# COMBINING DIELECTRICS IN MULTILAYER MICROWAVE BOARDS

by . . .

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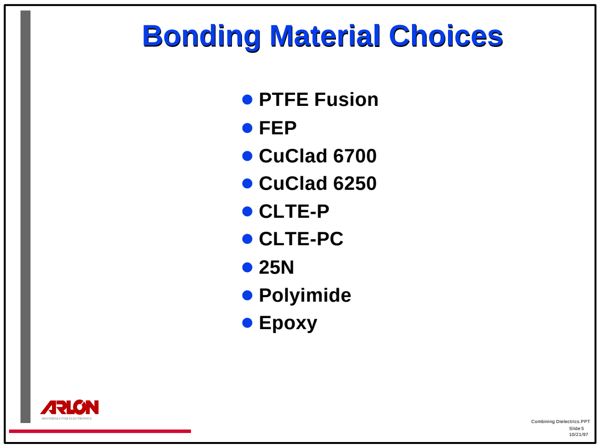
This article will examine some of the different material options that are available to bond other dielectrics together to make a multilayer board and discuss the characteristics that are important to consider when making the material selection for the board.

Mixing different materials in the same board allows multilayers to be constructed in many different ways that may either improve performance or reduce costs, and often achieve both. Some new methods and materials can also facilitate sequential lamination that allows further use of blind and buried vias and can incorporate microwave and digital functions in the same board. Some of the combinations can be fabricated using conventional PWB processes while others require a careful selection of materials and an understanding of the order in which they must be put together in order to avoid manufacturability problems.



**Bonding Material Choices**

- PTFE Fusion
- FEP
- CuClad 6700
- CuClad 6250
- CLTE-P
- CLTE-PC
- 25N
- Polyimide
- Epoxy

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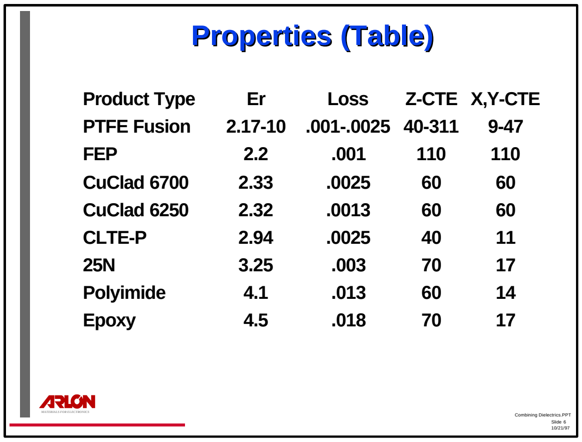
**Figure 1**

Figure 1 is a listing of common materials that are used to bond laminates together to either form stripline circuits or more complex multilayer boards. Polytetrafluoroethelene fusion has been used for many years and is a process by which you exceed the melting point of the thermoplastic polymer of the laminate and fuse different layers together.

The next five items are thermoplastic fluoropolymers with lower melting points than PTFE, allowing bonding of PTFE based laminates without melting the layers. 25N is a low loss thermoset that can be used in a wide variety of applications. The last 2 are conventional thermoset products that can also be used in certain locations of microwave boards where the loss is not critical such as between planes, or as the portion of the board that handles lower frequency digital functions.



**Properties (Table)**

| Product Type | Er | Loss | Z-CTE | X,Y-CTE |
|---|---|---|---|---|
| PTFE Fusion | 2.17-10 | .001-.0025 | 40-311 | 9-47 |
| FEP | 2.2 | .001 | 110 | 110 |
| CuClad 6700 | 2.33 | .0025 | 60 | 60 |
| CuClad 6250 | 2.32 | .0013 | 60 | 60 |
| CLTE-P | 2.94 | .0025 | 40 | 11 |
| 25N | 3.25 | .003 | 70 | 17 |
| Polyimide | 4.1 | .013 | 60 | 14 |
| Epoxy | 4.5 | .018 | 70 | 17 |

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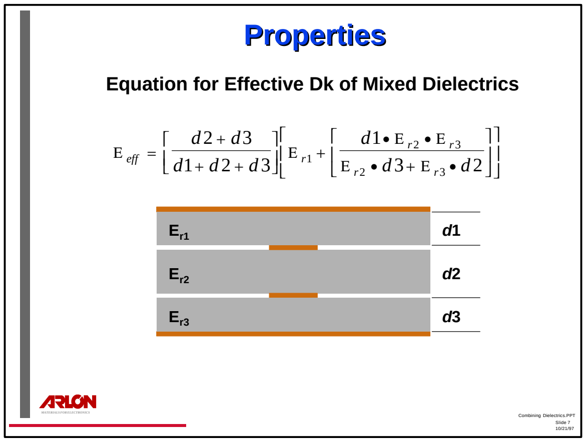
**Figure 2**

Figure 2 is a table of relative properties that show some of the values that can be expected from the different materials that are important in designing a board. The PTFE values only indicate the range of values that are available in different PTFE based products. The tolerances are relatively tight for a given product type but there is a wide variety of product constructions available, each with different values and are chosen based on the design target.

FEP films and the 2 CuClad films are common thermoplastic bonding plies used to join other PTFE laminates together. They are normally used as just a thin bond line with the PTFE material making up the majority of the dielectric space so that their impact on electrical performance is minimal, but they do have normally attractive electrical performance. They are un-reinforced however so they contribute nothing mechanically to the board and can sometimes degrade the mechanical integrity of the board.

CLTE-P is also a thermoplastic fluoropolymer that is usually matched with CLTE laminate. This is a glass fabric reinforced material with ceramic fillers that provide good electrical and mechanical stability. The low CTEs are even better than most thermoset products and can significantly enhance reliability particularly in high layer count boards and those with surface mounted components.

Many boards are being constructed with mixtures of PTFE and thermosets such as epoxy and polyimide. The high loss of these products generally make them unusable in the RF or microwave portion of a mixed dielectric board but because they are thermosets, they can add stiffness, dimensional stability, reliability, and thermal stability to multilayer boards when used in layers that do not have critical high frequency signals.



**Properties**

Equation for Effective Dk of Mixed Dielectrics

$$E_{eff} = \left[\frac{d2+d3}{d1+d2+d3}\right]\left[E_{r1} + \left[\frac{d1 \bullet E_{r2} \bullet E_{r3}}{E_{r2} \bullet d3 + E_{r3} \bullet d2}\right]\right]$$

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Figure 3

Mixing different dielectrics in the same board can add some difficulties in predicting the performance of the composite. In single or dual stripline configurations, a different material on each side of the line can seriously affect performance. The equation in Figure 3 has been used in some cases to help get a little better estimate of the effective dielectric constant of a mixed dielectric space which in turn can be used to plug into impedance modeling equations. Different materials can be mixed but it gets more complicated to understand the effects if they are mixed in the same dielectric space.

From a fabrication standpoint, the bonding temperature that must be used for each product is the most important. These are shown in Figure 4. Fusion bonding requires temperatures up to 650 degrees F and often exceeds the capability of most printed circuit fabricators. This limits the source of supply to those that have specifically installed equipment capable of this and generally are those that have targeted microwave circuit boards.

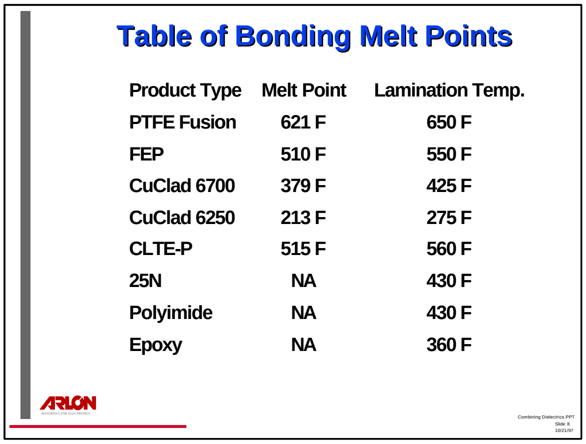

**Table of Bonding Melt Points**

| Product Type | Melt Point | Lamination Temp. |
|---|---|---|
| PTFE Fusion | 621 F | 650 F |
| FEP | 510 F | 550 F |
| CuClad 6700 | 379 F | 425 F |
| CuClad 6250 | 213 F | 275 F |
| CLTE-P | 515 F | 560 F |
| 25N | NA | 430 F |
| Polyimide | NA | 430 F |
| Epoxy | NA | 360 F |

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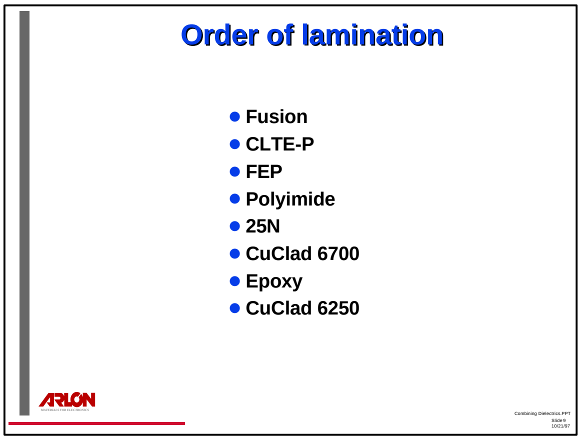
Figure 4

The bonding films offer 3 different bonding temperature ranges. Remember that these are thermoplastic films and will re-melt every time their melt point is exceeded. Most of these melt above the normal use temperature but assembly conditions may limit their application. FEP has the highest melting point of the 3 films and therefore requires the highest laminating temperature. It is also more suited to applications that will see multiple soldering cycles during assembly. 6700 is in the middle and can see limited and careful soldering during assembly. It's laminating temperature is in the region where most circuit fabricators can bond the multilayer without pushing the capabilities of their normal equipment. 6250 is a low temperature bond film which makes laminating simple and may reduce stresses in a board but is too low for any board that will see subsequent soldering operations.

The CLTE-P polymers will bond at about the same temperature as FEP film and actually could be used in the same laminating cycle.

25N, Polyimide, and Epoxy are thermosets so once they are laminated, they will never re-melt in any subsequent soldering or thermal excursions. These would be the best choice for harsh assembly operations.



**Order of lamination**

- Fusion
- CLTE-P
- FEP
- Polyimide
- 25N
- CuClad 6700
- Epoxy
- CuClad 6250

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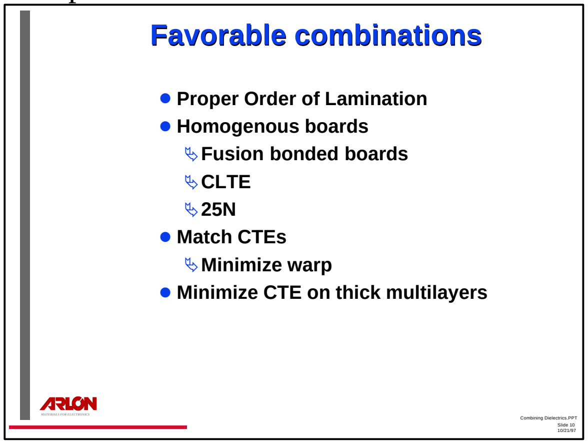
**Figure 5**

If different materials are to be used in the same board in a sequentially laminated process, they must be done in the order shown in Figure 5, generally starting with the highest melting point and proceeding down in melt temperature. We do not want to re-melt the previously bonded subassemblies with the subsequent laminating cycle. This could cause layer distortion, circuit swimming, or delamination. The thermoset products would not re-melt but would be subject to polymer degradation if the see a long lamination cycle above their ideal laminating temperature. The order of lamination then generally matches the descending lamination temperature rather than the order of melt points.



**Favorable combinations**

- Proper Order of Lamination
- Homogenous boards
  - Fusion bonded boards
  - CLTE
  - 25N
- Match CTEs
  - Minimize warp
- Minimize CTE on thick multilayers

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**Figure 6**

The preferred combination of materials is indicated in Figure 6 and would be a design that allows for the proper order of lamination described in the previous slide. This is manufacturable by many fabricators and allows for a wide variety of dielectrics to be used to help satisfy the electrical design needs.

Boards with a homogenous dielectric are generally the best overall choice. They provide for uniform and predictable electrical performance and are the simplest to construct and fabricate. This has historically been done with fusion bonding but these become limited to just a few layers of simple circuitry and requires very high laminating temperatures.

CLTE is the most stable microwave material available that is based on PTFE chemistry and had a matching prepreg that provides for homogenous dielectrics. It processes similar to other PTFE microwave substrate materials

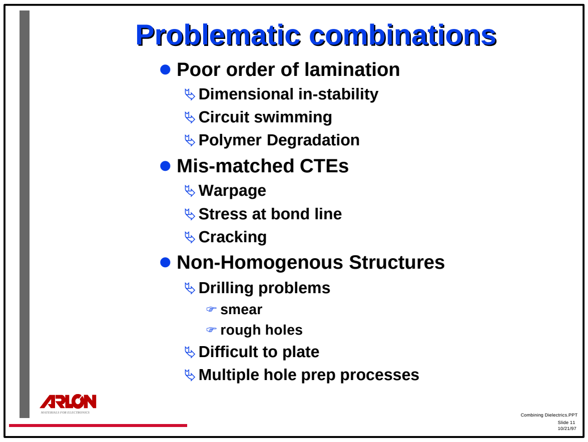
25N is a relatively new product that also has a matching prepreg. 25N handles more like a polyimide and is processed down more conventional fabrication lines.

A caution in selecting different materials for the same board is to try to closely match the expansions of the different layers. A non-symmetrical buildup or mis-matched materials will likely cause a finished board to warp or distort and may even delaminate on thermal cycling.

If the multilayer approaches or starts to exceed 1/16 to 3/32 inch, we must further select materials with a low Z expansion if there will be small plated through holes connecting the layers.

Figure 7 lists some of the conditions that we try to avoid. Being forced by design to laminate in the wrong order could cause layers to get stretched or distorted, or at least move enough to be unable to hit the internal pads with a plated through hole and make a reliable connection. If the melt point of the laminate is exceeded, the circuit lines could start to float around, or “swim”.

Mis-matched CTEs were previously mentioned and careful selection of materials is important to avoid these problems.



**Problematic combinations**

- Poor order of lamination
  - Dimensional in-stability
  - Circuit swimming
  - Polymer Degradation
- Mis-matched CTEs
  - Warpage
  - Stress at bond line
  - Cracking
- Non-Homogenous Structures
  - Drilling problems
    - smear
    - rough holes
  - Difficult to plate
  - Multiple hole prep processes

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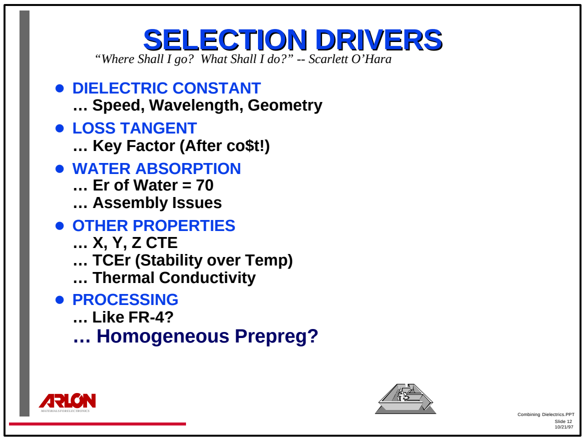
**Figure 7**

Any non-homogenous combinations cause some challenges and difficulties to the fabricator. Setting optimum drill parameters for the plated through holes can be a real problem. Without a lot of work and experimentation, we can have problems with resin smear that will prevent connection the inner layers or rough holes that could trap process solutions. These are difficult to plate uniformly and could affect the reliability of the plated through hole.

Multiple hole preparation steps may be necessary to properly condition the different materials to get them to accept plating without skipping or plating voids. These added steps increase complexity and cost.



**SELECTION DRIVERS**

*"Where Shall I go? What Shall I do?" -- Scarlett O'Hara*

- DIELECTRIC CONSTANT
  ... Speed, Wavelength, Geometry
- LOSS TANGENT
  ... Key Factor (After co$t!)
- WATER ABSORPTION
  ... Er of Water = 70
  ... Assembly Issues
- OTHER PROPERTIES
  ... X, Y, Z CTE
  ... TCEr (Stability over Temp)
  ... Thermal Conductivity
- PROCESSING
  ... Like FR-4?
  ... Homogeneous Prepreg?

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**Figure 8**

The key drivers in selecting materials for microwave multilayer boards are listed in Figure 8. The dielectric constant is often the first and is usually driven by the circuit application and design, although many designs can work around this to gain other advantages.

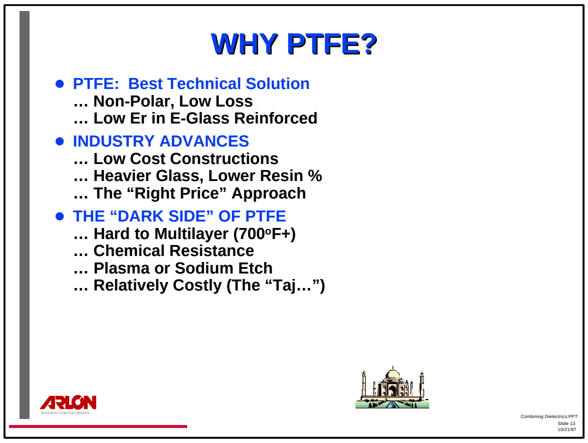
The loss is the next key to certain microwave circuits. We can look to utilize low loss materials on the circuits where it is required and use a different lossier dielectric in not critical areas to gain additional advantages.

Cost is always at the top of the list of those "other advantages".

Material water absorption is always a concern with boards that have tightly controlled dielectric properties. With water having a dielectric constant of 70, it can quickly change the electrical performance with even slight amounts absorbed.

Other considerations are the CTE of the layers as well as the finished board to control assembly problems and improve reliability. The TCEr can be a key factor where the board may be exposed to large temperature fluctuations. If the dielectric constant changes a lot over temperature, the circuit may not function properly at other than room temperature. Thermal conductivity can be important in removing heat from components or to enable handling higher power.

Everyone wants a material to process "just like FR-4" since it is a low cost standard process. The only thing I know of that processes just like FR-4 is FR-4 and sometimes it doesn't even work that way. I also stress again the ideal of having a homogenous material to simplify both design and fabrication.



**WHY PTFE?**

- PTFE: Best Technical Solution
  ... Non-Polar, Low Loss
  ... Low Er in E-Glass Reinforced
- INDUSTRY ADVANCES
  ... Low Cost Constructions
  ... Heavier Glass, Lower Resin %
  ... The "Right Price" Approach
- THE "DARK SIDE" OF PTFE
  ... Hard to Multilayer (700°F+)
  ... Chemical Resistance
  ... Plasma or Sodium Etch
  ... Relatively Costly (The "Taj...")

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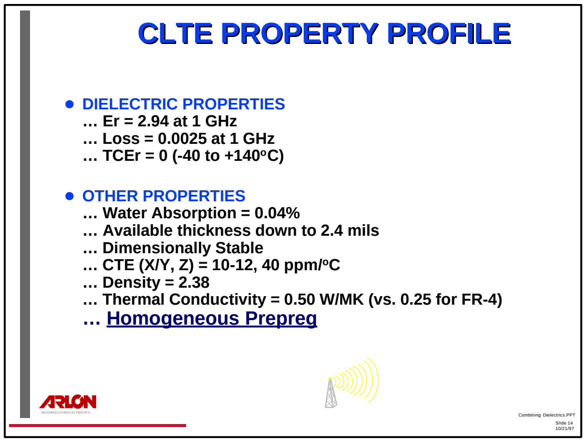
**Figure 9**

Why PTFE? (Figure 9) From a technical standpoint, it is still the performance leader electrically for low loss circuits. It can have a low dielectric constant with E-glass as a reinforcement to give it good stability and handling

New advances have provided PTFE advantages at significantly reduced cost compared to historical standards. This is done using other glass fabrics and lower PTFE resin contents which can be built up to standard thicknesses using fewer layers. We have taken the approach to try to build materials at the right price target rather than always trying to hit the ultimate in performance at the expense of cost.

The "Dark Side of PTFE" is that it is difficult to laminate by itself due to the high temperatures involved. It is inherently so chemically resistant to everything that it makes plated through holes difficult. The best process still in use requires a sodium etch that is hazardous, smelly and limited in shelf life and control parameters. Plasma has been used more and more as an alternative.

And, PTFE is still relatively costly for commercial applications. We sometimes look at it as trying to build the Taj Mahal to house our circuits when all we need is a backyard shed.



### CLTE PROPERTY PROFILE

- DIELECTRIC PROPERTIES
  ... Er = 2.94 at 1 GHz
  ... Loss = 0.0025 at 1 GHz
  ... TCEr = 0 (-40 to +140$^{o}$C)
- OTHER PROPERTIES
  ... Water Absorption = 0.04%
  ... Available thickness down to 2.4 mils
  ... Dimensionally Stable
  ... CTE (X/Y, Z) = 10-12, 40 ppm/$^{o}$C
  ... Density = 2.38
  ... Thermal Conductivity = 0.50 W/MK (vs. 0.25 for FR-4)
  ... Homogeneous Prepreg

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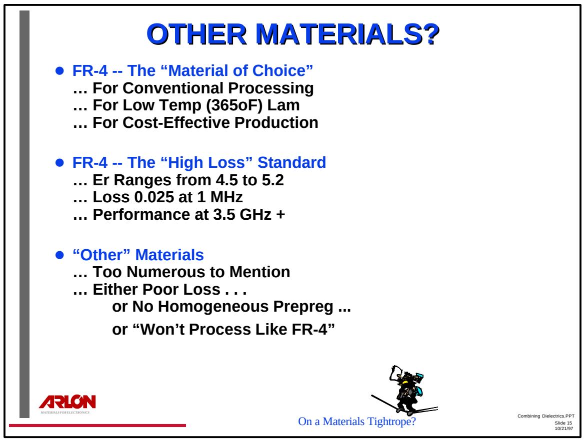
**Figure 10**

Figure 10 shows a PTFE product that meets most of the selection drivers is CLTE. It has a tightly controlled dielectric constant with a low loss at high frequencies. The dielectric constant is also extremely stable over a wide temperature range.

The water absorption is only .04 % so the circuit is unaffected by moisture. Dielectric layers are available in thicknesses down to 2.4 mils making it a good building block for high layer count boards. The CTE is lower than other laminates including thermosets making it appropriate for many different designs. It also has a Prepreg that has the same properties as the laminate making homogenous boards possible with relatively easy PTFE type fabrication methods



### OTHER MATERIALS?

- FR-4 -- The "Material of Choice"
  ... For Conventional Processing
  ... For Low Temp (365oF) Lam
  ... For Cost-Effective Production
- FR-4 -- The "High Loss" Standard
  ... Er Ranges from 4.5 to 5.2
  ... Loss 0.025 at 1 MHz
  ... Performance at 3.5 GHz +
- "Other" Materials
  ... Too Numerous to Mention
  ... Either Poor Loss . . .
      or No Homogeneous Prepreg ...
      or "Won't Process Like FR-4"

On a Materials Tightrope?

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**Figure 11**

For other choices, FR-4 has always been the baseline to try to design on since it offers conventional processing , relatively low temperature processing, and high volume low cost processes. (Figure 11)

FR-4 is also the high loss standard. The dielectric constants are higher than most designs would like, the high loss knocks it out of most high frequency designs so performance above 1 GHz is questionable and is just about impossible to use above 3.5 GHz.

There are many other conventional thermoset products available that are too numerous to get into here. They almost all have similar deficiencies of poor loss characteristics, do not have a matching prepreg or wont process in a standard FR-4 process line.

In our effort to develop a better material that came closer to achieving an ideal product, we tried to find how we could best merge our experience with producing both thermoset materials and microwave materials (Figure 12). 2nd generation cyanates were thought to be a bridge between these two with a dielectric constant of about 3.8 and a loss of .01, somewhere between epoxies and PTFEs. Cracking and processing difficulties prevented this product from working to it's fullest potential.

**ARLON 25N**
**Development Drivers**

- FUSION OF MICROWAVE AND CONVENTIONAL
  - ... 2nd Generation = Cyanates
  - ... Er=3.8, d.f.=0.01
  - ... Processing and Cracking Issues
- DEVELOPMENT GOALS
  - ... Er < 3.5,    Loss < 0.003
  - ... Low Water Absorption
  - ... Er Stable over Temperature
  - ... Conventional Processing
- DEVELOPMENT APPROACH
  - ... Low Polarity Resins
  - ... Standard E-Glass (co$t)
  - ... Std. Coating, Lamination

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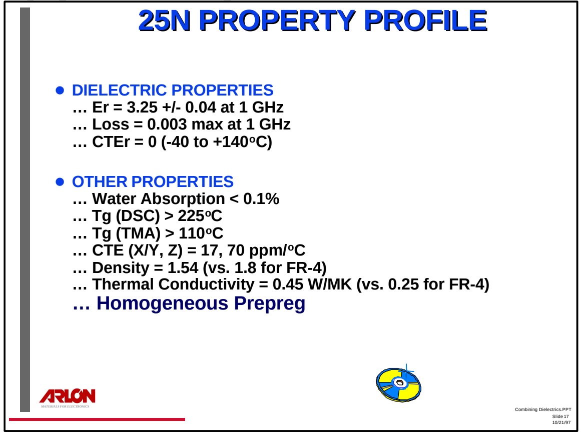
Figure 12

We still wanted a product that had a dielectric constant less than 3.5, a loss of less than .003, low water absorption, stable over temperature, and process in most fabrication processes.

To achieve these, we needed a resin system with low polarity to achieve the electrical targets, could be coated on standard E-glass, and would utilize our existing coating and laminating equipment to keep the costs well in control.



**25N PROPERTY PROFILE**

- DIELECTRIC PROPERTIES
  - ... Er = 3.25 +/- 0.04 at 1 GHz
  - ... Loss = 0.003 max at 1 GHz
  - ... CTEr = 0 (-40 to +140°C)
- OTHER PROPERTIES
  - ... Water Absorption < 0.1%
  - ... Tg (DSC) > 225°C
  - ... Tg (TMA) > 110°C
  - ... CTE (X/Y, Z) = 17, 70 ppm/°C
  - ... Density = 1.54 (vs. 1.8 for FR-4)
  - ... Thermal Conductivity = 0.45 W/MK (vs. 0.25 for FR-4)
  - ... Homogeneous Prepreg

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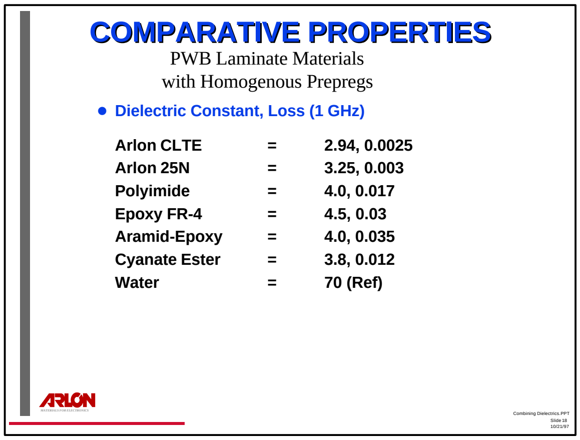
Figure 13

The 25N product does achieve most of the selection drivers including a low dielectric constant of 3.25, a loss of less than .003, and stable over temperature (Figure 13).

It also has a very low water absorption for electrical stability in humid environments. Other characteristics make it very similar to conventional thermoset resins and it does have a matching prepreg to provide for homogenous multilayer boards.



**COMPARATIVE PROPERTIES**
PWB Laminate Materials
with Homogenous Prepregs

- Dielectric Constant, Loss (1 GHz)

Arlon CLTE = 2.94, 0.0025
Arlon 25N = 3.25, 0.003
Polyimide = 4.0, 0.017
Epoxy FR-4 = 4.5, 0.03
Aramid-Epoxy = 4.0, 0.035
Cyanate Ester = 3.8, 0.012
Water = 70 (Ref)

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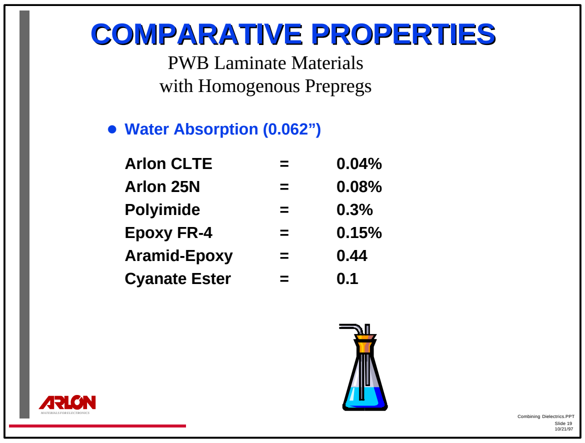
Figure 14

The table in Figure 14 compares some of the products available that have matching prepregs. The CLTE provides the lowest dielectric constant and loss followed closely by the 25N. All of the other thermoset materials are generally too lossy for the high frequency portions of a board but all could be used in combination with each other to achieve various design targets for electrical, thermal or mechanical properties.



**COMPARATIVE PROPERTIES**
PWB Laminate Materials
with Homogenous Prepregs

- Water Absorption (0.062")

Arlon CLTE = 0.04%
Arlon 25N = 0.08%
Polyimide = 0.3%
Epoxy FR-4 = 0.15%
Aramid-Epoxy = 0.44
Cyanate Ester = 0.1

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Figure 15

A comparison of water absorption properties in Figure 15 shows a similar pattern with CLTE still a performance leader and 25N close behind. The others should be used in less critical portions of the boards.

## Summary

Many different combinations of materials are being used today to build complex multilayer boards with RF or microwave circuits included. Materials are combined to optimize boards for cost reduction, stiffness or rigidity, ease of fabrication, miniaturization, and other factors. There are lots of potential advantages but also many possible pitfalls.

If it is possible to design around a material that has matching prepregs that enable a homogenous board to be built, many of the pitfalls can be avoided.