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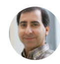

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Detection and Reliability Risks of Counterfeit Electrolytic Capacitors

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***Abstract*—Counterfeit electronics have been reported in a wide range of products, including computers, medical equipment, automobiles, avionics, and military systems. Counterfeiting is a growing concern for original equipment manufacturers (OEMs) in the electronics industry. Even inexpensive passive components such as capacitors and resistors are frequently found to be counterfeit, and their incorporation into electronic assemblies can cause early failures with potentially serious economic and safety implications. This study examines counterfeit electrolytic capacitors that were unknowingly assembled in power supplies used in medical devices, and then failed in the field. Upon analysis, the counterfeit components were identified, and their reliability relative to genuine parts was assessed. This paper presents an offline reliability assessment methodology and a systematic counterfeit detection methodology for electrolytic capacitors, which include optical inspection, X-Ray examination, weight measurement, electrical parameter measurement over temperature, and chemical characterization of the electrolyte using Fourier Transform Infrared Spectroscopy (FTIR) to assess the failure modes, mechanisms, and reliability risks. FTIR was successfully able to detect a lower concentration of ethylene glycol in the counterfeit capacitor electrolyte. In the electrical properties measurement, the distribution of values at room temperature was broader for counterfeit parts than for the authentic parts, and some electrical parameters at the maximum and minimum rated temperatures were out of specifications. These techniques, particularly FTIR analysis of the electrolyte and electrical measurements at the lowest and highest rated temperature, can be very effective to screen for counterfeit electrolytic capacitors.**

***Index Terms*—Accelerated testing, aluminum electrolytic capacitors, chemical analysis, counterfeit aluminum electrolytic capacitors, failure analysis, Fourier transform infrared spectroscopy, reliability assessment.**

Acronyms and Abbreviations

OEMs	Original equipment manufacturers
FTIR	Fourier transform infrared spectroscopy
ESR	Equivalent series resistance
GIDEP	Government-Industry data exchange program
EDS	Energy dispersive X-ray spectroscopy
ATR	Attenuated total reflectance
IR	Infrared
DF	Dissipation factor
IR	Insulation resistance
LC	Leakage current

I. Introduction

COUNTERFEIT electronic components are a problem not only for the electronics industry but also to the society as a whole, which depends on electronics from transportation to home care equipment. Original equipment manufacturers (OEMs) are concerned about counterfeiting because counterfeit parts can compromise the reliability of their final products [1]–[3]. Concern about counterfeiting has generally focused on high-cost components, such as integrated circuits. However, less expensive passive components, such as capacitors and resistors, can also cause serious system reliability problems. In the past, counterfeit electrolytic capacitors with faulty electrolytes have resulted in failures of electronic equipment made by big companies like Dell, IBM, HP, and Intel [4].

Electrolytic capacitors are known for their reliability problems, and are often the weakest link in the reliability of power electronics systems [5]–[7]. The most common failure mode for liquid aluminum electrolytic capacitors is the gradual degradation of electrical parameters, including a decrease in capacitance, or an increase in equivalent series resistance (ESR). Electrolytic capacitors can also experience catastrophic failures where there is complete loss of functionality due to a short or open circuit [8], [9].

In this study, we evaluate inexpensive Nichicon electrolytic capacitors that cost about five dollars each. The lead times for these electrolytic capacitors through authorized distribution channels can be several weeks or months. The 2011 earthquake and tsunami in Japan put additional pressure on the supply chain for capacitor raw materials and parts, further extending lead times. Production at leading capacitor manufacturers, including Nippon Chemi-con, Nichicon, and Rubycon, was disrupted in Japan to varying degrees [10]. OEMs are under pressure to find parts quickly, and many of them purchases part from second- and third-tier suppliers. The unfortunate

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consequence is that counterfeit capacitors are making their way into the market, and into systems.

This was not the first time that Nichicon capacitors were found to be counterfeit. In October 2011, Nichicon posted an alert on their website that counterfeit Nichicon electrolytic capacitors were turning up in the market, and these capacitors could cause early failures in end products [11]. The present study discusses an electrolytic capacitor labeled as Nichicon, 220 μF, rated at 400 volts. The part number was LGU2G221MELA. As of April 2014, there were no current advisories under the Government-Industry Data Exchange Program (GIDEP) for this particular Nichicon part.

Aluminum electrolytic capacitors were used by a medical electronics company in a power supply. A contract manufacturer for the electronics company purchased aluminum electrolytic capacitors from a parts broker because the parts were not available from the authorized distributors or independent suppliers. Authorized distributors typically obtain parts from the manufacturers and are contractually authorized by the part manufacturers to store, kit, and distribute the parts. Independent suppliers may not be contractually authorized by the part manufacturers to distribute parts, and these suppliers may procure these parts and distribute them from their warehouses. Parts brokers try to fulfill orders by obtaining parts from wherever they can find them quickly.

Around 4000 power supply units were manufactured using the aluminum electrolytic capacitors obtained from a part broker. By the time it was discovered that the capacitors were counterfeit, about 2000 units with counterfeit capacitors had been assembled and shipped to the field.

An investigation was performed to assess the reliability of the counterfeit capacitors, estimate how long they are likely to survive, and determine the failure mechanisms. Ten power supplies were returned to the company or identified during production as failures as a result of the failed counterfeit capacitors. The field failure history showed that some of the counterfeit capacitors were failing within just a few months, and exhibiting evidence of venting, low capacitance, high dissipation factor, high ESR, and high leakage current.

A. Initial Analysis

We performed an initial analysis on 10 counterfeit and 2 authentic capacitors. Only 2 authentic Nichicon capacitors were provided for this study as the power supply manufacturer wanted to keep the authentic capacitors to replace the field-failed counterfeit capacitors. External visual and optical information was performed. Fig. 1 shows a counterfeit capacitor (right), and an authentic capacitor (left). The authenticity of a part can be verified by visual inspection of the markings, and comparing the dimensions. These characteristics were compared with datasheet information, and with known authentic parts. Other externally observable characteristics that are different from the authentic part were checked.

When the counterfeit capacitor was compared with an authentic Nichicon capacitor, it was found that the ink from the markings on the counterfeit capacitor was missing in some regions, shown within the small rectangles in Fig. 1. The text on the counterfeit capacitors was bigger than the text on authentic capacitors. Solder that was observed on the end terminations of the counterfeit capacitors was confirmed to be residue from the removal process. The part datasheet specified the diameter to be a maximum of 25 ± 1 mm, and length specifications were 40 ± 2 mm. Table I shows the measured dimensions of the counterfeit capacitors. All the dimensions of the counterfeit capacitors were observed to be within specifications.

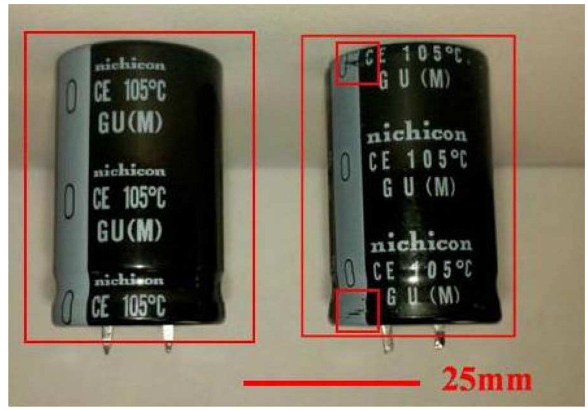

Fig. 1. Image showing the counterfeit capacitor on the right in the red rectangle. The capacitor on the left is an authentic Nichicon capacitor.

TABLE I
DIMENSIONS OF 10 COUNTERFEIT CAPACITORS

	Diameter	Height
Mean	25.17 mm	40.83 mm
Standard Deviation	0.06	0.62
Minimum	25.07 mm	39.85 mm
Maximum	25.25 mm	41.58 mm
Specifications Limit	25 +1 (mm)	40± 2(mm)

TABLE II
WEIGHT OF COUNTERFEIT CAPACITORS BEFORE AND AFTER 10 DAYS OF HIGH TEMPERATURE EXPOSURE

	Weight before (grams)	Weight after (grams)
1	28.5192	28.3067
2	26.5516	26.3585
3	27.761	27.5542
4	24.8551	24.6582
5	24.9737	24.7194
6	27.1063	26.9171
7	27.4954	27.1913
8	27.7758	27.6013
9	26.4153	26.3096
10	30.9511	30.7885
Mean	*27.2405*	*27.0405*
Standard Deviation	*1.76*	*1.77*
Minimum	*24.8551*	*24.6582*
Maximum	*30.9511*	*30.7885*

TABLE III
ELECTRICAL PROPERTIES AT ROOM TEMPERATURE

	120Hz	120Hz		
	Capacitance (μF)	Dissipation Factor	Insulation Resistance (M-ohm)	Leakage Current (μA)
Authentic-1	188.68	0.0580	5.48	73
Authentic-2	188.36	0.0603	6.67	60
Mean	*195.06*	*0.0400*	*2.72*	*165*
Standard Deviation	*1.92*	*0.01*	*0.91*	*64.52*
Maximum	*198.21*	*0.0649*	*4.49*	*314*
Minimum	*192.22*	*0.0297*	*1.27*	*89*
Specifications	*220 ±20%*	*<0.15*	*>0.45M Ohms*	*<880 μA*

TABLE IV
ELECTRICAL PROPERTIES AT -25°C TEMPERATURE

	120Hz	120Hz		
	Capacitance (μF)	Dissipation Factor	Insulation Resistance (M-Ohm)	Leakage Current (μA)
Authentic-1	180.35	0.4061	7.14	56
Authentic-2	180.33	0.3755	7.30	45
Mean	*189.82*	*0.23*	*5.05*	*80.80*
Standard Deviation	*1.49*	*0.09*	*0.74*	*11.75*
Maximum	*191.75*	*0.3984*	*6.15*	*98*
Minimum	*187*	*0.1306*	*4.08*	*65*
Specifications	*N.A.*	*N.A.*	*>0.45M Ohms*	*<880 μA*

We performed an initial weight measurement of the 10 counterfeit capacitors. The same 10 capacitors were subjected to 10 days of high temperature (110°C) exposure, and the weight was measured again. Table II shows the details of weight measurement. It can be seen that the weight varied between 24.86 grams and 30.95 grams for the counterfeit capacitors. This variation indicates poor quality control. Variations in weight were perhaps due to varying amounts of electrolyte in the counterfeit capacitors.

We measured the electrical parameters over temperature. Capacitance, dissipation factor, insulation resistance, and leakage current were measured for 10 counterfeit, and 2 authentic electrolytic capacitors at room temperature, at the lowest rated temperature (-25°C), and at the highest rated temperature (105°C). Table III and Table IV show the measured values of electrical properties of the authentic capacitors, plus the mean, standard deviation, maximum values, and minimum values for the ten counterfeit capacitors at room temperature, and -25°C, respectively. All measurements at room temperature and at -25°C were within the specifications provided in the datasheets. However, there was a lot of variation in the measured insulation resistance, leakage current, and dissipation factor values among the 10 counterfeit capacitors, even at room temperature. Fig. 2 through Fig. 4 show histograms of the measured electrical parameters which show the variation in electrical properties. Table V shows the measured electrical properties of the counterfeit and authentic capacitors at 105°C. At 105°C, the leakage current and insulation resistance values of 6 of the 10 capacitors were out of specification. Dissipation factor values at -25°C and 105°C were not provided in the datasheet. The values that were out of specification are shown in bold italic font.

The purity of the aluminum foil should be greater than 98% [12], or else impurities such as copper, magnesium, iron, and zinc can cause hydrogen generation at the cathode. We analyzed the aluminum foils of the authentic and counterfeit capacitors for purity using energy dispersive X-ray spectroscopy (EDS). The purity levels of the foils of both the authentic and counterfeit capacitors were found to be more than 99%.

B. Elevated Temperature (110°) Exposure and Analysis

Ripple current is known to increase the core temperature of an electrolytic capacitor by 5–10°C [13]. To simulate the effect of ripple current on the electrolytic capacitors, an exposure temperature of 110°Cwas used (105°C (rated temperature) $+5^{\circ}$C (temperature rise due to ripple current). Ten counterfeit

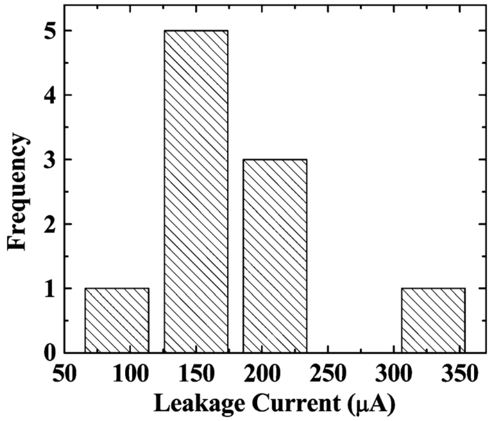

Fig. 2. Histogram showing variation in leakage current values of the ten counterfeit capacitors at room temperature.

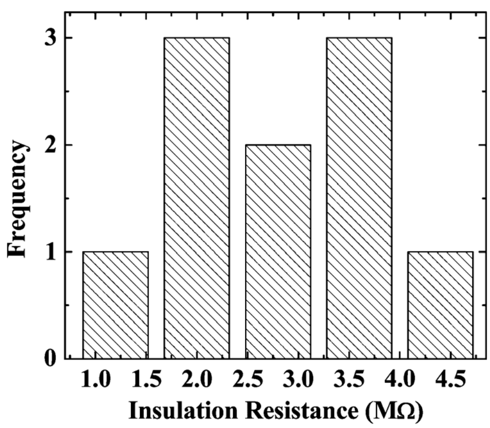

Fig. 3. Histogram showing variation in insulation resistance values of the ten counterfeit capacitors at room temperature.

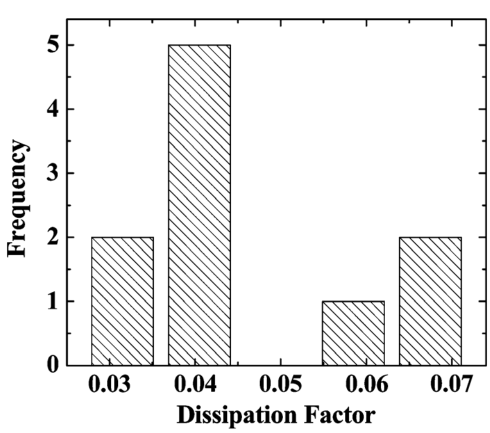

Fig. 4. Histogram showing variation in dissipation factor values of the ten counterfeit capacitors at room temperature.

capacitors and one authentic capacitor were exposed to 110°C for 10 days. Electrical properties including capacitance, dissipation factor, insulation resistance, and leakage current were measured before and after the exposure. Table VI, Table VII, and Table VIII provide the measurements performed at room temperature, −25°C, and 105°C, respectively, after exposure. The electrical measurements performed at room temperature and at −25°C were within the specifications provided in the data sheet of the authentic Nichicon capacitor. The tables for these two temperatures contain the mean, standard deviation, and minimum and maximum values of the measured properties for the counterfeit capacitors. The leakage current values for all the counterfeit capacitors were out of specification at 105°C, as shown in bold italic font in Table VIII. A high leakage current suggests that the electrolyte was not healing the dielectric oxide layer for the counterfeit capacitors. The leakage current of one of the capacitors was not measured due to the crack that formed on the capacitor seal after the 10-day high temperature exposure. There was a chance of the cracked capacitor exploding while charging during leakage current measurement.

The dissipation factor value of one capacitor was found to be higher than the specified value. Upon closer inspection, it was observed that the seal was cracked in the counterfeit capacitor that showed a higher dissipation factor. Most other counterfeit capacitors also showed some bulging. Bulging can happen either due to hydrogen gas generation at the cathode when the electrolytic capacitor is biased with an applied voltage, or if the electrolyte volatility it high and it is not suited for high temperature use. Bulging in counterfeit capacitors after high temperature exposure for just 240 hours suggests that the electrolyte is unstable at elevated temperatures. There was no hydrogen generation in this case because there was no voltage applied in this high temperature exposure. Fig. 5 shows the crack in the seal of the counterfeit electrolytic capacitor.

X-ray inspection of the counterfeit capacitors after 10 days at a high temperature confirmed the bulging. X-ray imaging was carried out to verify the internal attributes of parts such as spacers, terminations, and quality. The X-ray micrograph on the left in Fig. 6 shows the base of an authentic capacitor. The micrograph on the right shows an X-ray image of the base of a counterfeit capacitor, which showed bulging, as shown within the black box. Most of the counterfeit capacitors showed some amount of bulging after exposure to 110°C for 10 days. Fig. 7 shows an X-ray image of the snap-in leads of a counterfeit capacitor on the left, and the authentic capacitor on the right. Note that due to the crack and a bend in the seal, the snap-in terminals appear bent.

The plastic sleeve of one of the counterfeit capacitors had shrunk and split after the high temperature exposure. This result indicates that the plastic was not of good enough quality to survive at high temperatures. An image of the counterfeit capacitor with the shrunken plastic sleeve is shown in Fig. 8.

We repeated the weight measurements after 10-days of high temperature exposure at 110°C. The average weight loss after 10 days of high temperature exposure for the counterfeit capacitors was 0.2 grams, and the standard deviation was 0.053. The weight loss of the one authentic capacitor was 0.043 grams. This means that the weight loss rate (electrolyte evaporation rate) for the counterfeit capacitor was higher than the weight loss rate of the authentic capacitor.

C. Elevated Temperature (110°), and Rated DC Voltage (400 Volts) Exposure and Analysis

We exposed ten counterfeit capacitors to 110°C, biased with 400 Volts of DC voltage, for 10 days. The capacitance, dissipation factor, insulation resistance, and leakage current were measured before and after the exposure. After the exposure, the

TABLE V
ELECTRICAL PROPERTIES AT 105°C TEMPERATURE (THE VALUES IN BOLD ITALIC FONT ARE OUTSIDE THE SPECIFICATIONS)

	120Hz	120Hz		
	Capacitance (μF)	Dissipation Factor	Insulation Resistance (M-ohm)	Leakage Current (μA)
Authentic-1	196.3	0.0265	1.40	286
Authentic-2	198.69	0.0257	1.60	371
Counterfeit 1	208.02	0.0305	***0.20***	***1960***
2	204.57	0.0268	***0.38***	***1060***
3	205.34	0.025	0.71	560
4	201.57	0.0261	0.47	850
5	202.8	0.0345	***0.24***	***1702***
6	207.4	0.0246	***0.39***	***1020***
7	209.04	0.0243	***0.19***	***2080***
8	201.46	0.0239	0.55	725
9	205.85	0.0356	1.11	359
10	206.93	0.0254	***0.11***	***3702***
Mean	205.30	0.03	0.44	1401.80
Standard Deviation	2.67	0.00	0.30	998.54
Maximum	209.04	0.0356	1.11	3702
Minimum	201.46	0.0239	0.11	359
Specifications	N.A.	N.A.	>0.45M Ohms	<880 μA

TABLE VI
ELECTRICAL PROPERTIES AT ROOM TEMPERATURE AFTER 10 DAYS OF HIGH TEMPERATURE EXPOSURE

	120Hz	120Hz		
	Capacitance (μF)	Dissipation Factor	Insulation Resistance (M-ohm)	Leakage Current (μA)
Good-2(Nichicon)	185.86	0.0595	5.97	67
Mean	*193.53*	*0.06*	*1.54*	*338.67*
Standard Deviation	*2.17*	*0.04*	*0.99*	*158.57*
Maximum	*196.98*	*0.1564*	*3.81*	*562*
Minimum	*190.25*	*0.031*	*0.71*	*105*
Specifications	*220 ±20%*	*<0.15*	*>0.45M Ohms*	*<880 μA*

seals of two counterfeit capacitors were cracked, and electrolyte leaked. The safety vent of another electrolytic capacitor was found open, and leaking electrolyte. "All ten of the counterfeit electrolytic capacitors showed some bulging. The capacitance, dissipation factor, insulation resistance, and leakage current of the ten counterfeit capacitors shown in Table IX were measured before the high temperature bias exposure. After the exposure, the electrical parameters were again measured, as shown in Table X. The seven capacitors that did not leak had low insulation resistance (high leakage current), and the insulation resistance of the remaining 3 capacitors was not measured due to cracks in the seals or venting issues. The insulation resistance for a good capacitor according to the datasheet of the authentic Nichicon capacitor should be greater than 0.45 MΩ. All seven counterfeit capacitors failed since they all had insulation resistance values below 0.45 MΩ after the exposure. Fig. 9 shows the insulation resistance values of the seven capacitors before and after the temperature bias test.

TABLE VII
ELECTRICAL PROPERTIES AT −25°C AFTER 10 DAYS OF HIGH TEMPERATURE EXPOSURE

	120Hz	120Hz		
	Capacitance (µF)	Dissipation Factor	Insulation Resistance (M-ohm)	Leakage Current (µA)
Authentic-2	178.33	0.3756	9.30	43
Mean	*182.45*	*0.48*	*4.13*	*121.67*
Standard Deviation	*14.24*	*0.36*	*1.52*	*85.61*
Maximum	*189.72*	*1.4197*	*6.15*	*341*
Minimum	*142.63*	*0.1462*	*1.17*	*65*
Specifications	*N.A.*	*N.A.*	*>0.45M Ohms*	*<880 µA*

TABLE VIII
ELECTRICAL PROPERTIES AT 105°C AFTER 10 DAYS OF HIGH TEMPERATURE EXPOSURE (THE VALUES IN BOLD ITALIC FONT ARE OUT OF SPECIFICATION)

	120Hz	120Hz		
	Capacitance (µF)	Dissipation Factor	Insulation Resistance (M-ohm)	Leakage Current (µA)
Authentic-2	197.94	0.0278	0.98	410
Counterfeit-1	204.59	0.0376	***0.05***	***7375***
Counterfeit-2	203.7	0.0254	***0.06***	***6421***
Counterfeit-3	206.62	0.0235	***0.08***	***5156***
Counterfeit-4	199.3	0.0256	***0.14***	***2950***
Counterfeit-5	204.24	0.0454	(cracked seal)	(cracked seal)
Counterfeit-6	205.25	0.0258	***0.04***	***8971***
Counterfeit-7	203.64	0.0242	***0.23***	***1720***
Counterfeit-8	198.34	0.0216	***0.31***	***1303***
Counterfeit-9	203.41	0.0378	***0.45***	***885***
Counterfeit-10	205.78	0.0267	***0.30***	***1350***
Mean	*203.49*	*0.03*	*0.18*	*4014.56*
Standard Deviation	*2.67*	*0.01*	*0.14*	*3033.10*
Maximum	*206.62*	*0.0454*	*0.45*	*8971*
Minimum	*198.34*	*0.0216*	*0.04*	*885*
Specifications	*N.A.*		*>0.45M Ohms*	*<880 µA*

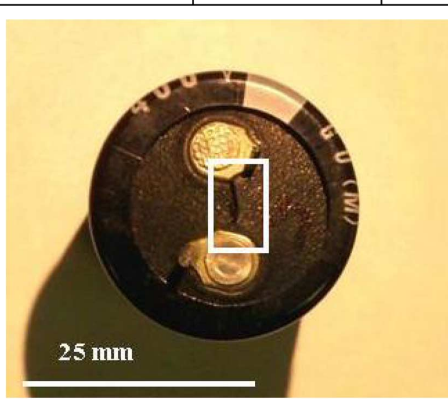

Fig. 5. Image showing the crack in the seal of the counterfeit electrolytic capacitor.

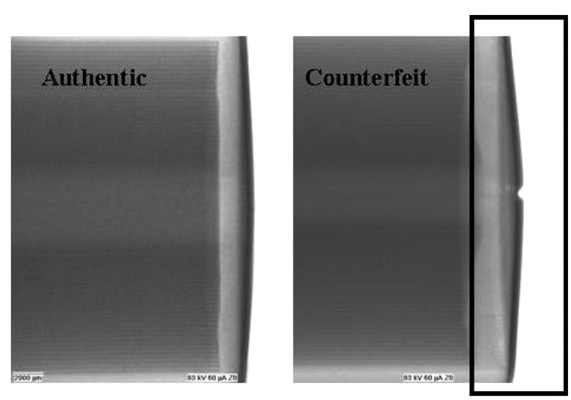

Fig. 6. X-ray of the base of an authentic and a counterfeit electrolytic capacitor.

D. Analysis of Seven Failed Counterfeit Capacitors Received From the OEM

Seven failed capacitors were received from the power supply manufacturer for analysis. Four of these were production failures, and the other three were field failures, as shown in Table XI.

We inspected the failed capacitors optically. A capacitor which experienced field failure was vented, as shown in Fig. 10.

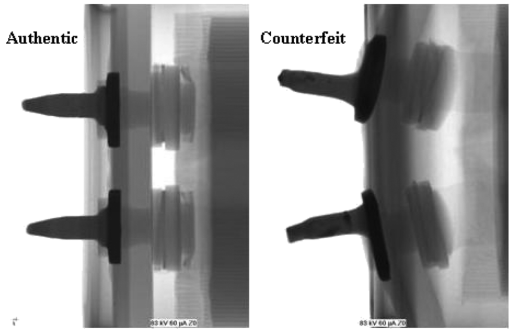

Fig. 7. X-ray image of the snap-in leads of an authentic capacitor and a cracked counterfeit capacitor.

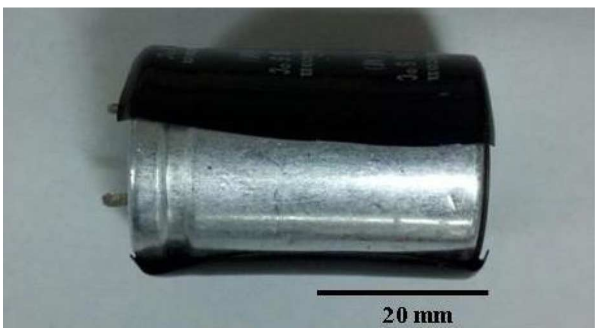

Fig. 8. A counterfeit capacitor with a shrunken plastic sleeve.

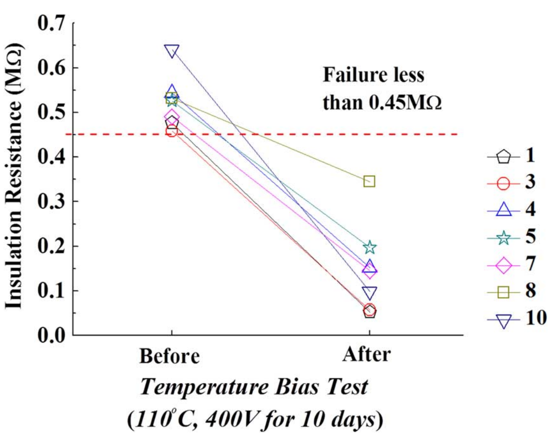

Fig. 9. Plot showing that seven counterfeit capacitors failed due to a decrease in insulation resistance after temperature bias test. The other three capacitors failed because the seal ruptured, and they were not charged for insulation resistance measurement.

Fig. 11 shows the left capacitor with the top off, as described by the OEM. The right capacitor has the top on. We performed the X-ray analysis of the failed capacitors. It revealed that the top part of the capacitors looked different from the non-failed counterfeit capacitors. Fig. 12 shows an X-ray image of the tops of 2 failed counterfeit capacitors that look different (in the black box) from the X-ray of the top part of the non-failed counterfeit capacitor shown in Fig. 13. This difference was due to high pressure either due to hydrogen gas formation or unstable electrolyte which resulted in the bulging of capacitors. The electrical properties of the failed capacitors were measured. The leakage current was measured after charging the capacitors at 50 volts, because if it were charged at 400 volts there would be an explosion hazard. The electrical properties of four capacitors were found to be out of specification, as shown in bold italic font in Table XII. For the remaining three capacitors, the electrical properties were within specifications.

TABLE IX
ELECTRICAL PROPERTIES AT ROOM TEMPERATURE BEFORE 10 DAYS OF HIGH TEMPERATURE BIAS EXPOSURE

	120 Hz	120 Hz	
	Capacitance(μF)	DF	IR (M-Ohm)
Counterfeit-1	200.36	0.0498	0.4762
Counterfeit-2	201.18	0.0637	0.4902
Counterfeit-3	193.84	0.0694	0.4587
Counterfeit-4	206.19	0.0427	0.5435
Counterfeit-5	200.82	0.0587	0.5263
Counterfeit-6	198.32	0.077	0.5618
Counterfeit-7	239.62	0.0738	0.4902
Counterfeit-8	201.49	0.0368	0.5319
Counterfeit-9	202.8	0.041	0.5000
Counterfeit-10	203.13	0.0415	0.6410
Mean	204.775	0.05544	0.5220
Standard Deviation	12.662	0.015	0.053
Maximum	239.62	0.077	0.6410
Minimum	193.84	0.0368	0.4587
Specifications	220±20%	<0.15	>0.45MΩ

E. Chemical Analysis

The composition of capacitor electrolyte is proprietary, so manufacturers usually do not disclose their formulas, and this proprietary feature can be used as an advantage in the development of methodologies to identify counterfeit electrolytic capacitors based on specific characteristics of chemical compounds. Typically, a capacitor electrolyte consists of solvents, solutes, some additives [14], and less than 5% water by weight [15]. Ethylene glycol and gamma butyrolactone are common examples of solvents. A solute can be a conductive salt which usually is a resultant of the chemical reaction between an acid and a base. Additives can include corrosion inhibitors, depolarizers, hydrogen absorbers, and conductivity enhancers.

We used FTIR to determine the chemical components of the electrolyte of the counterfeit and authentic capacitors. Because capacitor electrolytes are mostly organic, they are easily detected by infrared radiation. Thus infrared spectroscopy becomes a suitable tool to identify and compare the chemical components. FTIR equipment was used to perform infrared spectroscopy on the capacitor electrolyte. FTIR equipment was used in attenuated total reflectance (ATR) mode. ATR

TABLE X
ELECTRICAL PROPERTIES AT ROOM TEMPERATURE AFTER 10 DAYS OF HIGH TEMPERATURE BIAS EXPOSURE

	Capacitance (μF)	DF	IR (M-Ohm)	Status
Counterfeit-1	198.67	0.0695	*0.0525*	
Counterfeit-2	204.19	0.0738		*Seal Cracked/Electrolyte Leak*
Counterfeit-3	193.05	0.113	*0.0572*	
Counterfeit-4	244.41	0.0907	*0.1515*	
Counterfeit-5	199.8	0.0642	*0.1969*	
Counterfeit-6	165.71	1.095		*Seal Cracked/Electrolyte Leak*
Counterfeit-7	196.29	0.0643	*0.1449*	
Counterfeit-8	195.15	0.0917	*0.3448*	
Counterfeit-9	0.094	0.5655		*Vent Open*
Counterfeit-10	209.28	0.0606	*0.0986*	
Mean	*180.6644*	*0.229*	*0.1495*	
Standard Deviation	*66.3014*	*0.341*	*0.1008*	
Maximum	*244.41*	*1.095*	*0.3448*	
Minimum	*0.094*	*0.0606*	*0.0525*	
Specifications	*220±20%*	*<0.15*	*>0.45MΩ*	

TABLE XI
DETAILS OF SEVEN FAILED CAPACITORS RECEIVED FROM THE COMPANY

S/N	Failure Mode	Power Supply Type
24845	Field failure - leaked from bottom of cap	150W
7411	Production failure - top bubbled	300W
24535	Field failure - low capacitance	300W
24912	Field failure - vented	150W
7207	Production failure - top bubbled	300W
7188	Production failure	300W
Top off	Production failure - bubbled	300W

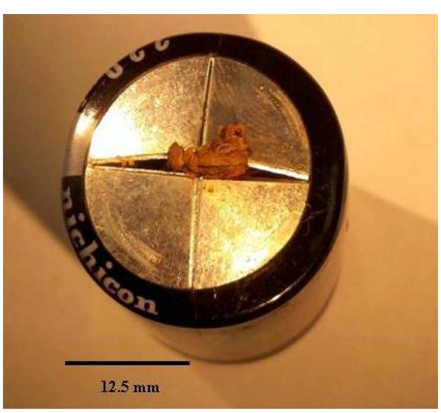

Fig. 10. Field-failed capacitor showing venting.

allows the inspection of samples directly from the capacitor with a minimal preparation [16], which avoids the removal of evidence in identification of counterfeit electrolytes. In usual transmittance mode, due to sample preparation, some information about the chemical composition may get lost. Nicolet Spectra libraries and the NIST Chemistry WebBook databases were consulted to compare the IR spectra.

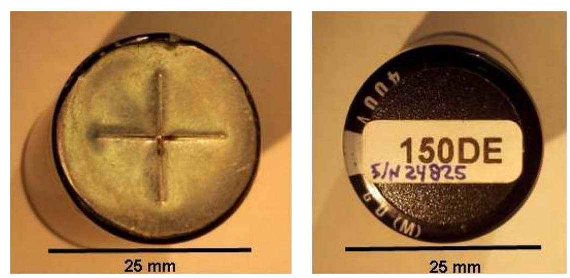

Fig. 11. Capacitor with top-off shown in the left image. Right image shows the normal counterfeit capacitor with top-on.

In the present work, we obtained the electrolyte directly from the paper layer inside the authentic Nichicon and counterfeit capacitor. We squeezed the electrolyte out of the paper layer, and placed it on top of the reflective element of the ATR assembly. In the IR spectrum shown in Fig. 14, organic functional groups from the capacitor electrolytes of this study are shown. The authentic capacitor electrolyte revealed aliphatic hydrocarbon, aliphatic carboxylic acid salt, and primary aliphatic alcohol; nevertheless the counterfeit electrolyte did not contain the peak that corresponds to the aliphatic carboxylic acid salt. The FTIR spectrum revealed that the main solvent found in the capacitor electrolyte (authentic and counterfeit) was ethylene glycol. Also the FTIR peaks of the counterfeit capacitor have a higher percentage transmittance than the peaks of the authentic capacitor. From the comparison of FTIR peaks of counterfeit and authentic electrolyte, it appeared that the concentration of ethylene glycol in the counterfeit electrolyte was less than that in the authentic electrolyte. To validate this hypothesis, FTIR spectra of different concentrations of ethylene glycol solution varying from 100% to 70% were collected. It was found, as shown in Fig. 15, that as the concentration of ethylene glycol decreased,

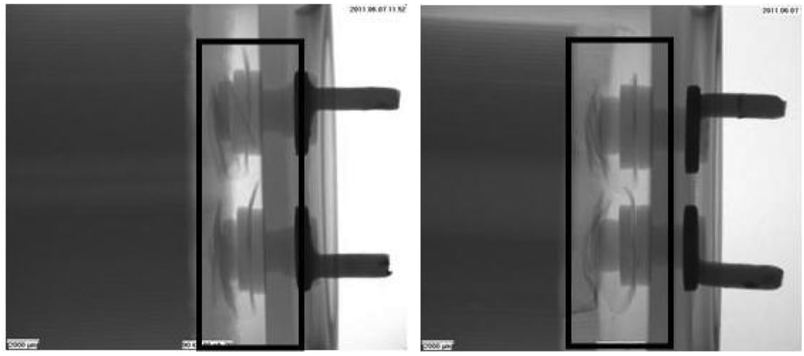

Fig. 12. X-ray image of top part of the failed capacitors.

TABLE XII
PROPERTIES MEASURED AT ROOM TEMPERATURE (VALUES IN BOLD ITALIC FONT ARE OUT OF SPECIFICATION)

	Capacitance (μF)	DF	ESR (m-Ohm)	Leakage Current (μA)	Weight (Grams)
Authentic part	186.77	0.0521	217.97	12	
24825(Field Failure)	196.55	0.0309	97.57	56	32.5185
7411	200.88	0.1305	493.27	***536***	26.0208
24535(Field Failure)	***0.0696***	***2.2815***	***7.7512 k ohm***	40	29.8912
24912(Field Failure)	***13.29***	***1.7935***	***23121***	***151650***	23.8299
7207	213.51	0.1078	259.66	***2380***	26.4477
7188	191.55	0.037	155.51	16	33.4325
Top off	174.99	0.0564	214.2	18	29.2433

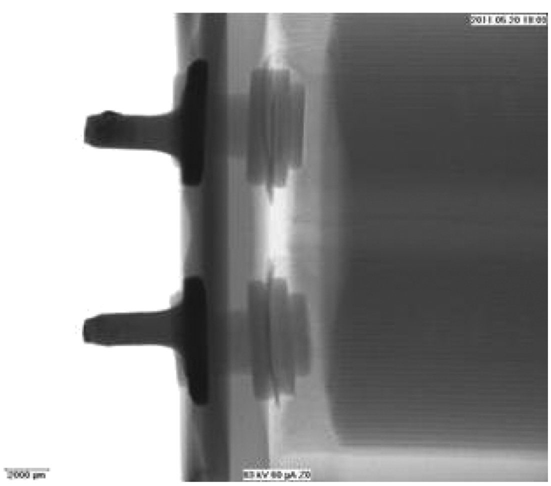

Fig. 13. X-ray image of top part of a good (non-failed) counterfeit capacitor.

the transmittance increased. This effect validates the hypothesis that the counterfeit electrolyte has less ethylene glycol and perhaps more water.

F. Failure Time Estimation of Counterfeit Electrolytic Capacitors

The primary failure mechanism of an aluminum electrolytic capacitor is the loss of electrolyte through and around the seal over the period of its life. Capacitor manufacturers use an electrolyte loss of greater than 30% of the initial electrolyte weight as a rule of thumb to define failure. At that point, the equivalent series resistance (ESR) value of the capacitor increases beyond a safe level, causing too much heat generation in the capacitor, and the capacitance value begins to decrease rapidly with time.

TABLE XIII
EXTRAPOLATED FAILURE TIMES OF THE CAPACITORS AT 85°C

Capacitor Serial No.	Failure Time (Hours)
1	23433
2	15713
3	44190
4	26269
5	21166
6	38581
7	15377
8	21826
9	50948
10	32050

We performed a test to provide an approximate evaluation of the failure time of the counterfeit electrolytic capacitors at

TABLE XIV
EXTRAPOLATED FAILURE TIMES OF THE CAPACITORS AT 115°C

Capacitor Serial No.	Failure Time (Hours)
1	3313
2	2255
3	4775
4	8667
5	2387
6	7309
7	1197
8	7180
9	3178
10	943

45°C ambient temperature, assuming that the capacitors fail due to evaporation of electrolyte. Failure time is defined as a 30% weight loss in the electrolyte present in the capacitor, the critical degradation number. We calculated the electrolyte quantity in the counterfeit capacitors experimentally by evaporating the electrolyte from the capacitors at high temperature (110°C) until the weight of the capacitor became stable. Electrolyte was found to account for one third the weight of the counterfeit capacitors. Two sets of 10 counterfeit capacitors were used in this failure time estimation study. An initial weight measurement of all capacitors was performed. After the weight measurement, 10 capacitors were kept in a chamber at 85°C, and the other 10 were kept at 115°C. Weight measurement of the capacitors was performed every day for 10 days. For each day, 10 weight readings for each temperature set (85°C and 115°C) were taken.

After gathering the weight data for 10 days, we analyzed the distribution of time to failure of all the capacitors at both temperatures using Weibull++ software. We used the degradation analysis folio to perform this analysis for both sets of temperatures (85°C and 115°C). Inspection times (in hours), degradation (percentage electrolyte evaporated), and unit ID for the capacitors were entered in the software. The model for extrapolation was chosen as linear because previous CALCE work has shown that the initial 30% loss of electrolyte can be modeled as linear. The values of the lifetime of the capacitors were then extrapolated using the software. The values obtained for all of the capacitors at 85°C are given in Table XIII. The values of failure times obtained for all the capacitors at 115°C are given in Table XIV.

After obtaining the failure time values from the Weibull++ software, we plugged the values into ALTA 7 software. The "Accelerated Life Data Analysis" portfolio was used in ALTA 7. The failure times obtained, and the temperatures of the test (358.15 K, and 388.15 K) were inserted into ALTA 7, and the model used for running ALTA 7 was Arrhenius. The failure distribution used was Weibull. The ambient temperature in which the counterfeit electrolytic capacitors are normally used is 45°C. If we add a 5°C core temperature rise due to ripple current, the maximum temperature that the capacitors would experience would be 50°C. Using ALTA 7, the lifetime at 50°C was predicted. Fig. 16 shows the Weibull plot obtained for 50°C using the life data from 85°C and 115°C. As per the Weibull chart, the failure time of 5% of the population at 50°C is approximately 11.4 years.

The analysis of weight loss during aging at elevated temperatures indicated that the counterfeit capacitors could survive for many years if they fail by the mechanism of gradual electrolyte evaporation through intact seals. Nevertheless, the field failure history showed that some of the counterfeit capacitors were failing within just a few months, and exhibiting evidence of venting, low capacitance, high dissipation factor, high ESR, and high leakage current. If these failures were due to electrolyte loss, it is likely that their short lifetimes were a result of imperfect or degraded seals or other quality defects, or due to electrical stresses experienced in the circuit. Also, the capacitors tested with the high temperature bias test exhibited venting, seal cracking, low capacitance, high ESR, and high leakage current, which suggests that there could be other failure mechanisms acting along with the electrolyte evaporation mechanism.

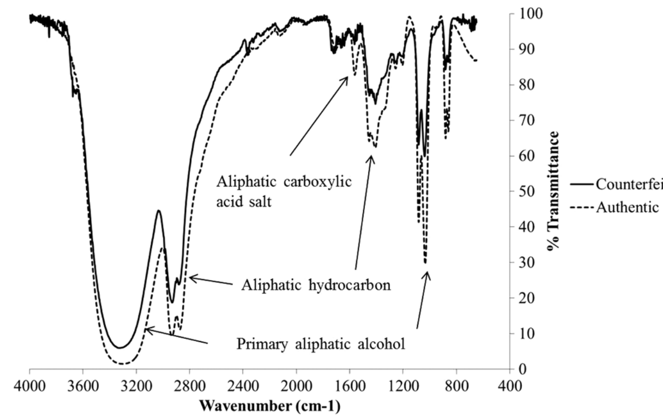

Fig. 14. Comparison of FTIR spectra between an authentic Nichicon electrolyte and counterfeit electrolyte.

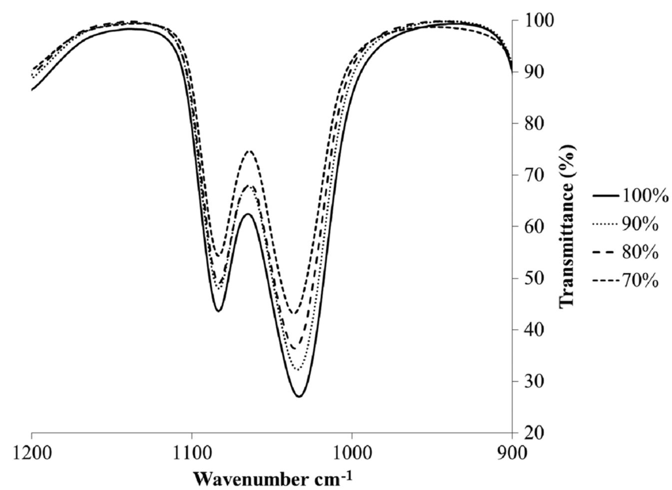

Fig. 15. Comparison of FTIR spectra between different solutions of water and ethylene glycol.

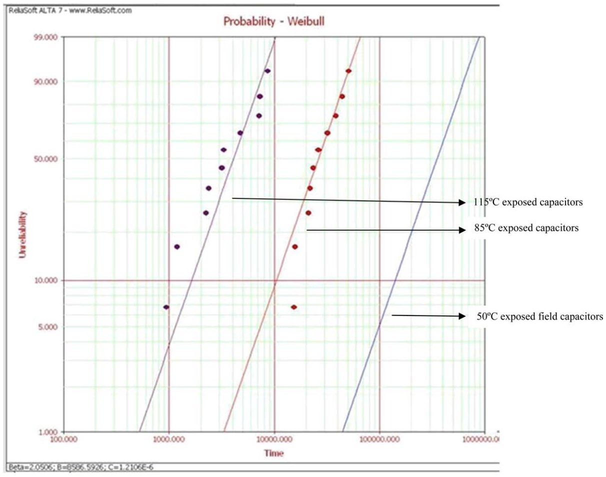

Fig. 16. Weibull plot obtained from ALTA 7.

There may be competing causes of failure other than electrolyte evaporation. These causes may include poor formulation of electrolyte (liquid electrolyte reheals the dielectric (aluminum oxide) layer, when voltage is applied to the capacitor), causing the electrolyte to be unable to heal localized damage to the dielectric layer; or degradation of electrolyte (decrease in ionic conductivity), leading to an increase in ESR and dissipation factor, and causing an internal pressure rise that produces venting or leakage. Electrolyte formulation is frequently a problem in low quality or counterfeit electrolytic capacitors, and evidence has already been presented that the electrolyte was not formulated properly for use at the rated operating conditions.

II. Discussion

In the FTIR spectra, we observed that there were differences between counterfeit capacitor and authentic capacitor electrolyte. There was no carboxylic acid salt detected in the counterfeit capacitor electrolyte; and the concentration of ethylene glycol, which is the main solvent in the electrolyte, was lower. The concentration of water was higher in the counterfeit capacitor electrolyte. The chemical differences between the authentic and counterfeit electrolytes can explain the observed failure modes like venting, drop in capacitance, increase of ESR, and leakage current in the counterfeit capacitors.

As the boiling point of ethylene glycol and water is 197°C, and 100°C, respectively, the lower concentration of ethylene glycol, and higher concentration of water in the counterfeit electrolyte will decrease the boiling point of the counterfeit electrolyte, and increase the counterfeit electrolyte volatility. Higher volatility of the counterfeit electrolyte can increase the pressure inside the capacitor body. This pressure can cause bulging of capacitor at high temperatures, resulting in venting failures. Increased pressure inside the capacitor can increase the spacing, thus reducing the overlap area between cathode and anode foils. This increased spacing causes a decrease in capacitance, and an increase in ESR value. The increased pressure can also cause damage to the dielectric oxide layer, resulting in higher leakage current.

We observed in the tests that more counterfeit capacitors failed due to high leakage current after the high temperature bias test than after the high temperature exposure test alone. This failure is due to higher stresses on the dielectric oxide layer of counterfeit capacitors, when rated voltage was applied along with high temperature. Usually the authentic electrolyte heals the dielectric oxide layer when a voltage bias is applied. But, because of the faulty composition of the counterfeit electrolyte, it was not able to heal the oxide layer, thus causing more leakage current failures in temperature and voltage tests than just temperature testing.

III. Conclusions & Recommendations

Counterfeit electrolytic capacitors cause grave concern to original equipment manufacturers, and have resulted in millions of dollars in losses to companies like Dell, Apple, HP, and Intel in the past. Undetected counterfeit electrolytic capacitors can increase the risk of failure, and thus reducing the reliability of power electronics.

To validate the authenticity of the capacitors' electrolytes, FTIR was used to compare the chemical composition of the authentic and counterfeit electrolytes. We found that the counterfeit electrolyte has a lower concentration of solvent (ethylene glycol), and lacked carboxylic acid salt, which made the counterfeit electrolyte unstable at high temperatures. This problem led to early failures of the counterfeit electrolytic capacitors.

To evaluate the electrical parameters of counterfeit electrolytic capacitors, the electrical properties were measured at room temperature before using them in the power supply. Though all the electrical properties were determined to be within specifications as per the datasheet of the authentic capacitors at room temperature, the distribution of values at room temperature was broader for counterfeit parts than for the authentic parts, and some electrical parameters at the maximum and minimum rated temperatures were out of specifications. If the capacitors do not fail due to the inferior quality of the electrolyte, or due to defective seals, then they are expected to fail due to gradual evaporation of the electrolyte through intact seals. In such cases, 5% of the population at 50°C is predicted to fail within approximately 11.4 years in the field.

Original equipment manufacturers, and other industry members that use capacitors in power supplies, should perform measurements of electrical parameters at the maximum and minimum rated temperatures, and chemical analysis of the electrolyte. One way to perform chemical analysis of the capacitor electrolyte is to dissemble the capacitor and use a spectroscopy technique like FTIR with an ATR assembly. The application of these methods will reduce failures due to counterfeit capacitors. In view of the prevalence of counterfeit parts in the supply chain, it is recommended that lot acceptance procedures be adopted that are tailored to the risk of counterfeiting, as well as the likelihood and criticality of failures associated with each component. In addition to its value for counterfeit detection, FTIR is a useful technique for other chemical or residue analysis in failure analysis, and reliability studies. Counterfeiting is an ongoing problem. A systematic methodology like the one developed can be applied to other electronic components.

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