Understanding of Long-Term Stability and Acceleration Factor

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Automotive Topics

- Long-Term Stability (Life-Time Shift)
  - for specs centered around a zero or a mean value
  - for parameters defined as an absolute value
- Thermal Acceleration Factor (AF)
  - Arrhenius equation and the Acceleration Factor
  - Effect of AF on the life of a product
  - Q100 Grade 1 vs 0 based on Thermal Profile

Long-Term Stability

Normal Gaussian Distribution

Standard deviation and confidence intervals

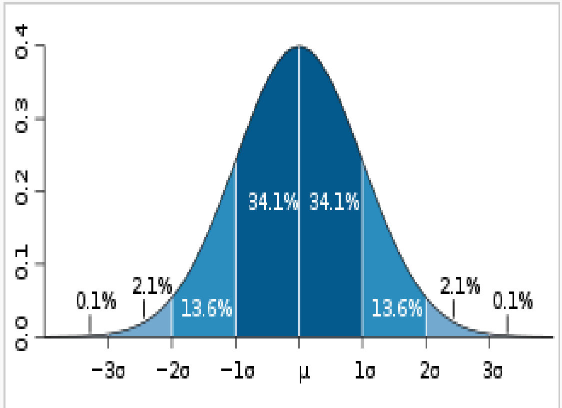
[edit]

About 68% of values drawn from a normal distribution are within one standard deviation σ away from the mean; about 95% of the values lie within two standard deviations; and about 99.7% are within three standard deviations. This fact is known as the *68-95-99.7 rule*, or the *empirical rule*, or the *3-sigma rule*. To be more precise, the area under the bell curve between $\mu - n\sigma$ and $\mu + n\sigma$ is given by

$$F(\mu + n\sigma;\ \mu, \sigma^2) - F(\mu - n\sigma;\ \mu, \sigma^2) = \Phi(n) - \Phi(-n) = \operatorname{erf}\left(\frac{n}{\sqrt{2}}\right),$$

where erf is the error function. To 12 decimal places, the values for the 1-, 2-, up to 6-sigma points are:[16]

n	$\operatorname{erf}\left(\frac{n}{\sqrt{2}}\right)$	i.e. 1 minus ...	or 1 in ...
1	0.682 689 492 137	0.317 310 507 863	3.151 487 187 53
2	0.954 499 736 104	0.045 500 263 896	21.977 894 5080
3	0.997 300 203 937	0.002 699 796 063	370.398 347 345
4	0.999 936 657 516	0.000 063 342 484	15,787.192 7673
5	0.999 999 426 697	0.000 000 573 303	1,744,277.893 62
6	0.999 999 998 027	0.000 000 001 973	506,797,345.897



Dark blue is less than one standard deviation from the mean. For the normal distribution, this accounts for about 68% of the set, while two standard deviations from the mean (medium and dark blue) account for about 95%, and three standard deviations (light, medium, and dark blue) account for about 99.7%.

Life-Time Shift Qual Guidelines

In a case of specs centered around zero or a mean value like Vos, Vos Drift, Vref, AOL, etc., they may shift over 10-year life up to:

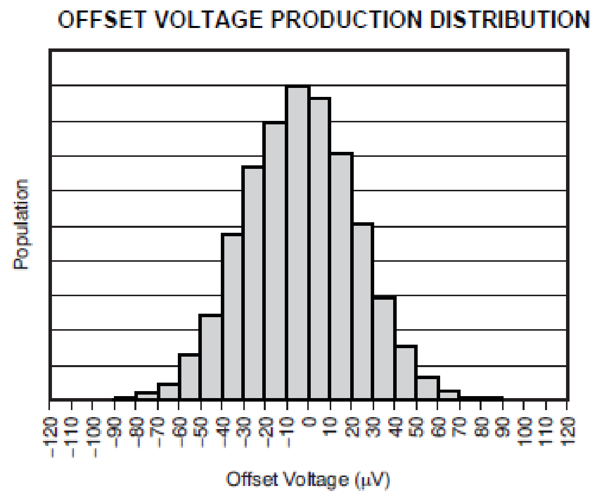
+/-100% of the max (min) PDS specified value

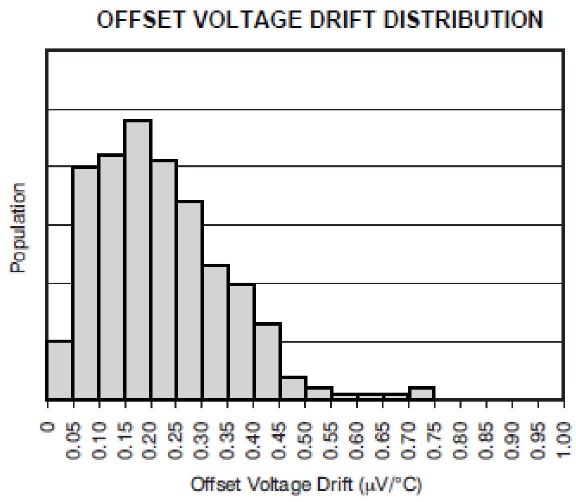
In a case of parameters specified as an absolute value like IQ, Slew Rate (SR), Isc, etc. they may shift over 10-year life up to:

+/-10% of the max (min) PDS specified value

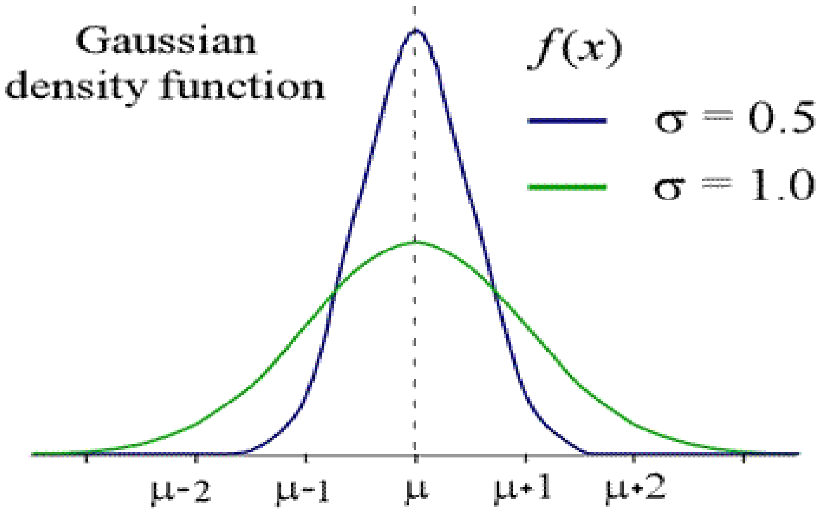
Understanding Statistical Distributions
(specs centered around a zero)

PARAMETER		CONDITIONS	OPA140, OPA2140, OPA4140			UNIT
			MIN	TYP	MAX	
OFFSET VOLTAGE						
Offset Voltage, RTI	V_{OS}	$V_S = \pm 18V$		30	120	μV
Over Temperature		$V_S = \pm 18V$			**220**	**μV**
Drift	dV_{OS}/dT	$V_S = \pm 18V$		±0.35	**1.0**	**μV/°C**





Long-Term Shift for Normal Gaussian Distributions
(Centered around a Mean Value)



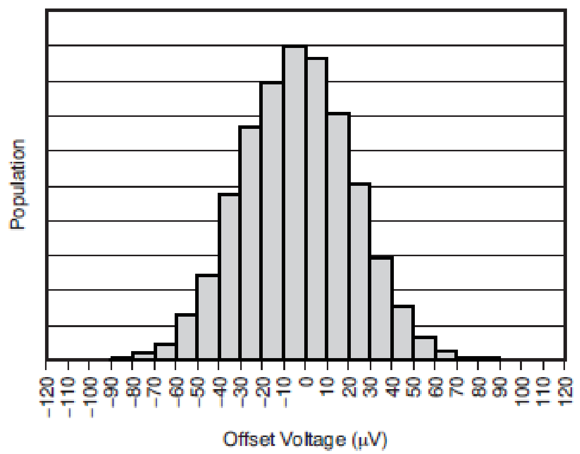
$$f(x) = \sqrt{\frac{1}{4\pi\sigma^2}}\, e^{-(x-\mu)^2/2\sigma^2}$$

Initial PDS Distribution (blue) vs Long-Term Parametric Shift (green)

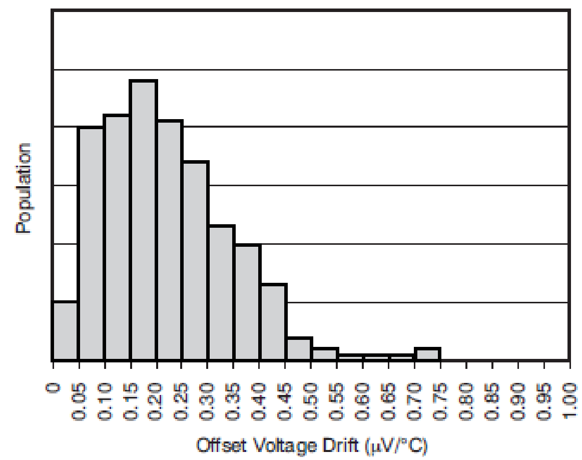
Life-Time Vos and Vos Temp Drift Shift

PARAMETER		CONDITIONS	OPA140, OPA2140, OPA4140			UNIT
			MIN	TYP	MAX	
OFFSET VOLTAGE						
Offset Voltage, RTI	V_{OS}	$V_S = \pm 18V$		30	120	μV
Over Temperature		$V_S = \pm 18V$			220	μV
Drift	dV_{OS}/dT	$V_S = \pm 18V$		±0.35	1.0	μV/°C

OFFSET VOLTAGE PRODUCTION DISTRIBUTION



OFFSET VOLTAGE DRIFT DISTRIBUTION



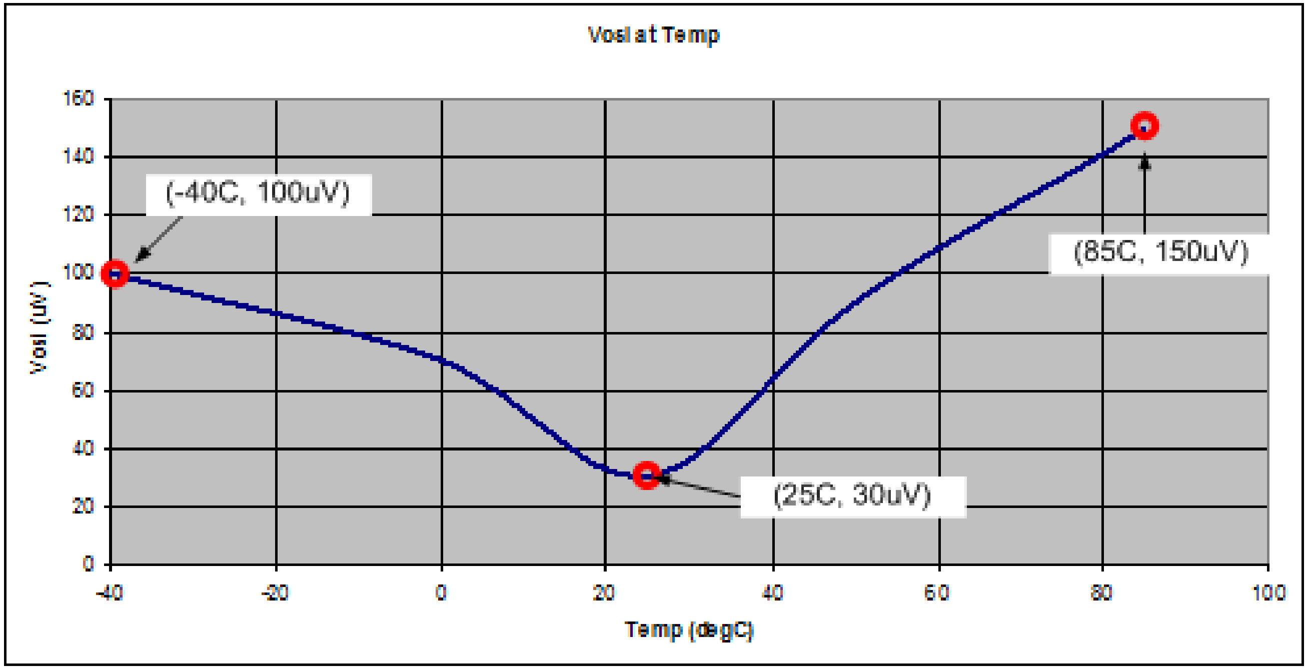
Max LT Vos = 240uV

Max LT Vos Drift = 2.0uV/C

Life-Time Max Shift (ten-year) = Max Initial Value

Long-Term Max Spec = 2 * Initial Spec

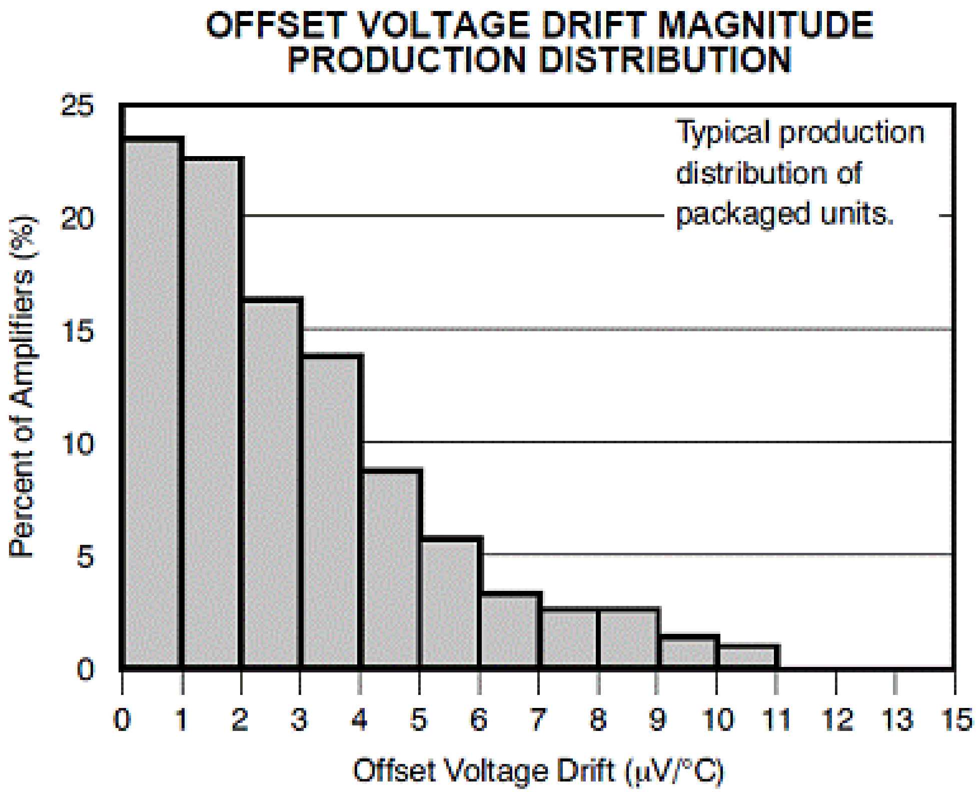
Drift Slope – Common Definition



$$\frac{\Delta V_{os}}{\Delta T} = \frac{\left|V_{os}(T_1) - V_{os}(25C)\right| + \left|V_{os}(T_2) - V_{os}(25C)\right|}{\left|T_1 - T_2\right|}$$

$$\frac{\Delta V_{os}}{\Delta T} = \frac{\left|100\mu V - 30\mu V\right| + \left|150\mu V - 30\mu V\right|}{\left|85C - (-40C)\right|} = 1.52\ \frac{\mu V}{^{\circ}C}$$

What is the Vos Drift Maximum Value?



Use of the Statistics to Determine
Relative Maximum Value

Estimating a value of standard deviation (sigma)

n	$\mathrm{erf}\left(\frac{n}{\sqrt{2}}\right)$	i.e. 1 minus ...	or 1 in ...
1	0.682 689 492 137	0.317 310 507 863	3.151 487 187 53
2	0.954 499 736 104	0.045 500 263 896	21.977 894 5080
3	0.997 300 203 937	0.002 699 796 063	370.398 347 345
4	0.999 936 657 516	0.000 063 342 484	15,787.192 7673
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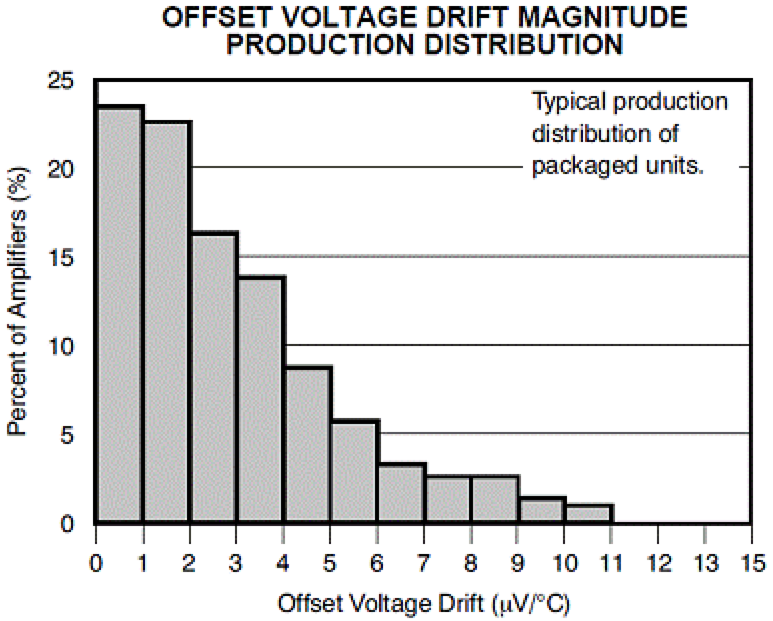


Knowing one-sigma is about ~4uV/C, customer may assume the maximum offset drift to be:

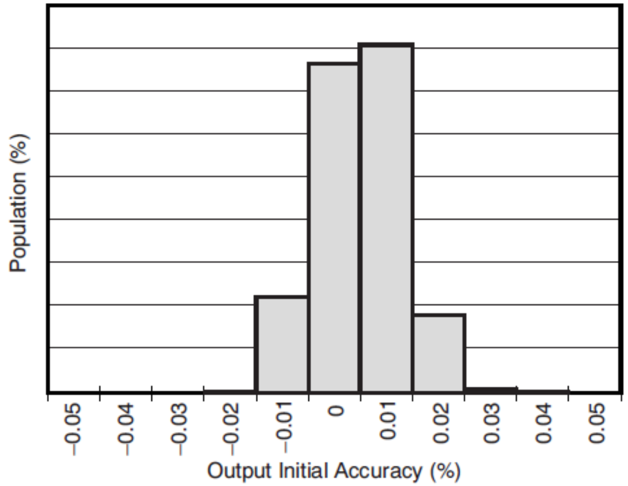
12uV/C (3*sigma) where 1 out of 370 units will NOT meet this max spec
16uV/C (4*sigma) where 1 out of 15,787 units will NOT meet this max spec
20uV/C (5*sigma) where 1 out of 1,774,277 units will NOT meet this max spec
24uV/C (6*sigma) where 1 out of 506,797,345 units will NOT meet this max spec

Life-Time Reference Voltage Initial Accuracy Shift

(specs centered around a mean value)

PARAMETER			CONDITIONS	PER DEVICE MIN	PER DEVICE TYP	PER DEVICE MAX	UNIT
REF5020 (V_{OUT} = 2.048V)[1]							
OUTPUT VOLTAGE							
Output Voltage		V_{OUT}	2.7V < V_{IN} < 18V		2.048		V
Initial Accuracy:	High-Grade			–0.05		0.05	%

OUTPUT VOLTAGE INITIAL ACCURACY

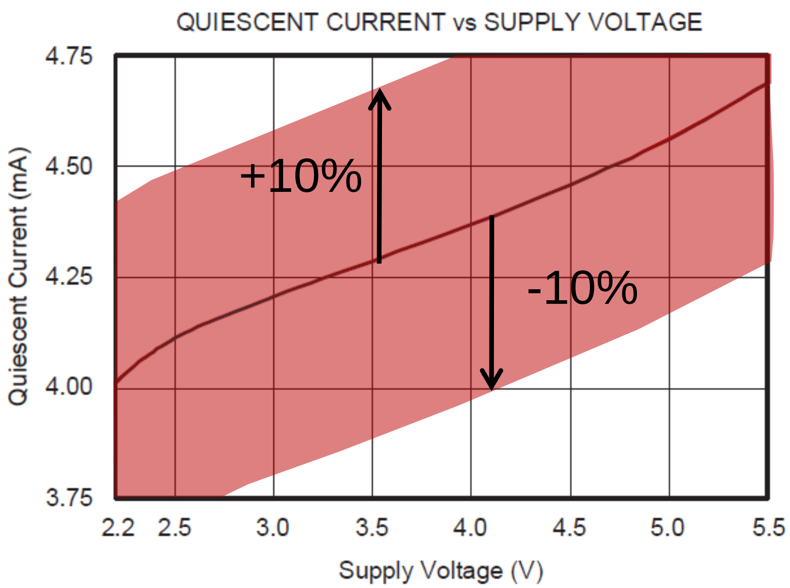


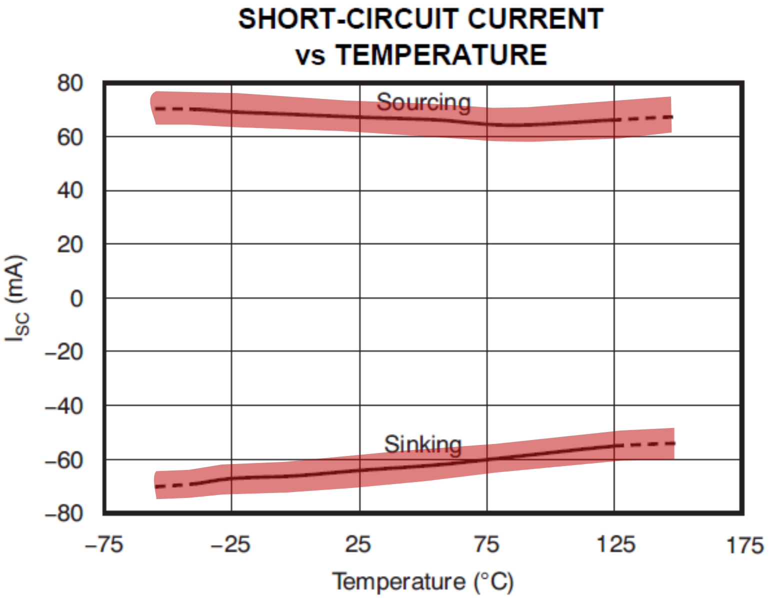
Max LT Vref = +/-0.1%

Long-Term IQ and Isc Shift

(specs centered around an absolute value)

PARAMETER		CONDITIONS	OPA827AI			UNIT
			MIN	TYP	MAX	
Quiescent Current (per amplifier)	I_Q	I_{OUT} = 0A		4.8	5.2	mA
Short-Circuit Current	I_{SC}		±55	±65		mA

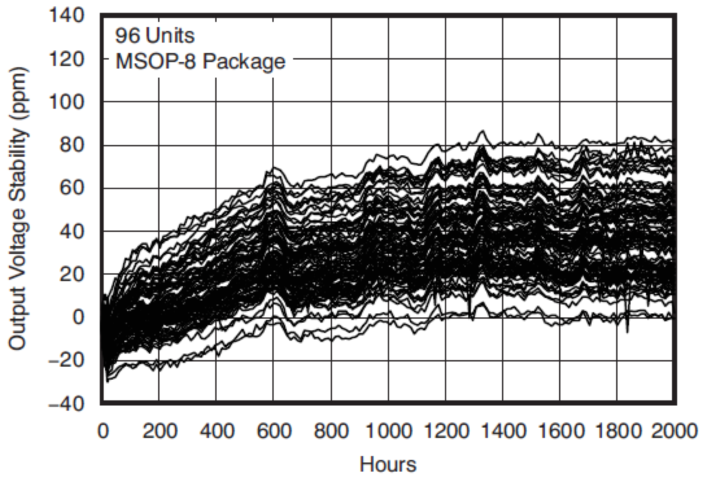




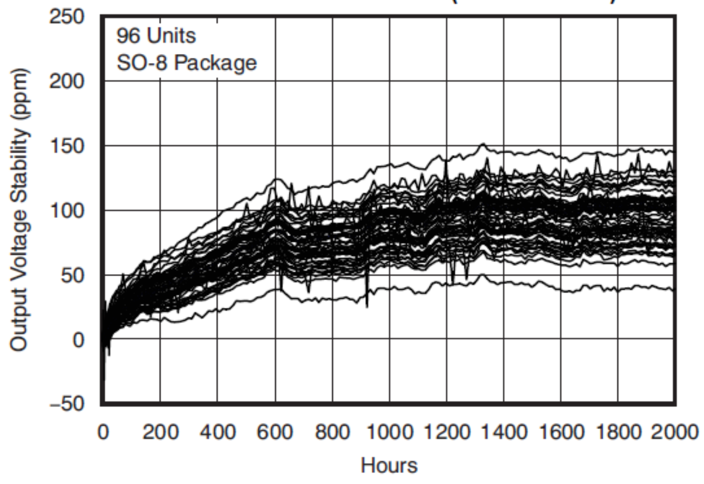
Long-Term Vref Stability

PARAMETER	CONDITIONS	REF50xx			UNIT
		MIN	TYP	MAX	
LONG-TERM STABILITY					
MSOP-8	0 to 1000 hours		50		ppm/1000 hr
MSOP-8	1000 to 2000 hours		5		ppm/1000 hr
SO-8	0 to 1000 hours		90		ppm/1000 hr
SO-8	1000 to 2000 hours		10		ppm/1000 hr

REF50xx
LONG-TERM STABILITY (2000 HOURS)



REF50xx
LONG-TERM STABILITY (2000 HOURS)



Life-Time Shift Formula

To illustrate the life-time shift for an actual IC, let's consider the long-term stability of the low-noise, low-drift REF5025 precision voltage reference and its output initial accuracy specification.

Figure 3 shows the initial accuracy of REF5025 output voltage of +/-0.05% and the long-term stability for 0 to 1000 hours specified at 50ppm. As explained above, the long-term shift of the REF5025 must not exceed the life-test shift of +/-100% of the max/min initial accuracy; therefore, the maximum output voltage shift after 10 years (87,600 hours), under constant operation at room temperature, must be less than +/-0.05%, or an equivalent of +/-500ppm.

PARAMETER	CONDITIONS	REF50xx			UNIT
		MIN	TYP	MAX	
LONG-TERM STABILITY					
MSOP-8	0 to 1000 hours		50		ppm/1000 hr
MSOP-8	1000 to 2000 hours		5		ppm/1000 hr

PARAMETER		CONDITIONS	PER DEVICE			UNIT
			MIN	TYP	MAX	
REF5020 (V_{OUT} = 2.048V)(1)						
OUTPUT VOLTAGE						
Output Voltage	V_{OUT}	2.7V < V_{IN} < 18V		2.048		V
Initial Accuracy: High-Grade			–0.05		0.05	%

Figure 3 - Excerpts from REF5025 datasheet

Since the long-term shift clearly cannot be a linear function of time and simultaneously satisfy both conditions, the shift rate must initially be higher (having a steeper slope) and then gradually slow down (becoming more linear) over time. Therefore, it may be estimated by the square-root function normalized to 1000^{th} of hours and shown below in Figure 4.

Output Voltage Shift = 50ppm*√[time(hours)/1000hrs]

Life-Time Shift Estimation Graph

Output Voltage Shift = 50ppm*√[time(hours)/1000hrs]

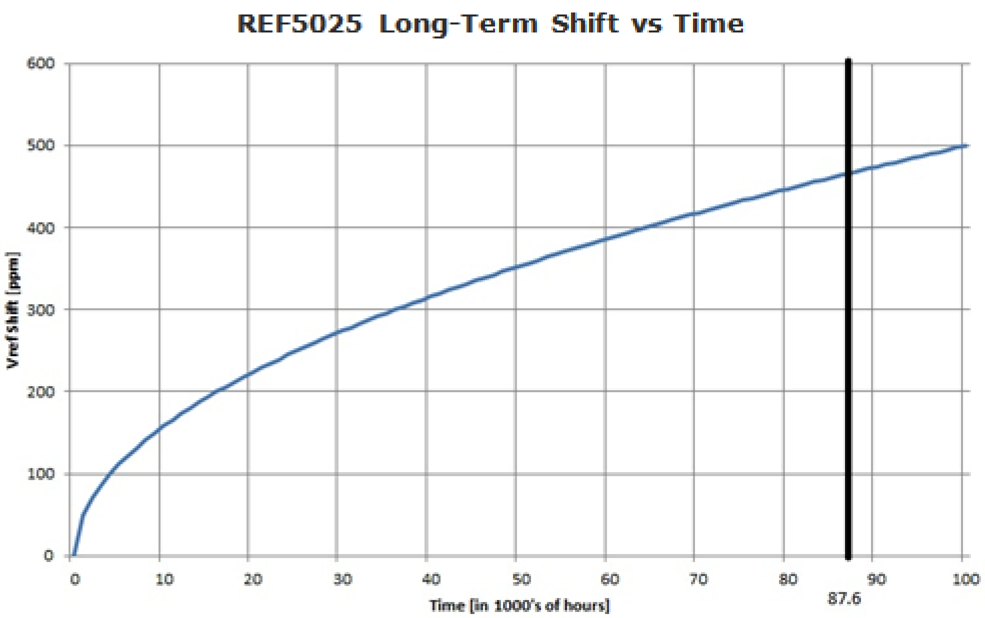


Figure 4 – REF5025 long-term stability

For example, after 25,000 hours of nonstop operation in the field, the typical output voltage shift in the REF5025 can be calculated using above equation, 50ppm*√25=250ppm, while after 10 years (87,600 hours) the shift would be 50ppm*√87.6=468pp. Therefore, at the end-of-life the REF5025 output voltage shift as expected is within the 500ppm allowable shift which equals to 0.05% of the datasheet maximum initial accuracy spec.

Life-Time Shift Rule Summary

You may estimate the maximum expected parametric shift over any given period of time by using:

- **100% of the max (min) PDS guaranteed value in the case of specs centered around a mean value** (Vos, Vos Drift, Vref, AOL, etc.)

- **10% of the max (min) guaranteed value for parameters specified as an absolute value** (IQ, slew rate, Isc, etc).

One may pro-rate the shift based on the expected ten-year life of the product

It needs to be understood that the long-term shift is NOT exactly a linear function of time – the shift is greater (curve is steeper) initially and slows down (become linear) over time. Therefore, the linear character of shift usually excludes the first month due to continuing self-curing of the molding compound used for packaging of IC.

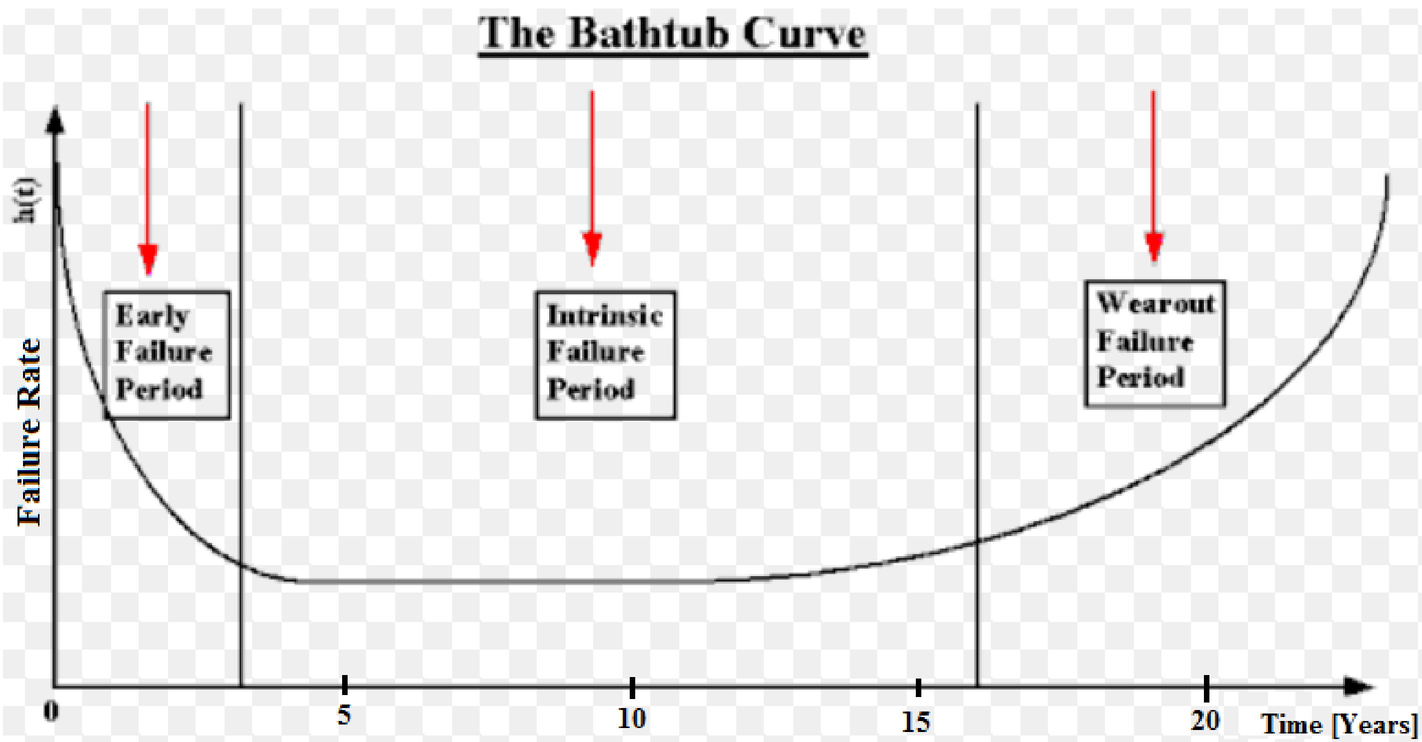
Acceleration Factor

HTOL (High Temperature Operating Life)

- HTOL is used to measure the constant failure rate region at the bottom of the bathtub curve as well as to assess the wear-out phase of the curve for some use conditions.
- Smaller sample sizes than EFR but are run for a much longer duration
- Jedec and QSS default are Ta=125C for 1000 hours
- Q100 calls for 1000 hours at max temperature for the device’s grade
- Most modern IC’s undergo HTOL at Ta=150C for 300 hours

Semiconductor Quality and Reliability

	Early life failure rate	MTBF / FIT		Early life failure rate supporting data				MTBF / FIT supporting data						
Part number	ELFR-DPPM	MTBF	FIT	Conf level (%)	Test temp (°C)	Sample size	Fails	Usage temp (°C)	Conf level (%)	Activation energy (eV)	Test temp (°C)	Test duration (hours)	Sample size	Fails
OPA192ID	22	4.89×10^9	0.2	60	125	41306	0	55	60.0	0.7	125	1000	57098	0



Tambient = 25C

The Arrhenius Equation

The Arrhenius equation is a simple, but remarkably accurate, formula for the temperature dependence of the reaction rate constant of a process.

Process Rate (PR) = $Ae^{-(Ea/kT)}$

A = A constant

Ea = Thermal activation energy in electron-volts (eV)

k = Boltzman's constant, 8.62×10^{-5} eV/K

T = Absolute temperature in degrees Kelvin (Deg C + 273.15)

Acceleration Factor

Acceleration Factors are the ratio of the Process Rate at two temperatures.

$$AF(T1\ to\ T2) = PR2\ /\ PR1 = Ae^{-(Ea/kT2)}\ /\ Ae^{-(Ea/kT1)}$$

$$AF(T1\ to\ T2) = e^{(Ea/k)(1/T1\ -\ 1/T2)}$$

A = A constant (has canceled out of the formula)

Ea = Thermal activation energy in electron volts (eV)

k = Boltzman’s constant, 8.62×10^{-5} eV/K

T = Absolute temperature in degrees Kelvin (degrees C + 273.15)

Typical Thermal Profile Equivalent Life

Hours	IC Temperature [degC]	AF (with no load)	Grade 1 Equiv. Life at Junction Temp [hrs]	Grade 1 Percent of Life Test [%]
17	15			
34	25			
134	35			
252	45			
319	55			
588	**65**			
336	75			
756	85			
1260	95			
1932	**105**			
1680	115			
840	125			
252	**135**			
8400		**Total equivalent**		

Hours	IC Temperature [degC]	AF (with no load)	Grade 0 Equiv. Life at Junction Temp [hrs]	Grade 0 Percent of Life Test [%]
17	15			
34	25			
134	35			
252	45			
319	55			
588	**65**			
336	75			
756	85			
1260	95			
1932	**105**			
1680	115			
840	125			
252	**135**			
8400		**Total equivalent**		

Acceleration Factors (case 1)

Calculate the thermal acceleration factor (AF) between the stress test temperature at 150C and the product operating temperature at **65C:**

T1 (application) = 65C -> 338K

T2 (life-test stress) =150C -> 423K

Ea=0.7eV

AF(65C to 150C) = $e^{(0.7eV/8.62x10^{-5})(1/338 - 1/423)}$ = **124.94**

This means every hour of stress at 150C is equivalent to around 125 hours of use in the application at 65C junction temperature.

Thus, 300 hour life-test at 150C (Grade 1) would cause similar shift as 37,482 hours (124.94*300hrs) at 65C while 1000 hour life-test at 150C (Grade 0) would cause similar shift as 124,940hours (124.94*1000hrs) in the field at 65C. Thus 588 hours operation at 65C represents about 1.5% of expected product life for grade 1 and 0.47% for grade 0.

Hours	IC Temperature [degC]	AF (with no load)	Grade 1 Equiv. Life at Junction Temp [hrs]	Grade 1 Percent of Life Test [%]
588	65	124.94	37482	1.5687

Hours	IC Temperature [degC]	AF (with no load)	Grade 0 Equiv. Life at Junction Temp [hrs]	Grade 0 Percent of Life Test [%]
588	65	124.94	124940	0.4706

Acceleration Factors (case 2)

Calculate the thermal acceleration factor (AF) between the stress test temperature at 150C and the product operating temperature at **105C:**

T1 (application) = 105C -> 378K

T2 (life-test stress) =150C -> 423K

Ea=0.7eV

AF(105C to 150C) = $e^{(0.7eV/8.62x10^{-5})(1/378\ -\ 1/423)}$ = **9.83**

This means every hour of stress at 150C is equivalent to around 10 hours of use in the application at 105C junction temperature.

Thus, 300 hour life-test at 150C (Grade 1) would cause similar shift as 2,949 hours (9.83*300hrs) at 105C while 1000 hour life-test at 150C (Grade 0) would cause similar shift as 9,830 hours (9,83*1000hrs) in the field at 105C. Thus 1932 hours operation at 105C represents about 65% of expected product life for grade 1 and 19.6% for grade 0.

Hours	IC Temperature [degC]	AF (with no load)	Grade 1 Equiv. Life at Junction Temp [hrs]	Grade 1 Percent of Life Test [%]
1932	105	9.83	2949	65.5132

Hours	IC Temperature [degC]	AF (with no load)	Grade 0 Equiv. Life at Junction Temp [hrs]	Grade 0 Percent of Life Test [%]
1932	105	9.83	9830	19.6540

Acceleration Factors (case 3)

Calculate the thermal acceleration factor (AF) between the stress test temperature at 150C and the product operating temperature at **135C:**

T1 (application) = 135C -> 408K

T2 (life-test stress) =150C -> 423K

Ea=0.7eV

AF(135C to 150C) = $e^{(0.7eV/8.62x10^{\wedge}-5)(1/408\ -\ 1/423)}$ = **2.03**

This means every hour of stress at 150C is equivalent to around 2 hours of use in the application at 135C junction temperature.

Thus, 300 hour life-test at 150C (for Grade 1) would cause similar shift as 608 hours (2.03*300hrs) at 135C while 1000 hour life-test at 150C (for Grade 0) would cause similar shift as 2025 hours (2.03*1000hrs) in the field at 135C. Thus 252 hours operation at 135C represents about 41% of expected product life for grade 1 and 12% for grade 0.

Hours	IC Temperature [degC]	AF (with no load)	Grade 1 Equiv. Life at Junction Temp [hrs]	Grade 1 Percent of Life Test [%]
252	135	2.03	608	41.4719

Hours	IC Temperature [degC]	AF (with no load)	Grade 0 Equiv. Life at Junction Temp [hrs]	Grade 0 Percent of Life Test [%]
252	135	2.03	2025	12.4416

Summary of Thermal Profile Equivalent Life

Hours	IC Temperature [degC]	AF (with no load)	Grade 1 Equiv. Life at Junction Temp [hrs]	Grade 1 Percent of Life Test [%]
17	15	8094.55	2428366	0.0007
34	25	3142.42	942726	0.0036
134	35	1297.24	389171	0.0345
252	45	566.16	169849	0.1484
319	55	259.91	77972	0.4094
588	**65**	**124.94**	**37482**	**1.5687**
336	75	62.64	18793	1.7879
756	85	32.64	9793	7.7199
1260	95	17.62	5287	23.8319
1932	**105**	**9.83**	**2949**	**65.5132**
1680	115	5.65	1695	99.1051
840	125	3.34	1002	83.8392
252	**135**	**2.03**	**608**	**41.4719**
8400		**Total equivalent**	**Grade 1 does NOT meet thermal profile requirements**	**325.4**

Hours	IC Temperature [degC]	AF (with no load)	Grade 0 Equiv. Life at Junction Temp [hrs]	Grade 0 Percent of Life Test [%]
17	15	8094.55	8094555	0.0002
34	25	3142.42	3142421	0.0011
134	35	1297.24	1297238	0.0104
252	45	566.16	566162	0.0445
319	55	259.91	259907	0.1228
588	**65**	**124.94**	**124940**	**0.4706**
336	75	62.64	62643	0.5364
756	85	32.64	32643	2.3160
1260	95	17.62	17623	7.1496
1932	**105**	**9.83**	**9830**	**19.6540**
1680	115	5.65	5651	29.7315
840	125	3.34	3340	25.1518
252	**135**	**2.03**	**2025**	**12.4416**
8400		**Total equivalent**	**Grade 0 does meet thermal profile requirements**	**97.6**

Acceleration Factors Calculation Example

Calculate the thermal acceleration factor (AF) between the stress test temperature at 150C and the product junction temperature of **125C:**

T1 (application) = 125C -> 398K

T2 (life-test stress) =150C -> 423K

Ea=0.7eV

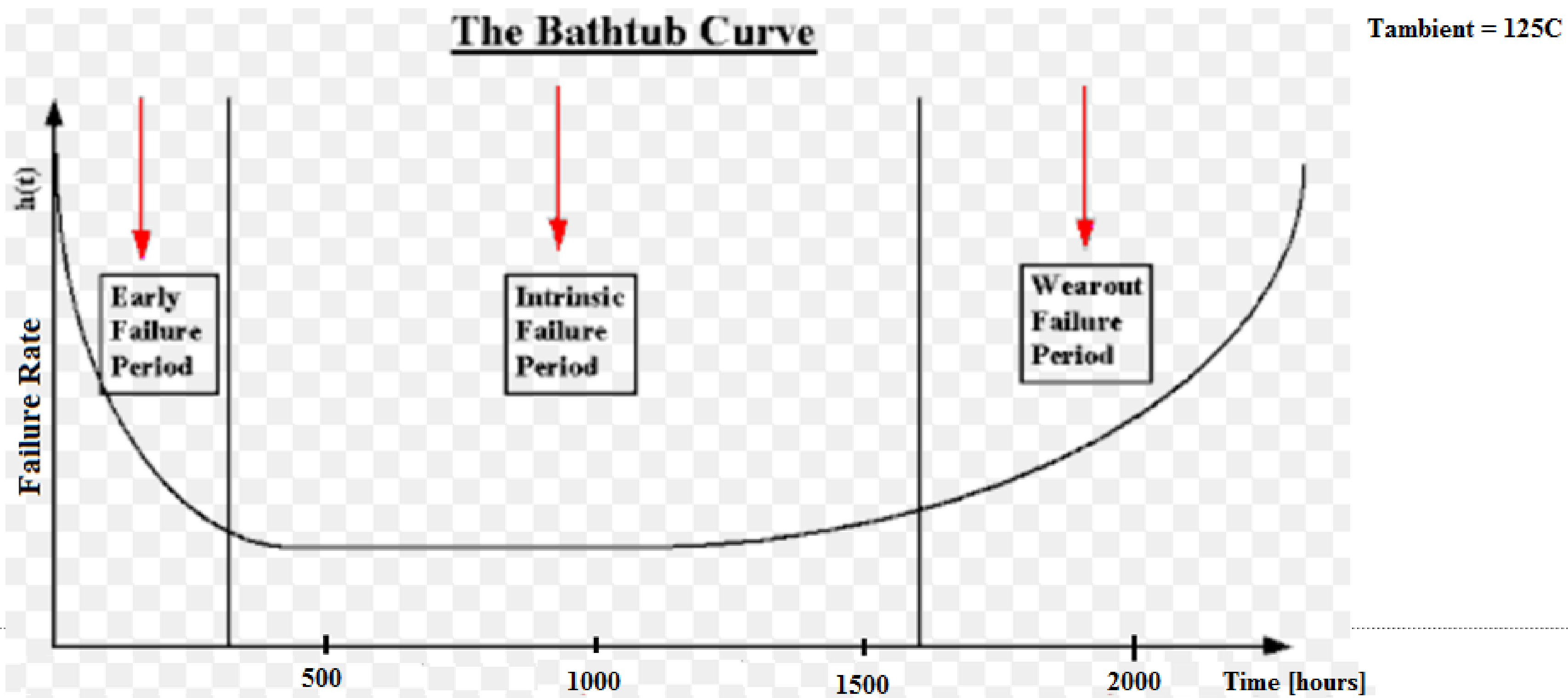
$$\textbf{AF(125C to 150C)} = e^{(0.7eV/8.62x10\hat{}-5)(1/398 - 1/423)} = \mathbf{3.34}$$

This means every hour of stress at 150C is equivalent to 3.34 hours of use in the application at 125 deg C junction temperature.

Thus, 300-hour life-test at 150C used to qualify the product would cause a similar shift as 1000 hours (300hrs*3.34), or about six weeks, in the field at 125C junction.

Semiconductor Quality and Reliability

	Early life failure rate	MTBF / FIT		Early life failure rate supporting data				MTBF / FIT supporting data						
Part number	ELFR-DPPM	MTBF	FIT	Conf level (%)	Test temp (°C)	Sample size	Fails	Usage temp (°C)	Conf level (%)	Activation energy (eV)	Test temp (°C)	Test duration (hours)	Sample size	Fails
OPA192ID	22	4.89×10^{9}	0.2	60	125	41306	0	55	60.0	0.7	125	1000	57098	0



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