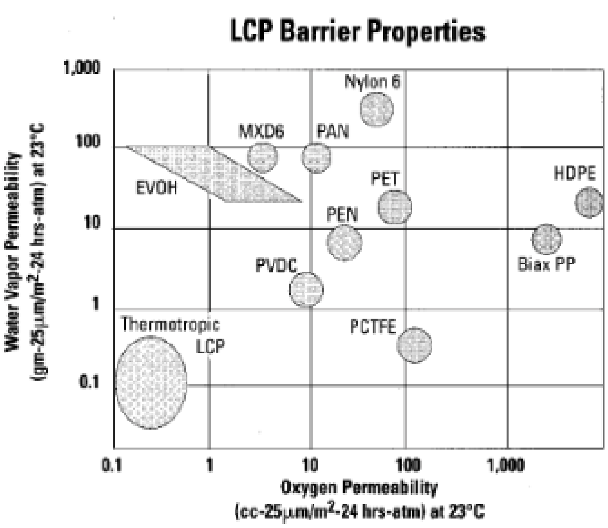


Figure 3 – Water vapor and oxygen permeability of plastics [4]

The associated very low water absorption percentage means that LCP packages do not create problems during soldering from the sudden vaporization of absorbed moisture that can cause package failures, such as delamination. The mechanical properties of HTP 1280 are a nearly ideal balance for electronic packages. This strong and tough but not brittle thermoplastic is inert and resistant to corrosives and solvents, non-flammable, and contains no halogens. Since LCP is a thermoplastic material it can be recycled by regrinding and remolding unlike thermoset epoxy molding compounds.

One of the most attractive properties of LCP is that the Coefficient of Thermal Expansion (CTE) is low and can be tailored. HTP-1280 is manufactured to be a close CTE match to copper, which is used as the leadframe material for ACP packages. This CTE compatibility results in a highly reliable, matched system that minimizes differential thermal stresses.

The term “near hermetic” refers to packages that pass gross leak testing and stringent reliability requirements shown on Table II, and are not exclusively made of metal and glass or ceramic. [5] Historically the term “hermetic” refers to cavity ceramic and metal or glass sealed metal packages that are welded or solder sealed to pass MIL STD 883, method 1013 fine leak specifications. This definition is based on the assumption that air cavity plastic packages are susceptible to significant diffusion of water vapor through the plastic over time. Unacceptably high levels of moisture inside of a package can cause catastrophic failure during soldering or corrosion inside of a package. The LCP material used in ACP challenges that assumption with a water vapor permeability rate similar to glass, a material considered “hermetic”.

<u>Sealing Epoxies</u>

The second element of the ACP package is the sealing epoxies used to seal the package. RJR has developed a moisture barrier epoxy that is preapplied to package lids and sidewalls used to seal packages during the backend assembly process. These epoxies are both solvent and solvent-free and meet ROHS and REACH requirements. For ease of use in the assembly process, RJR B-stages it’s epoxies. The B-staging, is a process that utilizes heat to remove the majority of solvent from an adhesive, thereby allowing a construction to be “staged”. In between adhesive application, assembly and curing, the product can be held for a period of time, without sacrificing performance.

<u>Copper Leadframes</u>

The third material used for ACP packages is the metal leadframe, which form the conductive elements of a package. Copper is the leadframe material used for ACP packages and the HTP1280 LCP molding compound is formulated to be a close CTE match. Copper is a very versatile choice for leadframes with great electrical and thermal conductivity at low cost. RJR adds features in the design of the leadframe to improve adhesion in order to provide a near hermetic package.

<u>Thermal Bases</u>

The fourth material used in an ACP package is the thermal base. Unlike ceramic packages that have limitations on base material choice because of the CTE mismatches, RJR’s package solutions can use different base materials, CuW, CPC, Copper and diamond materials, because the thermal base is glued to the sidewall as opposed to high temperature brazing. RJR epoxies can easily deal with the CTE of the different materials. Figure 4 is a representation of this flexibility. Through the use of copper thermal bases, the ACP technology has provided the best $/watt solution to the RF power market.

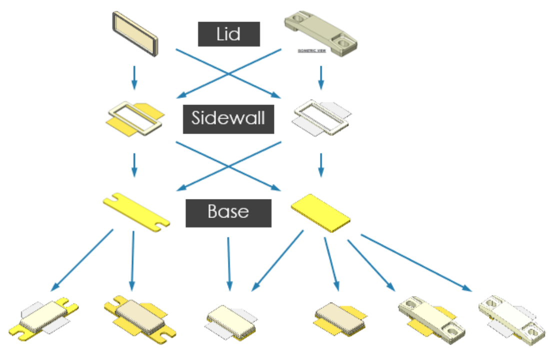


Figure 4 – Package Configurations

Process and Equipment

The ACP system approach to packaging focuses on the processes involved in producing high yield packages. The epoxies and molding compounds are optimized with carefully developed processes. Processes like injection molding and the application and B-staging of epoxy applied to sidewalls and lids are parts of the internal manufacturing flow. Coordinated material and process optimization results in high yield package production but not all elements of the air cavity package assembly processes are done internally at RJR. The sidewall to base and lid attach are processes that are performed during the package assembly cycle at customer locations worldwide. Recognizing that process control and consistency is key to high yield, RJR designs and manufactures equipment to support package assembly by the customer. The IsoThermal Sealer (ITS), shown in figure 5, is an elegant solution to the challenge of keeping package assembly consistent, controlled, simple and high yielding.[6] While sidewall to base and lid sealing with pre-applied B-staged epoxy can be done by a clip and bake method, optimum results are obtained with an ITS.

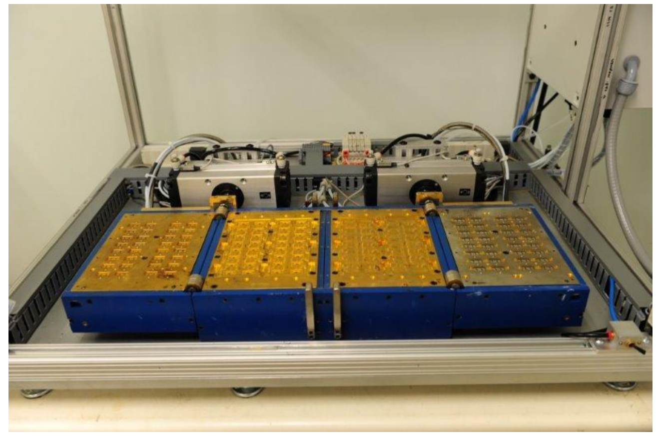


Figure 5 – IsoThermal Sealer (ITS)

The ITS is loaded with sidewalls with preapplied epoxy in one plate and thermal bases with the die attached in the opposite plate. The 2 plates are brought together accurately aligning the sidewalls and thermal bases which are sealed with an automatic programmed process cycle. The resulting component is know in the industry as a "header". Likewise, after wirebonding, headers are placed in one plate and lids with preapplied epoxy are placed on the other plate, repeating the process used to produce a header. A key feature of the ITS process is the heating of the header and lids to the optimum epoxy curing temperature and then bringing the covers into contact with the packages graphically shown in figure 6. This process sequence virtually eliminates blowouts and pinholes caused by the increase in internal pressure when the air inside the cavity expands during heating which can result from heating the cover and package clipped together.

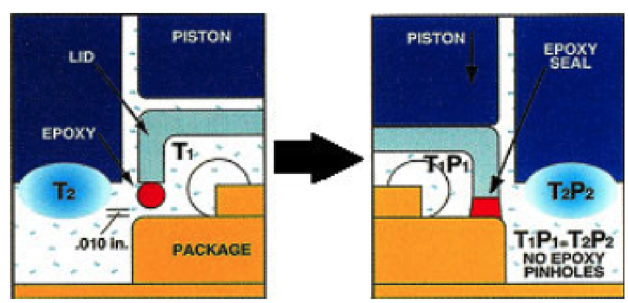


Figure 6 – The ITS sealing cycle advantage

While this pressure equalization enhancement alone contribute to higher yields, the speed and consistency of the programmable ITS cycle further enhances yields. The programs are optimized for specific sealing materials and package configurations by RJR to provide customers with the optimum process.

Package Design and Construction

The insert injection molding process allows the offering of fast time to market for specific popular sizes of RF Power packages. So, for example, 2 of the most popular sizes are the SW0800 and SW1230 for which RJR has specific mold tools. If a design requires one of these sizes, RJR has to simply design a new etched leadframe configuration and prototypes can be delivered in 4 weeks due to the reuse of manufacturing tooling.

Air-cavity plastic packages have several advantages compared to overmold or ceramic packages. The air-cavity package eliminates signal loss caused by the mold compound on the die surface. RF performance consistency is improved because there is no wire sweep due to the mold compound injection process. The ACP package is a higher performance and more cost-effective solution compared to ceramic because of the dielectric constant of the LCP and the use of a copper base. The package configuration options described earlier allows for better inventory management compared to a brazed ceramic package configuration since the base does not have to be attached to the sidewall until the assembly process is started. If the customer is using different styles of the existing outline, the base inventory can be shared for all the outlines unlike ceramic, were each style has an expensive thermal base already attached to the ceramic ring.

RJR's ACP packages have been fully qualified by multiple tier 1 customers and has been in volume production since 2009 with over 70 million packages used in the field with no failures reported to date. Package reliability testing includes Moisture Sensitivity Level 3, Temperature Cycling and High Temperature Storage testing. Results are summarized in Table II.

Table II – Package Reliability Data

	Stress	Abbv.	Ref.	Conditions	Duration/Accept**	Lot A	Lot B	Lot C
1	MSL 3	MSL3	J-STD-020D	IR = 245°C	End Point	0/100	0/100	0/100
2	Temperature Cycling	TC	JESD22-A104	-65°C to +150°C	1000 cycles / 0 Fail	0/77	0/77	0/77
3	High Temperature Storage Life	HTSL	JESD22-A103C	Condition B (150°C)	1008 hours/ 0 Fail	0/77	0/77	0/77

III. Air Cavity Plastic Package for MIMO

Today's air cavity plastic, medium-power package solutions can meet the requirements of Multiple-input, Multiple-output (MIMO) antenna arrays used in the 5G network, to be able to deliver high data rates to multiple users in dense urban areas. The typical package of choice for these applications is a QFN type package using a copper leadframe or laminate substrate array types. A leadframe based QFN is shown on figure 7 and a laminate one on figure 8. The leadframe one is made of 0.25mm thick copper with a NiPdAu plating finish similar to the ACP package. The laminate one is a 4-layer EM526 material with a 0.5mm coin for higher power applications. The plating is ENEPIG (Electroless Nickel Electroless Palladium Immersion Gold). If the customer needs about 30 GHz and or greater, then most overmold solutions will not work, so now the customer needs an air cavity QFN. Since these type formats are heavily populated with packages, RJR has developed a lid design that would seal all the package sites on the array with one lid. The package solution consists of a matrix lid panel that is attached to a populated laminate substrate or leadframe array. The lid design allows for the substrate assembly for wire bond and die attach to be no different than overmold packages except you put a cavity matrix lid on the array rather than putting it in a over mold press. The benefit is now an air cavity product that has been tested to 77 GHz.

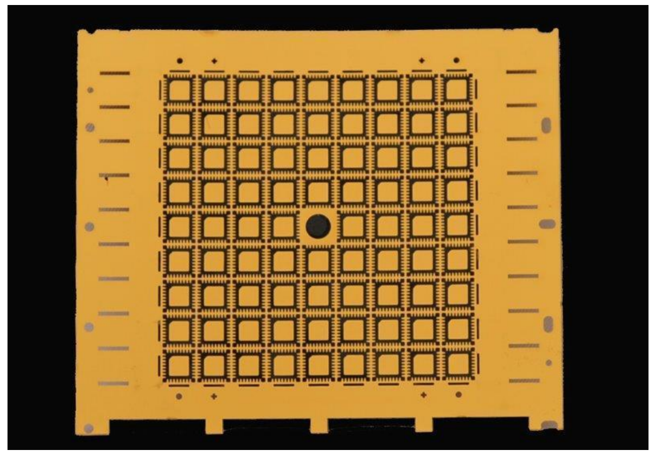


Figure 7 – Leadframe based QFN Array (RQFN)

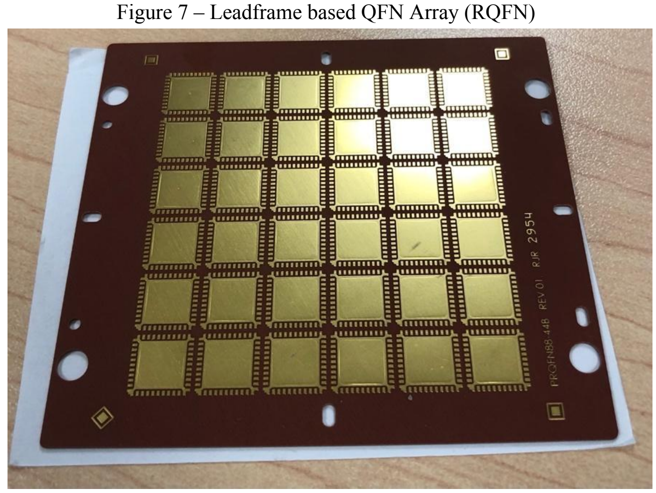


Figure 8 – Laminate based QFN Array

The RQFN version of the package has successfully completed reliability testing as summarized in Table III.

Table III – RQFN Package Reliability Data

Stress	Abbv.	Ref.	Conditions	Duration/Accept	Lot A	Lot B	Lot C
MSL 3	MSL3	J-STD-020D	IR = 260°C	End Point / 0 Fail	0/70	0/70	0/70
Temperature Cycling	TC	JESD22-A104	Condition G (-40°C to +125°C)	500 cycles / 0 Fail	0/210	0/40	
High Temperature Storage Life	HTSL	JESD22-A103C	Condition A (125°C)	1000 hours / 0 Fail	0/70	0/70	
Low Temperature Storage Life	LTSL	JESD22-A119	Condition A (-40°C)	1000 hours / 0 Fail	0/70	0/70	

An example of the matrix lid is shown in figure 9.

Figure 9 – Matrix Lid

The matrix lid is molded using LCP with a B-stage epoxy applied to it. This then is sealed to a laminate or leadframe QFN array. Then just like for a transfer molded non-air cavity package, the sealed packages are singulated using a dicing saw. A typical cross section of the finished package is depicted in Figure 10.

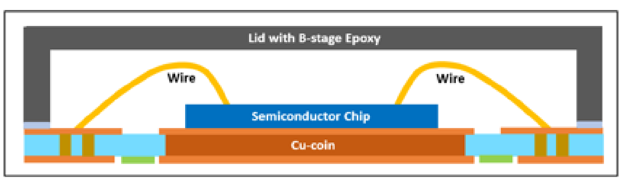


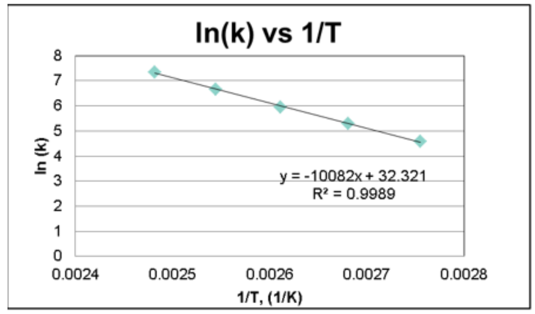
Figure 10 – QFN Type Package Cross Section

IV. B-Stage Epoxy & Sealing Equipment

A critical characteristic for B-stage epoxy is shelf-life. The shelf life describes the amount of time the epoxy can be stored and still be usable to seal the air cavity package. Depending on the epoxy, the minimum shelf life is 6 months but it can be extended up to a year. To obtain a longer shelf life, the epoxy has to be properly stored in cold temperature storage conditions (3ºC to 8ºC).

In order to further reduce costs over transfer mold packages, RJR has developed a fully automated assembly process for QFN type packages that use cassettes to load/unload components (array and matrix lid) for a fully automatic sealing line.

Through the use of Kinetics, RJR has developed a method to control the quality of the B-staged epoxy and predict shelf life by measuring gel time.



$$t_{gel} = -K(T)t + t_0$$

$$K(T) = Z\, e^{-\frac{E_a}{RT}}$$

Epoxy shelf-life data is summarized in Table IV

Table IV – Epoxy Shelf-life

T, °C	K(T)	Days	Gel time prediction, seconds
30	0.38561	28	1740
8	0.02850	365	1750
3	0.01488	365	1870

V. Conclusion

Prior to the introduction of RJR's Air cavity LCP plastic packages, customers only had the choice of using either a low cost and low performance overmold package or the more expensive, but higher performance ceramic packages. Both packages are non-hermetic and have a large cost differentials. When RJR introduced its air cavity LCP plastic package, it was a major cost down and performance improvement over ceramic packaging. Once the ACP package obtained market acceptance, it became the cheapest $/watt package available in the RF power market. Today, the material and assembly cost using RJR's isothermal sealing systems brings the cost differential to a small premium above overmolded packages.

Acknowledgment

John Ni and Karen Lynch.

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