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Terahertz NDE of Stressed Composite Overwrapped Pressure Vessels – Initial Testing

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Acronym List

COPV	Composite Overwrapped Pressure Vessel
NDE	Nondestructive Evaluation
T-ray	Terahertz radiation

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Abstract

Terahertz radiation nondestructive evaluation was applied to a set of Kevlar® (Dupont) composite overwrapped pressure vessel bottles that had undergone a series of thermal and pressure tests to simulate stress rupture effects. The bottles in these nondestructive evaluation tests were bottles that had not ruptured but had survived various times at the elevated load and temperature levels. Some of the bottles showed evidence of minor composite failures. The terahertz radiation did detect visible surface flaws, but did not detect any internal chemical or material degradation of the thin overwraps.

1. Introduction

Composite Over Wrapped Pressure Vessels (COPV's) are standard features in modern aerospace vehicles and spacecraft. The reliability and safety of these pressure tanks is critical as we seek to fly extended missions and missions to other planets. Tank failure could jeopardize life and mission. Identifying and understanding Nondestructive Evaluation (NDE) methods to test and certify pressure vessels is very important for mission assurance and safety. The NASA NDE Working Group (NNWG) initiated a stress-rupture study to understand one possible failure scenario specific to Kevlar® (Dupont) wrapped pressure vessels. This study involved manufacturing Kevlar over wrapped bottles, stressing the bottles, and examining the bottles with NDE methods.

One method of inspecting the stressed bottles is pulsed terahertz (THz) NDE. Pulsed THz can be considered the electromagnetic analogy to pulse ultrasonic methods. This relatively new inspection technology [1-3] is a non-contact and high-resolution inspection method. THz NDE operates in the frequency regime between 300 GHz and 3 THz. This is a region of the electromagnetic spectrum between the microwave and infrared bands. THz technology has found application for aerospace material NDE [4,5] and in other areas such as security application for chemical, biological, and weapons detection [6-8].

This paper evaluates the potential of THz NDE to inspect Kevlar COPV bottles for stress-rupture degradation that includes assessing the condition of the over wrapped Kevlar and the underlying aluminum structure. THz scans of the bottles were conducted and processed in various ways in attempt to highlight stress-rupture degradation.

2. COPV Test Samples

NASA's Marshall Space Flight Center (MSFC) manufactured one hundred Kevlar COPV test bottles by over wrapping Samtech International SK-1229, 6061 T6

aluminum liners with ATK Kevlar/epoxy prepreg. The 6.3 inch OD liners are 19.8 inches long with 0.080 inch nominal wall thickness. The Kevlar overwrap was made from a prepreg containing Kevlar 49 with a 4560 denier and UF3339-100 resin.

MSFC aged seventy-two bottles at specific temperatures and stress pressures to generate samples with various degrees of stress rupture damage. MSFC defined ultimate stress as 2540 psig. High stress was set at 80% ultimate stress and low stress was 65% ultimate stress. High temperature was 81°C and low temperature was 31°C. MSFC subjected Thirty-seven bottles to high temperatures and low stress Table 1 and thirty-five bottles to low temperatures and high stress Table 2. The remaining bottles were held as spare test articles or used as virgin bottles for baseline measurements.

Table 1 and Table 2 indicate bottle status at the end of the aging process. Figure 1 shows a series of COPV bottles that “Failed” or ruptured during aging. Figure 2 is a typical “Pulled” bottle. Pulled bottles showed some visible failure in the overwrap or completed aging without failure. Figure 2 also shows a strain gauge, thermocouple, and a grid of small rectangular silver markers attached to the bottles. As noted in Table 1, bottle number 89 was subjected to high temperature and low stress for 91 hours.

3. Experimental Set UP

NASA Langley Research Center (LaRC) performed pulsed terahertz NDE on 1 virgin and 16 pulled bottles. Figure 3 is a block diagram of the commercial instrumentation used to generate and detect terahertz radiation. A femtosecond Ti:S laser is used to both generate and detect terahertz radiation. In the transmitter, electrons are excited into conduction to produce a short burst of terahertz radiation when a laser light pulse impinges upon a low-temperature grown GaAs antenna. Transmitted radiation is focused onto the object under test. Reflected radiation from discontinuities in the test objects index of refraction is refocused onto another GaAs antenna acting as a receiver. A fast transient signal proportional to the terahertz radiation present at the receiver is generated when a laser pulse impinges on the receiving antenna. By sampling the receiver amplitude with an optically delayed laser pulse a terahertz signal with 2048 points and a 320ps time span is created.

The antennas are packaged into transmitter and receiver modules with fiber connections to the laser source and optical delay line. This fiber-optic connection results in modules that can be freely positioned for remote scanning. LaRC constructed an automated scanning and data acquisition system to inspect the Kevlar over wrapped bottles. The inspection system acquired and stored terahertz signals at 1mm intervals along the bottle axis in 1-degree increments around the circumference of the bottle. The resulting time domain terahertz data scans were stored for post processing such as examining signal amplitude, attenuation, time delay, and frequency

4. Results of Terahertz NDE

LaRC used several signal-processing methods to analyze the acquired terahertz data. First, the data was processed in the frequency domain to obtain narrow banded spectral ratios at 25 GHz intervals from 100 to 400 GHz. The data was also processed in the standard manner of peak-to-peak signal levels as well as the ratio of the Kevlar front wall peak-to-peak signal to the Kevlar back wall peak-to-peak signal. The time of flight to the back wall positive peak was measured along with the time delta between the front and back wall positive peaks. We also compared images generated from narrow band filtered THz signals to images produced with a microwave inspection system

Frequency domain spectral ratio images were generated from the high temperature and high stress data. It was postulated that a shift in the spectral minima observed for Kevlar and epoxy would highlight aging dependencies. Selected spectral ratio images are shown for the high temperature data in Figure 4 through 14 and for the high stress data in Figure 15 through 25. The images in each figure are on the same scale for comparison. The metallic markers on the Kevlar surface show up as dots in a regular grid pattern. In some cases strain gauges, strain gauge wire, and thermocouples can be seen. Overall, a striated pattern corresponds with the Kevlar windings; however, there is no visually apparent demarcation in these images to suggest aging.

A summary of the spectral ratio data is presented in Figure 26. The graph shows spectral power ratio from 100 to 400 GHz as a function of bottle number and age. The resulting trends exhibited no discernable aging dependency.

Standard signal amplitude images from the high temperature and high stress data are shown in Figure 27 and Figure 28. In general, amplitude images are subject to many influences such as material electrical properties, thickness of the part under test, and surface roughness, texture and orientation. These influences make it difficult to make quantitative assessments of an object, but allow for qualitative evaluations. The amplitude images showed general features of the COPV bottles, but did not show indications of aging.

Kevlar front wall to back wall amplitude ratio images from the high temperature and high stress data are shown in Figure 29 and Figure 30. The front wall echo is the reflection from the outside of the Kevlar overwrap. The back wall echo is the reflection from the Kevlar overwrap to liner interface. The echo ratio depends on the signal loss due to the Kevlar overwrap material. The images are fairly uniform and do not show any dependency on the state of the Kevlar and thus aging trends.

A graph of average back wall amplitude for the bottles is shown in Figure 31. The graph shows the back wall amplitude as a function of bottle number and age. A graph of the average front surface echo to back wall interface echo ratios is shown in Figure 32. The graph shows the echo ratios versus bottle number and age. The resulting trends for both graphs are flat and show no evidence of aging.

Kevlar back wall time of flight images made from the high temperature and high stress data are shown in Figure 33 and Figure 34. This data combines the effects of the Kevlar and resin index of refraction with the thickness of the layer. The data generally reflects the thickness of the layer with the dark range in the gray scale indicating thinner material and the brighter range indicating thicker material. The images are displayed on the same scale for comparison. There are bottles with significant variations and some with little variation but neither correlated with aging trends. In addition, it is not clear how the thickness variations affect the bottle's life condition without additional data indicating the bottle's effective age.

Positive peak delta images of the time difference between the front and back wall echo from the high temperature and high stress data are shown in Figure 35 and Figure 36. This processing is similar to the peak ratio method but does not correct for interface effects. As before, the images are on the same scale and there is no discernable trend with aging.

Narrow band frequency amplitude images from the high temperature and high stress data are shown in Figure 37 and Figure 38. Frequency amplitude images were generated from the time domain terahertz data after applying a 150GHz narrow band filter to mimic MSFC's Millimeter Wave (microwave) inspection results. This was done to investigate the origins of the anomalous short dark streaks in their images. Microscopic inspection of the bottles after identifying this anomaly indicated surface variations corresponding to the dark streaks. In particular, periodic thickness variations and small bumps resulting from manufacturing processes were observed. At 150GHz, the front to back wall phase front interference is maximized as the over wrap thickness approaches 1mm. Further examination of this anomaly is required to determine any contribution to bottle failure.

Table 1: High Temperatures and Low Stress.

S/N	HOURS	RUN	STATUS	S/N	HOURS	RUN	STATUS
23	49	1	Failed	70	194	2	Failed
77	45	1	Failed	33	232	2	Pulled
16	426	1	Failed	20	75	2	Failed
56	426	1	Failed	82	91	3	Failed
49	323	1	Failed	88	172	3	Failed
13	424	1	Failed	94	95	3	Failed
26	24	1	Failed	66	274	3	Failed
65	114	1	Failed	99	163	3	Pulled
78	225	1	Failed	31	163	3	Pulled
59	286	1	Failed	71	163	3	Pulled
1	106	1	Failed	9	49	4	Pulled
42	231	2	Failed	91	49	4	Pulled
89	91	2	Failed	85	49	4	Pulled
44	117	2	Failed	83	0.25	4	Failed
17	231	2	Pulled	Spare19	6	4	Pulled
90	231	2	Pulled	92	6	5	Failed
21	127	2	Failed	53	6	5	Pulled
46	232	2	Pulled	30	49	5	Pulled
				12	6	5	Pulled

Table 2: Low Temperatures and High Stress.

S/N	HOURS	RUN	STATUS	S/N	HOURS	RUN	STATUS
84	190	1	Failed	64	92	2	Failed
15	198	1	Failed	54	9	2	Failed
47	238	1	Failed	73	121	3	Failed
80	110	1	Failed	3	216	3	Pulled
32	74	1	Failed	7	216	3	Pulled
98	334	1	Failed	2	216	3	Pulled
55	312	1	Failed	4	120	3	Failed
97	285	1	Failed	37	216	3	Pulled
43	251	1	Failed	58	38	4	Failed
75	362	1	Pulled	62	72	4	Pulled
79	202	1	Failed	6	72	4	Pulled
93	214	2	Failed	27	72	4	Pulled
68	212	2	Failed	95	72	4	Pulled
11	180	2	Failed	100	72	5	Pulled
5	217	2	Pulled	60	72	5	Pulled
48	66	2	Failed	86	72	5	Pulled
24	176	2	Pulled	38	52	5	Failed
74	57	2	Failed	52-FBG	292	5	Pulled



Figure 1: Typical damage of Kevlar COPV bottles that suffered failure.



Figure 2: COPV pulled before failure due to Fiber damage.

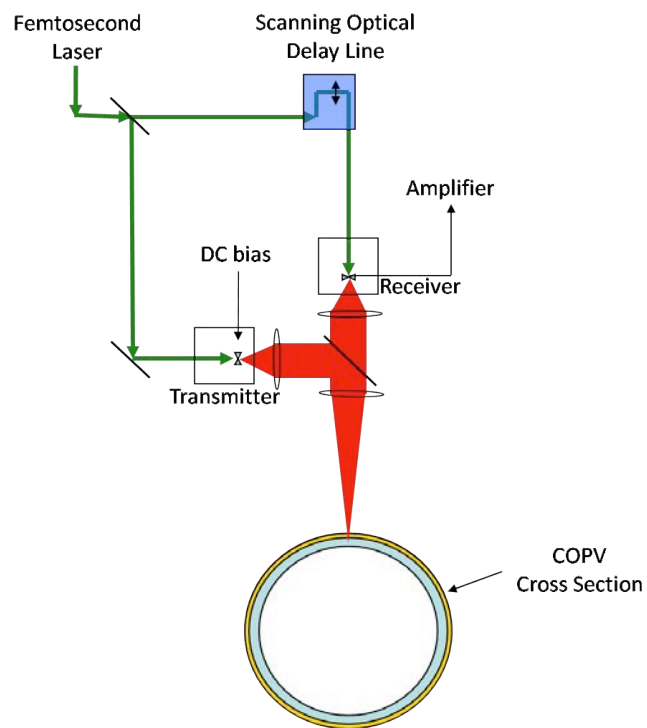
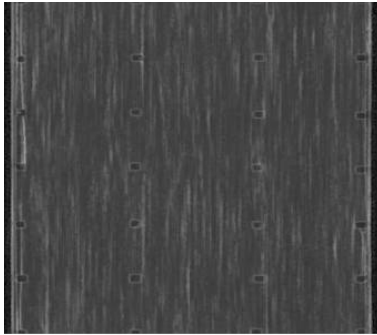
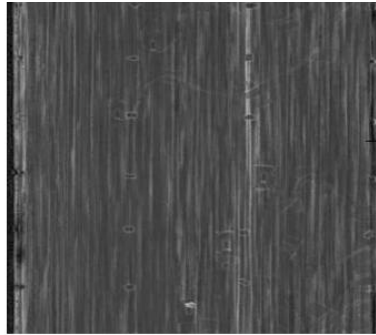


Figure 3: Block diagram illustrating terahertz NDE on COPV cylinders.



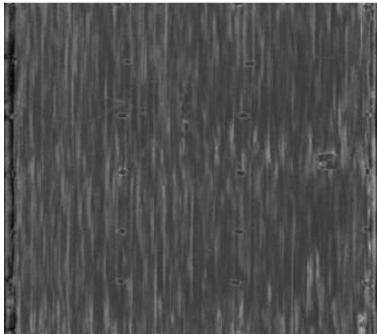
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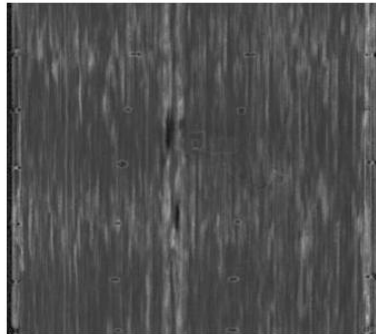
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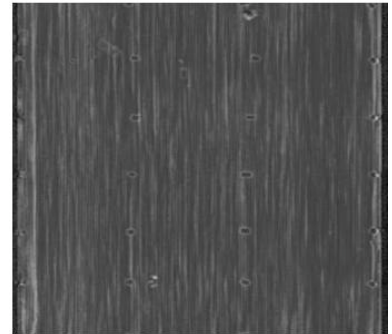
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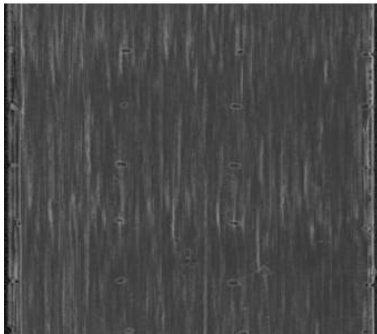
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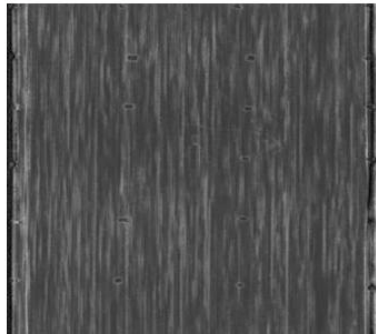
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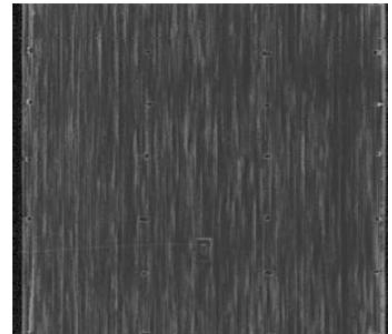
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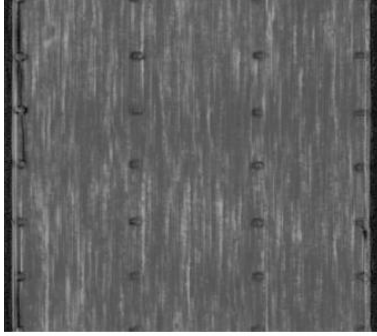


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Figure 4: 100GHz images of high temperature aged bottles.



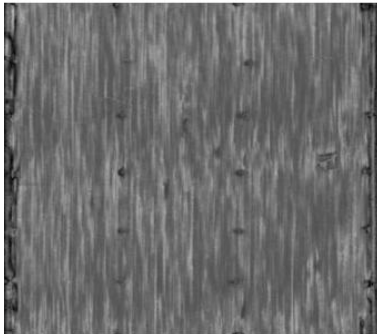
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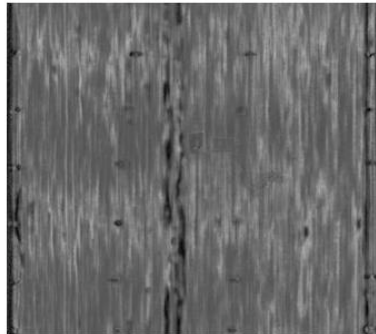
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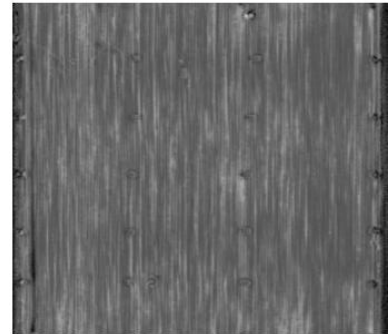
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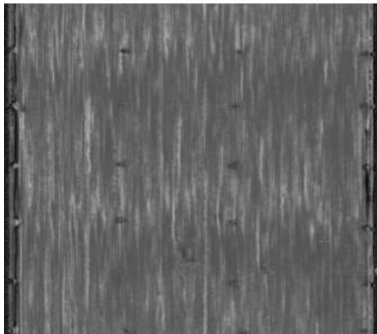
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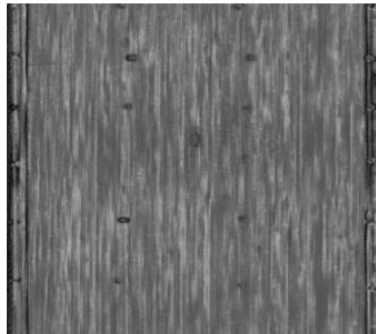
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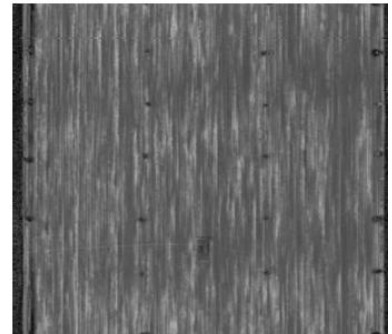
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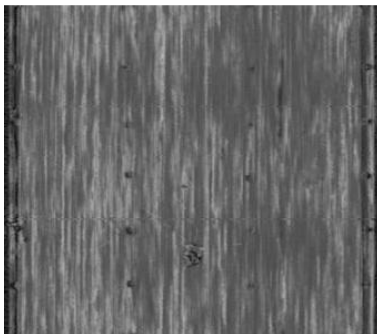
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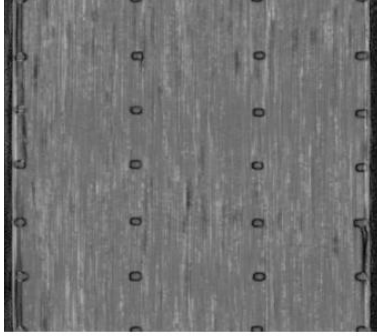


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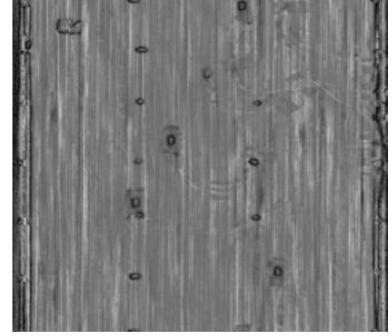
Figure 5: 150GHz images of high temperature aged bottles.



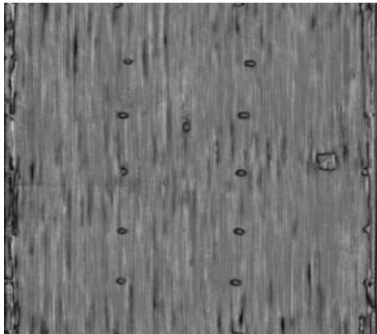
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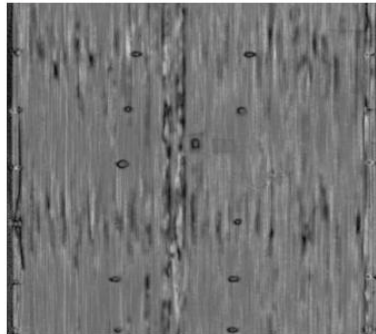
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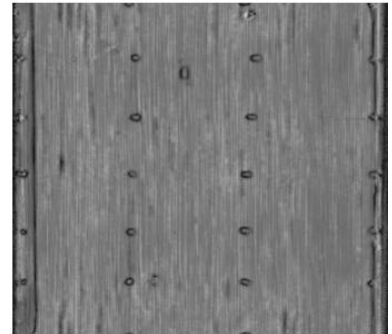
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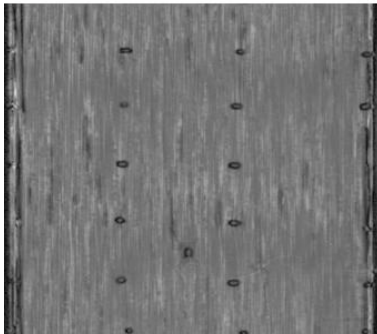
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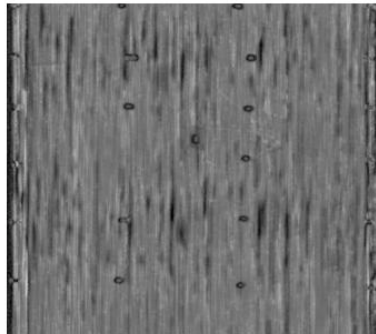
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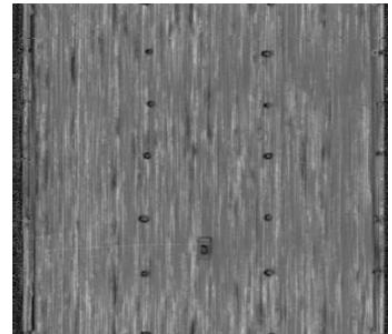
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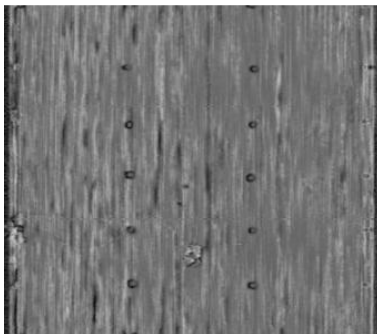
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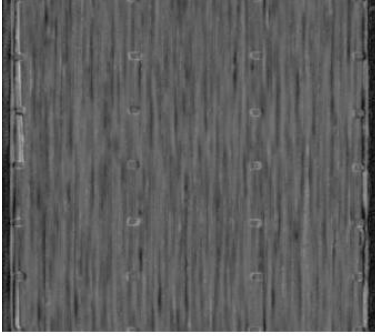


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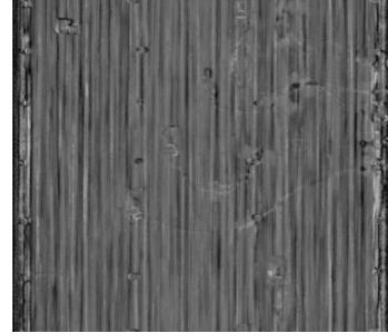
Figure 6: 175GHz images of high temperature aged bottles.



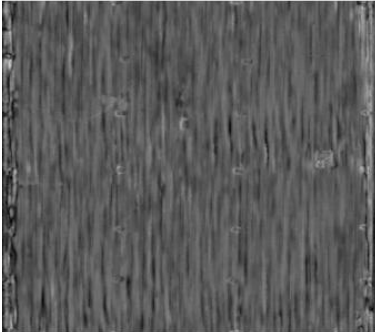
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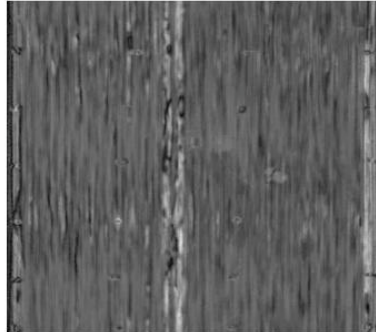
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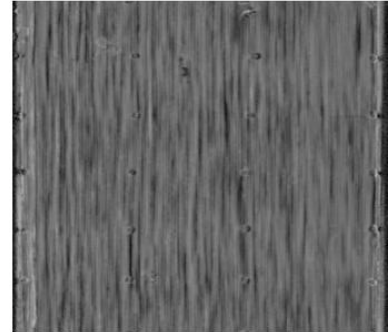
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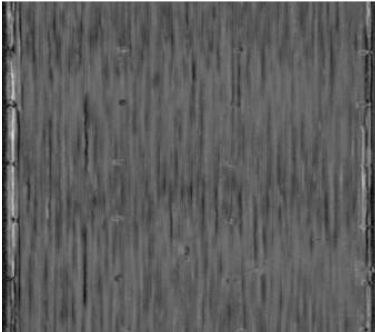
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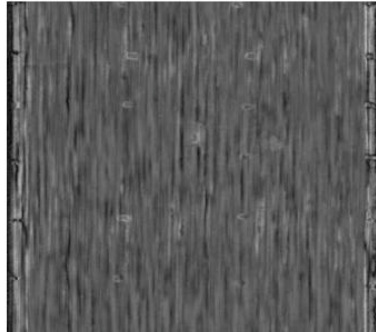
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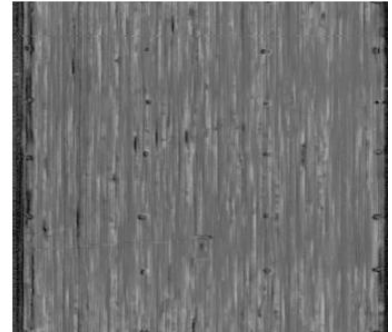
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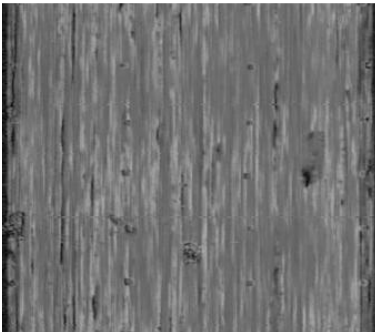
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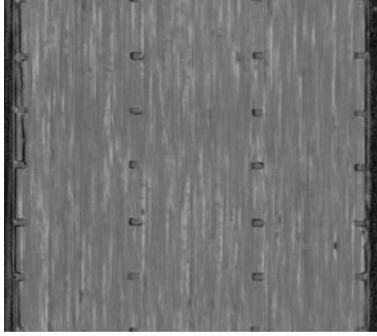


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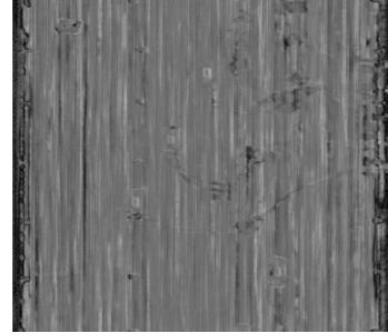
Figure 7: 200GHz images of high temperature aged bottles.



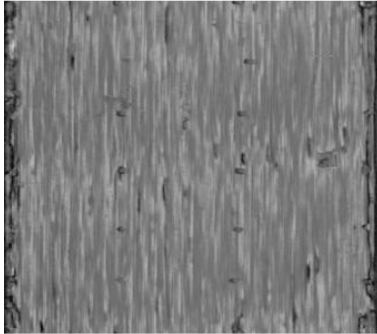
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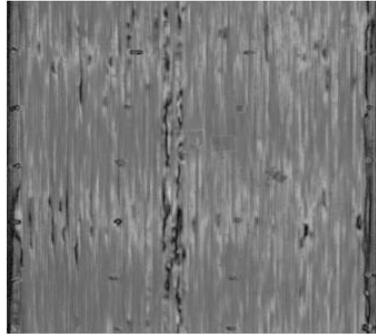
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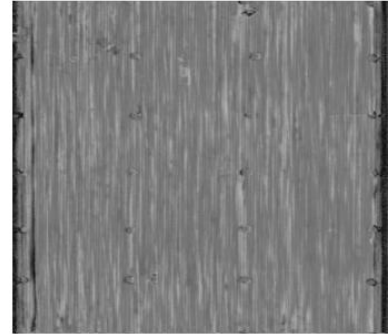
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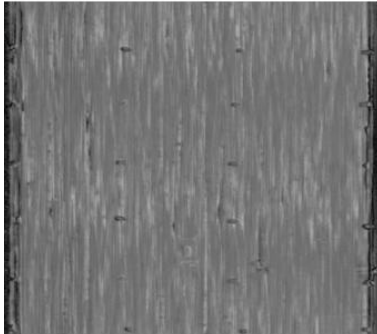
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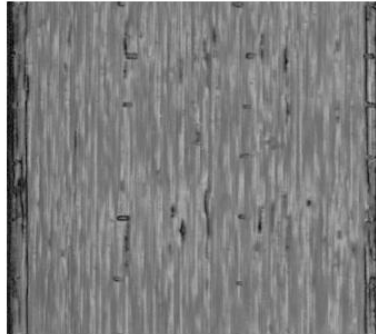
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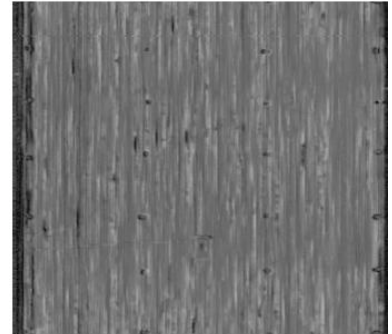
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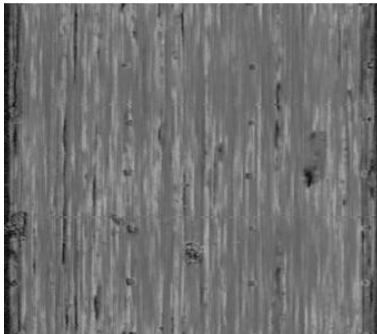
S/N 99, 163 hours



S/N 90, 231 hours

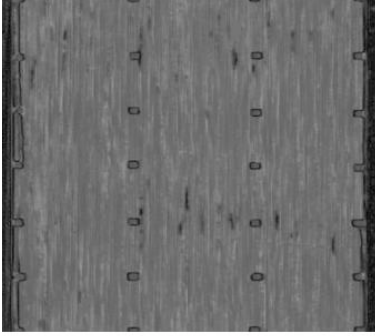


S/N 46, 235 hours

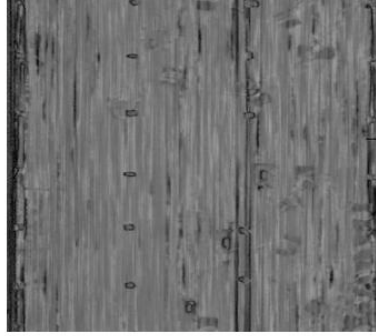


S/N 56, 426 hours

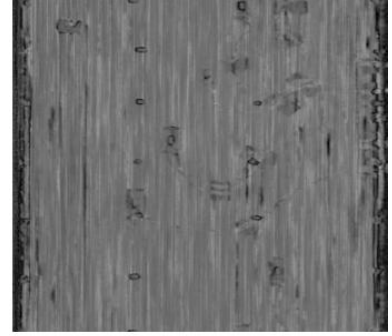
Figure 8: 250GHz images of high temperature aged bottles.



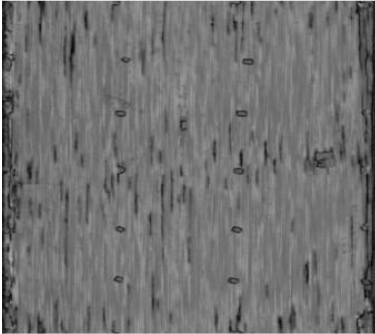
S/N 28, Virgin



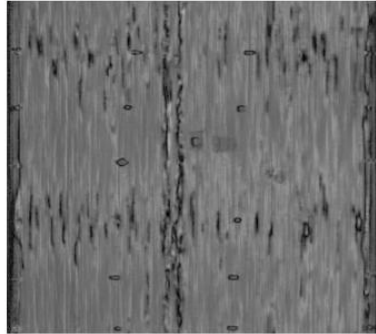
S/N 12, 6 hours



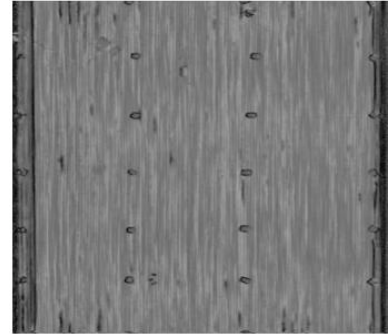
S/N 9, 49 hours



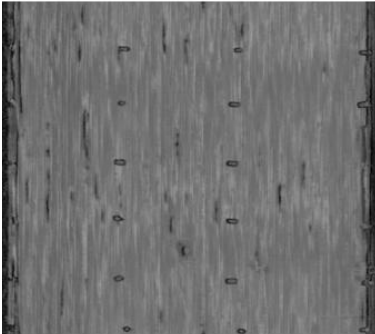
S/N 91, 49 hours



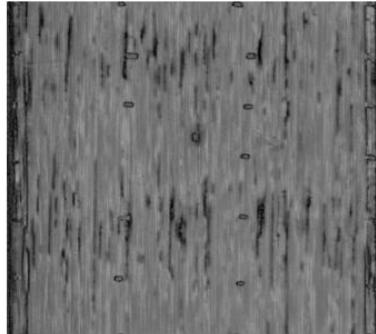
S/N 89, 91 hours



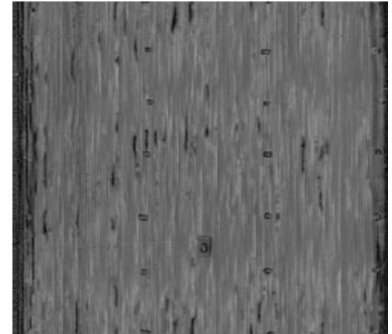
S/N 71, 163 hours



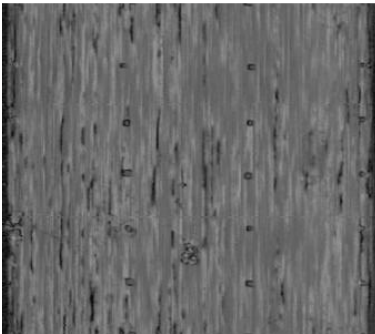
S/N 99, 163 hours



S/N 90, 231 hours

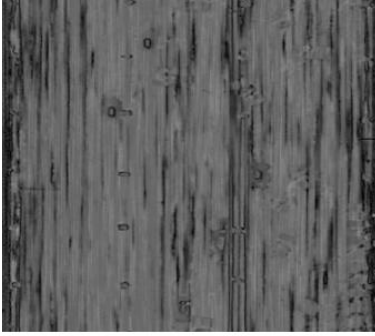


S/N 46, 235 hours

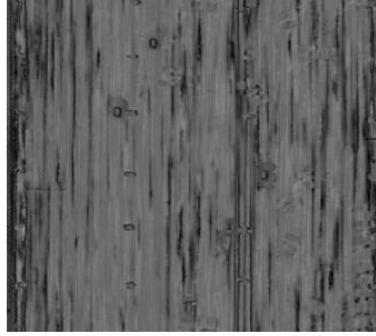


S/N 56, 426 hours

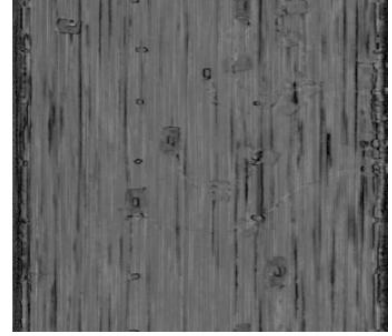
Figure 9: 275GHz images of high temperature aged bottles.



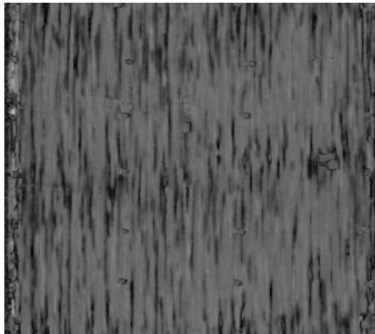
S/N 28, Virgin



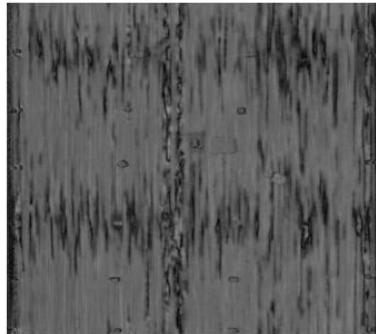
S/N 12, 6 hours



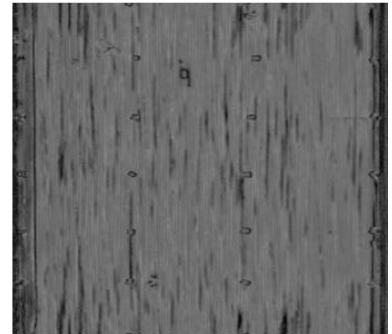
S/N 9, 49 hours



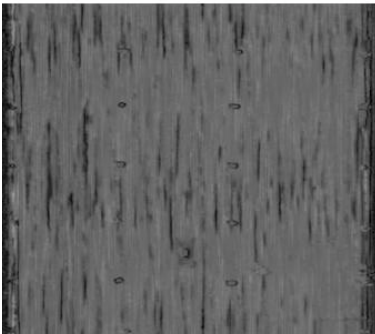
S/N 91, 49 hours



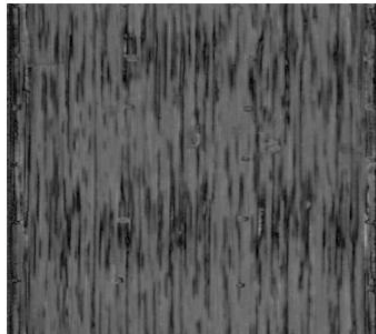
S/N 89, 91 hours



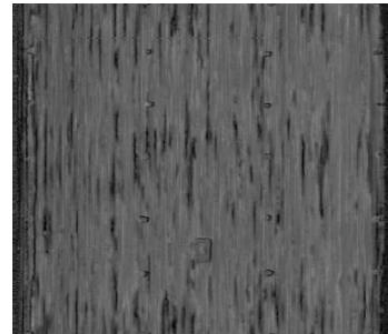
S/N 71, 163 hours



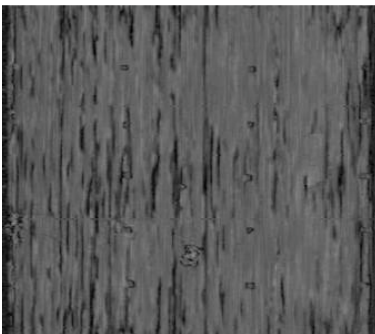
S/N 99, 163 hours



S/N 90, 231 hours

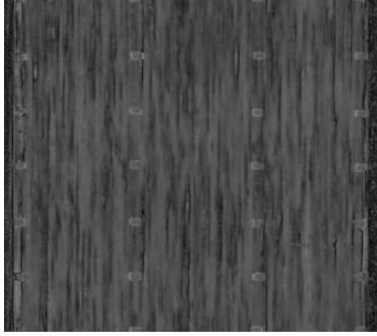


S/N 46, 235 hours



S/N 56, 426 hours

Figure 10: 300GHz images of high temperature aged bottles.



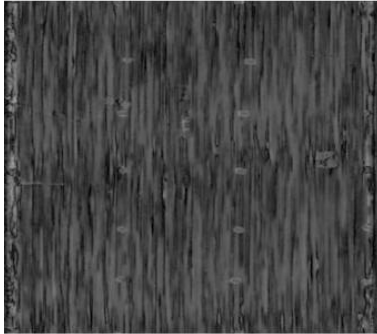
S/N 28, Virgin



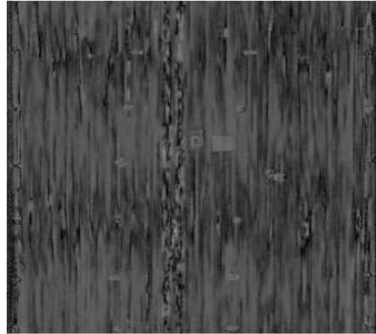
S/N 12, 6 hours



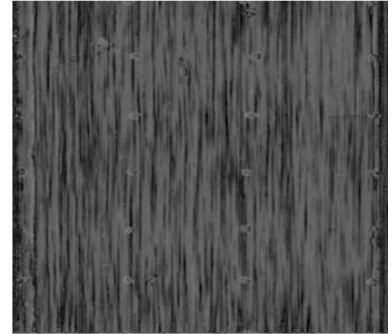
S/N 9, 49 hours



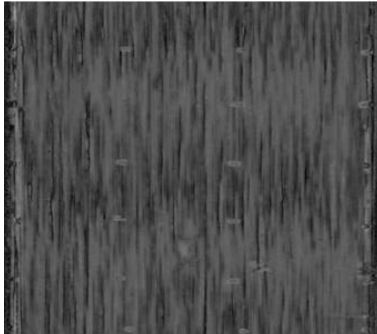
S/N 91, 49 hours



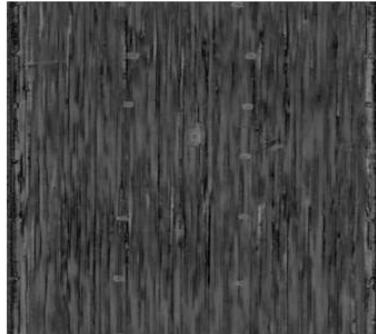
S/N 89, 91 hours



S/N 71, 163 hours



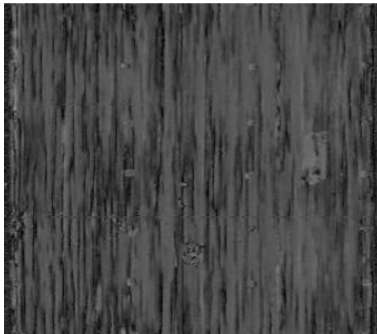
S/N 99, 163 hours



S/N 90, 231 hours



S/N 46, 235 hours

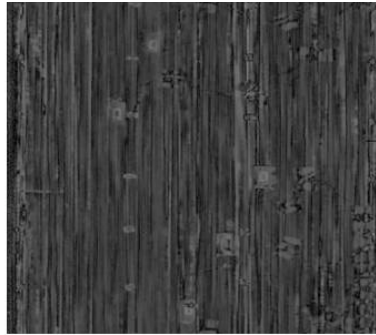


S/N 56, 426 hours

Figure 11: 325GHz images of high temperature aged bottles.



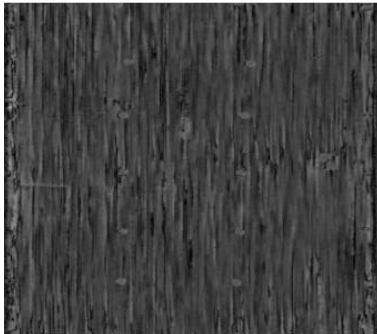
S/N 28, Virgin



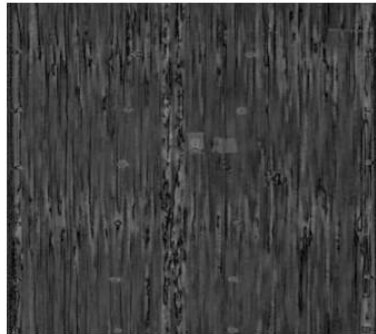
S/N 12, 6 hours



S/N 9, 49 hours



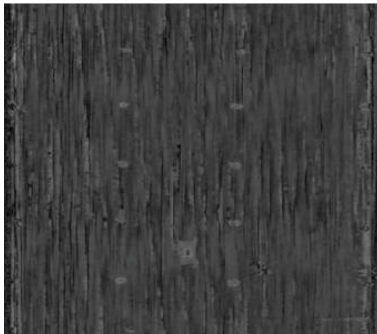
S/N 91, 49 hours



S/N 89, 91 hours



S/N 71, 163 hours



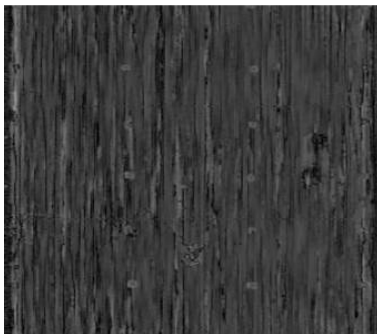
S/N 99, 163 hours



S/N 90, 231 hours



S/N 46, 235 hours



S/N 56, 426 hours

Figure 12: 350GHz images of high temperature aged bottles.



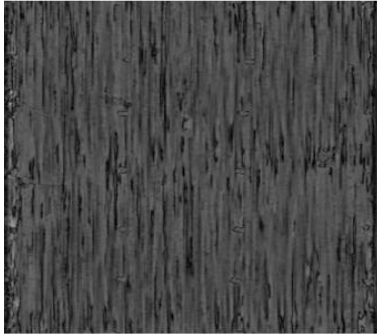
S/N 28, Virgin



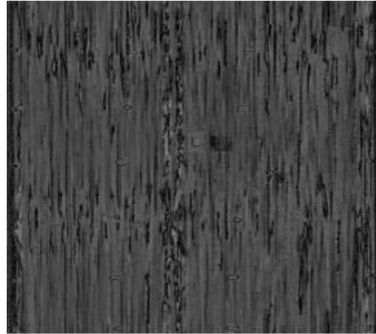
S/N 12, 6 hours



S/N 9, 49 hours



S/N 91, 49 hours



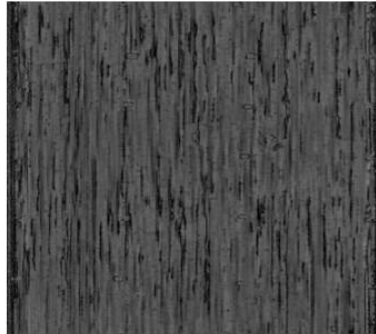
S/N 89, 91 hours



S/N 71, 163 hours



S/N 99, 163 hours



S/N 90, 231 hours

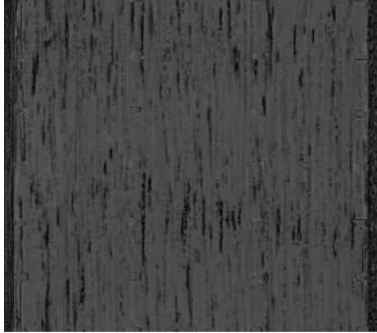


S/N 46, 235 hours



S/N 56, 426 hours

Figure 13: 375GHz images of high temperature aged bottles.



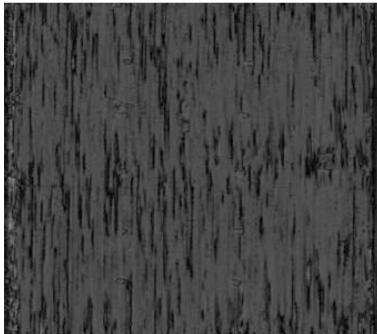
S/N 28, Virgin



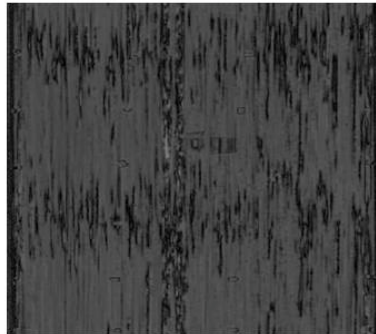
S/N 12, 6 hours



S/N 9, 49 hours



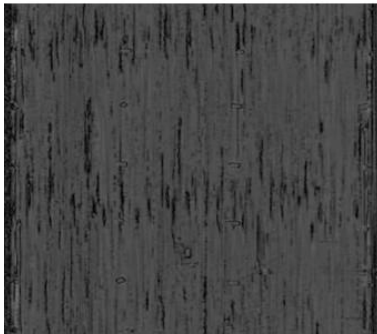
S/N 91, 49 hours



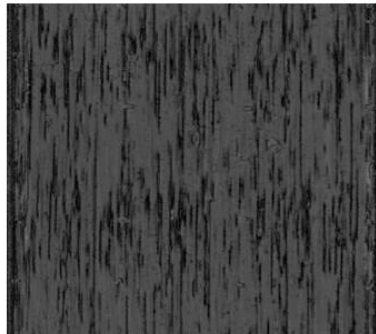
S/N 89, 91 hours



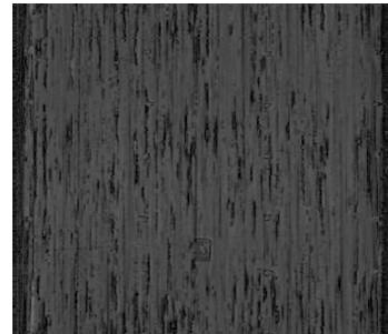
S/N 71, 163 hours



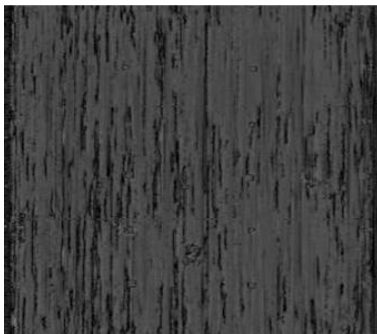
S/N 99, 163 hours



S/N 90, 231 hours

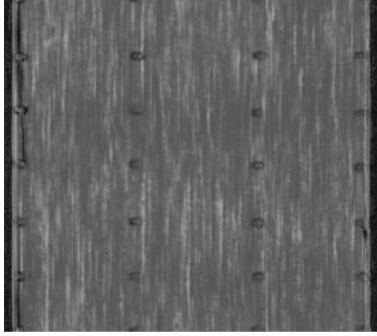


S/N 46, 235 hours

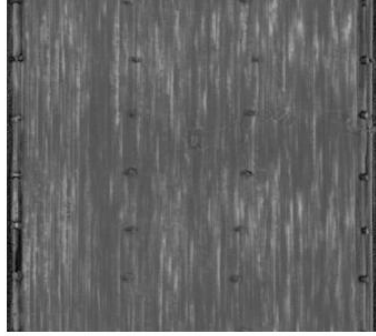


S/N 56, 426 hours

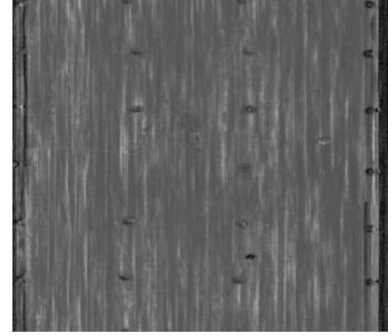
Figure 14: 400GHz images of high temperature aged bottles.



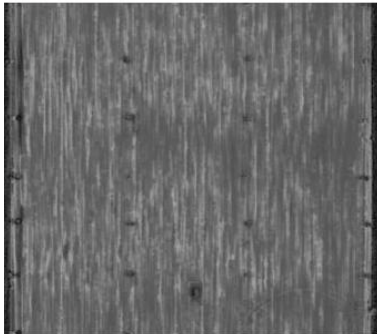
S/N 28, Virgin



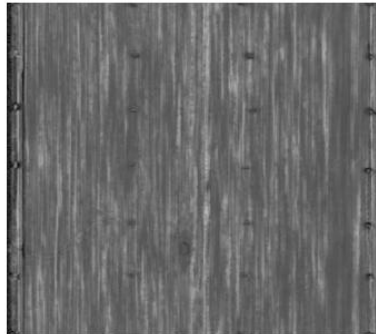
S/N 62, 72 hours



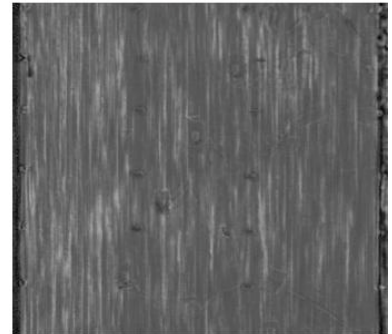
S/N 100, 72 hours



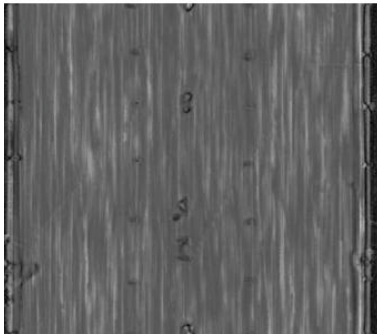
S/N 24, 176 hours



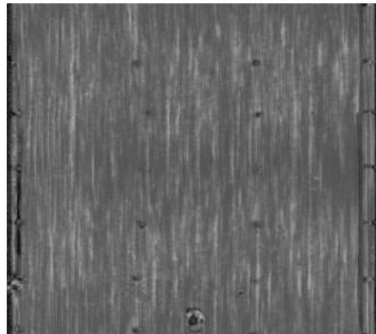
S/N 2, 216 hours



S/N 37, 216 hours

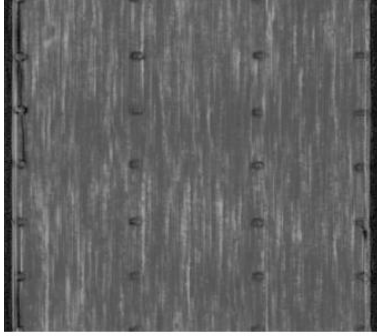


S/N 52, 292 hours

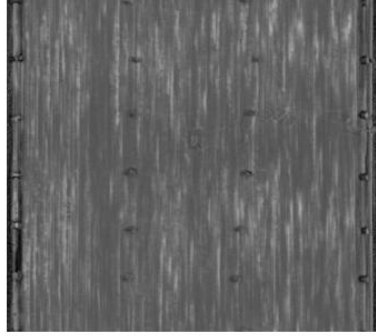


S/N 75, 362 hours

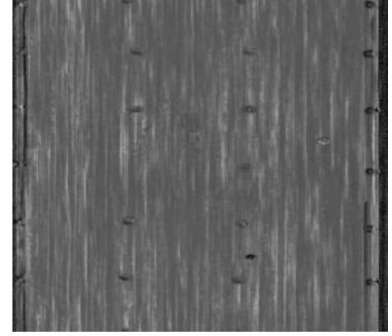
Figure 15: 100GHz images of high stress aged bottles.



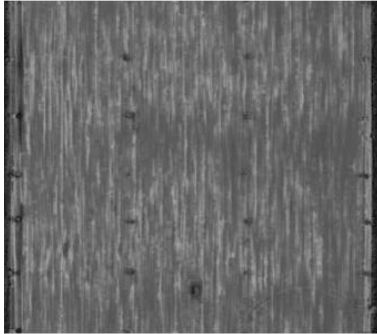
S/N 28, Virgin



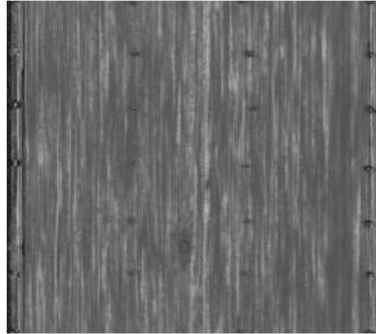
S/N 62, 72 hours



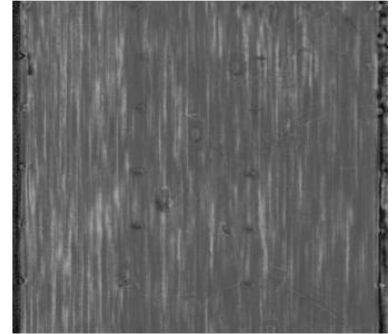
S/N 100, 72 hours



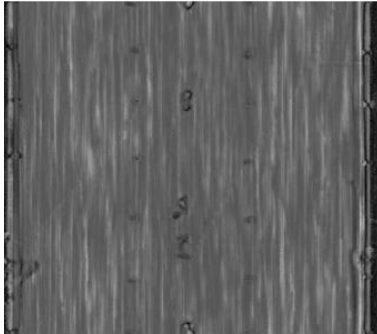
S/N 24, 176 hours



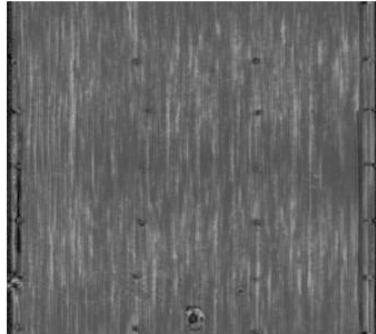
S/N 2, 216 hours



S/N 37, 216 hours

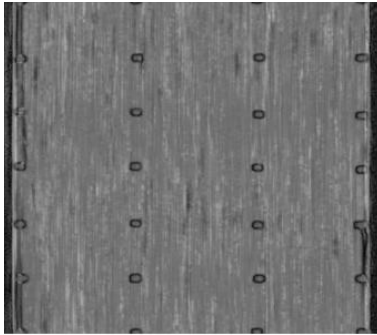


S/N 52, 292 hours

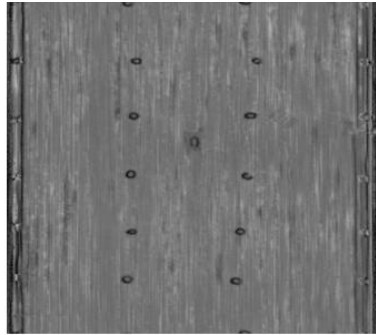


S/N 75, 362 hours

Figure 16: 150GHz images of high stress aged bottles.



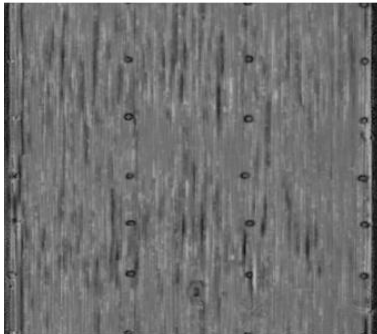
S/N 28, Virgin



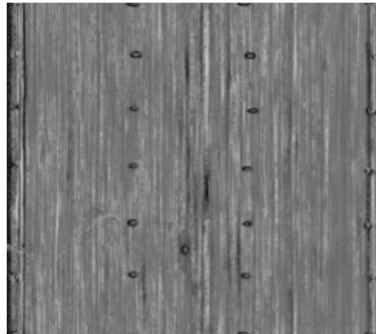
S/N 62, 72 hours



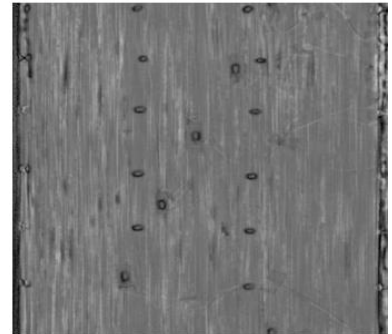
S/N 100, 72 hours



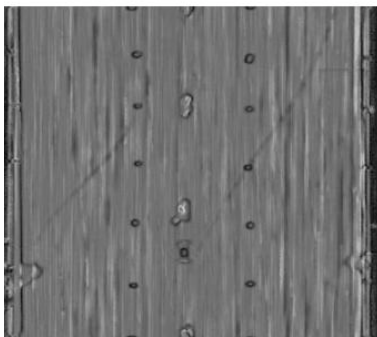
S/N 24, 176 hours



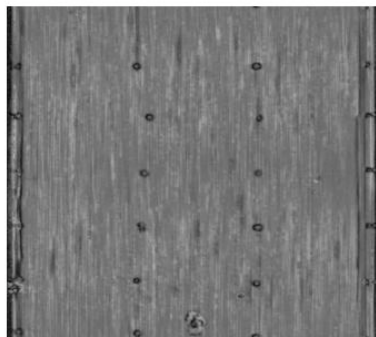
S/N 2, 216 hours



S/N 37, 216 hours

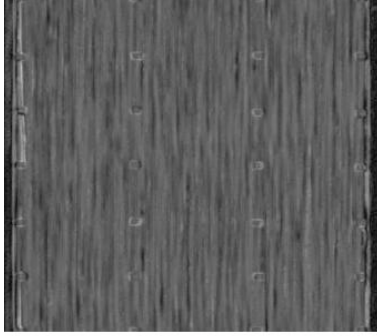


S/N 52, 292 hours

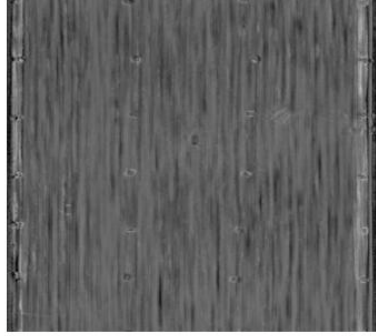


S/N 75, 362 hours

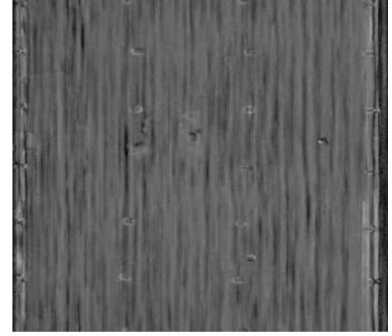
Figure 17: 175GHz images of high stress aged bottles.



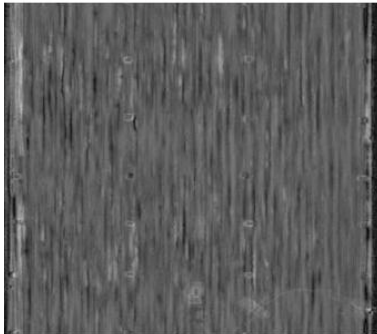
S/N 28, Virgin



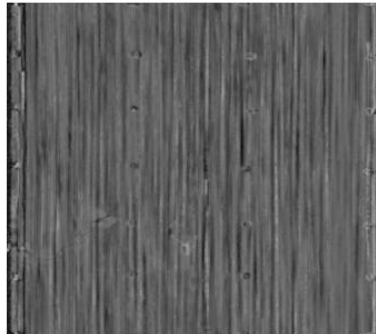
S/N 62, 72 hours



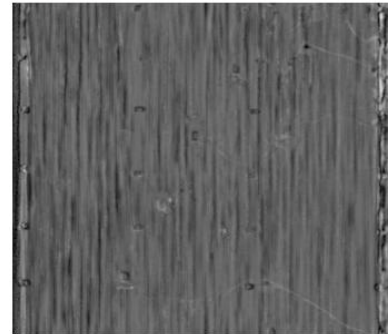
S/N 100, 72 hours



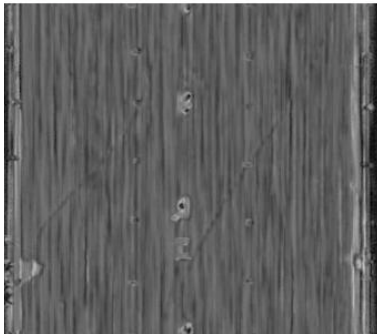
S/N 24, 176 hours



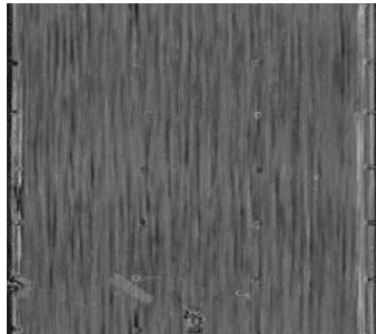
S/N 2, 216 hours



S/N 37, 216 hours

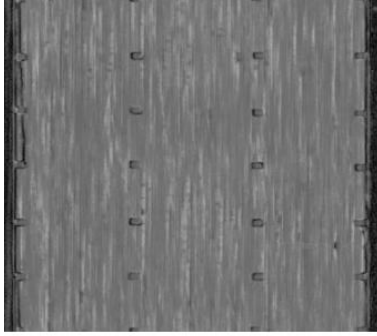


S/N 52, 292 hours

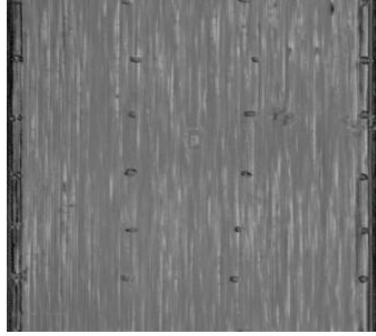


S/N 75, 362 hours

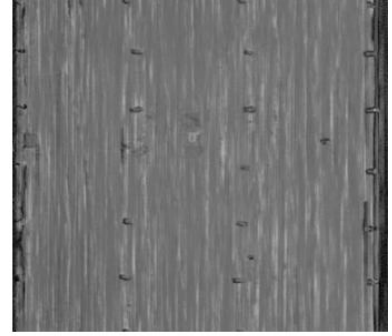
Figure 18: 200GHz images of high stress aged bottles.



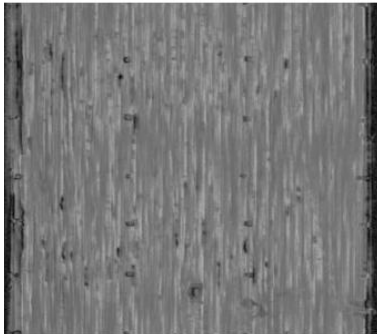
S/N 28, Virgin



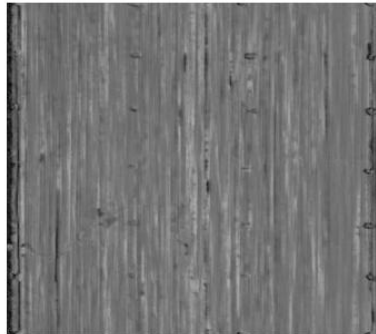
S/N 62, 72 hours



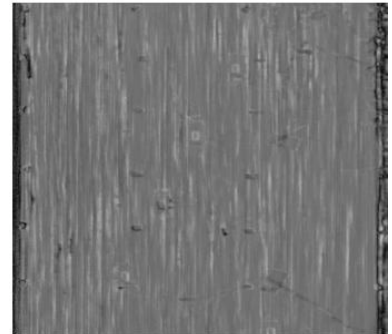
S/N 100, 72 hours



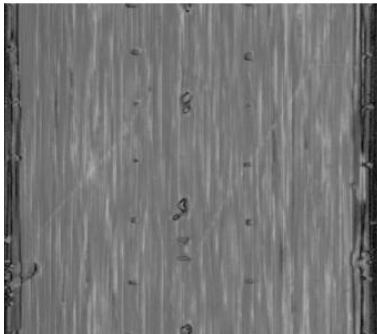
S/N 24, 176 hours



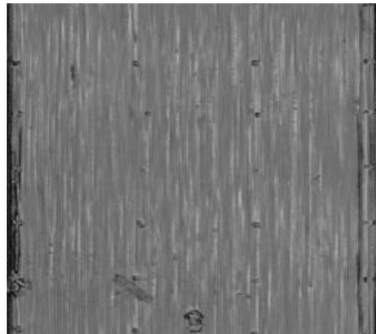
S/N 2, 216 hours



S/N 37, 216 hours

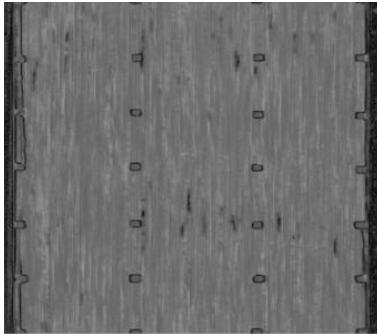


S/N 52, 292 hours

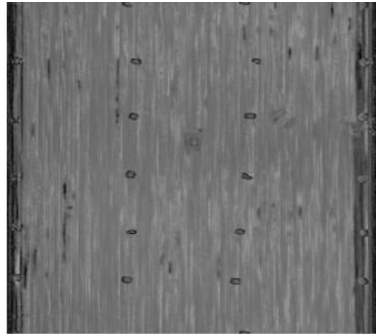


S/N 75, 362 hours

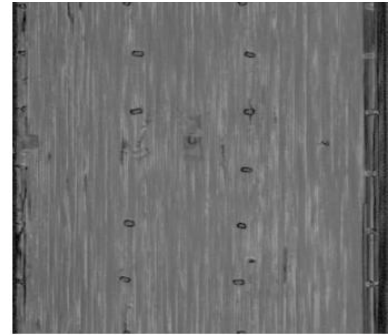
Figure 19: 250GHz images of high stress aged bottles.



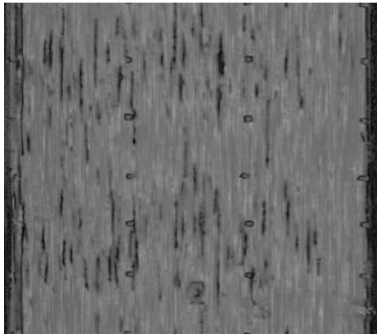
S/N 28, Virgin



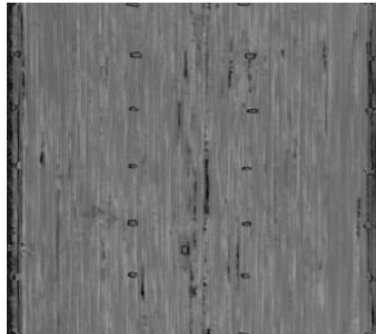
S/N 62, 72 hours



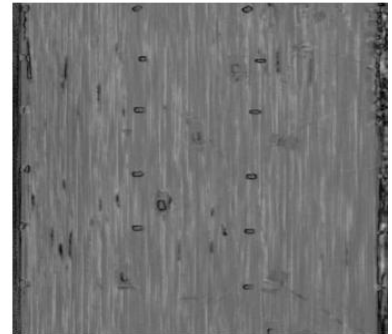
S/N 100, 72 hours



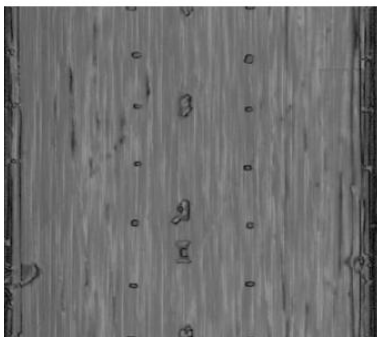
S/N 24, 176 hours



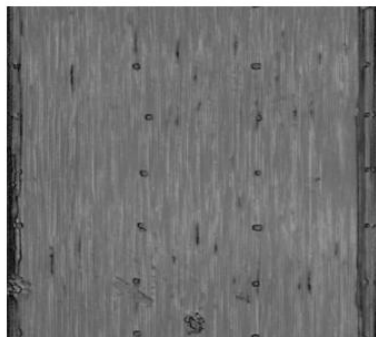
S/N 2, 216 hours



S/N 37, 216 hours

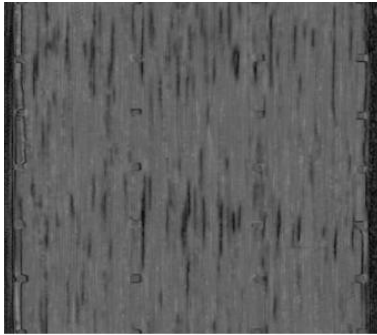


S/N 52, 292 hours

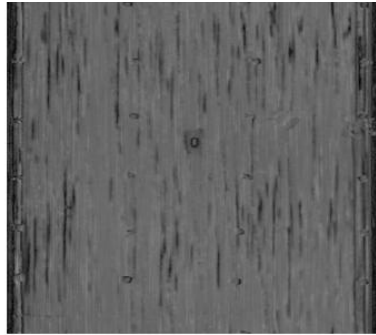


S/N 75, 362 hours

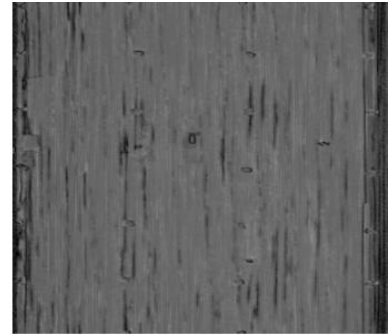
Figure 20: 275GHz images of high stress aged bottles.



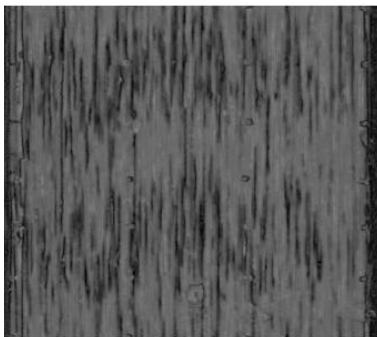
S/N 28, Virgin



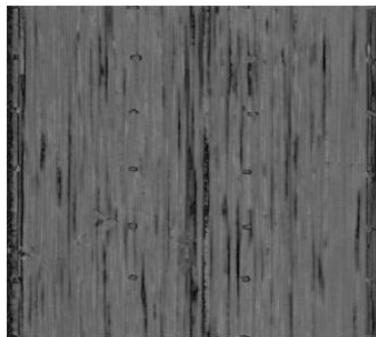
S/N 62, 72 hours



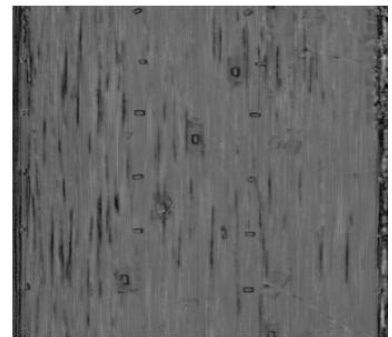
S/N 100, 72 hours



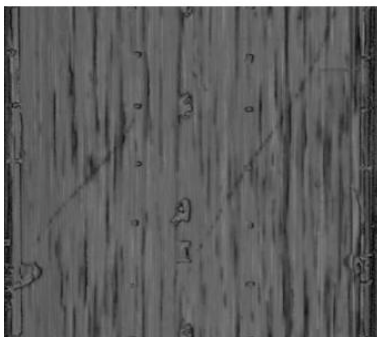
S/N 24, 176 hours



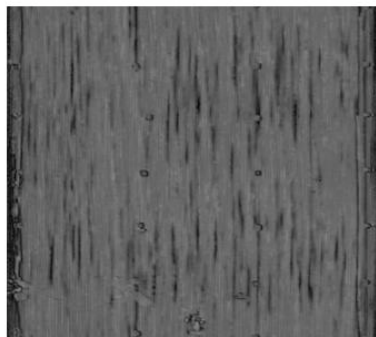
S/N 2, 216 hours



S/N 37, 216 hours

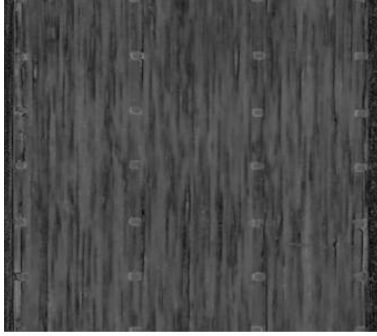


S/N 52, 292 hours

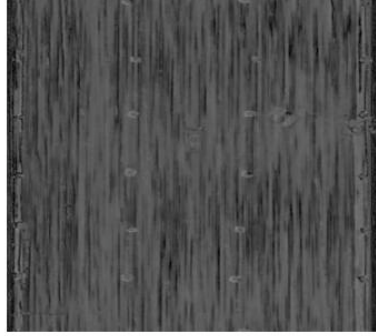


S/N 75, 362 hours

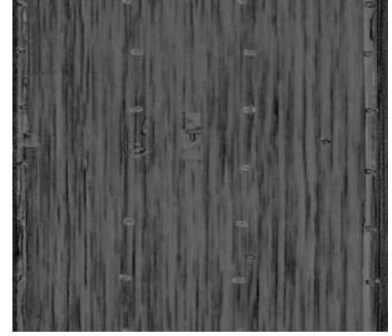
Figure 21: 300GHz images of high stress aged bottles.



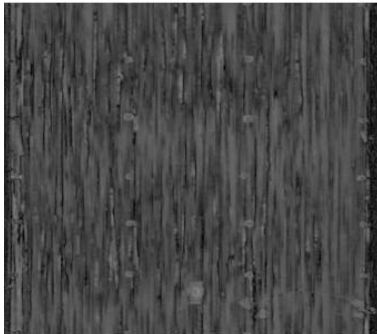
S/N 28, Virgin



S/N 62, 72 hours



S/N 100, 72 hours



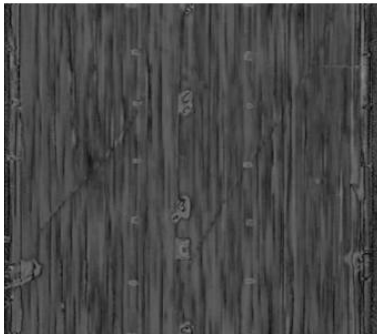
S/N 24, 176 hours



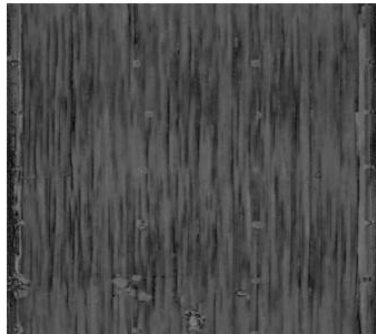
S/N 2, 216 hours



S/N 37, 216 hours



S/N 52, 292 hours



S/N 75, 362 hours

Figure 22: 325GHz images of high stress aged bottles.



S/N 28, Virgin



S/N 62, 72 hours



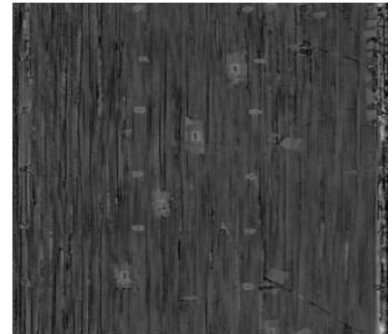
S/N 100, 72 hours



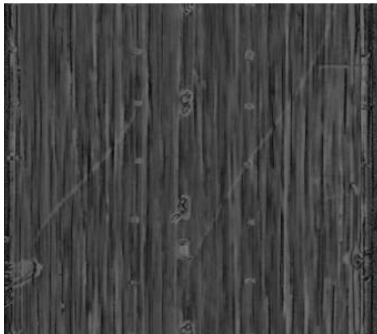
S/N 24, 176 hours



S/N 2, 216 hours



S/N 37, 216 hours

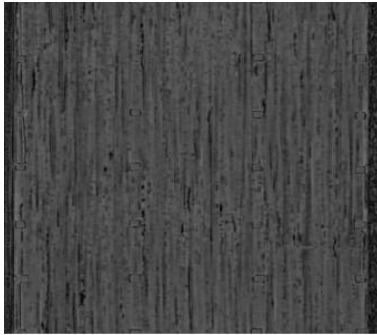


S/N 52, 292 hours

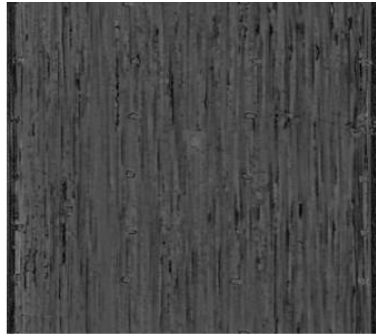


S/N 75, 362 hours

Figure 23: 350GHz images of high stress aged bottles.



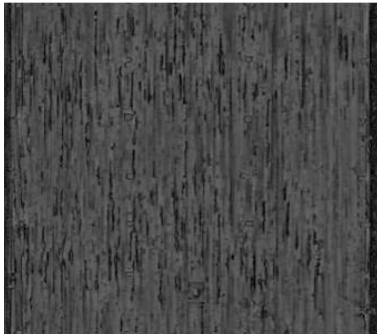
S/N 28, Virgin



S/N 62, 72 hours



S/N 100, 72 hours



S/N 24, 176 hours



S/N 2, 216 hours



S/N 37, 216 hours

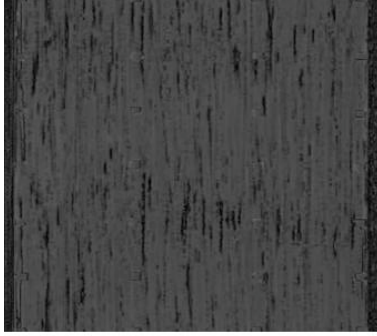


S/N 52, 292 hours

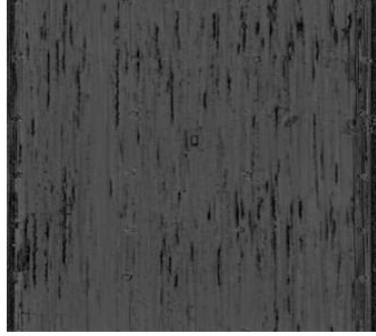


S/N 75, 362 hours

Figure 24: 375GHz images of high stress aged bottles.



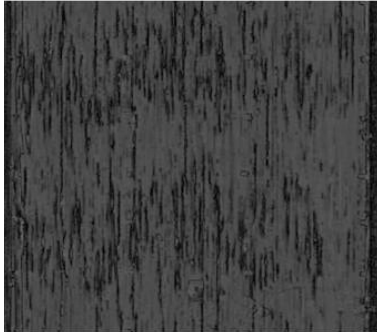
S/N 28, Virgin



S/N 62, 72 hours



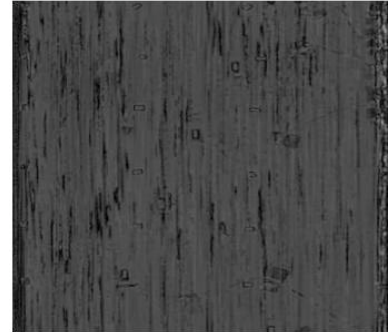
S/N 100, 72 hours



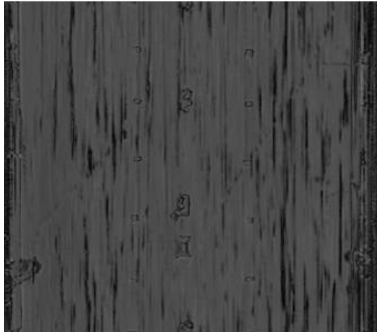
S/N 24, 176 hours



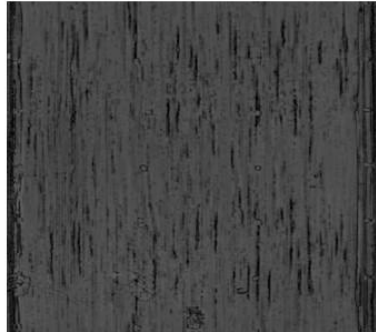
S/N 2, 216 hours



S/N 37, 216 hours



S/N 52, 292 hours



S/N 75, 362 hours

Figure 25: 400GHz images of high stress aged bottles.

Spectral Power Ratio vs. Age

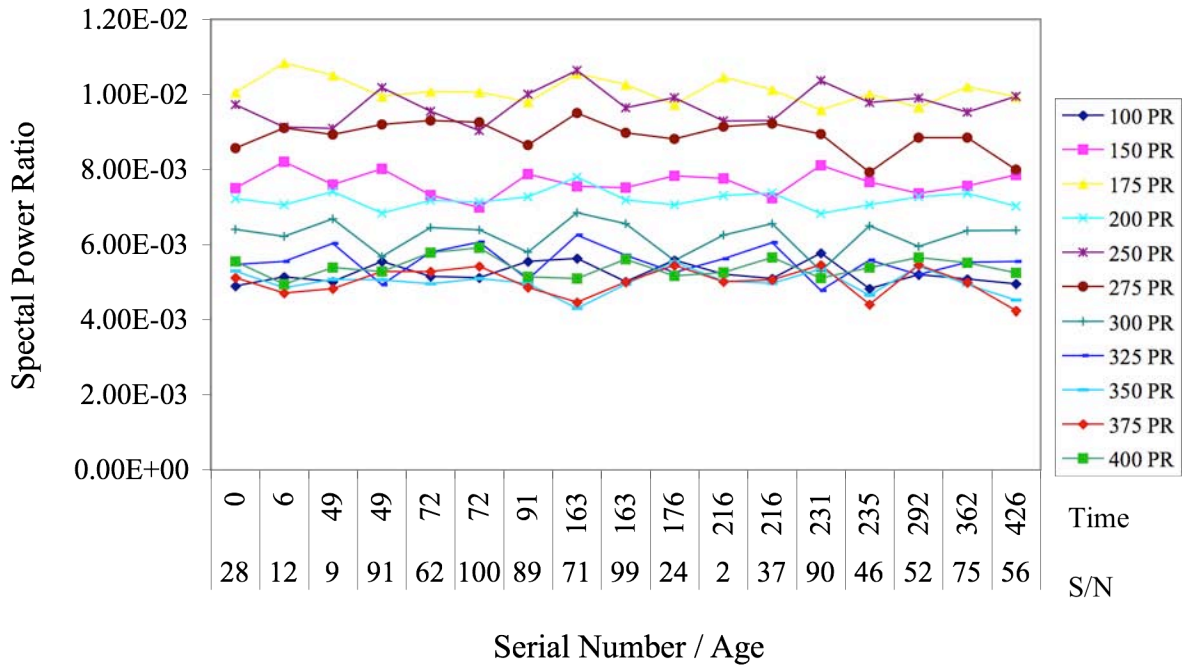
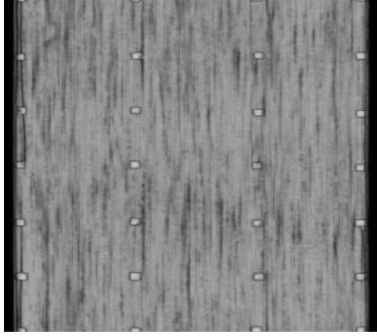
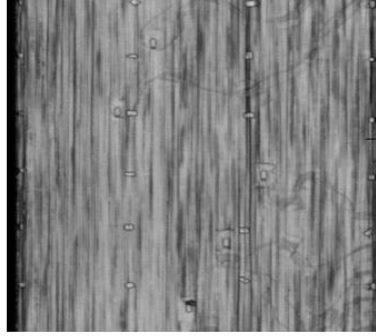


Figure 26: Average Spectral Power Ratio vs. test age.



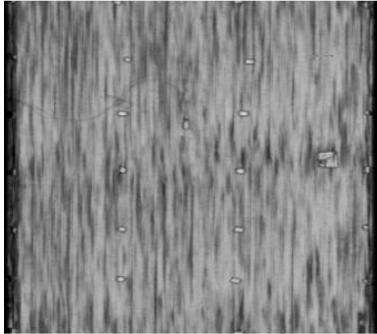
S/N 28, Virgin



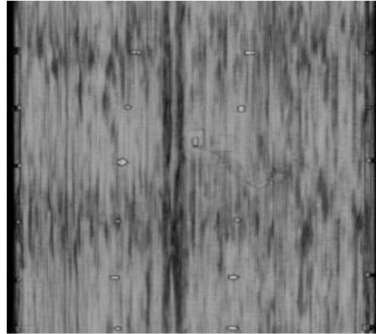
S/N 12, 6 hours



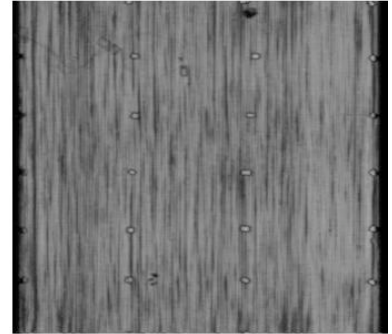
S/N 9, 49 hours



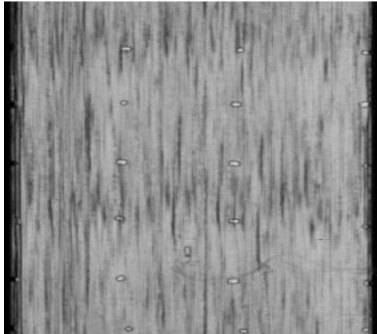
S/N 91, 49 hours



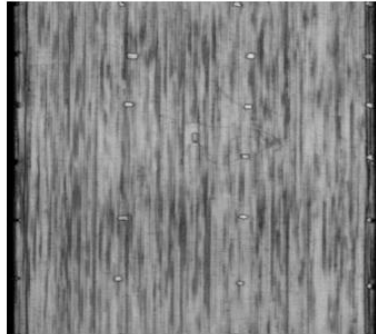
S/N 89, 91 hours



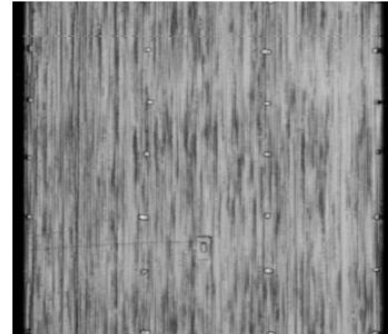
S/N 71, 163 hours



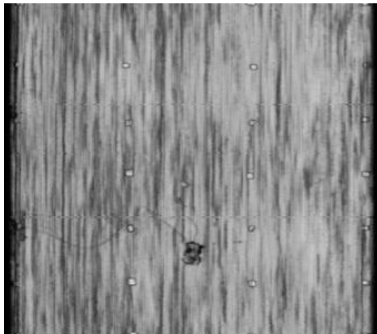
S/N 99, 163 hours



S/N 90, 231 hours

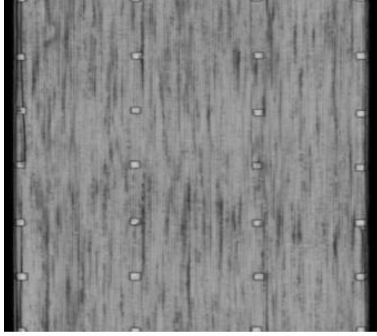


S/N 46, 235 hours

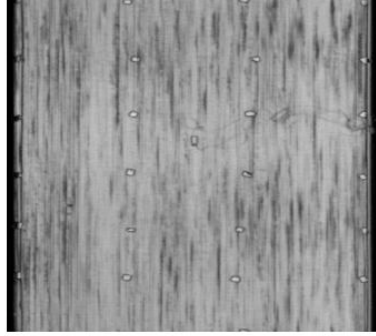


S/N 56, 426 hours

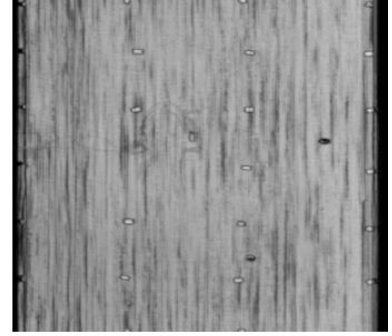
Figure 27: Peak-to-peak images of high temperature aged bottles.



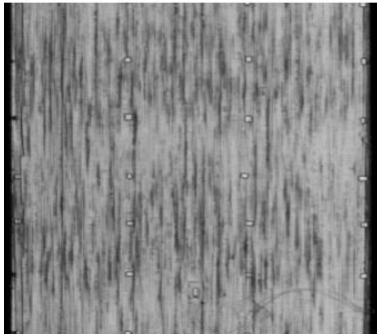
S/N 28, Virgin



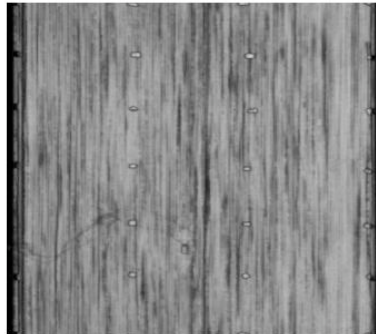
S/N 62, 72 hours



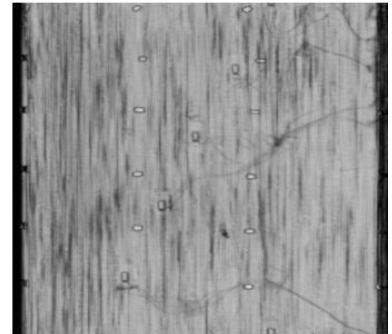
S/N 100, 72 hours



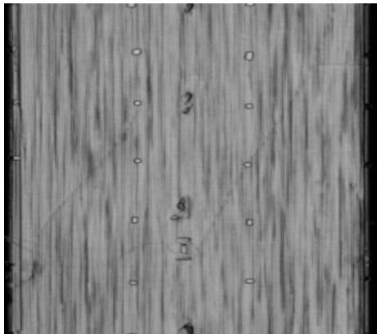
S/N 24, 176 hours



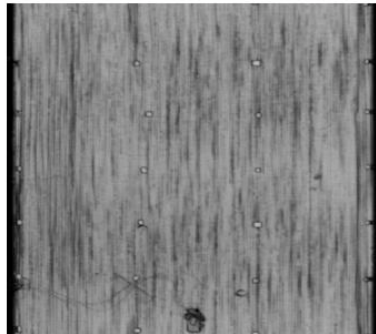
S/N 2, 216 hours



S/N 37, 216 hours

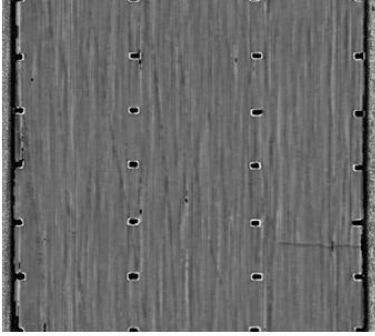


S/N 52, 292 hours

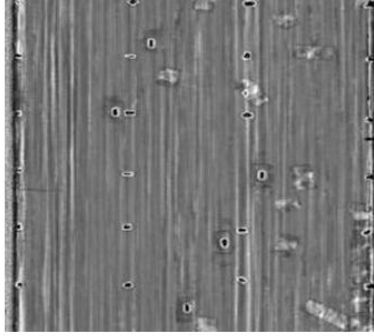


S/N 75, 362 hours

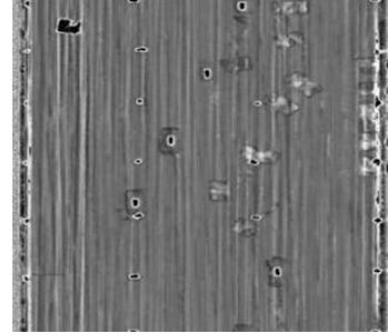
Figure 28: Peak-to-peak images of high stress aged bottles.



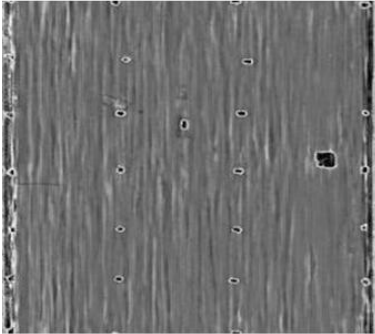
S/N 28, Virgin



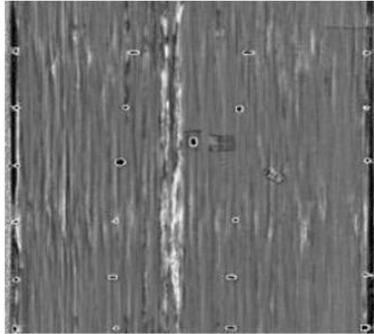
S/N 12, 6 hours



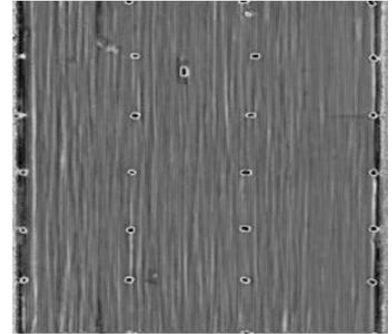
S/N 9, 49 hours



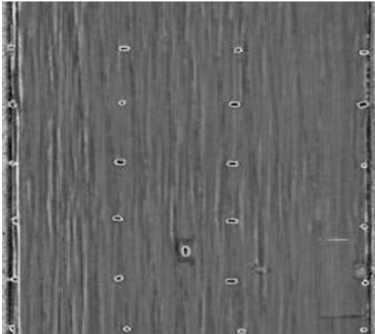
S/N 91, 49 hours



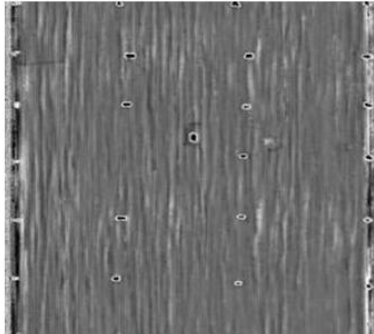
S/N 89, 91 hours



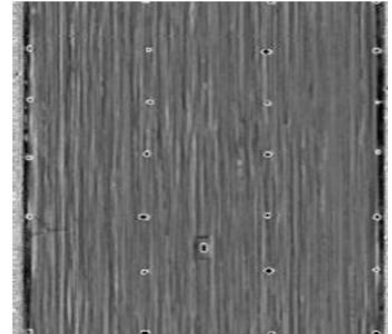
S/N 71, 163 hours



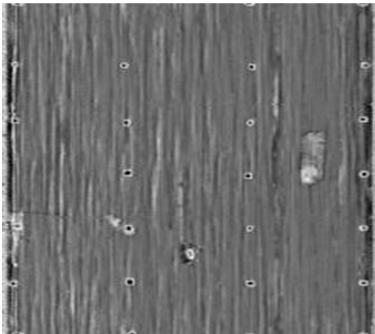
S/N 99, 163 hours



S/N 90, 231 hours

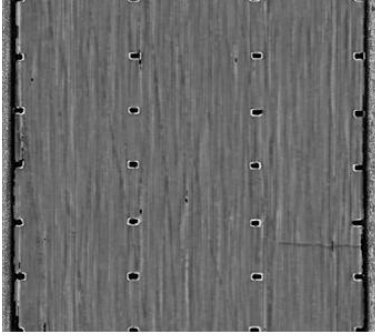


S/N 46, 235 hours

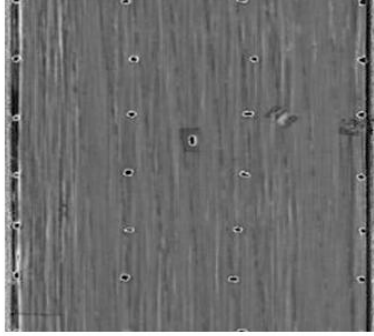


S/N 56, 426 hours

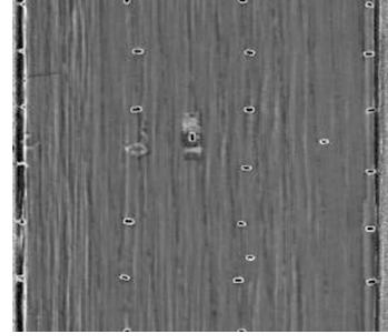
Figure 29: Peak-to-peak ratio images of high temperature aged bottles.



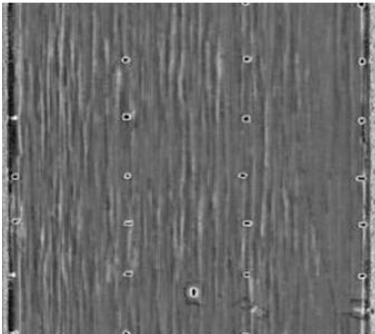
S/N 28, Virgin



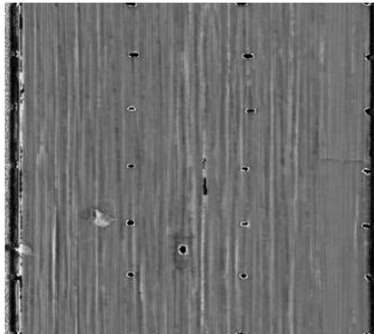
S/N 62, 72 hours



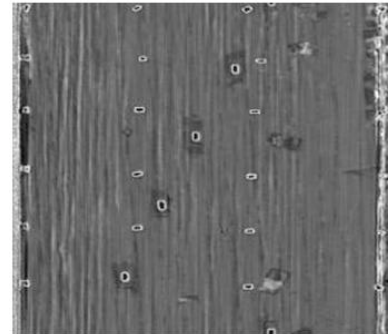
S/N 100, 72 hours



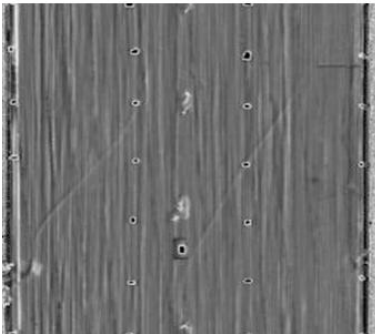
S/N 24, 176 hours



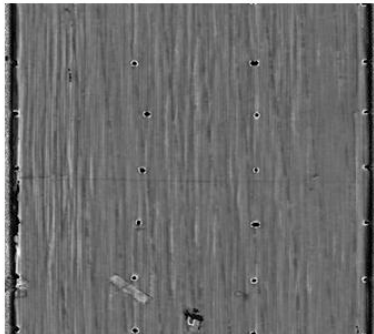
S/N 2, 216 hours



S/N 37, 216 hours

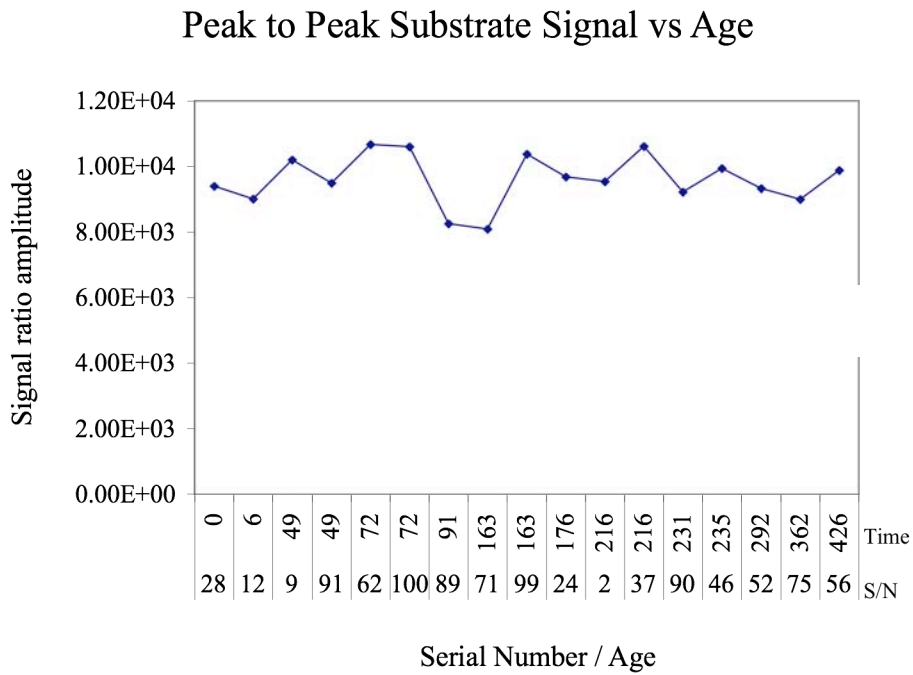


S/N 52, 292 hours



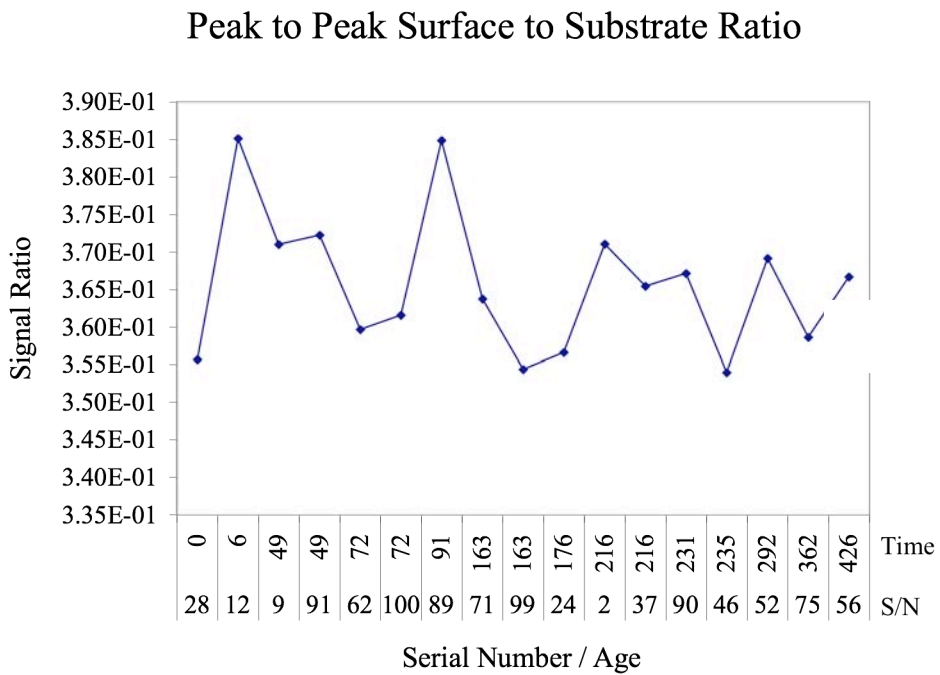
S/N 75, 362 hours

Figure 30: Peak-to-peak ratios images of high stress aged bottles.



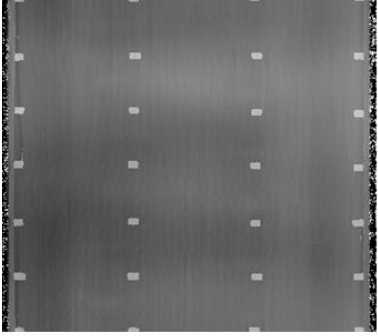
in

Figure 31: Peak-to-peak average substrate amplitude graph.

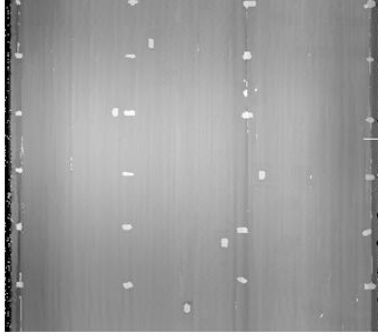


ratio

Figure 32: Peak-to-peak surface to substrate amplitude ratio graph.



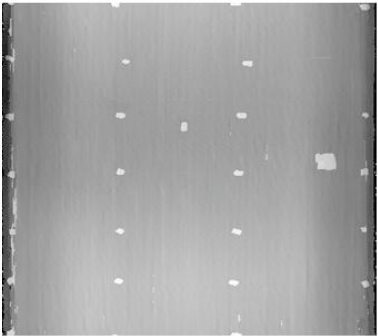
S/N 28, Virgin



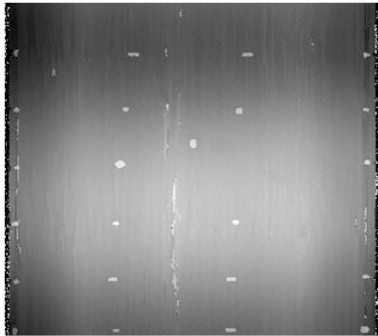
S/N 12, 6 hours



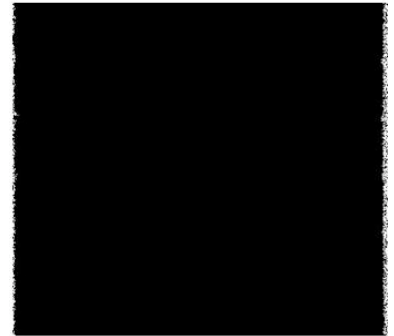
S/N 9, 49 hours



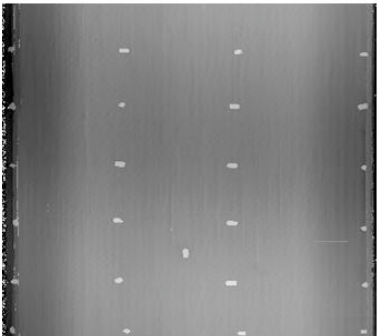
S/N 91, 49 hours



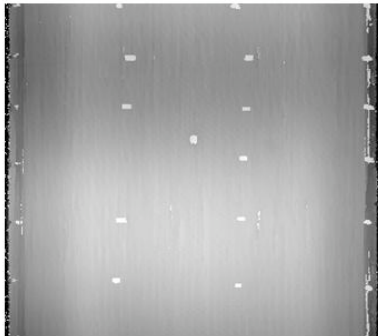
S/N 89, 91 hours



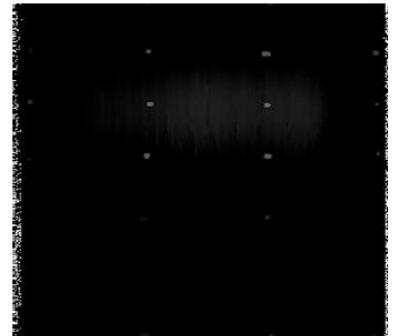
S/N 71, 163 hours



S/N 99, 163 hours



S/N 90, 231 hours

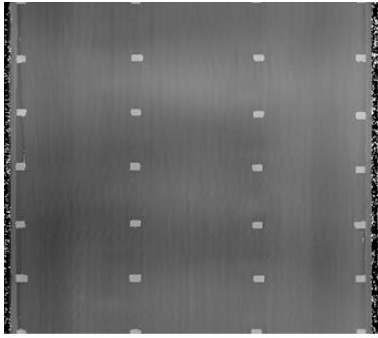


S/N 46, 235 hours

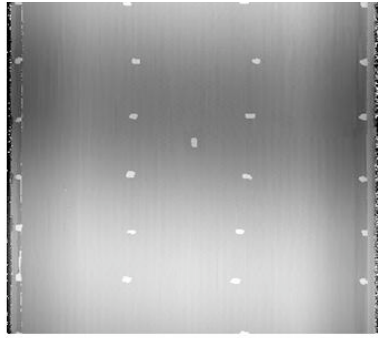


S/N 56, 426 hours

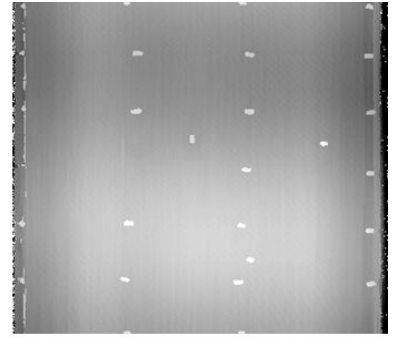
Figure 33: Time of flight images of high temperature aged bottles.



S/N 28, Virgin



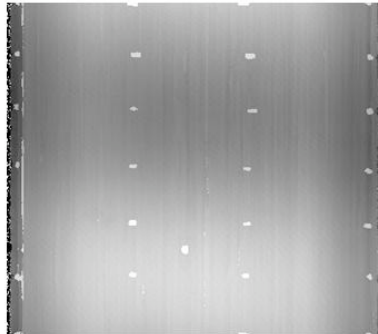
S/N 62, 72 hours



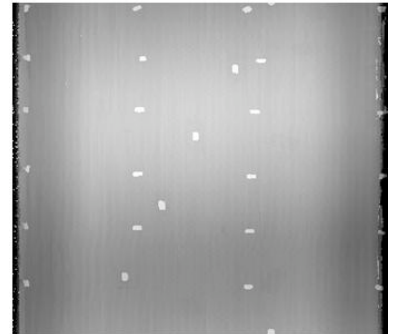
S/N 100, 72 hours



S/N 24, 176 hours



S/N 2, 216 hours



S/N 37, 216 hours

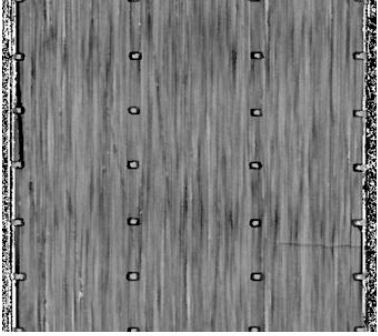


S/N 52, 292 hours

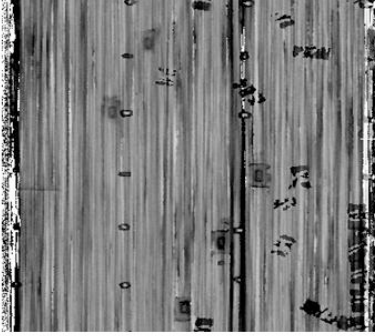


S/N 75, 362 hours

Figure 34: Time of flight images of high stress aged bottles.



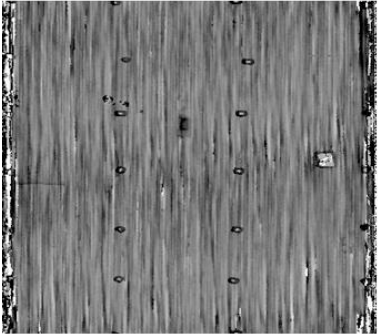
S/N 28, Virgin



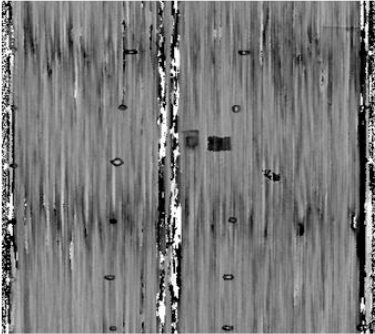
S/N 12, 6 hours



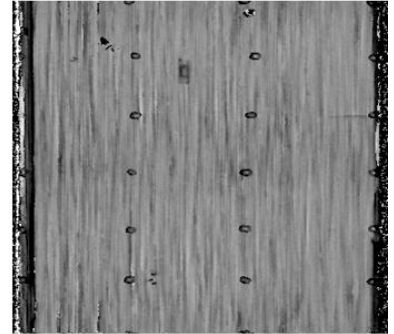
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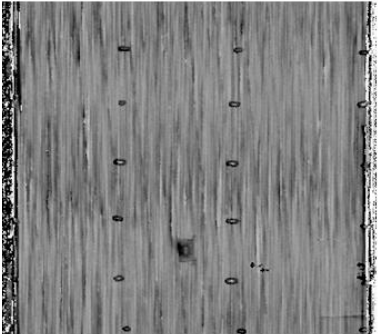
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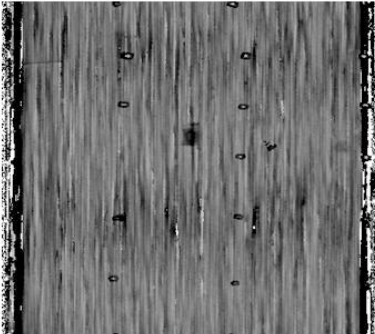
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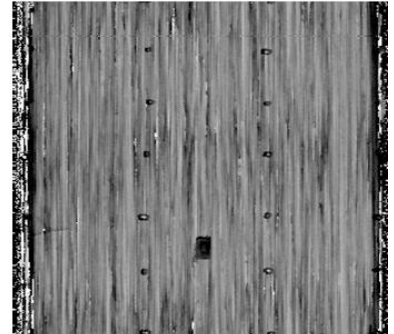
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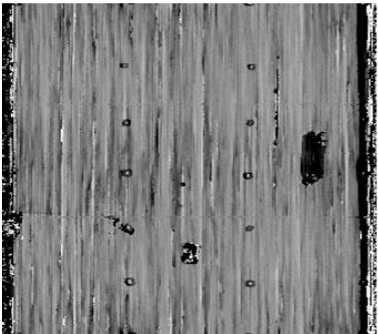
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S/N 90, 231 hours

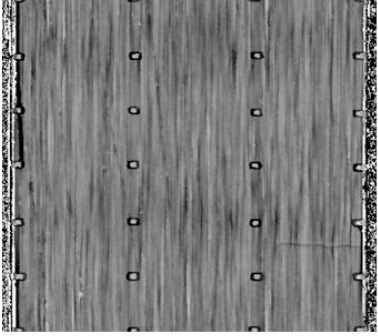


S/N 46, 235 hours

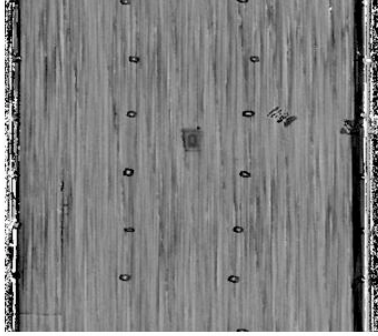


S/N 56, 426 hours

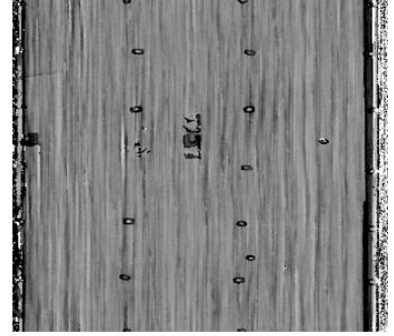
Figure 35: Positive Peak Delta images of high temperature aged bottles.



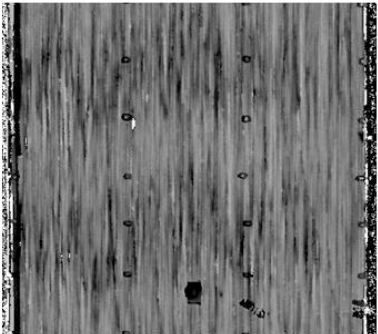
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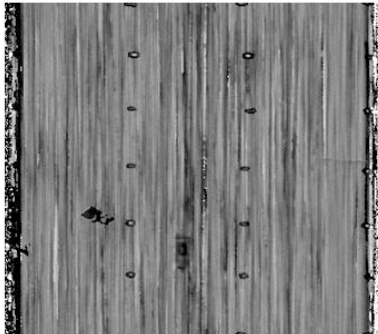
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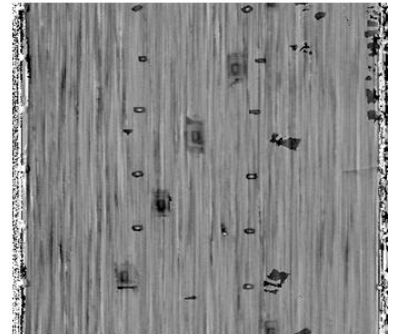
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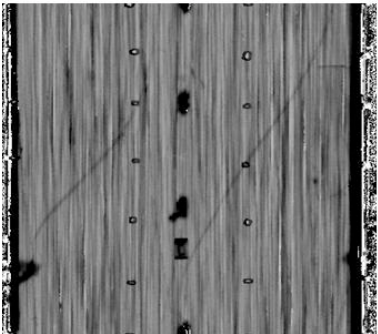
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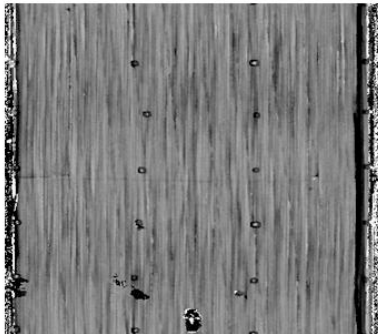
S/N 2, 216 hours



S/N 37, 216 hours

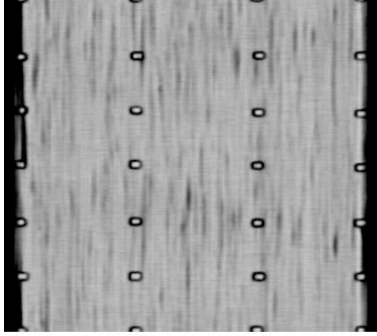


S/N 52, 292 hours

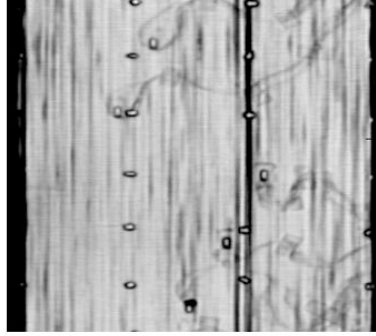


S/N 75, 362 hours

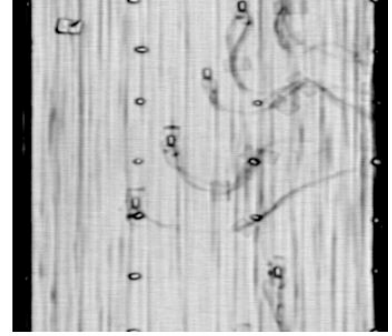
Figure 36: Positive Peak Delta images of high stress aged bottles.



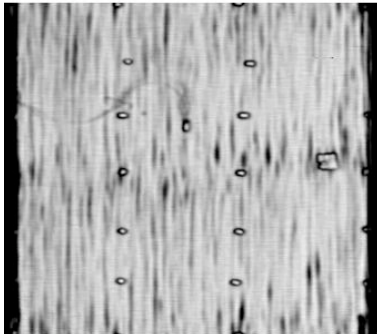
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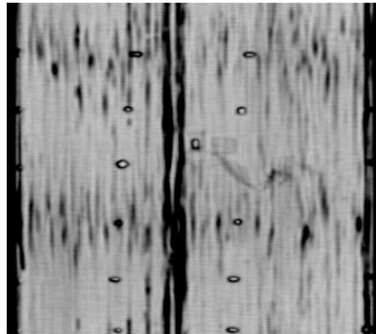
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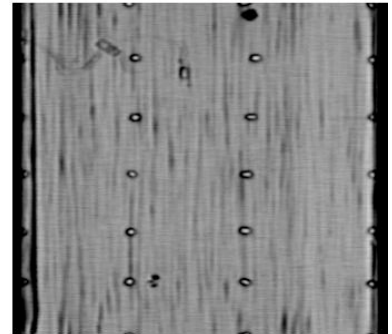
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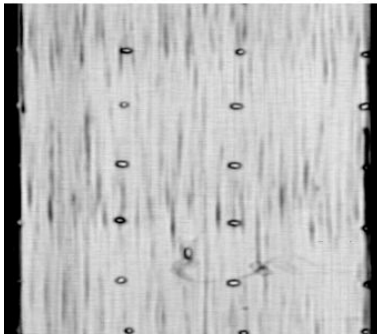
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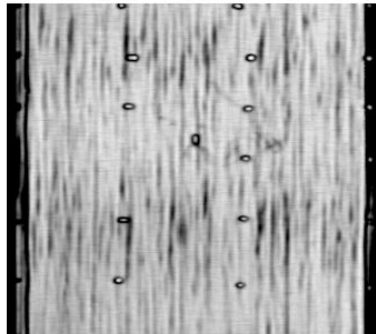
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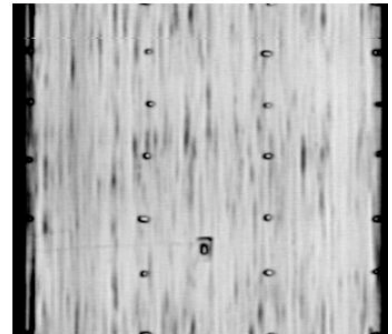
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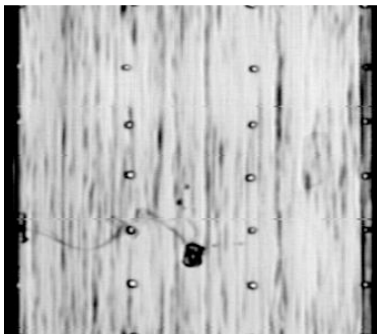
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S/N 90, 231 hours

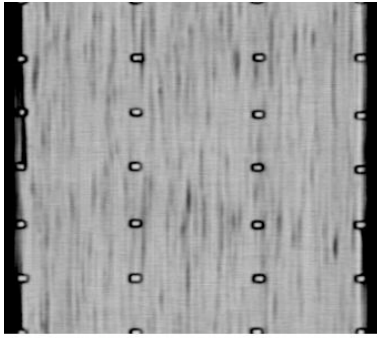


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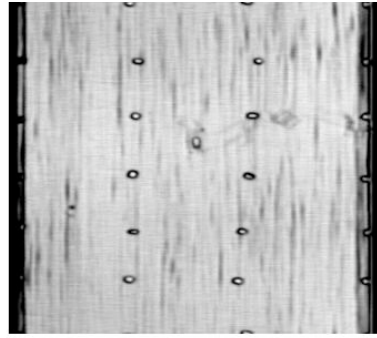


S/N 56, 426 hours

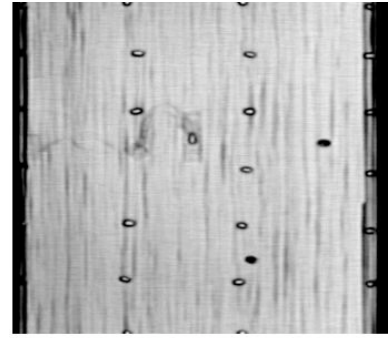
Figure 37: Peak-to-peak images of high temperature aged bottles at 150GHz.



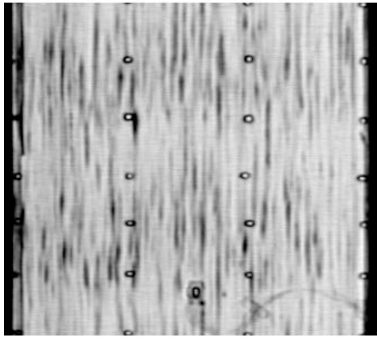
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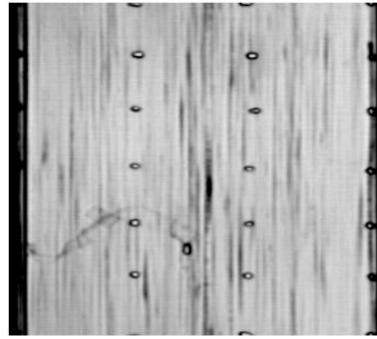
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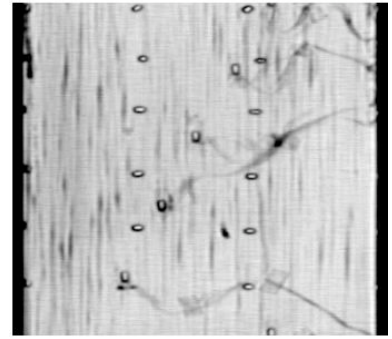
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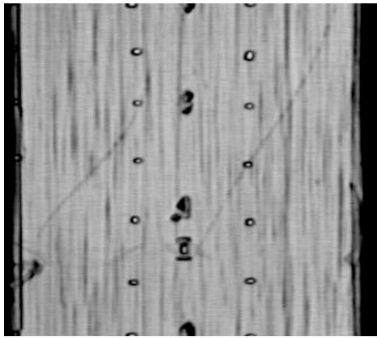
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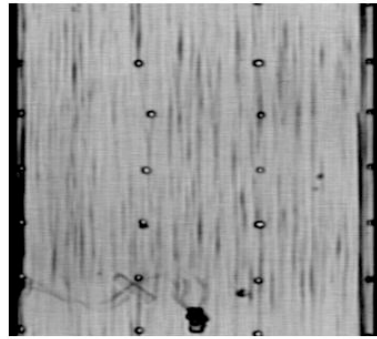
S/N 2, 216 hours



S/N 37, 216 hours



S/N 52, 292 hours



S/N 75, 362 hours

Figure 38: Peak-to-peak images of high stress aged bottles at 150GHz.

Conclusions

Kevlar over wrapped metal lined bottles were aged under either high temperature or high stress to induce damage in the over wrap materials. THz NDE was used to examine some of the temperature and pressure stressed COPV's for characteristics resulting from this induced stress. Electromagnetic waves from the inspection system interrogated the Kevlar over wrap and adhesive and were reflected from the metallic liner. Inspection data was processed in various ways in attempt to highlight stress-induced anomalies related to remaining life. The data was processed in the frequency domain to obtain narrow banded spectral ratios, processed in the standard manner of peak-to-peak signal levels, processed to examine the ratio of the Kevlar front wall peak-to-peak signal to the Kevlar back wall peak-to-peak signal, processed to examine time-of-flight of the back wall positive peak, processed to measured time difference between the front and back wall positive peaks, and processed to emulate a microwave inspection system.

Processing results did not indicate or show any anomalous features directly related to aging. However, thickness variations were identified and should be examined in further detail to see if this feature contributes to anomalous failure.

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REPORT DOCUMENTATION PAGE

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14. ABSTRACT Terahertz radiation nondestructive evaluation was applied to a set of Kevlar composite overwrapped pressure vessel bottles that had undergone a series of thermal and pressure tests to simulate stress rupture effects. The bottles in these nondestructive evaluation tests were bottles that had not ruptured but had survived various times at the elevated load and temperature levels. Some of the bottles showed evidence of minor composite failures. The terahertz radiation did detect visible surface flaws, but did not detect any internal chemical or material degradation of the thin overwraps.					
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