Current Leakage through Ceramic Capacitors

How Leakage Depends on Capacitor Properties and Time

Two colleagues measuring on the same test setup, using the same measurement instrument, and measuring at identical temperatures find two different power-down currents. How is that possible? The code executing on the devices is identical, but still, the two colleagues constantly measure a difference of approximately 500 nA. The answer to this difference is the timing aspect of the measurements. One of the colleagues measured the power-down current 250 ms after power-on, whereas the other colleague measured the power-down current long after the device had been powered on. The measurement conducted 250 ms after power-on showed the highest of the current consumptions. This discovery led to some debug work, and eventually, it was found that the current consumption difference was due to time-dependent current leakage through the bulk-decoupling capacitors used in the test setup. And this discovery is the reason for this application note, because how does current leak through ceramic capacitors?

KEY POINTS

- The amount of capacitance and capacitor construction material affect leakage current.
- Current consumption measurements can only be compared if they are conducted at the same point in time relative to the power-on event of the circuit.
- A larger capacitance has a larger leakage current compared to a small capacitance.
- Capacitor package size does not significantly influence the magnitude of the leakage through the capacitor.
- Leakage through a ceramic capacitor can be described by a power function and follows a straight line in a log-log plot.

1. Introduction

An ideal capacitor acts like an open circuit at a DC voltage, and it only conducts current when a voltage difference is applied across the device. Real capacitors, however, do exhibit DC leak current even when the voltage across the device is stable. Electrolytic capacitors and tantalum capacitors are known to have a high leakage current/low isolation resistance, whereas ceramic capacitors are known to have a low leakage current/high isolation resistance.

If a voltage step is applied across a capacitor, the time it takes to charge any type of capacitor through a resistor can be calculated as:

$$T_{Charge\ time} = 5 * \tau = 5 * R * C$$

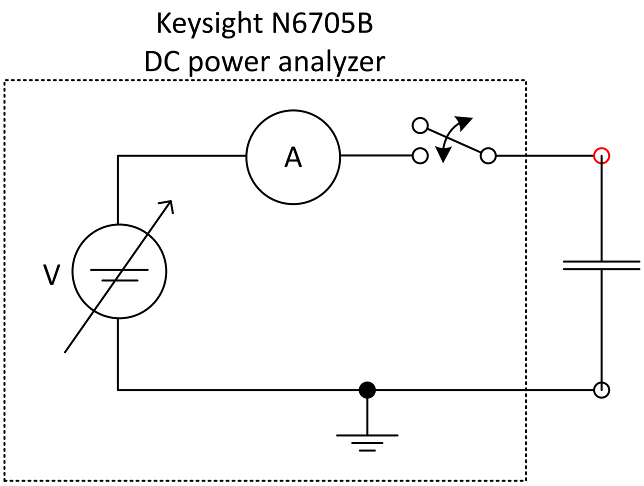
During the charge time, current will flow through the capacitor, and when $T_{charge\ time}$ has elapsed, only DC leakage current should flow through the capacity. However, the practical example given at the start of this application note shows that this is not the case. There is a time dependent capacitor leakage in play which lasts much longer than $T_{charge\ time}$.

But what causes this time-dependent capacitor leakage? Why isn't the leakage current steady state after 5 * τ? The cause of the time-dependent leakage current is dielectric absorption/dielectric repolarization. When the capacitor is subjected to a voltage step/change of charge, there is a "resistance"/slowness in the dielectric material which must be overcome before the entire volume of dielectric material is re-charged and the leakage current becomes steady state[1]. In the following text, the effect of dielectric absorption, which results in leakage current through the capacitor, will be examined.

The outcomes of current leakage measurements through 11 different ceramic capacitors will be shown and discussed.

2. Measurement Setup

The measurement setup used to measure the capacitor leakage current is shown in the figure below:



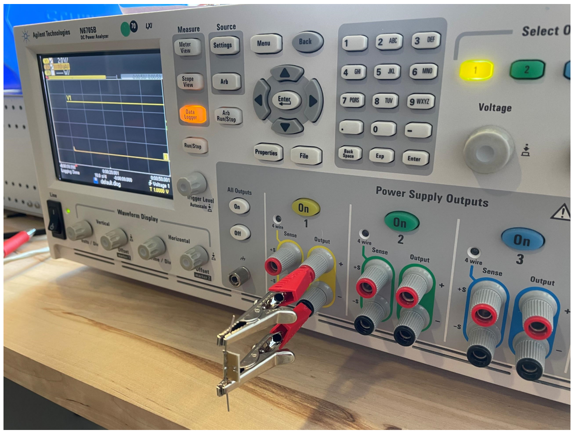


Figure 2.1. Capacitor Leakage Current Measurement Setup

The Keysight N6705B is a Source-Meter-Unit (SMU), which can supply and monitor its voltage and current output and record and display both.

The test capacitor is subjected to a voltage step, and the charge current of the capacitor is measured at a fixed time interval. The purpose of the measurements is to figure out the length of time current will flow through the capacitor and if this current flow is dependent on the following capacitor properties:

- Capacitance value: How does the amount of capacitance influence the leakage current through the capacitor?
- Package size: How does the physical package size of the capacitor influence the leakage current through a fixed amount of capacitance?
- Capacitor material: How does the material of the capacitor influence the leakage current through a fixed amount of capacitance?
- Voltage rating: How does voltage rating of a capacitor influence the leakage current through a fixed amount of capacitance?
- Bias voltage: How does the voltage step across a capacitor influence the leakage current through a fixed amount of capacitance?

The sample time selected for the current measurements is 10 ms, the voltage step height is 3.3 V, and the duration of the measurements for each experiment is set to 60 seconds. Sixty seconds was selected as the timeframe because the isolation quality of a capacitor is calculated as R_{30} / R_{60}, capacitor resistance measured 30 seconds after a charge pulse divided by capacitor resistance measured 60 seconds after the charge pulse.

3. Capacitor Selection

Below is an overview of the capacitors selected for measurements. There is no affiliation between the manufacturer of the capacitors and Silicon Labs, and the capacitor's selection criteria is based on availability:

Table 3.1. Capacitors Selected for Testing the Effect of Different Capacitance Values

Manufacturer	Mfr Part #	Series	Capacitance	Voltage Rating	Package Size	Temperature Range	Tolerance
Kemet	C1206X106J3RAC7800	X7R	10 µF	25 V	1206	-55 to 125 °C	+/-5%
Kemet	C1206C475J3RAC7800	X7R	4.7 µF	25 V	1206	-55 to 125 °C	+/-5%
Kemet	C1206C105J3RAC7800	X7R	1 µF	25 V	1206	-55 to 125 °C	+/-5%
Kyocera AVX	12063C104JAT2A	X7R	100 nF	25 V	1206	-55 to 125 °C	+/-5%

All the capacitors shown in Table 3.1 are made of the same material, X7R, and they have the same voltage rating, package size, temperature range, and tolerance. The capacitors only differ by capacitance value.

The capacitors selected to examine the leakage current dependency of package size are shown in Table 3.2:

Table 3.2. Capacitors Selected for Testing the Effect of the Package Size

Manufacturer	Mfr Part #	Series	Capacitance	Voltage Rating	Package Size	Temperature Range	Tolerance
Kyocera AVX	0402YC104JAT4A	X7R	100 nF	16 V	0402	-55 to 125 °C	+/-5%
Kyocera AVX	0603YC104JAT2A	X7R	100 nF	16 V	0603	-55 to 125 °C	+/-5%
Kyocera AVX	0805YC104JAT2A	X7R	100 nF	16 V	0805	-55 to 125 °C	+/-5%
Kemet	C1206C104J4RAC7800	X7R	100 nF	16 V	1206	-55 to 125 °C	+/-5%

The main difference between the capacitors shown in Table 3.2 is the package size, ranging from 0402 to 1206.

The capacitors selected to examine the effect of the capacitor material are shown in Table 3.3:

Table 3.3. Selected for Testing the Effect of the Construction Material

Manufacturer	Mfr Part #	Series	Capacitance	Voltage Rating	Package Size	Temperature Range	Tolerance
Kyocera AVX	1206ZD475JAT2A	X5R	4.7 µF	10 V	1206	-55 to 85 °C	+/-5%
Kemet	C1206C475J8NAC7800	X8L	4.7 µF	10 V	1206	-55 to 150 °C	+/-5%
Kemet	C1206C475J3RAC7800	X7R	4.7 µF	25 V	1206	-55 to 125 °C	+/-5%

Because the construction material of the capacitor determines its temperature range, the two parameters in the measurement series shown in Table 3.3 appear to be changing; however, you cannot separate the two properties from each other.

The capacitors selected for the voltage rating tests are shown in Table 3.4:

Table 3.4. Selected for Testing the Effect of the Capacitor Voltage Rating

Manufacturer	Mfr Part #	Series	Capacitance	Voltage Rating	Package Size	Temperature Range	Tolerance
Kemet	C1206X106J3RAC7800	X7R	10 µF	25 V	1206	-55 to 125 °C	+/-5%
Kemet	C0805X106J9RAC7800	X7R	10 µF	6.3 V	0805	-55 to 125 °C	+/-5%

Unfortunately, at the time of the measurements, it was not possible to obtain two capacitors where only the voltage rating differed, so in this test-set, two parameters differ: the voltage rating and the package size. But, since the effect of the package size is measured (as shown in Table 3.2), it will be possible to combine the results and judge the effect of the voltage rating on its own.

Finally, the capacitor chosen to examine the effect of the bias voltage is shown in Table 3.5:

Table 3.5. Selected for Testing the Effect of the Bias Voltage

Manufacturer	Mfr Part #	Series	Capacitance	Voltage Rating	Package Size	Temperature Range	Tolerance
Kemet	C1206X106J3RAC7800	X7R	10 µF	25 V	1206	-55 to 125 °C	+/-5%

4. Measurement Practicalities

Each of the capacitors is mounted on a small test PCB, where test leads are soldered to the test PCB.

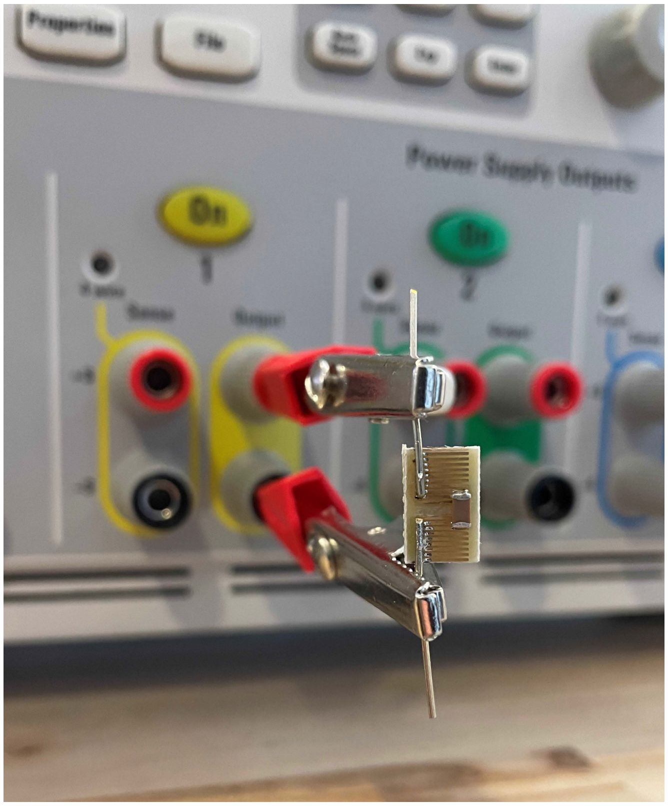


Figure 4.1. Capacitor Test Coupon

The test leads of the test coupon are connected to the N6705B DC power analyzer using two crocodile clips soldered onto two banana plugs. This enables a fast and easy handling of the test setup as well as reduces both resistance and inductance of possible test leads.

Before each initial test, the capacitors are discharged for any possible charge introduced during the assembly of the test coupons by shorting the test leads through a 2 Ω resistor for at least 10 seconds. If a capacitor has been used in a prior test, it is shorted through the 2 Ω resistor for at least 5 minutes. The purpose of shorting the capacitor is to remove any charge from the device which can obfuscate the measurements to be conducted.

The following sections describe the outcome of each of the five measurement series.

4.1 Leakage Depending on Capacitance Value

This section examines how the leakage current depends on the value of the capacitor.

The amount of charge (Q) a capacitor can store depends on the capacitance value and the voltage charging the capacitor:

$$Q = C * V$$

From the equation, you can see that a small capacitor can store a smaller amount of charge compared to a larger capacitor given the same charge voltage. But what about the leakage current? How does it depend on the capacitance value?

The four capacitors shown in Table 3.1 Capacitors Selected for Testing the Effect of Different Capacitance Values on page 4 have all been tested for leakage current when subjected to a voltage step of 3.3 V. The leakage current plotted against time is shown in the graph below:

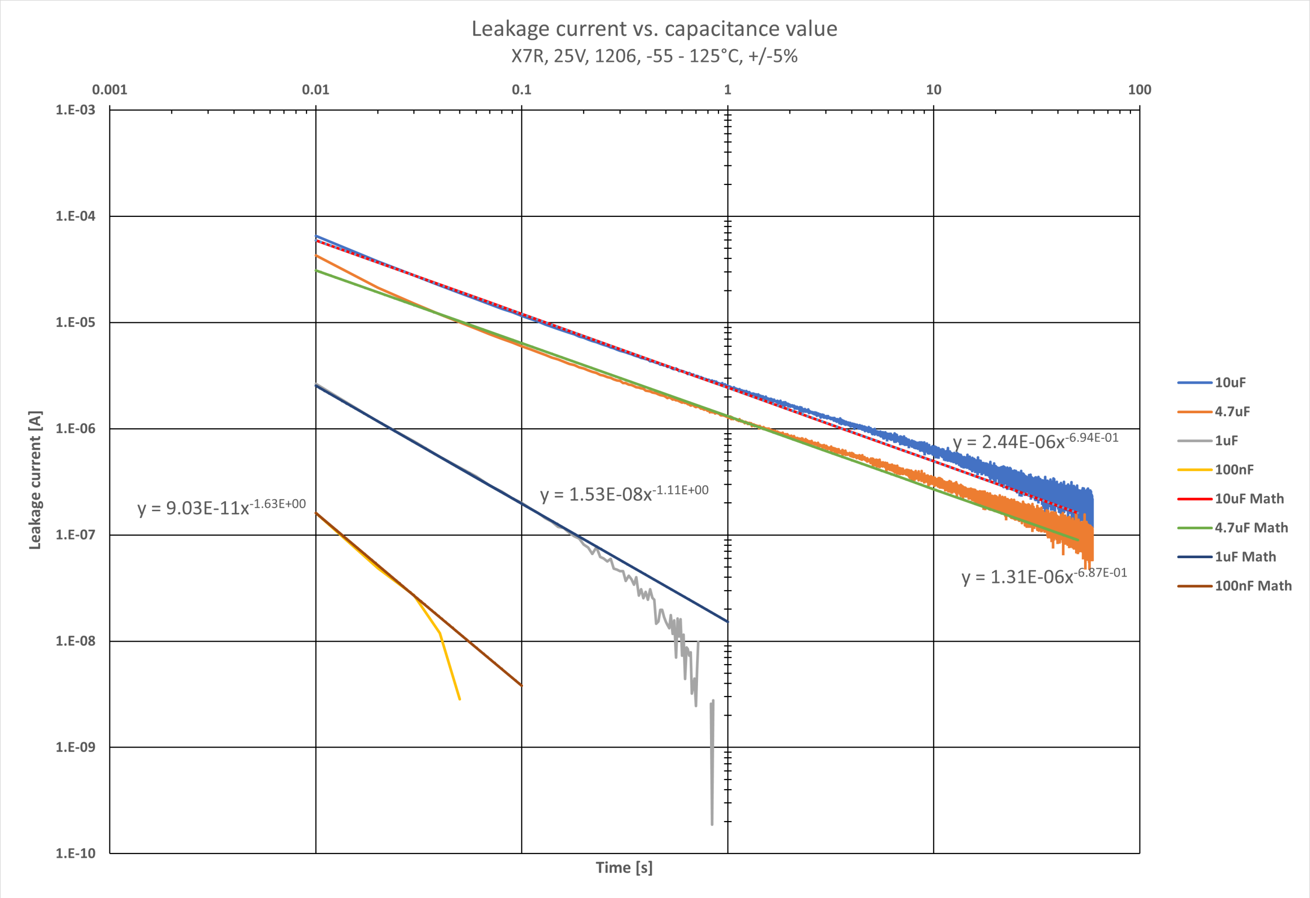


Figure 4.2. Capacitor Leakage versus Capacitance Value

Since the leakage current through the four different capacitors, shown as the blue, orange, gray, and yellow curves, can all be drawn as straight lines in a log-log graph, the leakage current as function of time can be described using a power function, where A and B are constants, and B is determining the slope of the curve:

$$I_{leakage}(t) = A * t^B$$

And sure enough, each of the measured curves can be approximated by a power function like shown on the graphs with the red, green, black, and brown curves.

The curves in the figure above reveal many interesting discoveries:

1. The leakage currents through the 10 µF and 4.7 µF capacitors are orders of magnitude larger than the leakage current through the 1 µF capacitor.
2. The leakage current through the 10 µF and the 4.7 µF capacitors are in the range well above single digit µAs even 1 second after the voltage step was applied across the capacitors.
3. The leakage current through the 10 µF and 4.7 µF capacitors are still noticeable even after 60 seconds.

The measurements show that if low leakage current is important to a design, it might pay off to use several small, parallel connected capacitors to provide the capacitance required instead of using a single, large capacitor. This trade-off depends on requirements to area, cost, and low leakage current.

4.2 Leakage Depending on Package Size

Does a 1206 sized capacitor leak more current compared to a 0402 capacitor?

The four capacitors shown in Table 3.2 Capacitors Selected for Testing the Effect of the Package Size on page 4 have all been tested for leakage current when subjected to a voltage step of 3.3 V. The leakage current plotted against time is shown in the graph below:

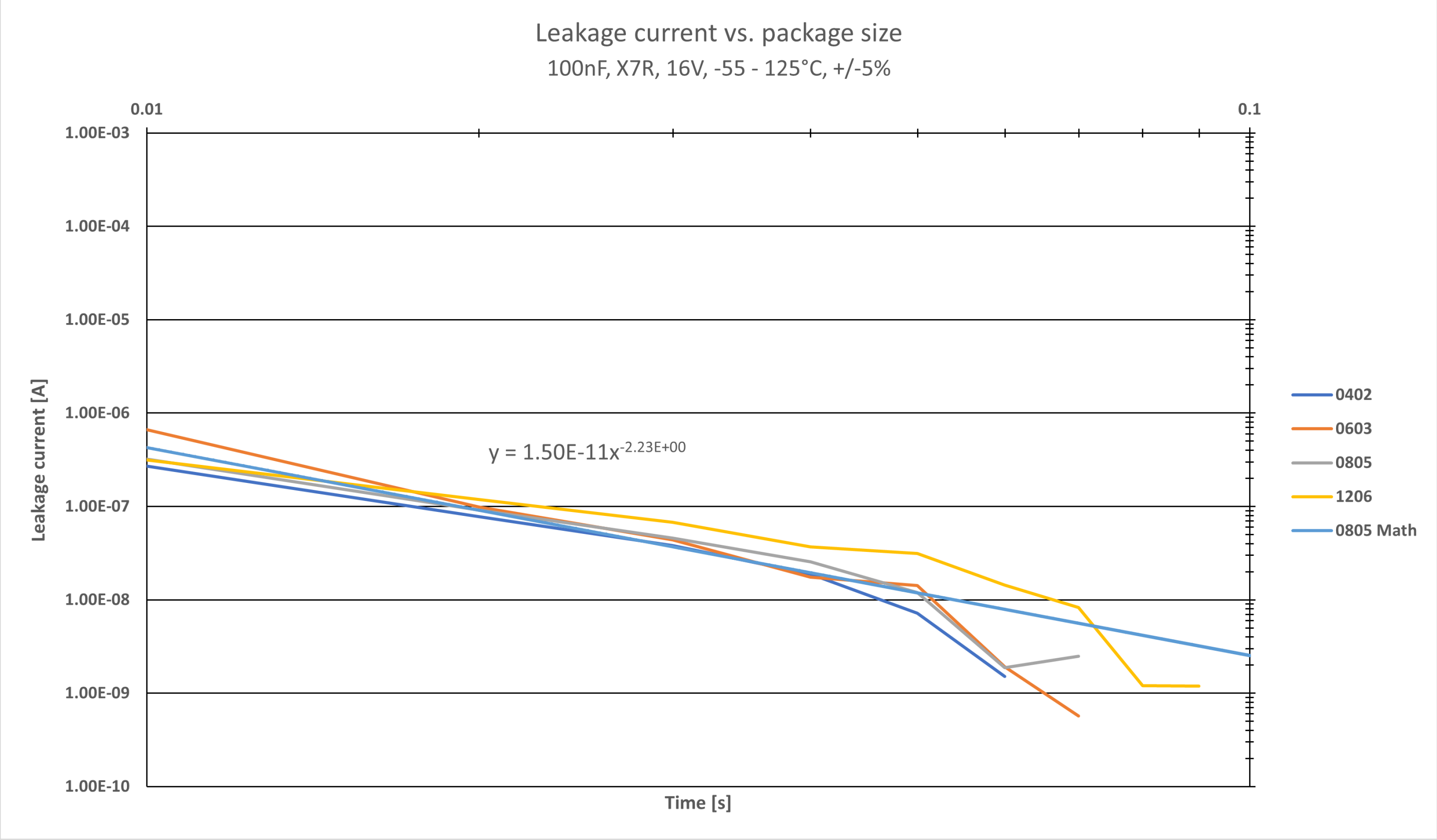


Figure 4.3. Capacitor Leakage versus Capacitor Package Size

The measured leakage currents for the four different package sizes are shown as the blue, orange, gray, and yellow curves in the log-log plot shown in the figure above.

The light blue, straight line shows the power-function approximation which can be derived from the 0805 measurements, and since there is not much difference between the four measurements, this single approximation can be used to represent all four measurements.

The measurements show no significant difference in the leakage current vs. time depending on the capacitor package size. The 1206 capacitor might leak a bit more compared to the other package sizes, but it is not a big difference, and there’s no evidence of a need to consider the capacitor package size as a serious means to reduce leakage current in a circuit.

4.3 Leakage Depending on Capacitor Material

How is the leakage current through the capacitor affected by the capacitor material (and indirectly temperature rating)?

The three capacitors shown in Table 3.3 Selected for Testing the Effect of the Construction Material on page 4 have all been tested for leakage current when subjected to a voltage step of 3.3 V. The leakage current plotted against time is shown in the graph below:

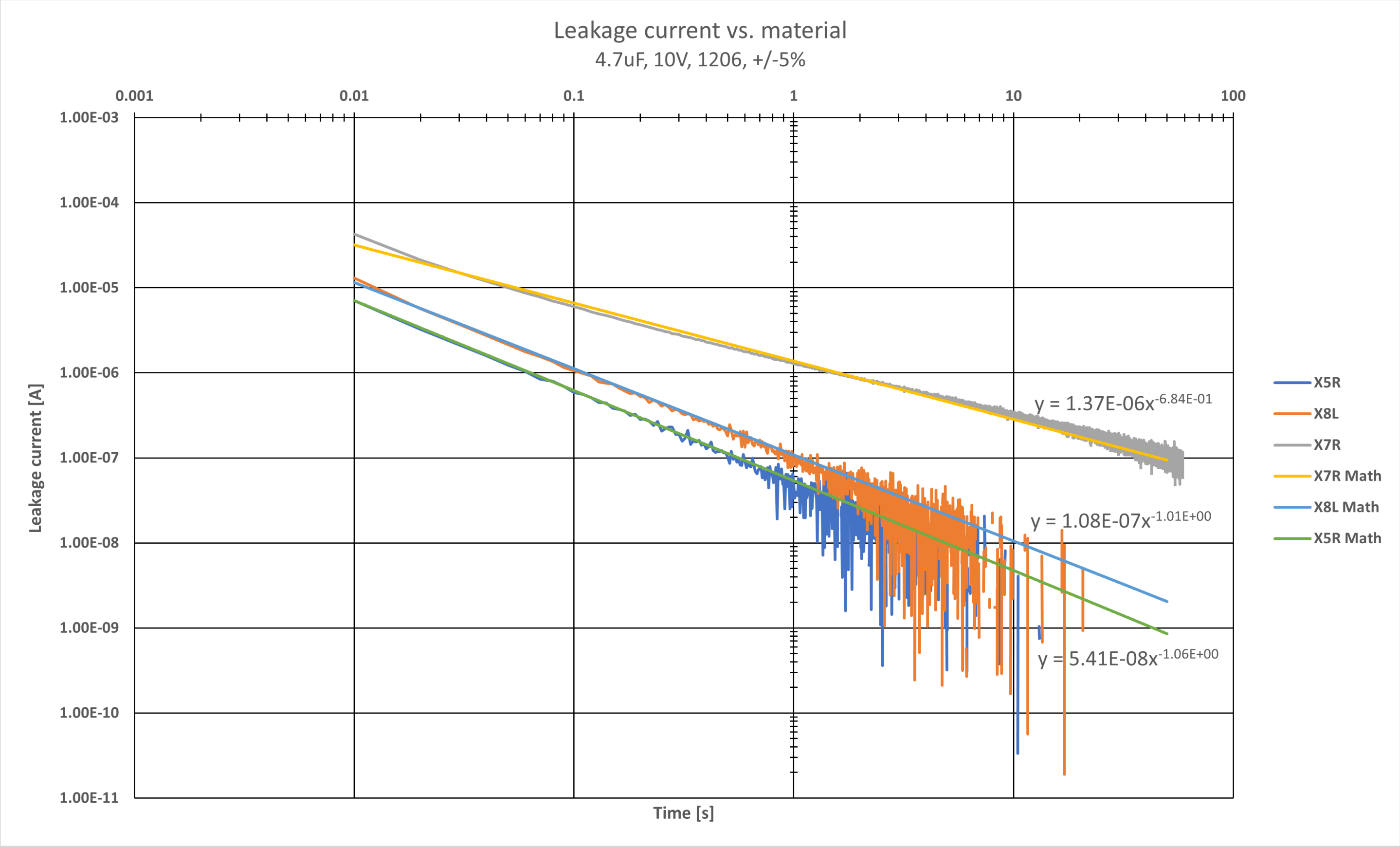


Figure 4.4. Capacitor Leakage versus Construction Material

The measured leakage currents for the three capacitors are shown as the grey, blue, and orange curves in the log-log plot shown in the figure above.

The yellow, light blue, and green straight lines are the power functions which can be derived from the measurements.

As the figure above illustrates, there is a significant difference between the leakage currents measured. The X7R, which has a temperature range of -55 °C to 125 °C, has an order of magnitude higher leakage current after 1 second compared to the two other materials tested. In fact, X5R, which is the one with the lowest temperature range, -55 °C to 85 °C, is the material with the smallest measured leakage current. The X8L, which is the one with the largest temperature range, -55 °C to 150 °C, has a bit higher leakage compared to the X5R, but X8L is still one order of magnitude better compared to the X7R capacitor.

So, if the temperature range of a product does not exceed the temperature range of X5R, and low leakage current is of importance, capacitors made of X5R should be used. If the temperature requirements of the product require an extended temperature range and leakage current is of importance, X8L capacitors seems to be superior to X7R capacitors.

4.4 Leakage Depending on the Capacitor Voltage Rating

Capacitors should never be operated at or close to their voltage ratings since this will shorten the lifespan of the device and decrease the capacitance. As a rule of thumb, the designer should not use bias voltages higher than half of the voltage rating of the capacitor. But does the leakage current through a capacitor depend on the voltage rating of the capacitor?

The two capacitors in Table 3.4 Selected for Testing the Effect of the Capacitor Voltage Rating on page 4 have both been tested for leakage current when subjected to a voltage step of 3.3 V. The leakage current plotted against time is shown in the graph below:

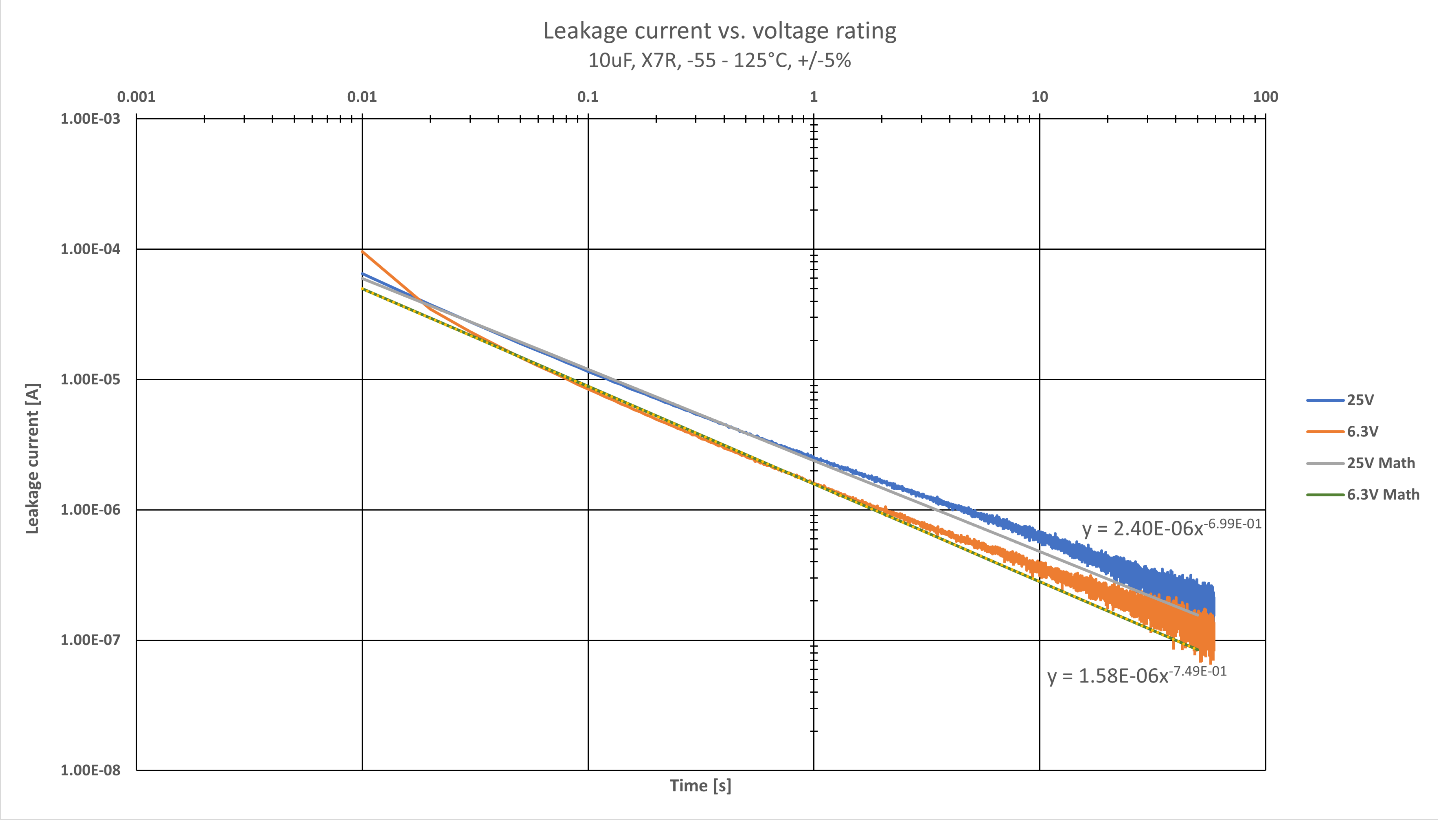


Figure 4.5. Capacitor Leakage versus Voltage Rating

As previously mentioned, the capacitors used in the measurement unfortunately do not have an identical package size. The 25 V rated capacitor is a 1206, whereas the 6.3 V rated capacitor is a 0805. But the measurements shown in Figure 4.3 Capacitor Leakage versus Capacitor Package Size on page 8 do not show a significant dependency of package size on the leakage current. Hence, it can be assumed that the difference in leakage currents shown in the figure above do indeed stem from the different voltage ratings of the two capacitors.

There is not a large difference between the leakage currents of a 25 V rated capacitor biased at 3.3 V and a 6.3 V rated capacitor biased at 3.3 V, but still, the 6.3 V rated capacitor’s leakage is lower than that of the 25 V rated capacitor. This suggests that, if low leakage current is of importance, then a lower voltage rated capacitor is preferred.

4.5 Leakage Depending on the Bias Voltage

As mentioned in the previous section, the bias voltage of a capacitor should not be larger than 0.5 * Voltage Rating. But still, what happens if the bias voltage is varied? How does the leakage current depend on the bias voltage?

The capacitor shown in Table 3.5 Selected for Testing the Effect of the Bias Voltage on page 5 is tested using the following voltage step sizes: 3.3 V, 5 V, 10 V, 15 V, and 20 V. The leakages through the capacitor are shown in the graph below:

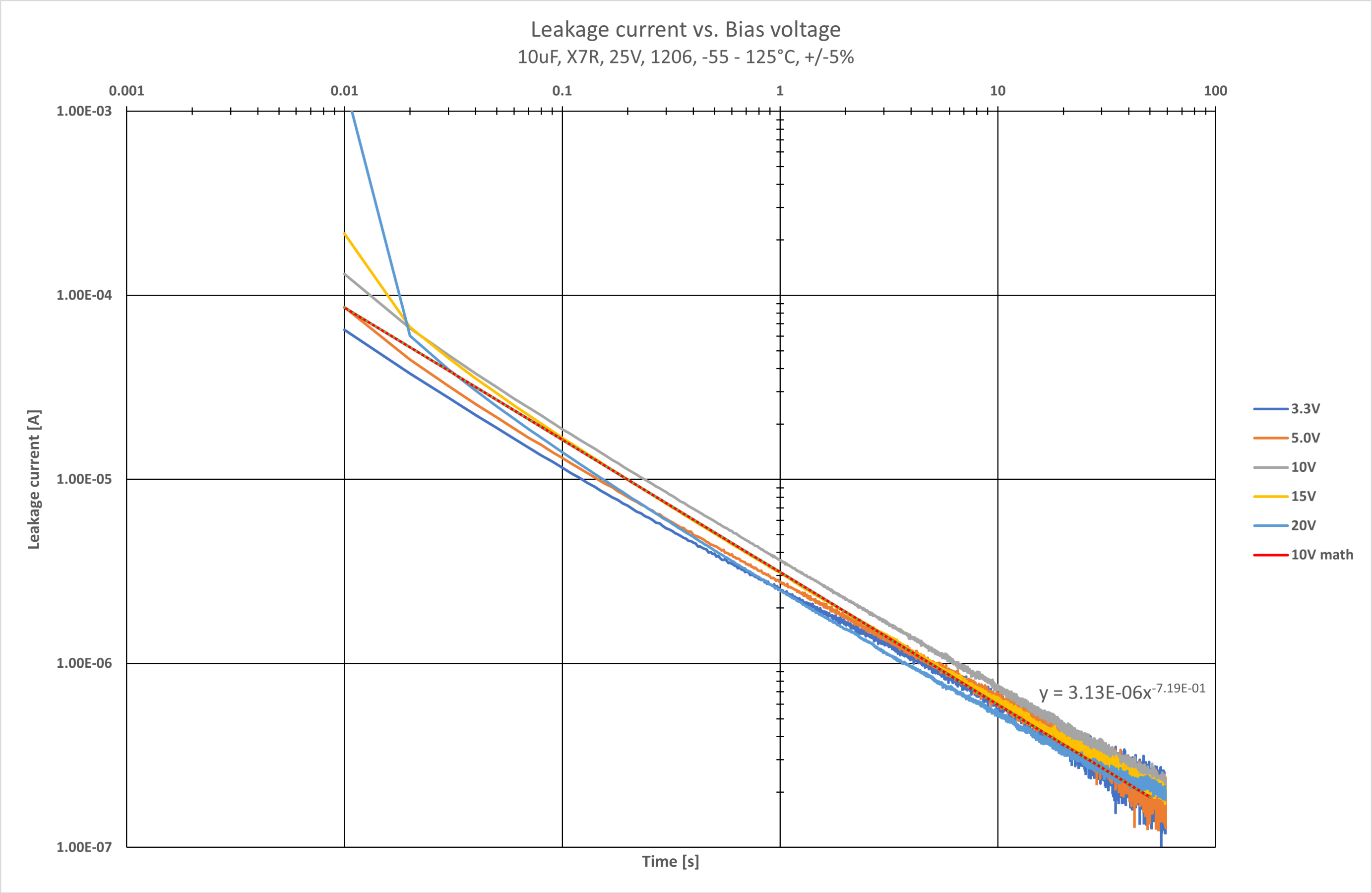


Figure 4.6. Capacitor Leakage versus Bias Voltage

The leakage currents measured for the blue, orange, gray, and yellow curves are fairly similar, suggesting that there is not a strong correlation between a high bias voltage and a large leakage current. Yes, the 15 V leakage current is higher than the 3.3 V leakage current in the time interval between 10 ms to 1 second, but after 1 second, the leakage currents are very similar.

From a design point of view, it is always preferable to avoid stressing a capacitor with a large bias voltage compared to the voltage rating, and the measurements shown in the figure above indicate that there is a small advantage with regards to the leakage current if the bias voltage is small compared to the rated voltage. Another advantage of using a component with a large voltage rating compared to the required DC bias voltage is the size of the effective capacitance value of the capacitor. The capacitance value decreases as the bias voltage approaches the voltage rating. For more information, please refer to this application note[3].

5. Conclusions

Based on the sets of measurements conducted and described in the previous five sections, the following learnings can be derived with regards to the behavior of leakage current through ceramic capacitors:

1. The leakage current through a capacitor does not reach steady state before a duration of multiple seconds or even minutes depending on the amount of capacitance and construction material of the capacitor. The measurements suggest waiting 10 seconds or more to ensure the leakage current to be below 1 µA for the ceramic capacitors measured in this application note.
2. The material of the capacitor has a big influence of the magnitude of the leakage current. X8L and X5R leak orders of magnitude less compared to X7R.
3. A larger capacitance has a larger leakage current compared to a small capacitance. In fact, it might be an advantage to connect multiple small capacitors in parallel compared to using one large capacitor.
4. The package size of a capacitor does not significantly influence the magnitude of the leakage through the capacitor.
5. There is a slight advantage in using a small bias voltage compared to the voltage rating of the capacitor.
6. The leakage through a ceramic capacitor can be described by a power function and follows a straight line in a log-log plot.

The most important learning is the fact that the time it takes for leakage current through a ceramic capacitor to reach a steady state must be counted in multiple seconds and not micro- or milliseconds.

This learning impacts all types of circuits containing capacitors which are subjected to voltage steps and where low leakage current is of importance:

- In a production test environment, where the power down current of an active circuit is measured, there is a risk that the current measured is not the power down current of the active components in the design, but instead the leakage current through the bulk-decoupling capacitors. For production tests, it is thus a good idea to perform the power down current measurements as the last step in the test sequence, that is, when the circuit has been powered for the maximum duration of time.
- In circuits which are switched on and off, e.g., transient energy harvesting circuits where the power is only available during a short interval such as when a button is pressed, the type of capacitor to use in the design should be carefully considered. To minimize the wasted current leakage through capacitors and maximize the amount of current available for the application, the measurements conducted in this application note suggests that the design should avoid X7R capacitors and use either X5R or X8L (depending on the temperature requirements). Use as high voltage rated capacitors as possible to avoid reduction of the capacitance value[3] and connect smaller capacitors in parallel to form larger capacitance.
- Current consumption measurements can only be compared if they are conducted at the same point in time relative to the power-on event of the circuit.
- Power down numbers stated in chip data sheets can only be verified if the measurement is performed on a circuit using the same type and number of capacitors as those used when the chip was characterized. Further, the timing of the current measurements is critical if comparable numbers are to be measured.
- Any analog signal processing circuit should use C0G, air, or some other high-quality dielectric. These slow memory effects/time-dependent current leakages will cause problems in integrators, filters, track-and-hold circuits, and many other analog circuits using capacitors[2].

As a final remark, time-dependent leakage through capacitors caused by dielectric absorption cannot be avoided, but its magnitude can be minimized by the careful selection of the capacitors used in a design. Further, whenever low current measurements are to be performed on circuits that are just powered on, the user should be aware that the leakage current through the decoupling capacitors might be what is measured and not the expected leakage current of the active circuits in the design.

6. References

1. https://www.idc-online.com/technical_references/pdfs/electrical_engineering/Dielectric_Absorption_Test.pdf.
2. United States Patent, US 6,294,945, System and Method for compensating the Dielectric Absorption of a Capacitor using the Dielectric Absorption of another Capacitor.
3. https://www.analog.com/en/technical-articles/temperature-and-voltage-variation-ceramic-capacitor.html.

7. Revision History

Revision 1.0

April 2023

- Initial version

IoT Portfolio
www.silabs.com/products

Quality
www.silabs.com/quality

Support & Community
www.silabs.com/community

SILICON LABS

Silicon Laboratories Inc.
400 West Cesar Chavez
Austin, TX 78701
USA

www.silabs.com