SAND2015-3975C

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Photos placed in horizontal position with even amount of white space between photos and header

Cracking in a Flame Sprayed Epoxy

Kurtis Ford

Mark Stavig

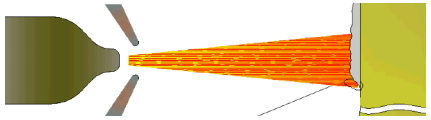
Robert Chambers

U.S. DEPARTMENT OF ENERGY

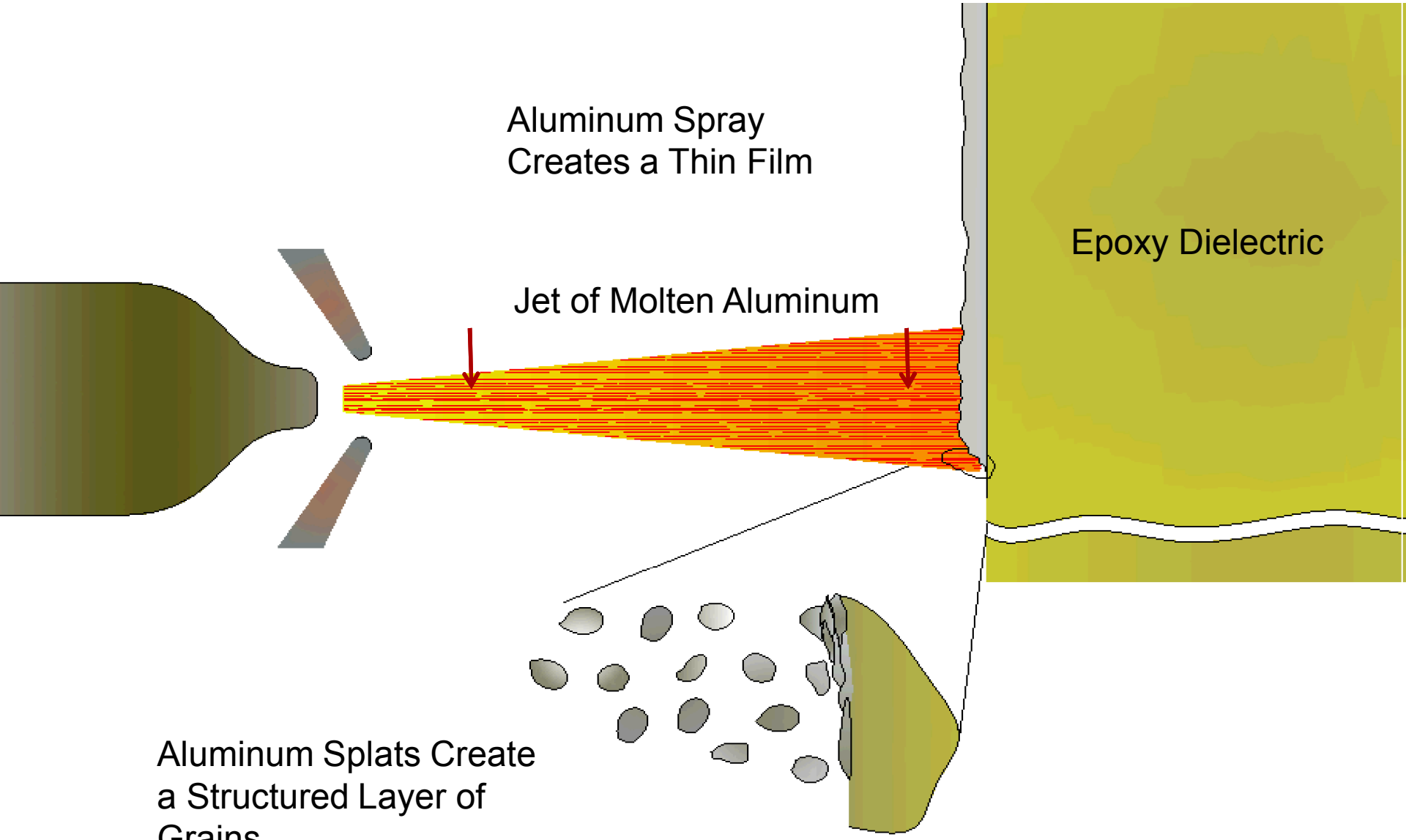
National Nuclear Security Administration

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Outline

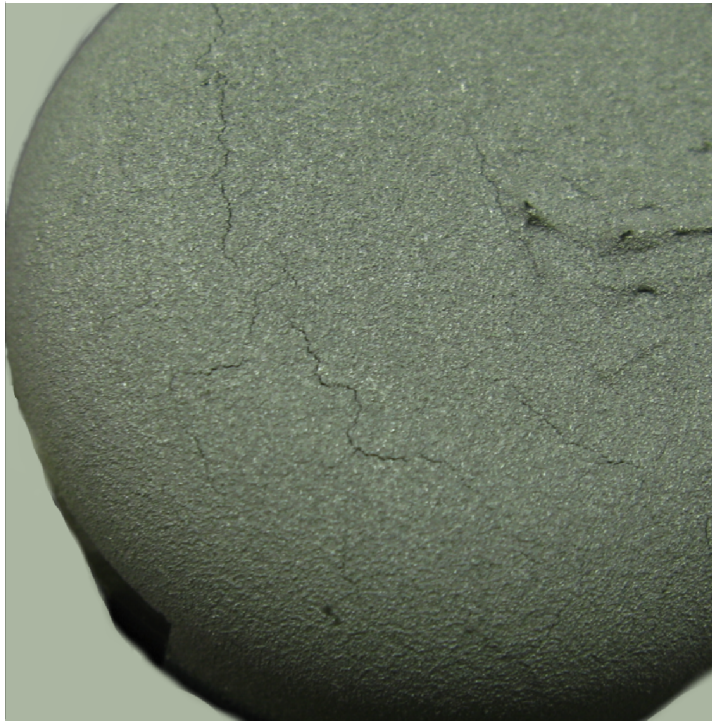
- Flame Spray 
- Problem Statement Electrical Experiment
- Surface Crack Experiment
- Film Thickness Experiments
- Taking it to Cold
- Conclusions

Aluminum Coated Epoxy Cylinder



Electrical Experiment Anomalies

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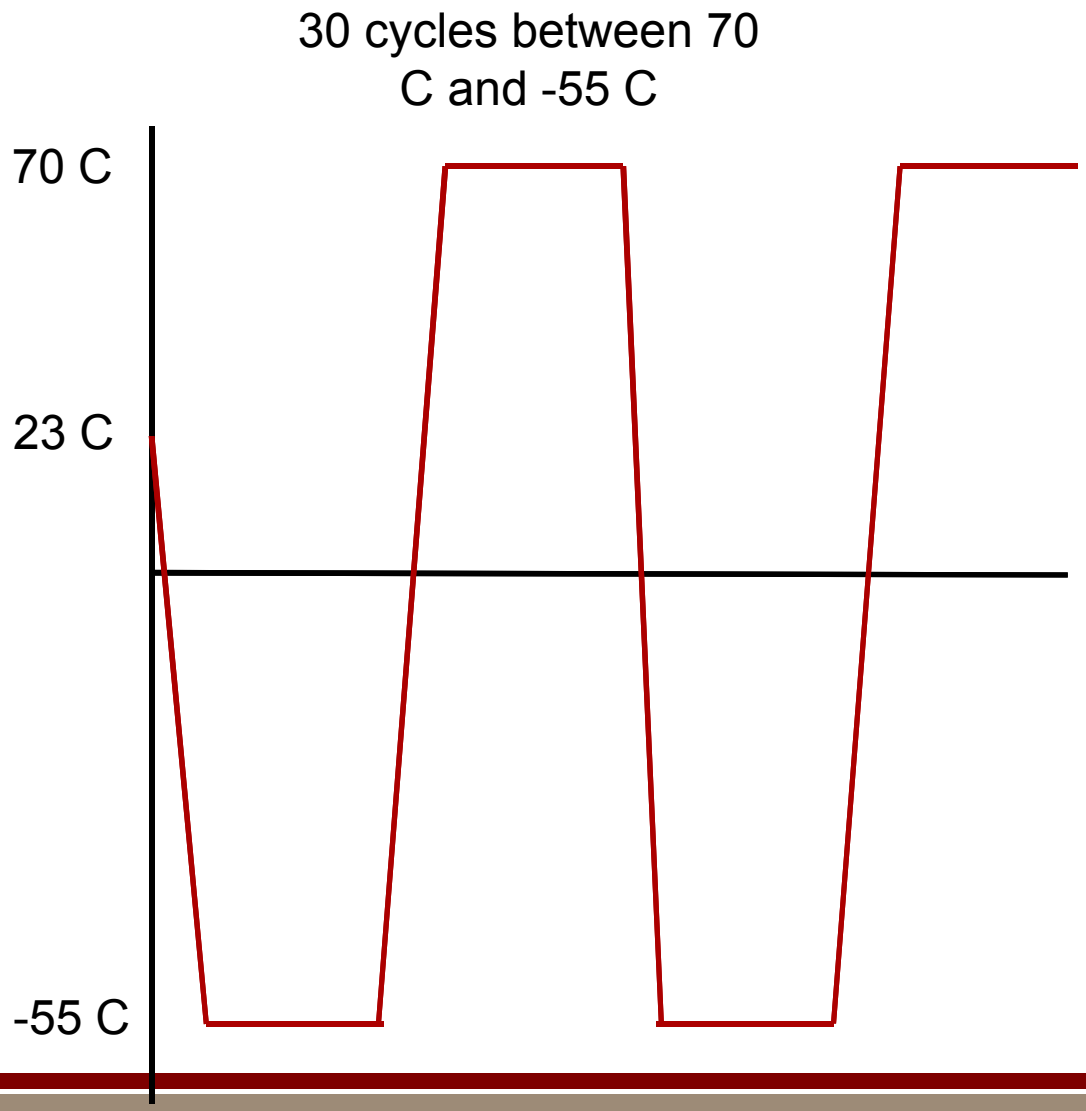


Surface Cracks at RT



Surface Cracks with Substrate Damage at 70 ^{o}C

No Cracks after High Temperature Cycle

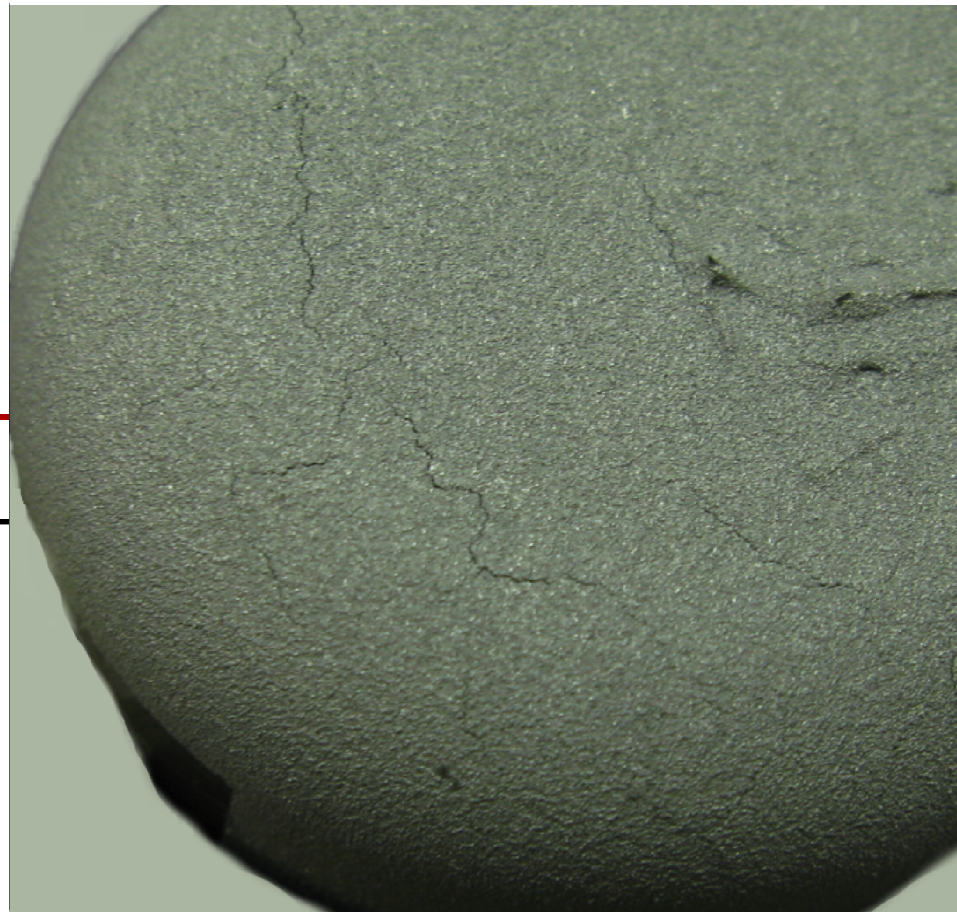


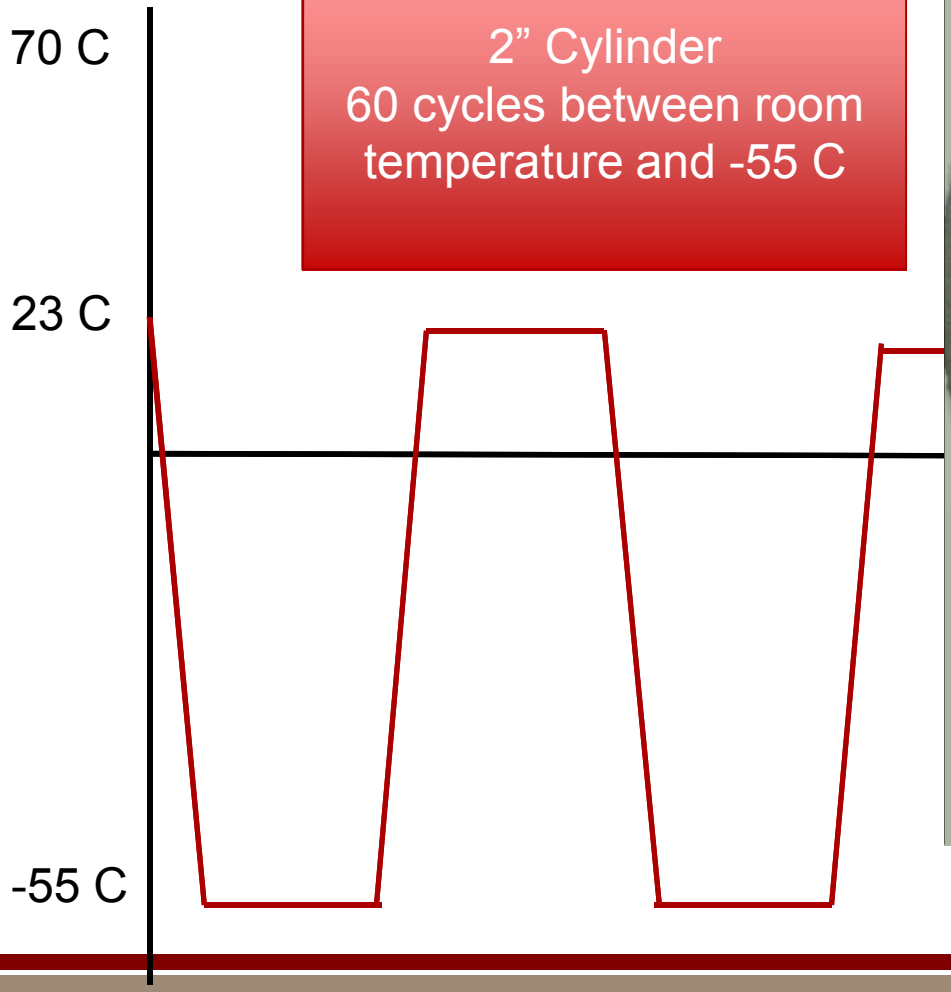
No Cracks Observed

Electrical Experiments at Cold

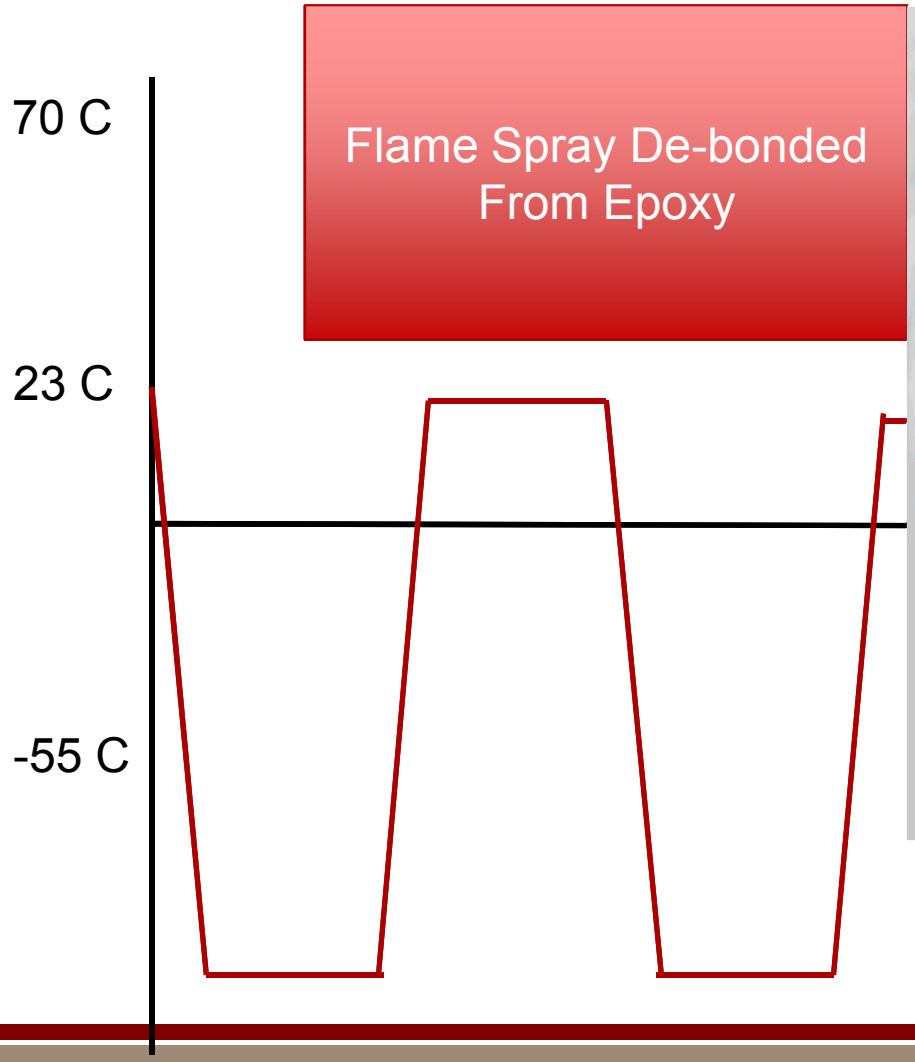
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2” Cylinder
60 cycles between room temperature and -55 C

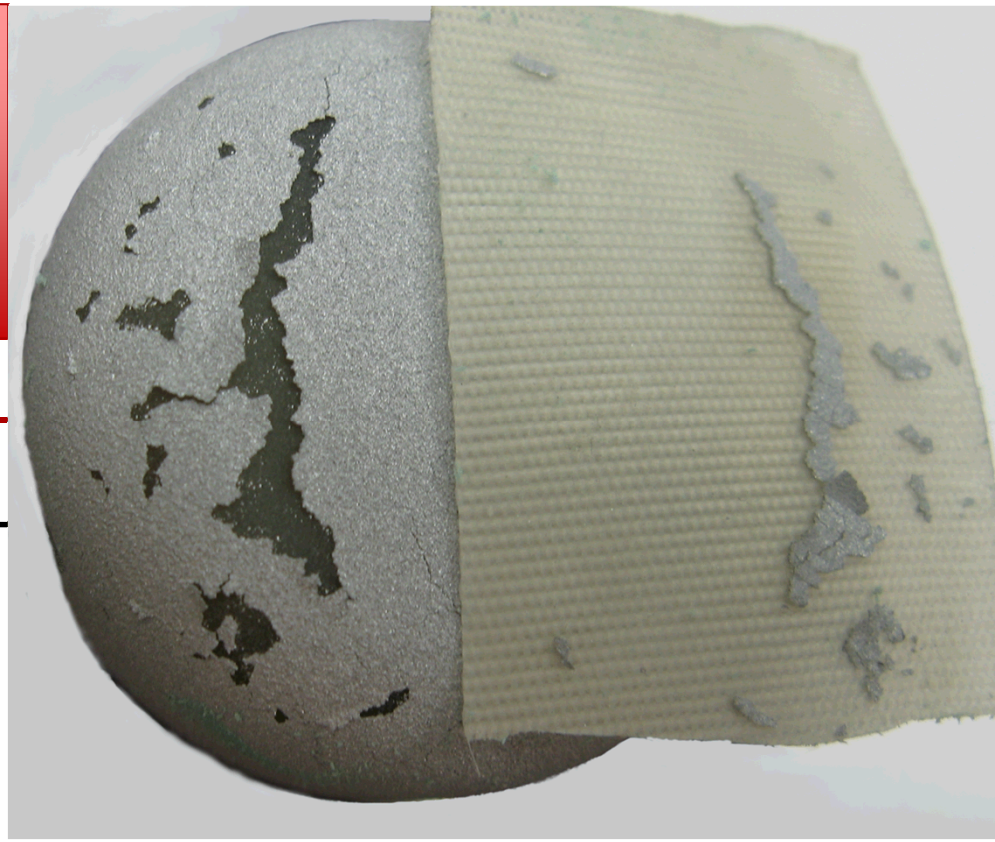




At Cold Flame Spray Delaminates

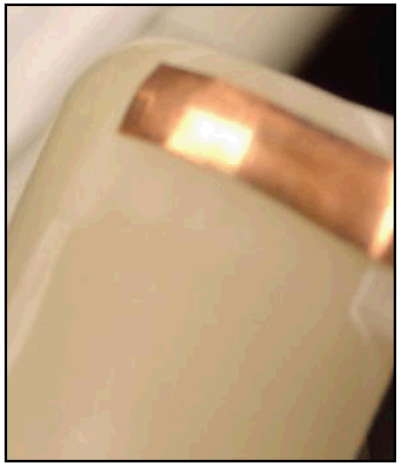


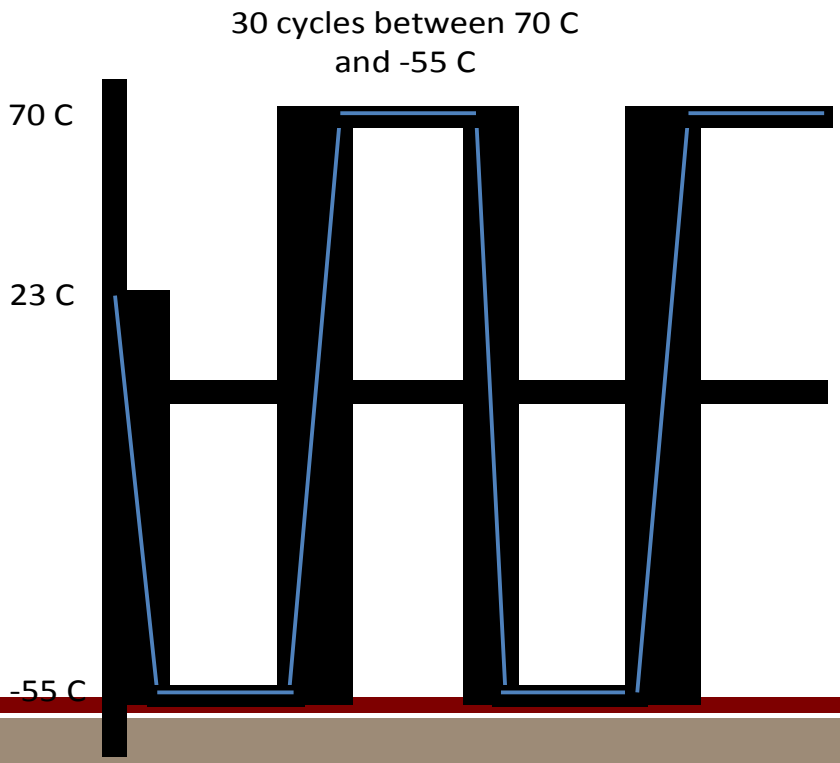
Flame Spray De-bonded From Epoxy



Cracks at Hot With an Inclusion

A Copper strip beneath flame spray on cylinder





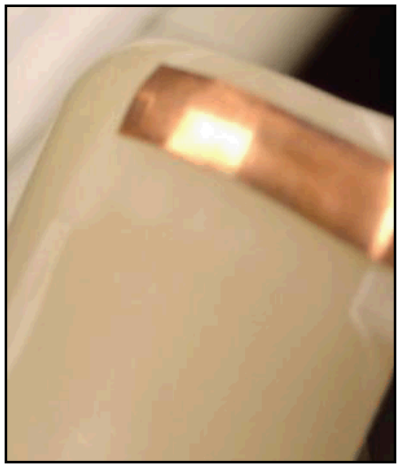


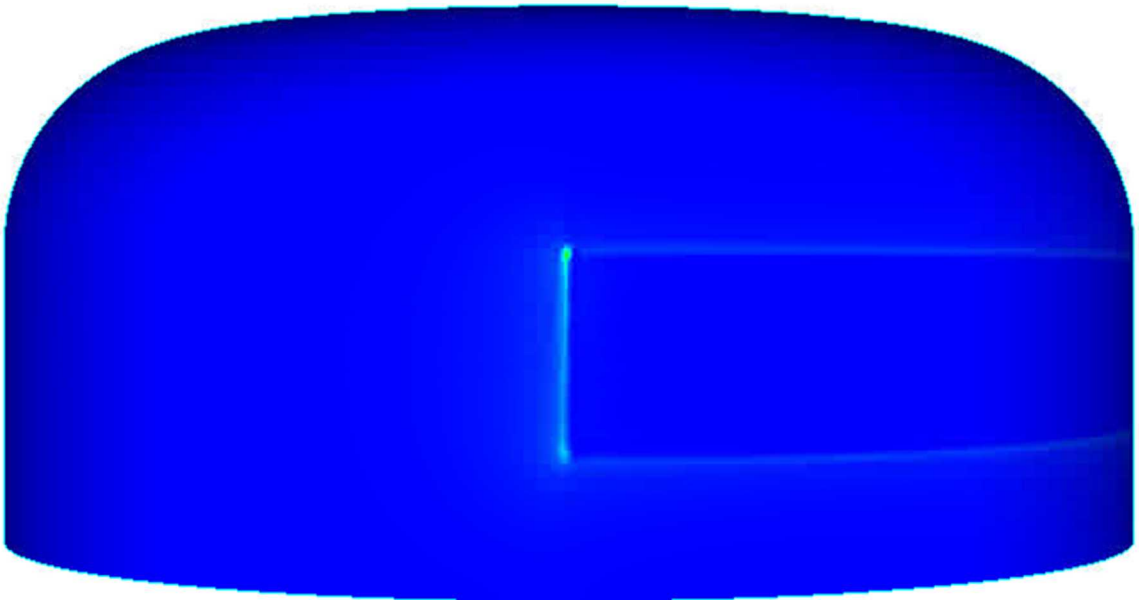
Copper Strip Alone is Not Responsible

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Copper Strip Does not exert enough force to create a crack

Crack could not be recreated experimentally without flame spray





Questions

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Can flame spray cracks penetrate the epoxy?

At What temperature would the cracks occur?

Does flame spray thickness of stiffness effect Cracking?

Did the delamination cracks occur at cold, and could they lead to substrate damage?

Experiments

1. Heat flame sprayed cylinders until cracks are observed

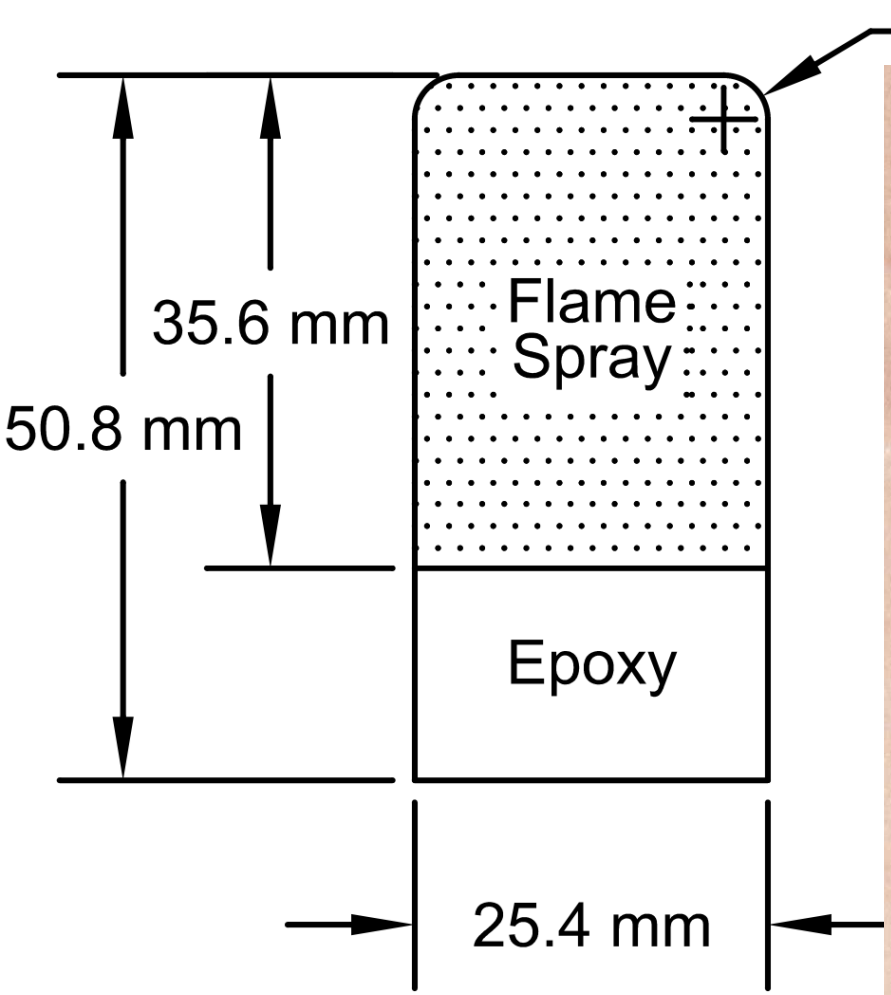
2. Heat different layers to correlate film thickness to crack modes

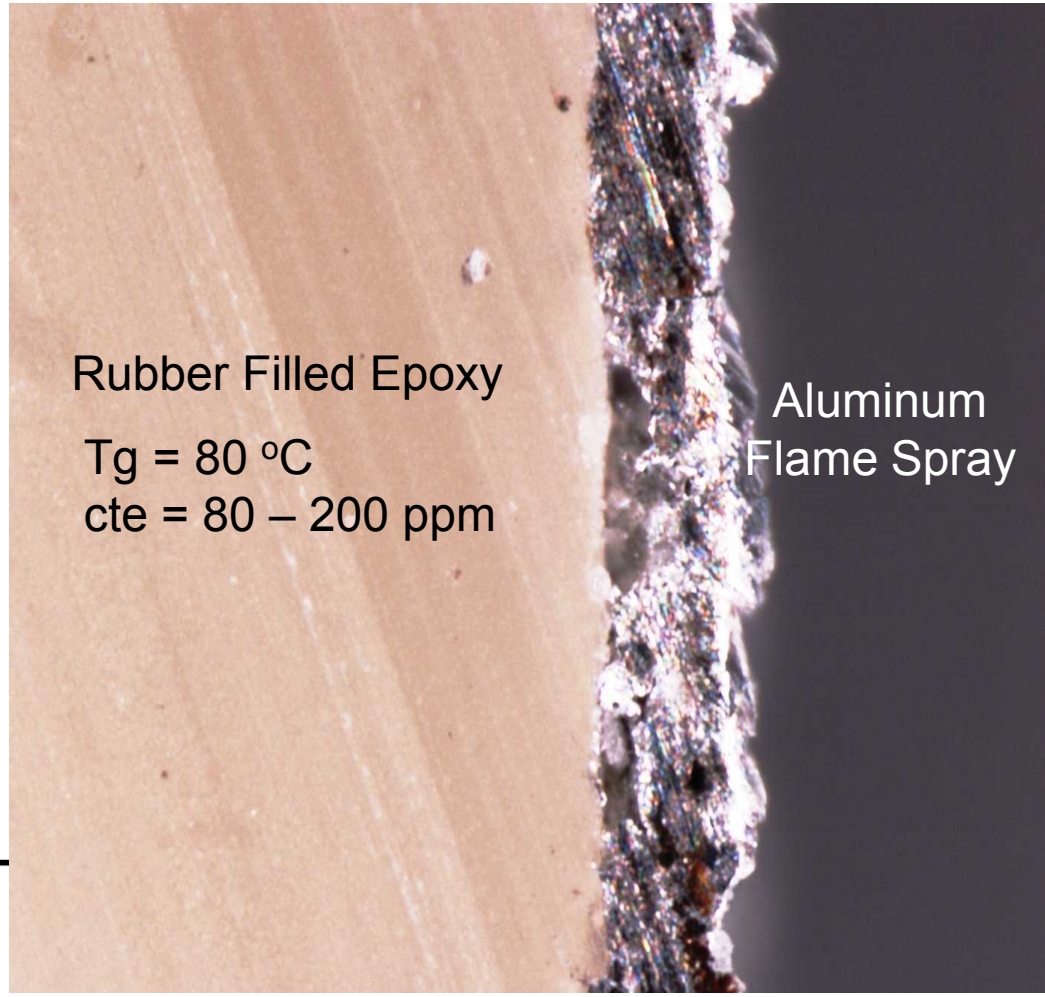
3. Cool down cylinders to create delaminated cracks



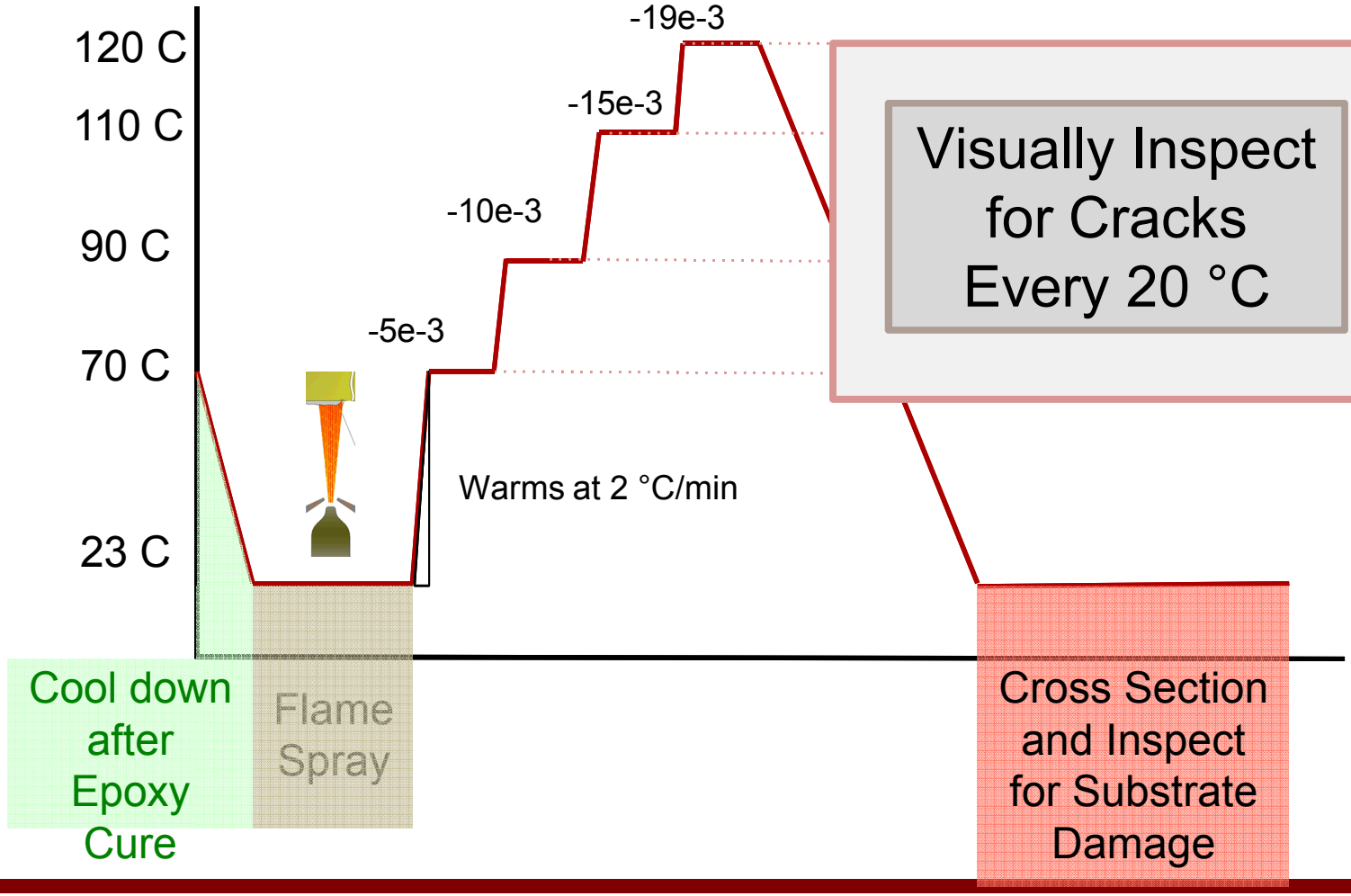


Experiment 1 Materials





Experiment 1



Unfilled 828/DEA Cylinders with Flame Spray

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70 °C

No Cracks



90 °C

Faint Channel Cracking

Unfilled 828/DEA Cylinders with Flame Spray

Sandia National Laboratories



90 °C

No Cracks



110 °C

Faint Channel Cracking

Unfilled 828/DEA Cylinders with Flame Spray

Sandia National Laboratories

Sample that was tak



110 °C



120 °C

Unfilled 828/DEA Cylinders with Flame Spray

Same sample reheated to T=120 C for 3 hou

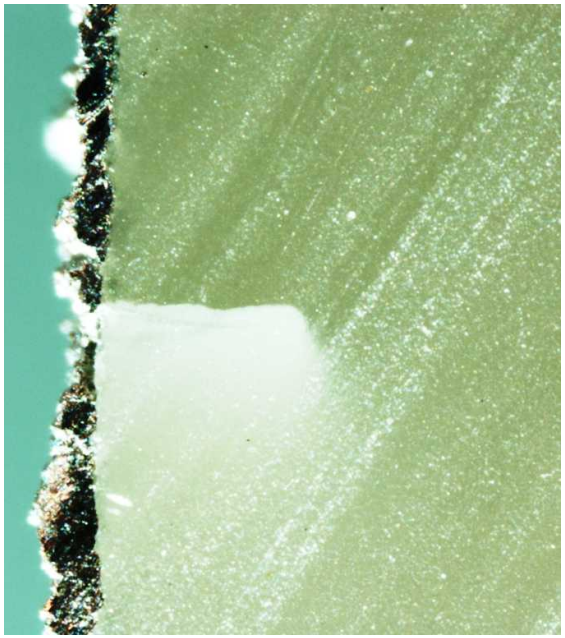


120 °C

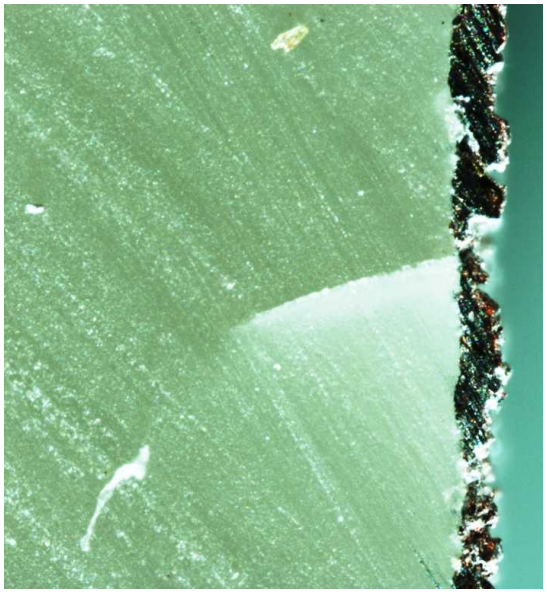


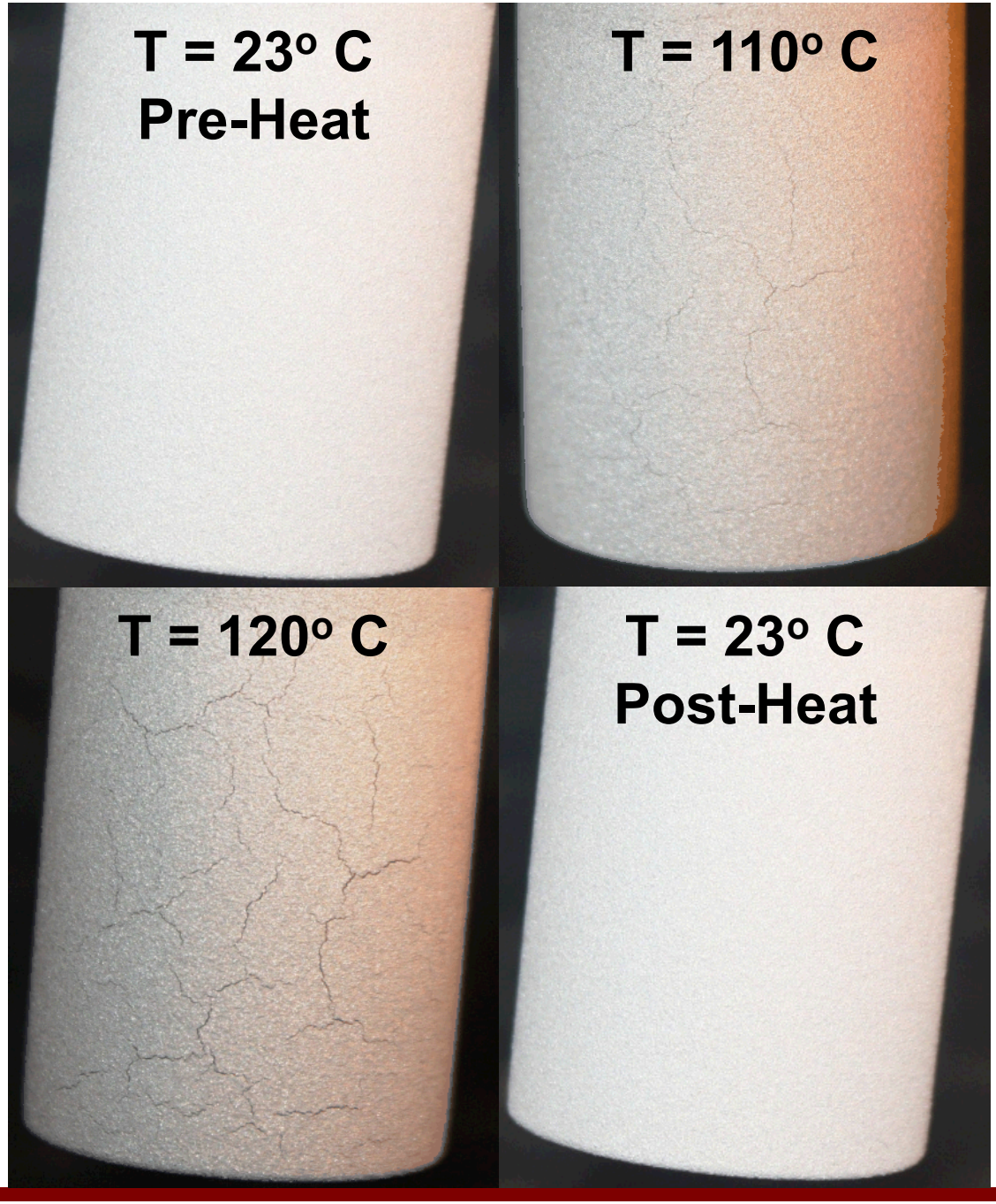
23 °C

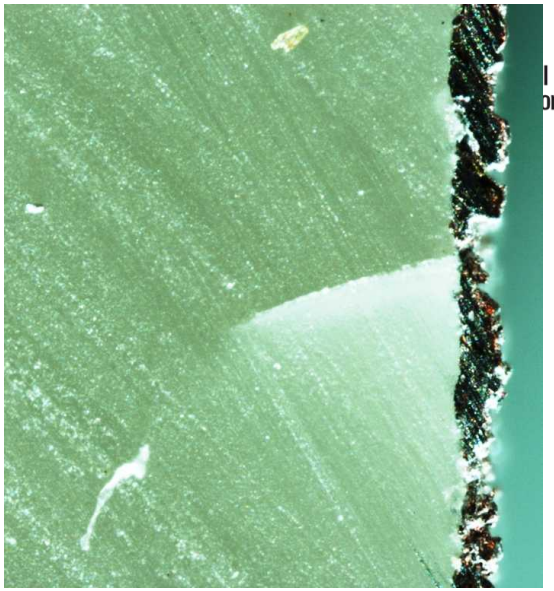
Substrate Damage



Substrate damage appears to correspond to the channel crack patterns, however not all surface cracks have substrate damage. The cracks are approximately 0.5 mm long







- Flame spray cracks can propagate into epoxy
- Tensile cracks close at room temperature

Questions

Can flame spray cracks penetrate the epoxy?

Substrate damage can occur at 120 °C

At What temperature would the cracks occur?

They exist in the flame spray at 90 °C

Is there a critical flame spray thickness for Cracking?

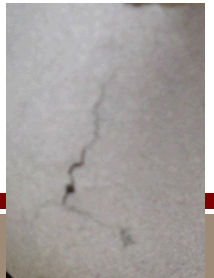
Experiments

1. Heat flame sprayed cylinders until cracks are observed

2. Heat different layers to correlate film thickness to crack modes

3. Cool down cylinders to create delaminated cracks

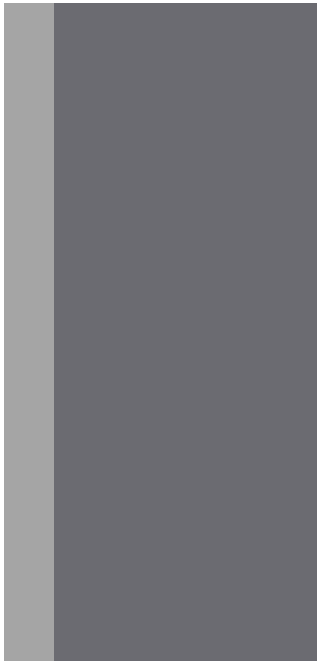




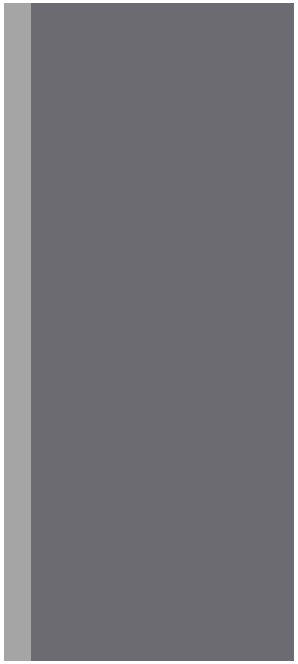
Compare Film Thickness



Twice Nominal Film = 0.2mm

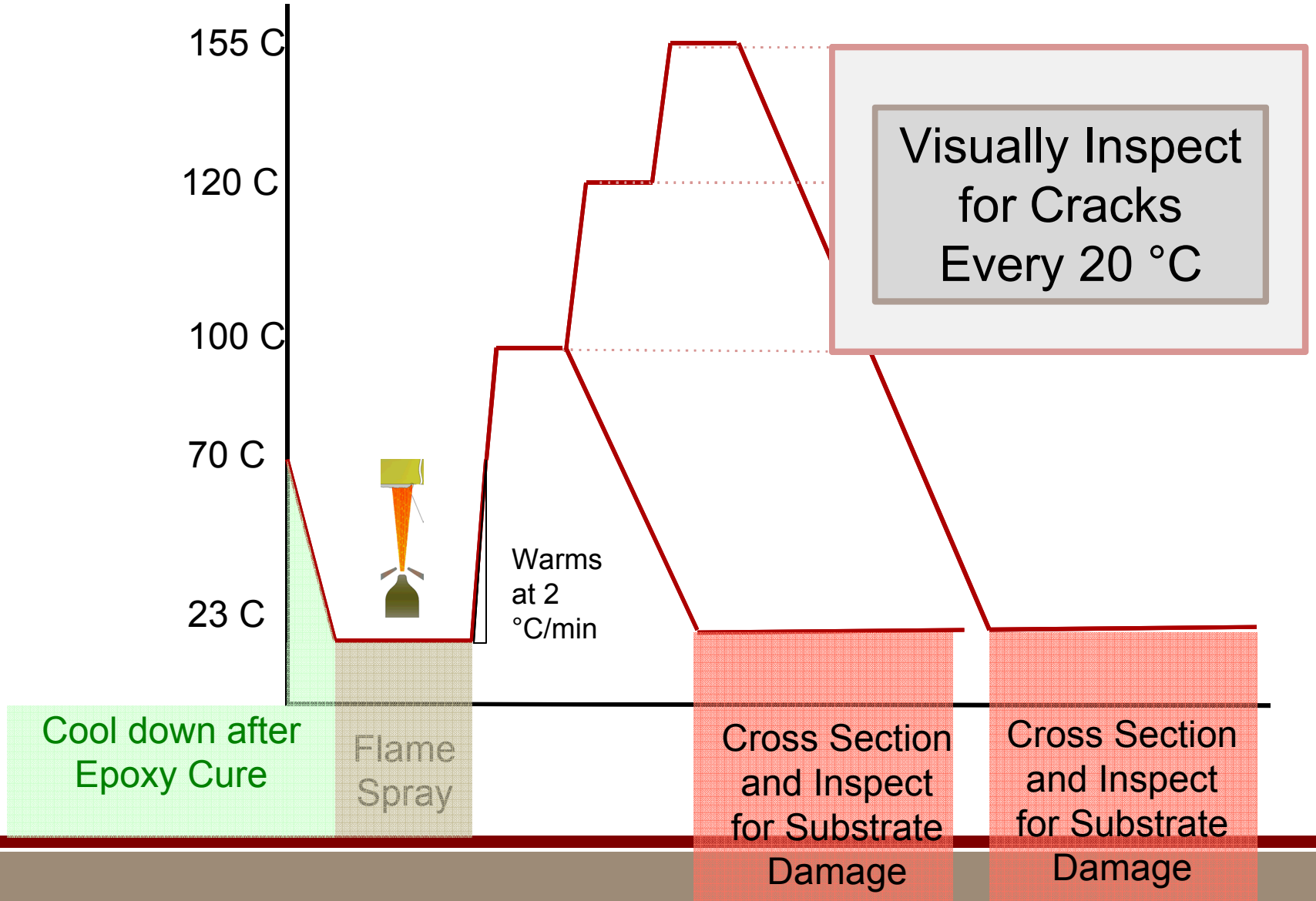


Nominal Film = 0.1mm

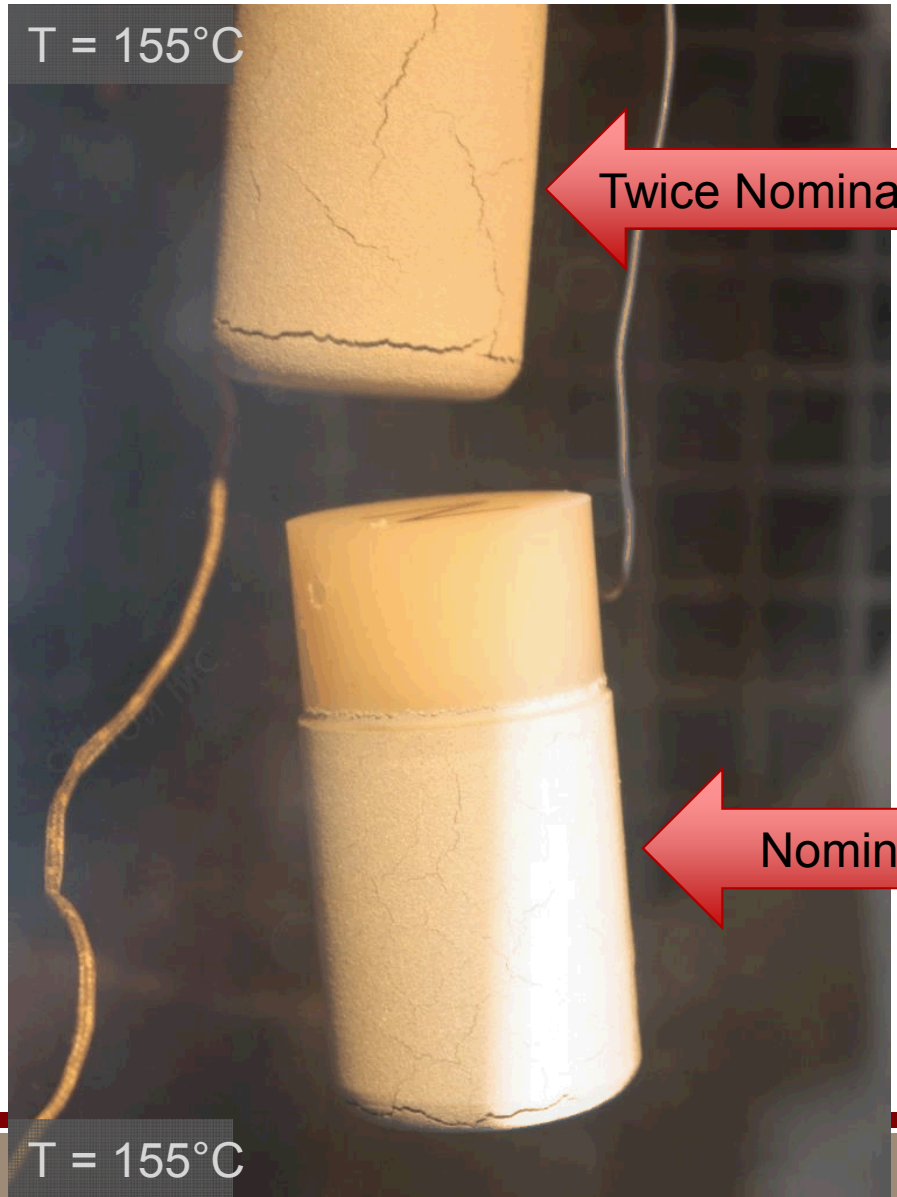


Half Nominal Film = 0.05 mm

Compare Film Thickness



Thin Film Thickness Results





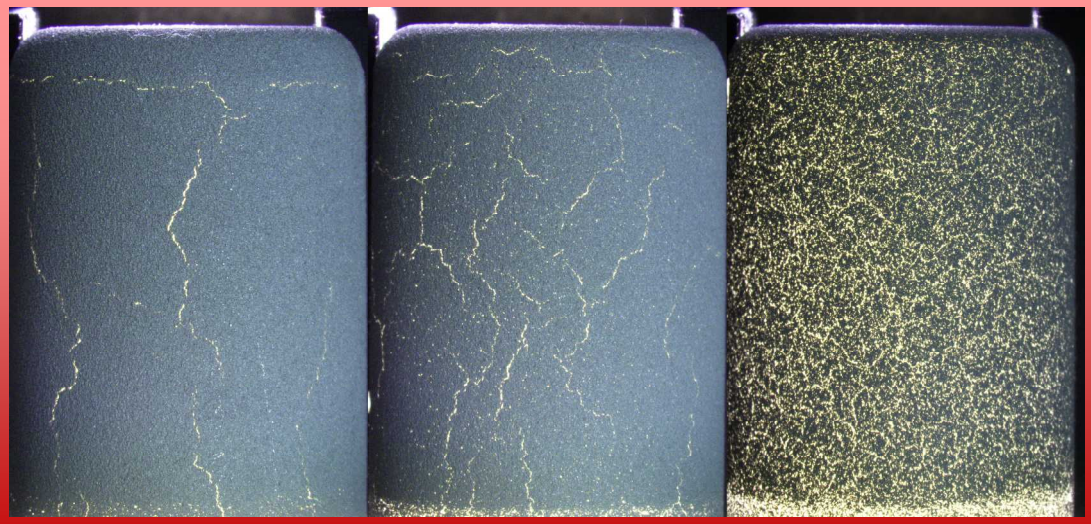
- Wider Surface Cracks in Twice Nominal Film
- More Channeling in Nominal Film
- No Cracks in Half Nominal

Iluminated Cross Section

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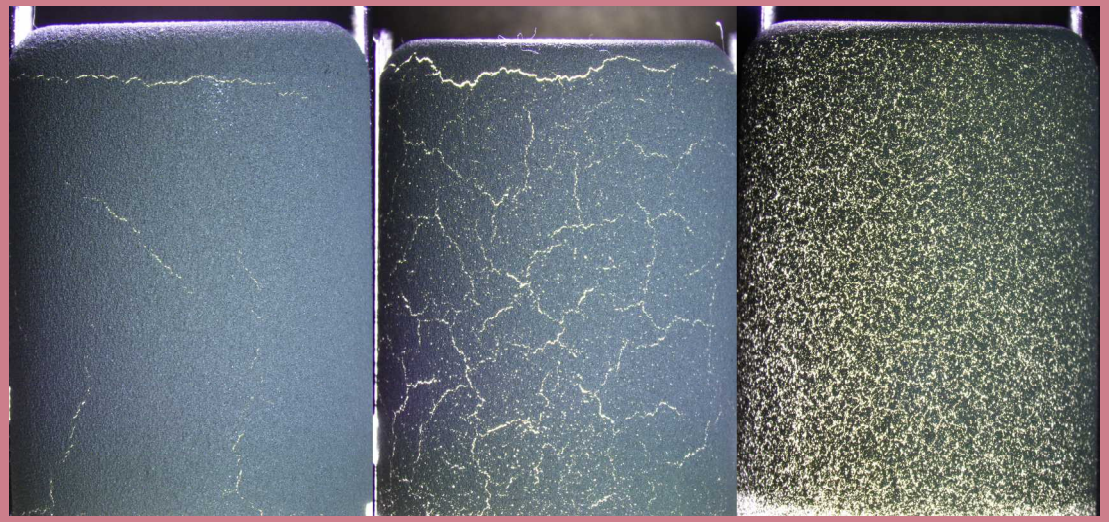
Soaked at 100°C

T = 23°C



Soaked at 155°C

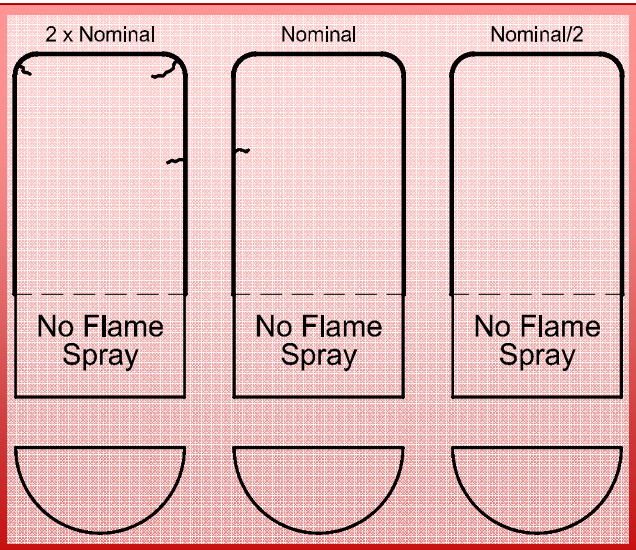
T = 23°C



Substrate Damage

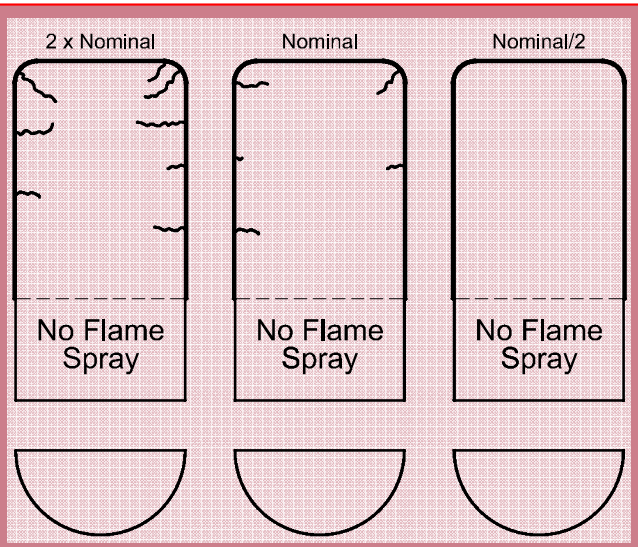
Soaked at 100°C

T = 23°C



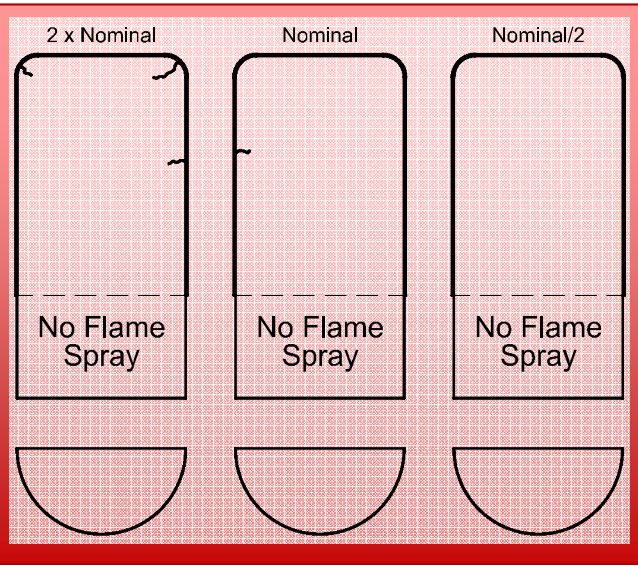
Soaked at 155°C

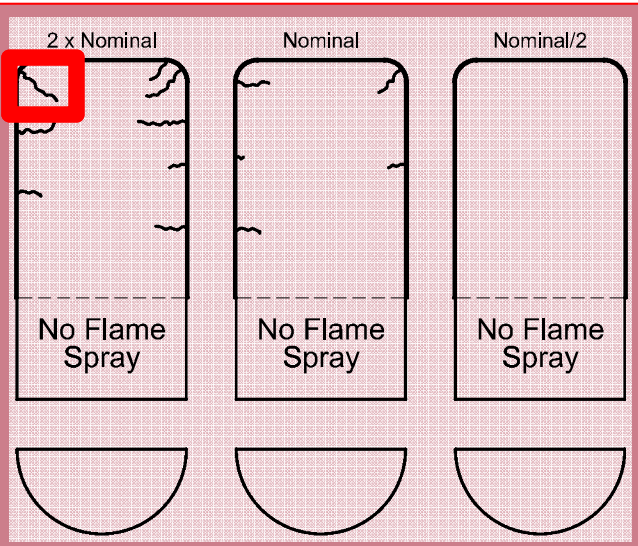
T = 23°C



Substrate Damage Picture







Macroscopic Substrate Damage Picture

Soaked at 155°C

T = 23°C



Questions

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Can flame spray cracks penetrate the epoxy?

Substrate damage can occur at 120 °C

At What temperature would the cracks occur?

They exist in the flame spray at 90 °C

What is the effect of flame spray thickness for Cracking?

Thicker flame spray increases substrate damage

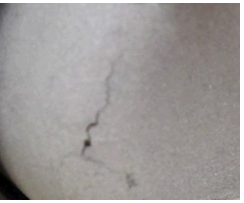
Thicker flame spray decreases channeling

Experiments

1. Heat flame sprayed cylinders until cracks are observed

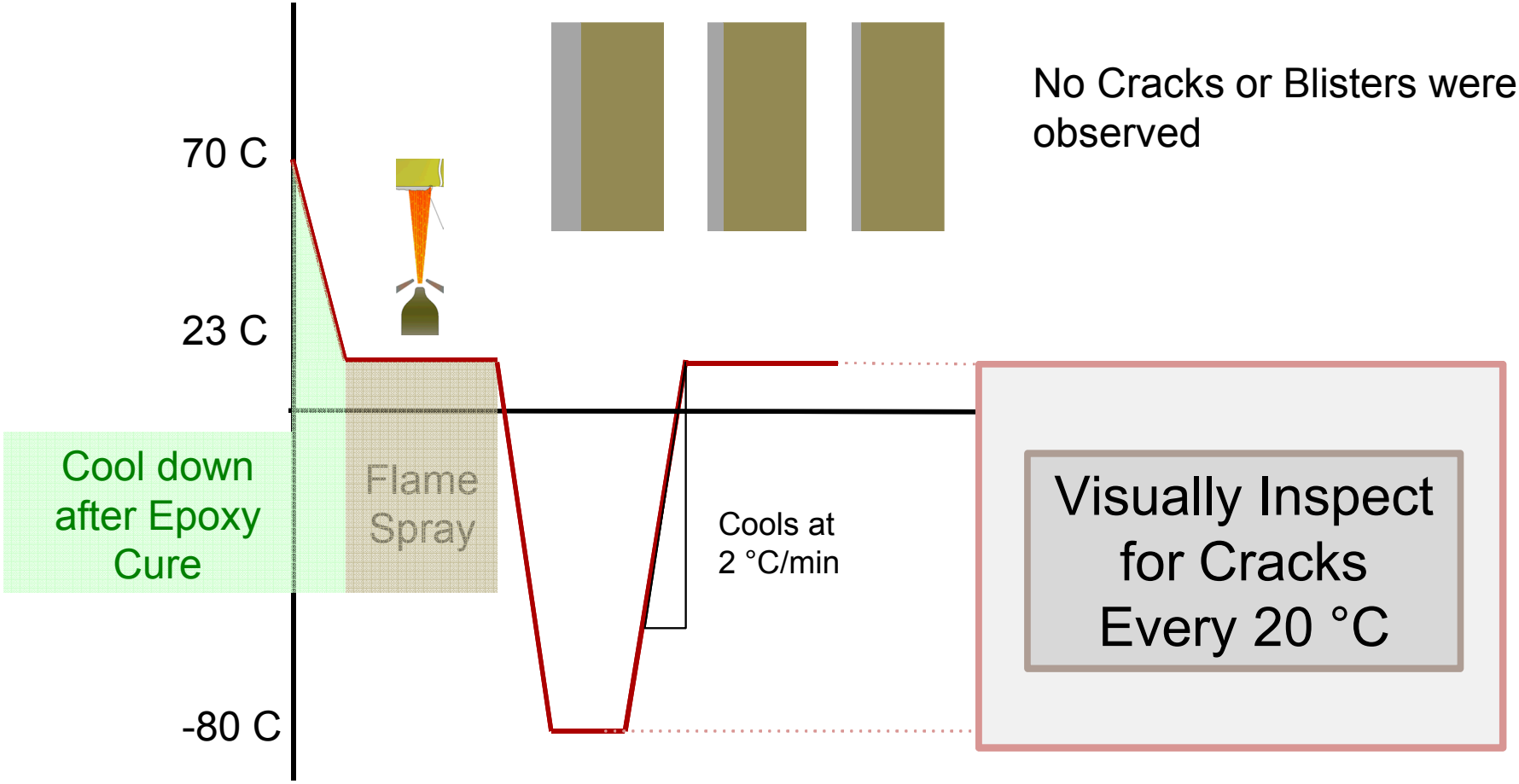
2. Heat different layers to correlate film thickness to crack modes

3. Cool down cylinders to create delaminated cracks





Compare Film Thickness



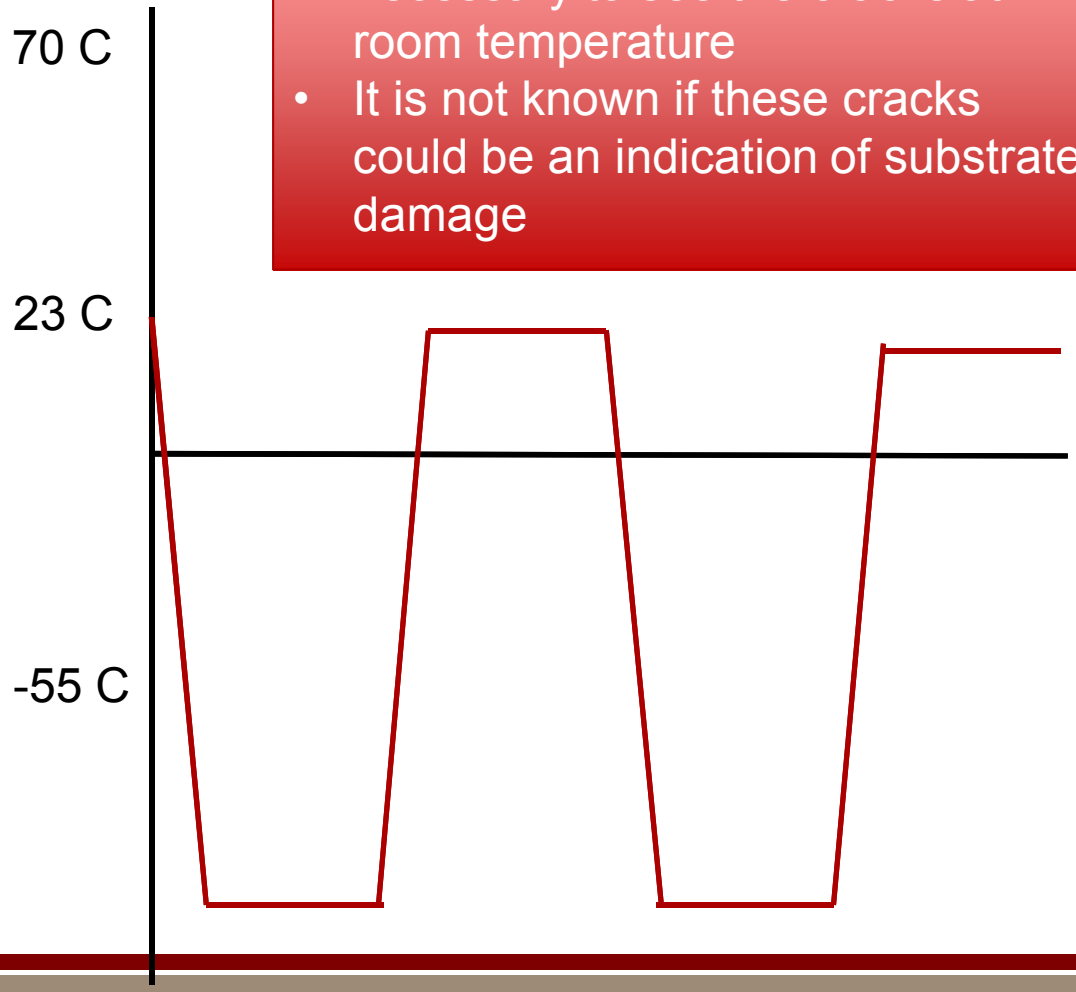
No Cracks or Blisters were observed

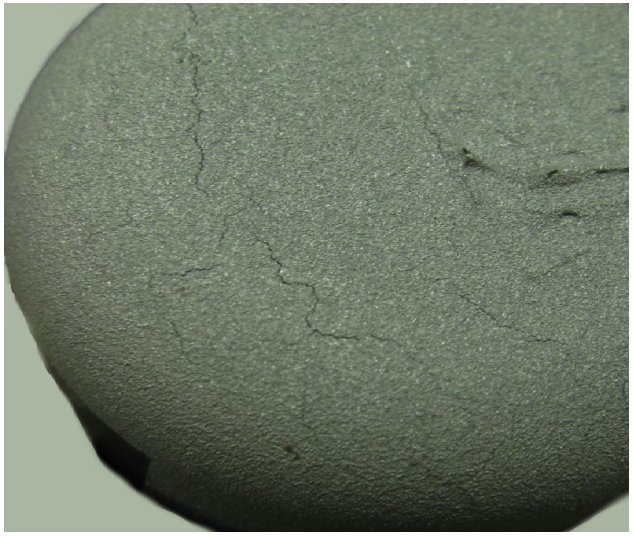
Conclusions

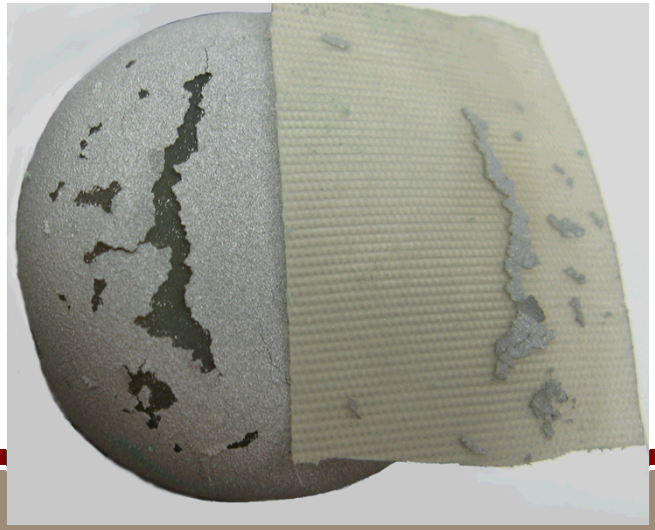
- Observable cracks at HT are not observable at RT
- Flame spray cracking can occur without damage to the substrate
- Substrate damage is possible with out visible room temperature cracks
- Substrate damage increases with flame spray thickness
  - Channeling decreases
- A single cycle to -80 C does not results in observable flame spray cracks or blisters

Conclusions Continued

- Delamination of the flame spray around the crack may be necessary to see the cracks at room temperature
- It is not known if these cracks could be an indication of substrate damage



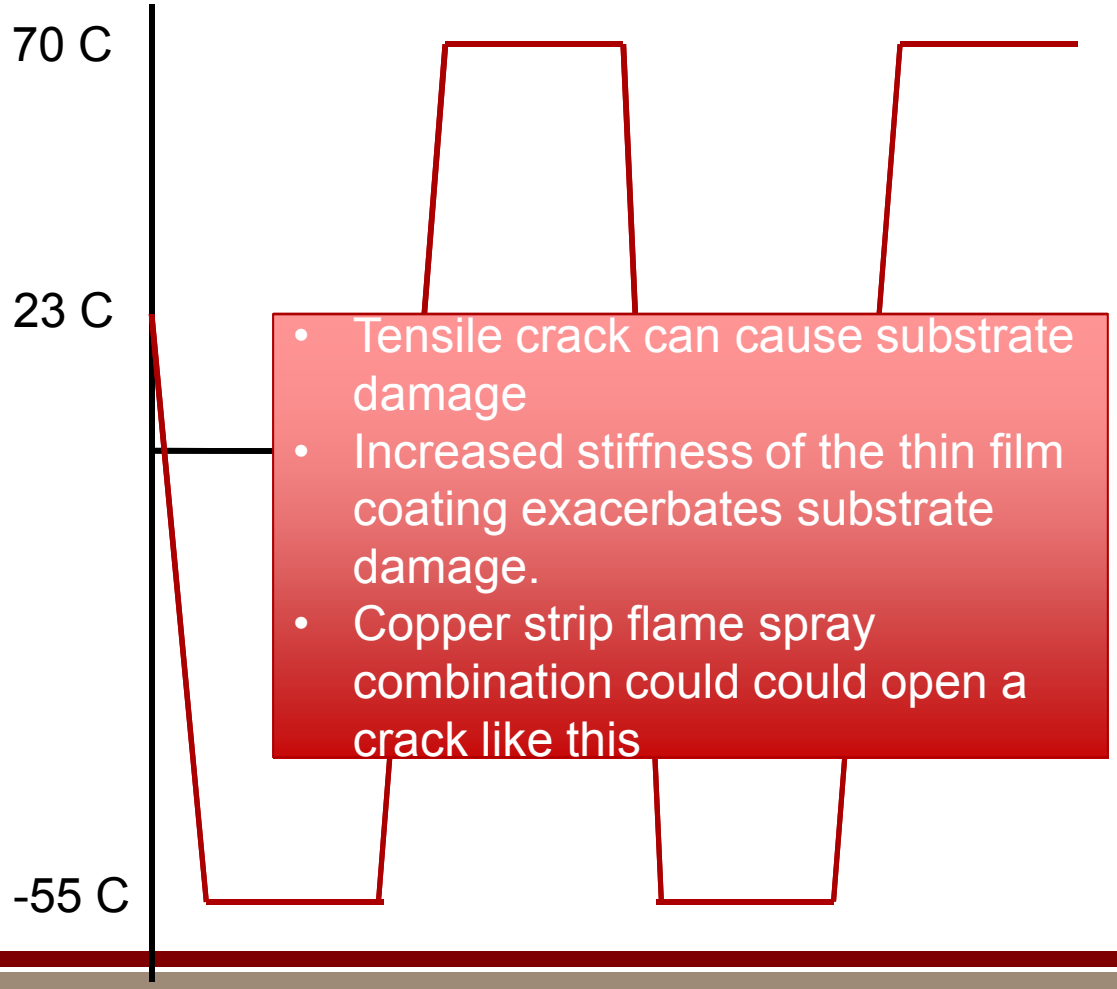




Final Conclusions

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30 cycles between 70 C and -55 C



- Tensile crack can cause substrate damage
- Increased stiffness of the thin film coating exacerbates substrate damage.
- Copper strip flame spray combination could could open a crack like this

A Copper strip beneath flame spray on cylinder



Test Method - 1

Goal:

Determine whether flame spray on epoxy cylinders cracks during heating

Approach:

- Flame spray cylinders (unfilled 828-DEA-CTBN)
- Heat samples to answer the following questions:
  - Does the flame spray (FS) coating crack at elevated temperatures?
  - If so, at what temperature do they crack?
  - Are the cracks visible at RT?
  - Do FS cracks propagate into the epoxy?
  - What are the predicted stresses/strains in the epoxy and FS (based on some assumed FS properties)?

Cylinder Geometry:
Diameter = 1”
Length= 1.5-2”

4 unfilled epoxy



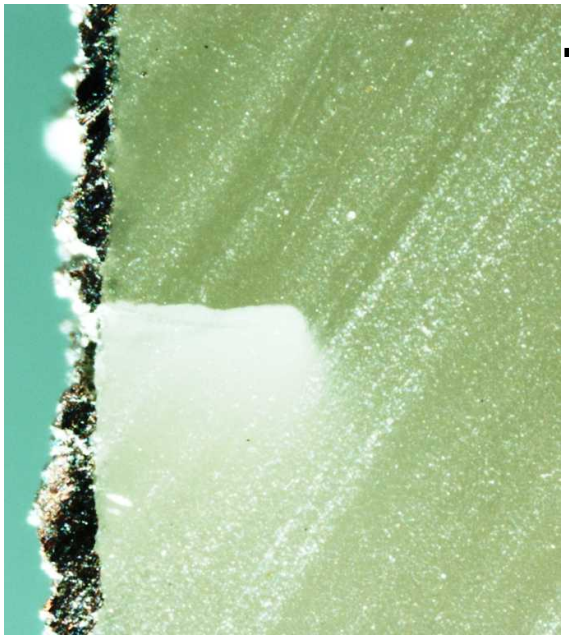
Results/Discussion

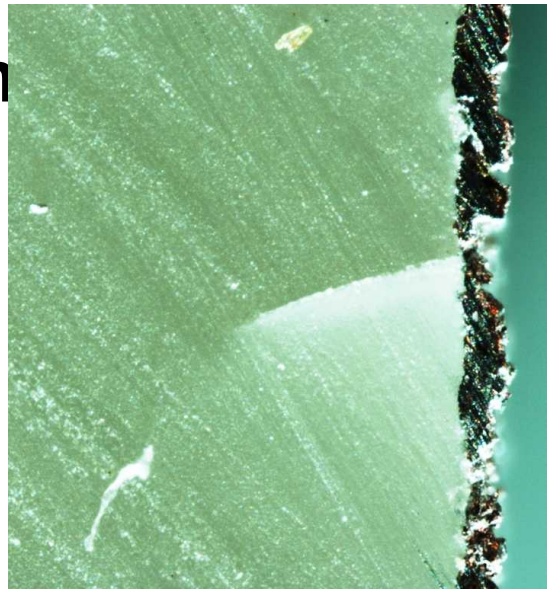
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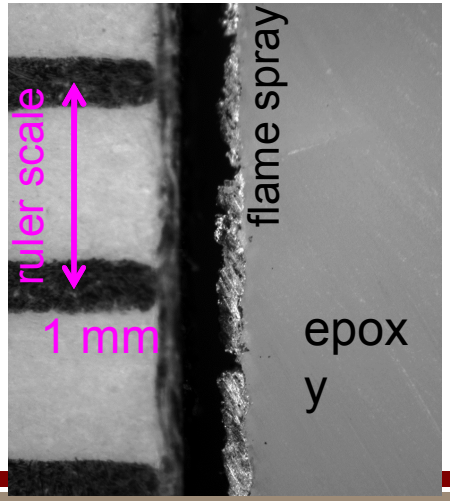
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Unfilled 828/DEA Cylinders with Flame Spray
Same sample reheated to T=120 C for 3 hours
Then sectioned in h

Pictures of epoxy cracks







flame spray ~ 0.10 mm thick

~ 4 mils

Discussion

- Channel cracking of Aluminum flame spray on Epon 828-DEA leads to substrate damage at high temperature
- Substrate Cracks close at room temperature
- Cracks increase with temperature

- Questions

- The first experiment only did 828-DEA, not 826 CTBN?

Test - 2

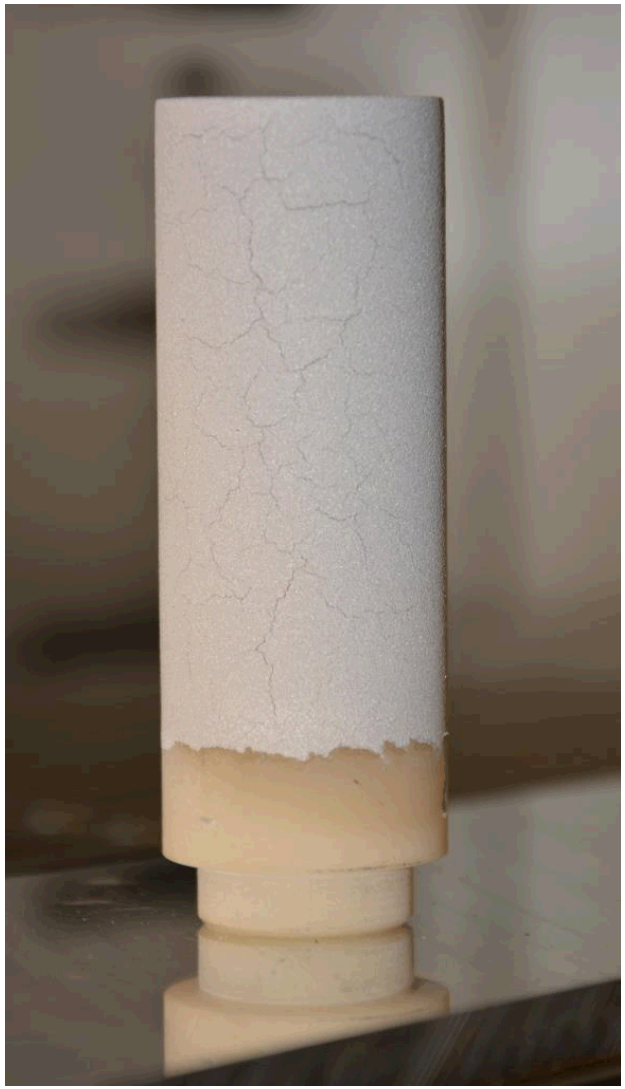
Goal:

Determine does epoxy filler change the nature of the cracking in the flame spray?

Approach:

- Flame spray cylinders with fillers CTBN and D32 GMB
- Heat samples to 120 C and examine:
  - At what temperature can the cracks be seen with the naked eye on each sample?
  - Does a linear extrapolation of the first two cracks predict the third?
- Heat samples to the highest threshold cracking and then cross section and inspect the epoxy.
  - Do the FS cracks propagate into the epoxy?
  - Are the depths of the crack dependent on the flame spray thickness.

CTBN Cracks Compared to GMB



Picture CTBN at 120 C



Picture GMB at 120 C

Discussion

- Channel cracking of Aluminum flame spray on Epon 828-DEA filled with CTBN but not with GMB
- Substrate Cracks close at room temperature in both cases

- Questions

- Were the clyinders the same size?
- Did they sit in the oven together?
- Do you have the temperature ramp rate?

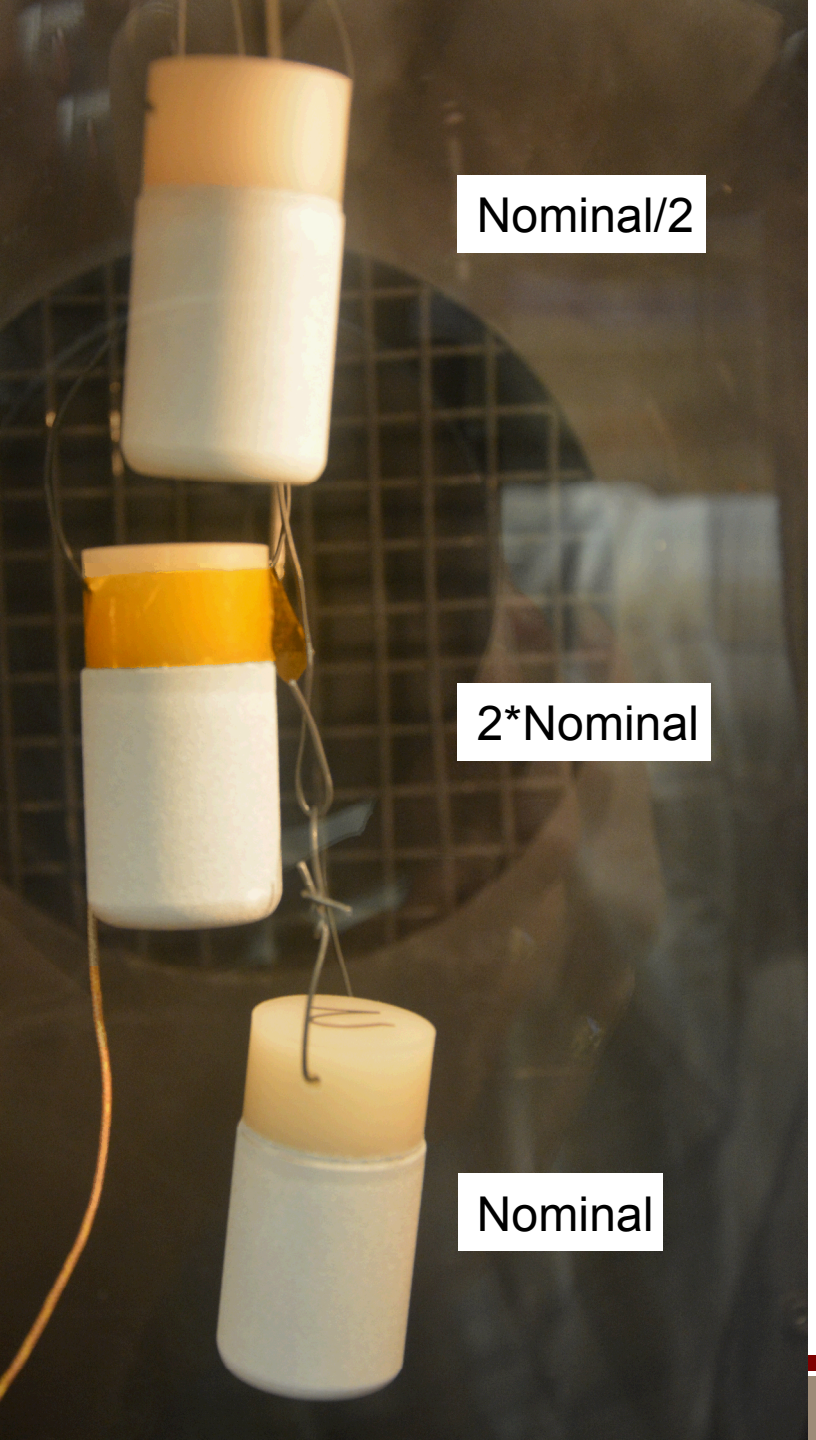
Test - 3

Goal:

Determine if the thickness of the flame spray changes the severity of the crack

Approach:

- Flame spray cylinders (828-DEA filled with CTBN) with three different thickness (nominal/2 nominal and 2*nominal)
- Heat samples to answer the following questions:
  - At what temperature can the cracks be seen with the naked eye on each sample?
  - Does a linear extrapolation of the first two cracks predict the third?
- Heat samples to the highest threshold cracking and then cross section and inspect the epoxy.
  - Do the FS cracks propagate into the epoxy?
  - Are the depths of the crack dependent on the flame spray thickness.

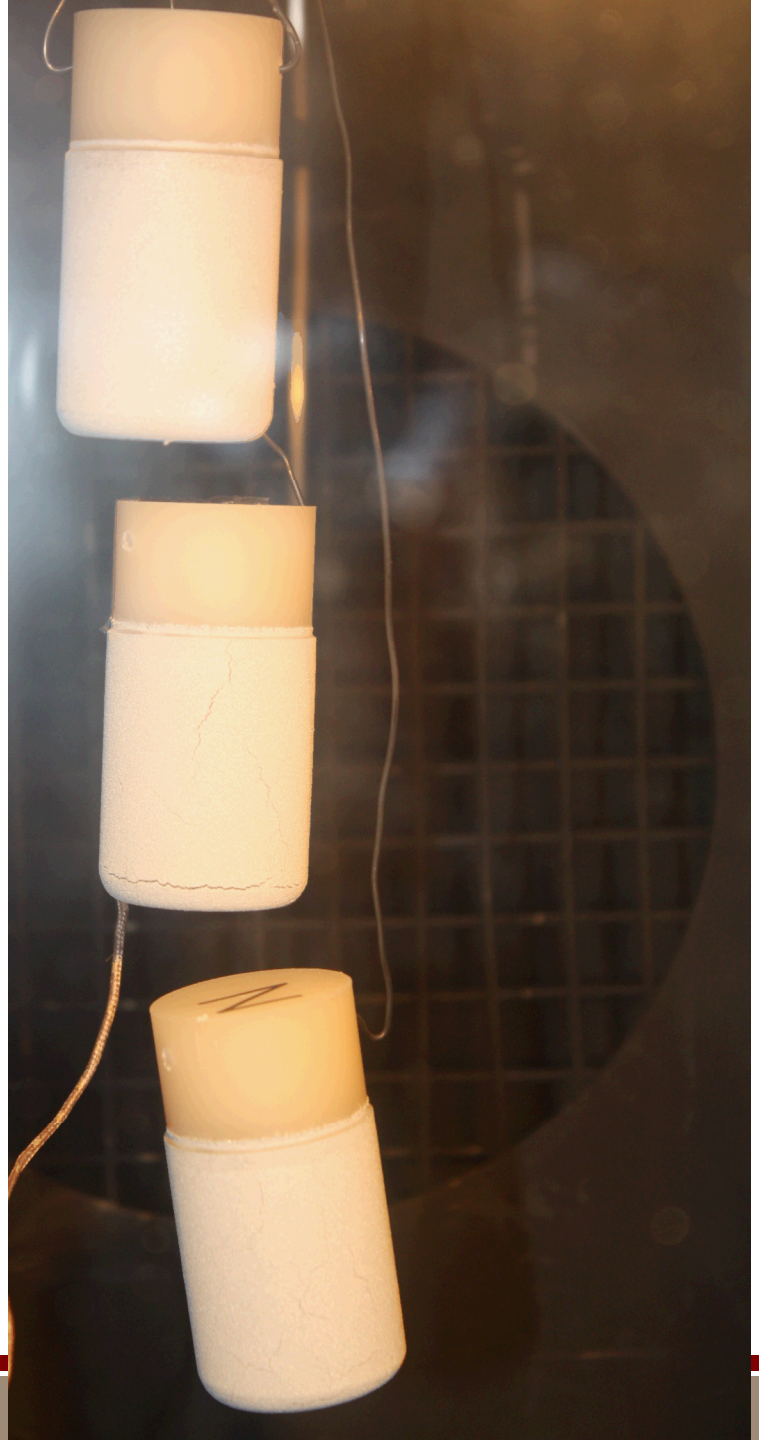


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Results at 100C



100 C	
Thickness	Substrate Crack
Nominal/2	0
Nominal	0
2*Nominal	X

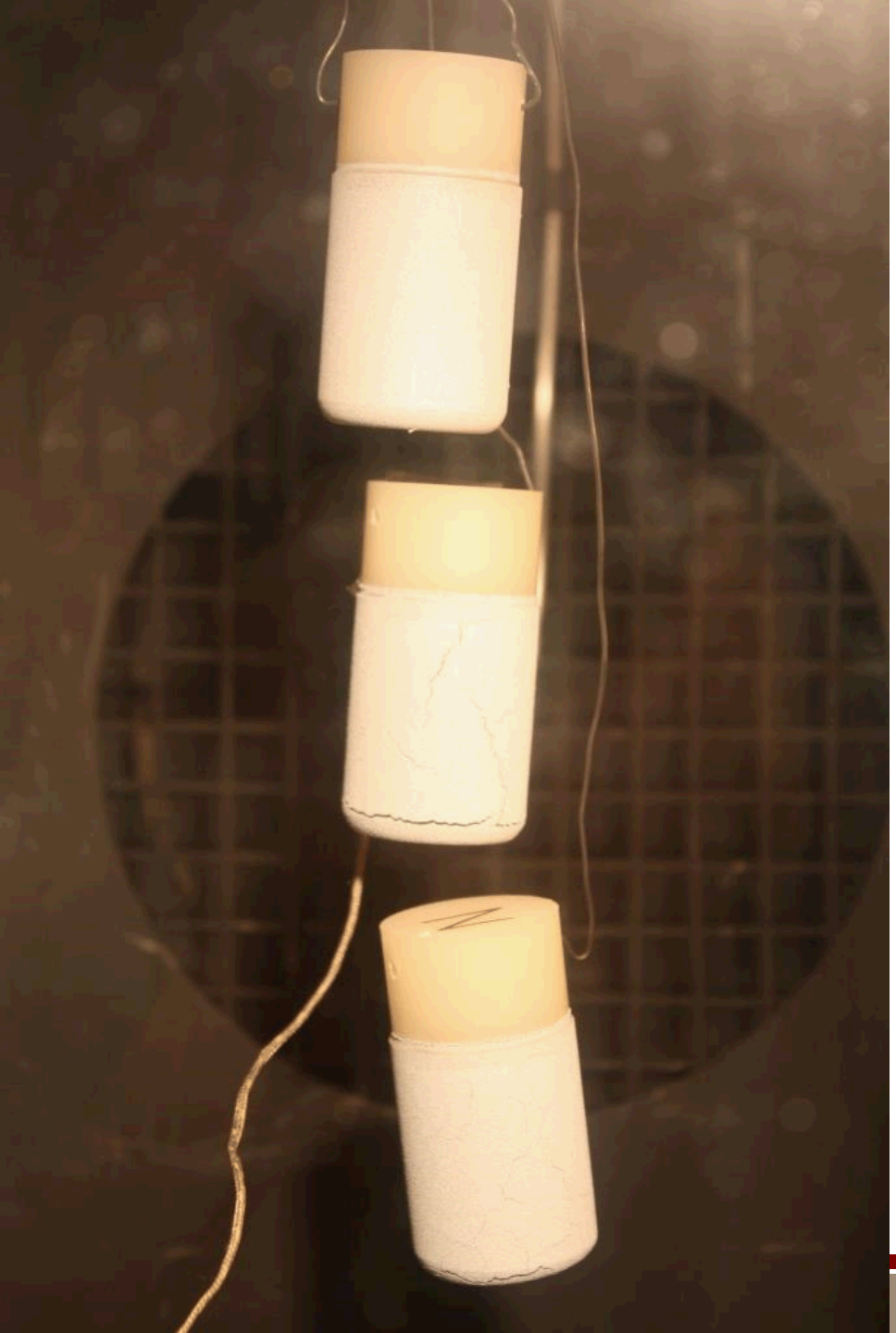


Results at 125C



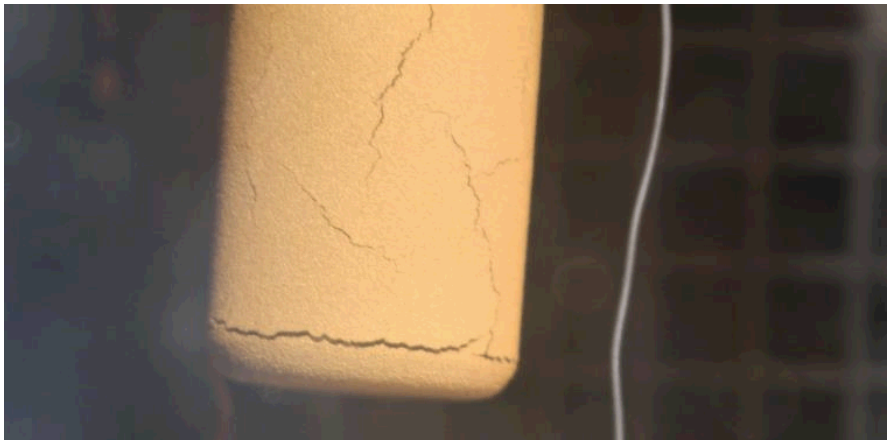
The chart is what I remember but I can't find picture proving it.

125 C	
Thickness	Substrate Crack
Nominal/2	0
Nominal	X
2*Nominal	X



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Results at 155C

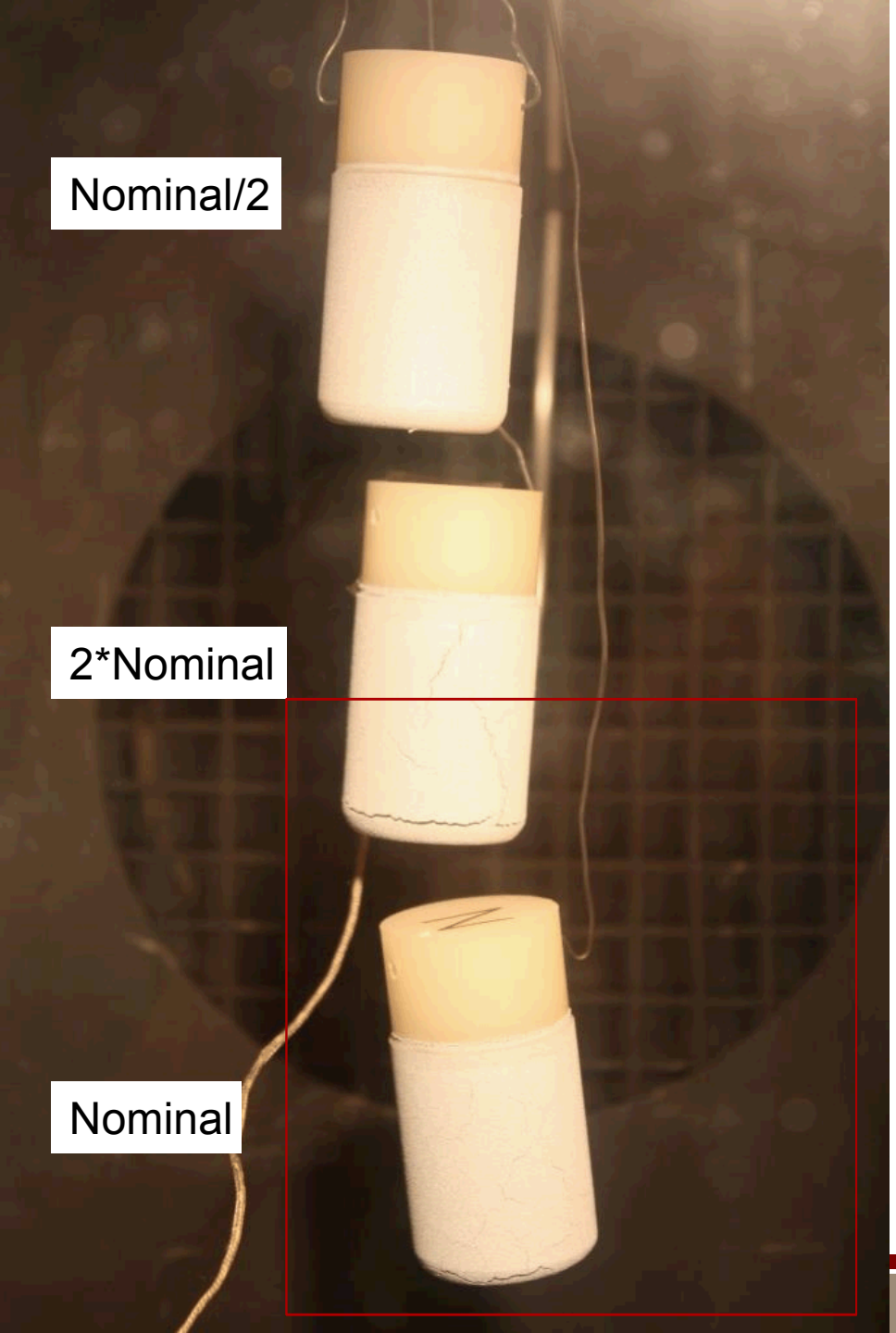


½ Nominal does not crack.

155 C	
Thickness	Substrate Crack
Nominal/2	0
Nominal	X
2*Nominal	X

Results at 155 C

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Substrate Damage

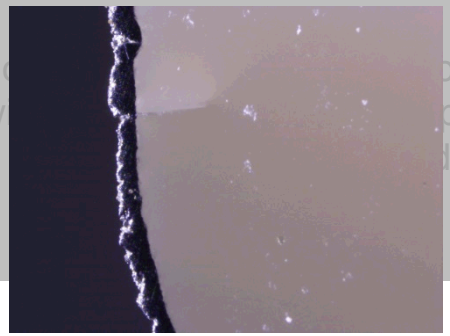
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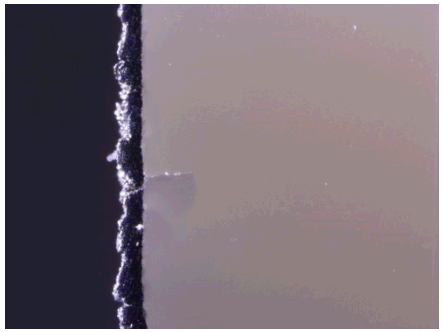
Flame Spray Coating on 826-CTBN/DEA Cylinders Heated to 100C

service in the national interest

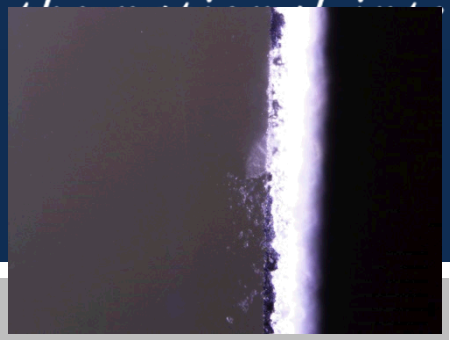
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Cracks on double thickness sample



Crack on nominal thickness sample

100 C	
Thickness	Substrate Crack
Nominal/2	0
Nominal	0
2*Nominal	X

- Sample with double the flame spray coating thickness had 3 cracks in the encapsulant and they were deeper than others
- Sample with nominal coating thickness had 1 crack
- Sample with ½ coating thickness had no cracks

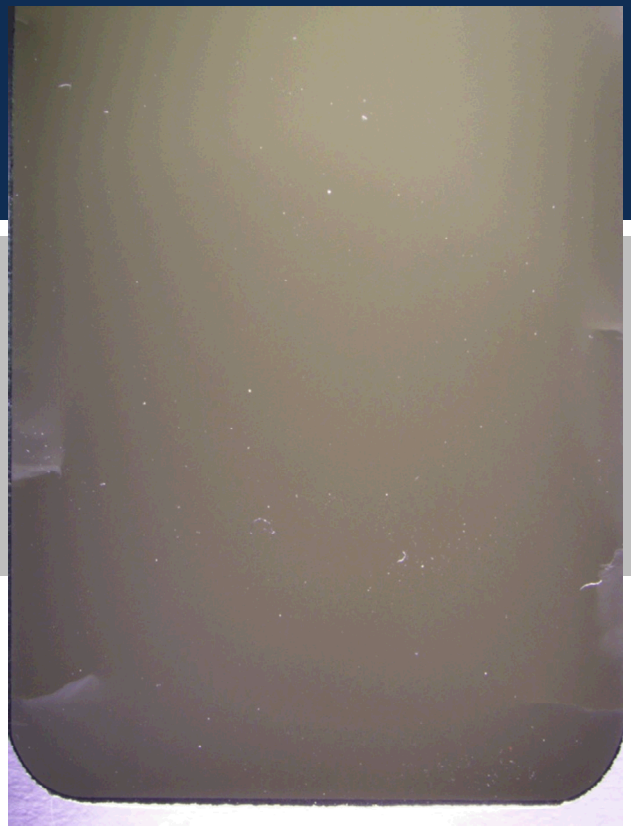
Substrate damage occurred before cracks in the flame spray were visible with the naked eyey

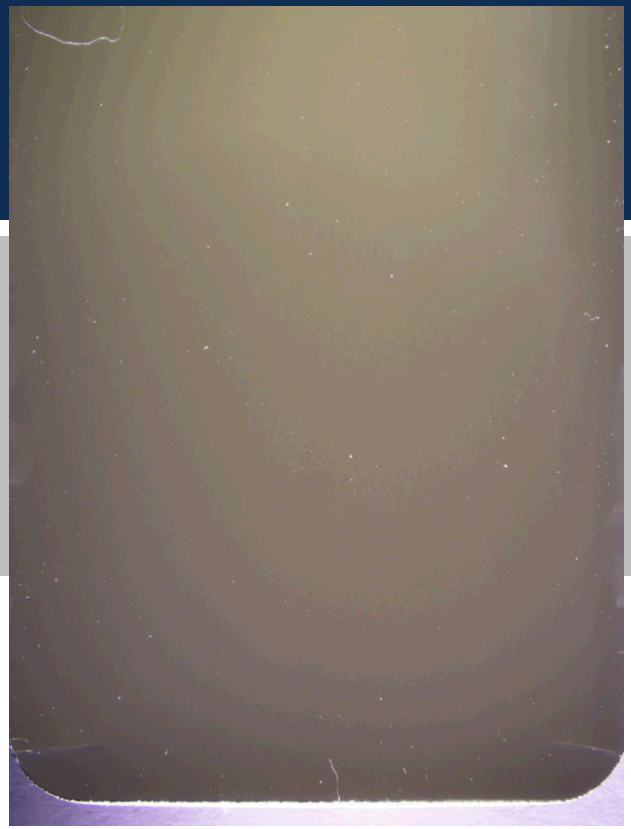
Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Flame Spray Coating on 826-CTBN/DEA Cylinders Heated to 154C

Exceptional service in the national interest

Sandia National Laboratories





- Sample with double the flame spray coating thickness had 8 cracks in the encapsulant and they were deeper than others
- Sample with nominal coating thickness had 5 cracks
- Sample with ½ coating thickness had no cracks

Cracks on double

Cracks on nominal

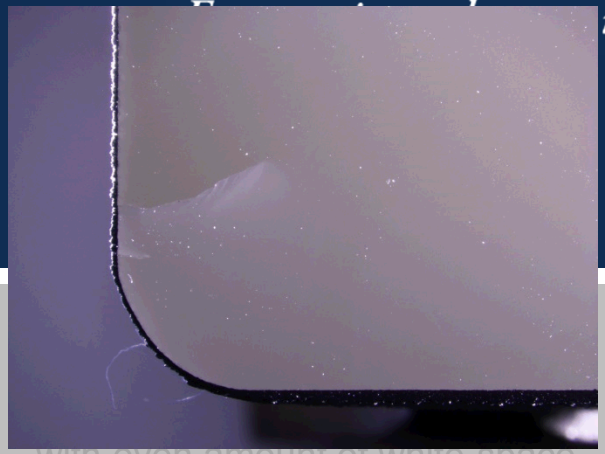
155 C	
Thickness	Substrate Crack
Nominal/2	X
Nominal	X
2*Nominal	X

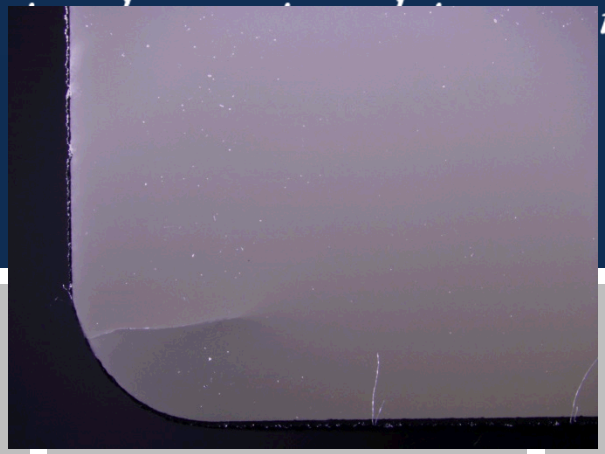
Substrate cracks occurred in the half thickness sample without substrate damage?

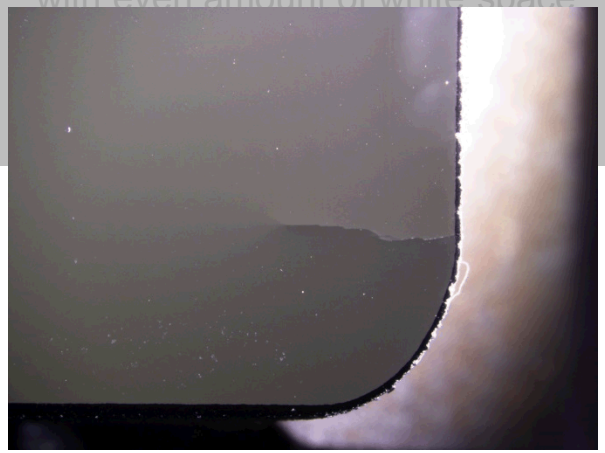
U.S. DEPARTMENT OF ENER

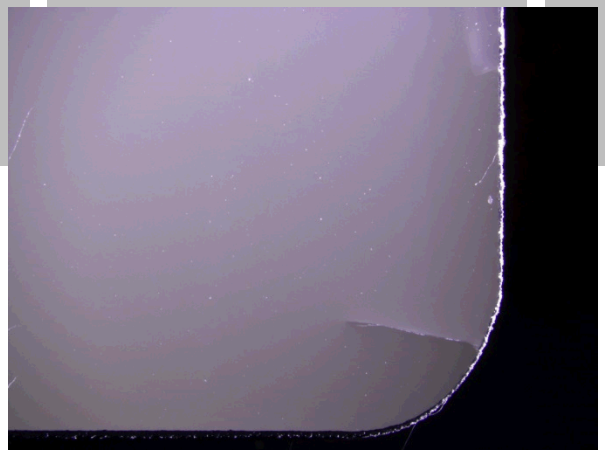
a Corporation, a wholly owned subsidiary of Lockheed Martin
der contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Flame Spray Coating on 826-CTBN/DEA Cylinders Heated to 154C







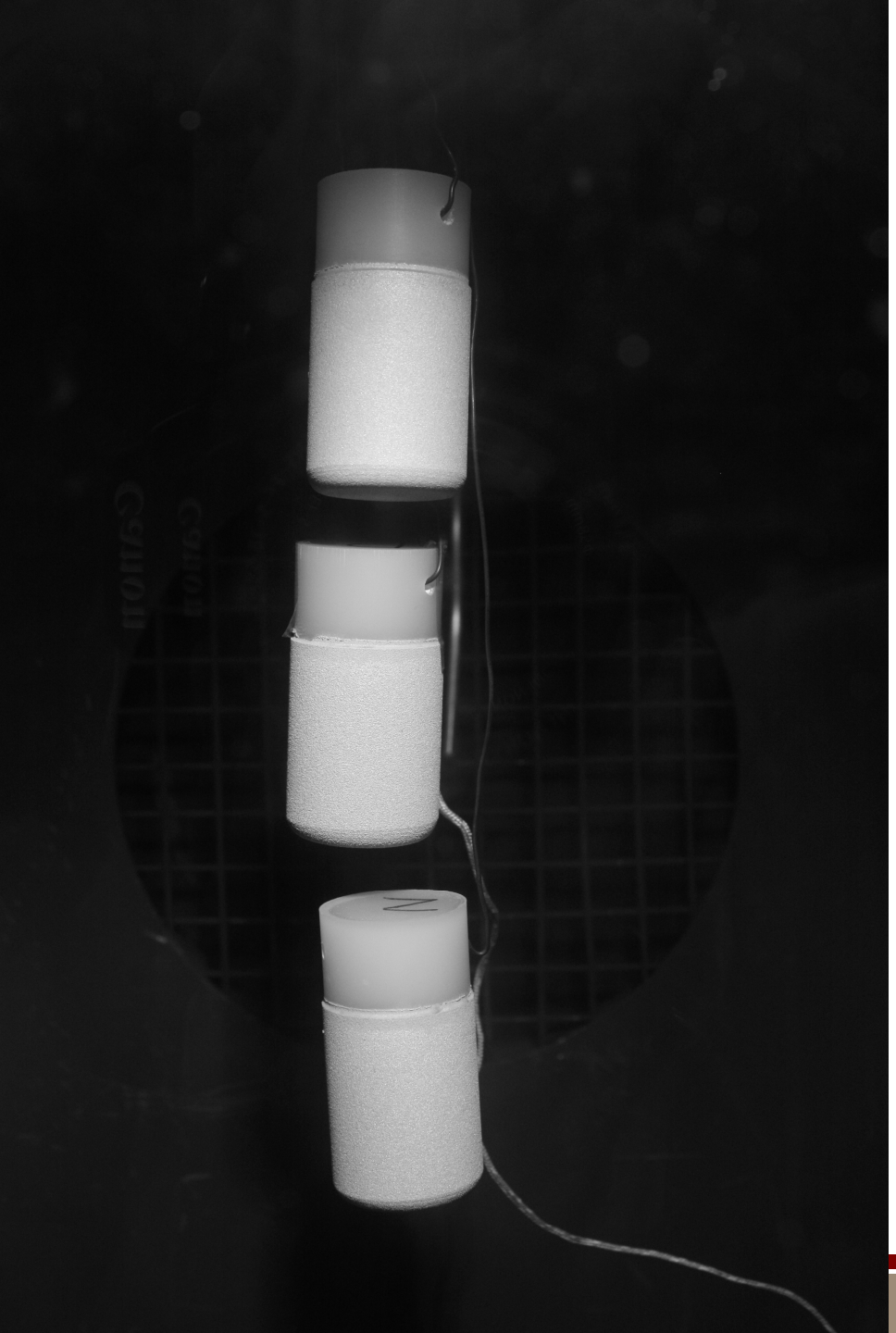


The area where largest cracks occurred was in the corners and are slightly deeper in the double thickness sample.

Cracks on double thickness sample

Cracks on nominal thickness sample

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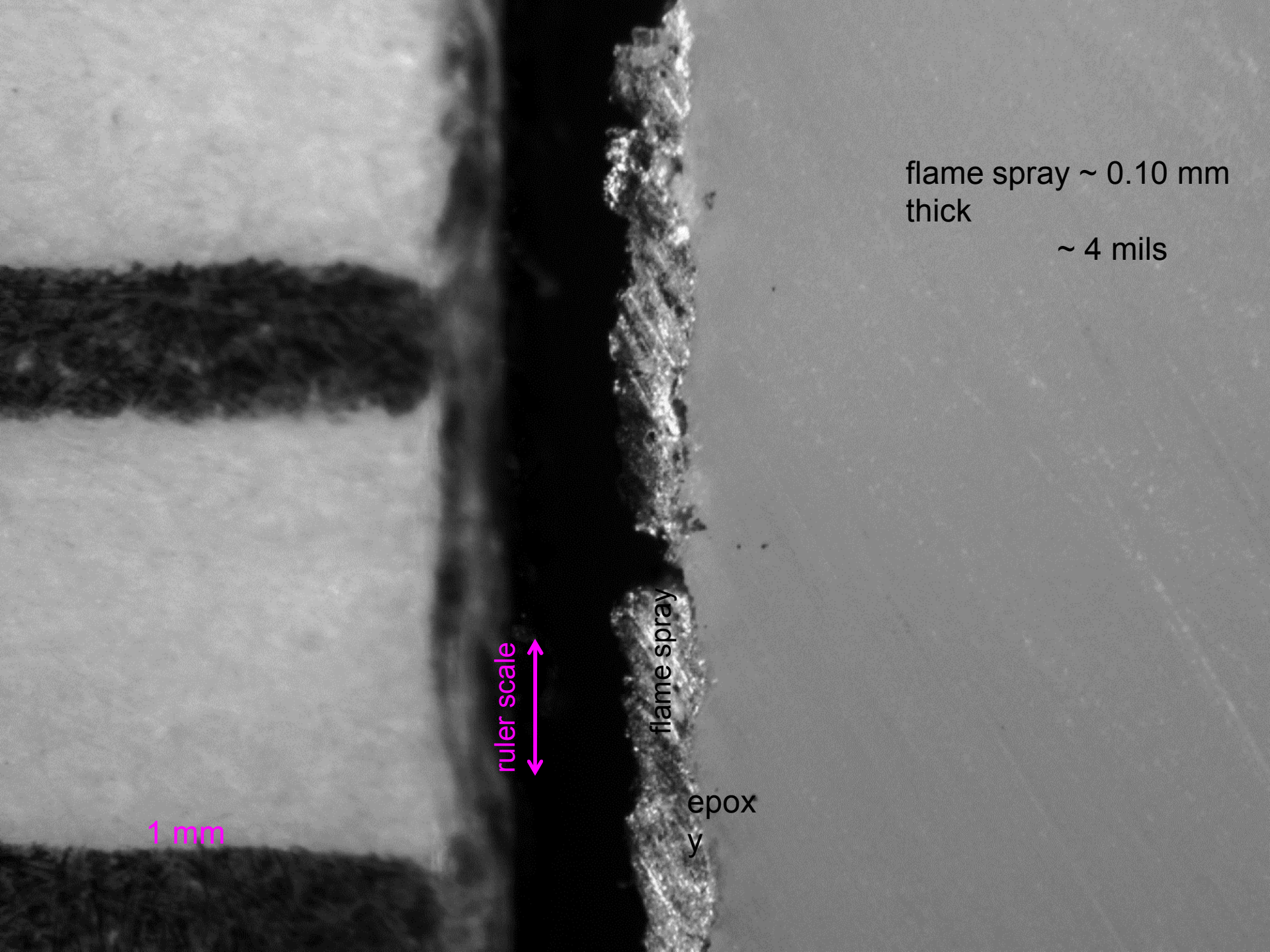


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1 Cycle to -80 C

No Cracks were observed after cycling to -80 C

80 C	
Thickness	Substrate Crack
Nominal/2	0
Nominal	0
2*Nominal	0

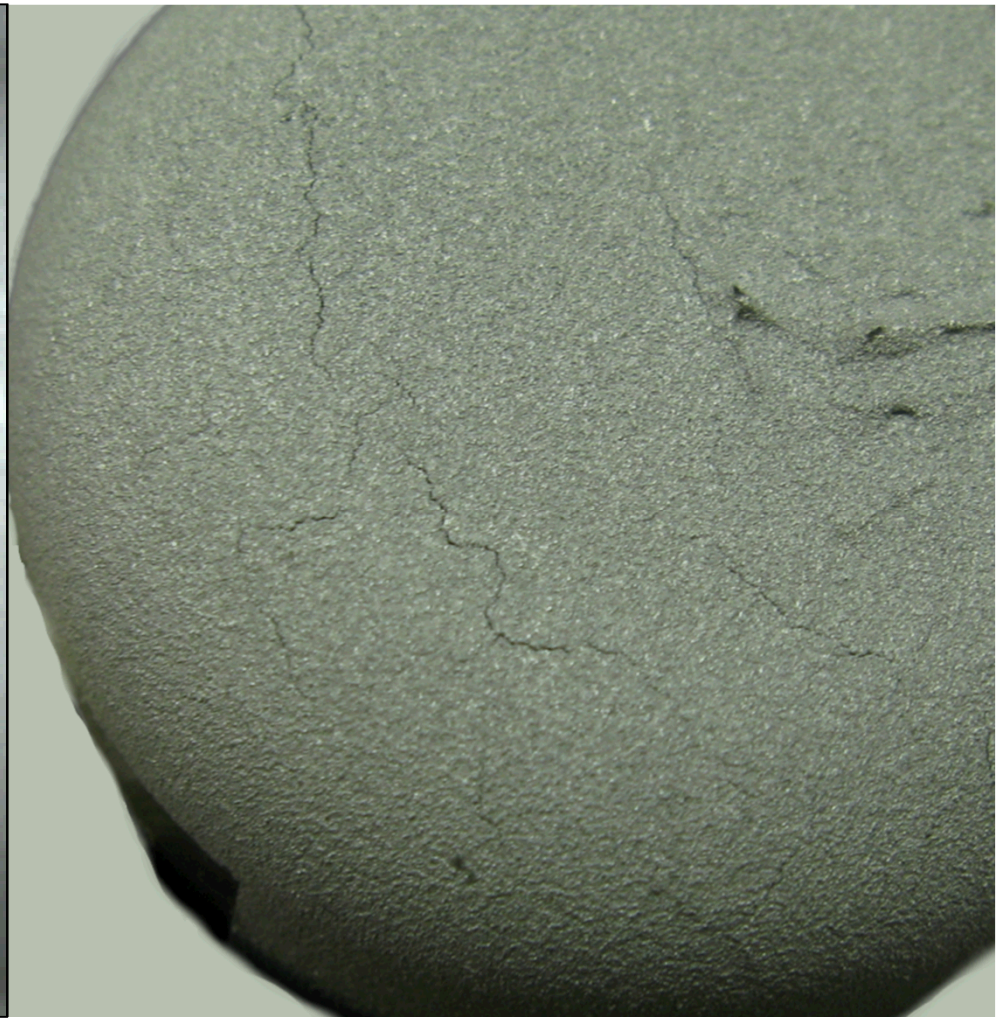

flame spray ~ 0.10 mm thick
~ 4 mils
ruler scale
flame spray
epox
y
1 mm

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