Application Note 42
June 1991

Voltage Reference Circuit Collection

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This application note is a guidebook of circuits featuring voltage reference ICs in various configurations. The circuits shown are both basic as well as complex and employ many popular IC references. Included are 2-terminal and 3-terminal references in series and shunt modes, for positive and negative polarities, in voltage and current boosted versions. Additional circuit information can be located in the references listed in the index. The reference works as follows, i.e., AN8, page 2 = Application Note 8, page 2; LTC1044 DS = LTC1044 data sheet.

DRAWING INDEX

DRAWING INDEX (Continued)

DRAWING INDEX (Continued)

*See also 2-Terminal References

VOLTAGE REFERENCE SELECTION GUIDE*

* COMMERCIAL 0°C to + 70°C
** LTZ1000 requires external control and biasing circuits.

VOLTAGE V_Z (VOLTS)	VOLTAGE TOLERANCE MAXIMUM $T_A = 25°C$	DEVICE	TEMPERATURE DRIFT, ppm/°C OR mV CHANGE	OPERATING CURRENT RANGE (OR SUPPLY CURRENT)	MAXIMUM DYNAMIC IMPEDANCE (Ω)	MAJOR FEATURE
1.235	±0.32%	LT1004C-1.2	20ppm (typ)	10µA to 20mA	1.5	Micropower
	±0.32%	LT1004CS8-1.2	20ppm (typ)	10µA to 20mA	1.5	Micropower
	±1%	LT1034BC-1.2	20ppm (max)	20µA to 20mA	1.5	Low TC Micropower with 7V Aux. Reference
	±1%	LT1034C-1.2	40ppm (max)	20µA to 20mA	1.5	Low TC Micropower with 7V Aux. Reference
	±2%	LM385-1.2	20ppm (typ)	15µA to 20mA	1.5	Micropower
	±1%	LM385B-1.2	20ppm (typ)	15µA to 20mA	1.5	Micropower
2.5	±0.5%	LT1004C-2.5	20ppm (typ)	20µA to 20mA	1.5	Micropower
	±0.8%	LT1004CS8-2.5	20ppm (typ)	20µA to 30mA	1.5	Micropower
	±0.2%	LT1009C	6mV (max)	400µA to 10mA	1.4	Precision
	±2.5%	LT1009S8	25ppm (max)	400µA to 20mA	0.6	Precision
	±0.2%	LT1019C-2.5	20ppm (max)	1.2mA	N/A	Precision Bandgap
	±4%	LM336-2.5	6mV (max)	400µA to 10mA	1.4	General Purpose
	±2%	LM336B-2.5	6mV (max)	400µA to 10mA	1.4	General Purpose
	±3%	LM385-2.5	20ppm (typ)	20µA to 20mA	1.5	Micropower
	±1.5%	LM385B-2.5	20ppm (typ)	20µA to 20mA	1.5	Micropower
	±3%	LT580J	85 (max)	1.5mA	N/A	3 Terminal Low Drift
	±1%	LT580K	40 (max)	1.5mA	N/A	3 Terminal Low Drift
	±0.4%	LT580L	25 (max)	1.5mA	N/A	3 Terminal Low Drift
	±0.4%	LT580M	10 (max)	1.5mA	N/A	3 Terminal Low Drift
4.5	±0.2%	LT1019C-4.5	20ppm (max)	1.2mA	N/A	Precision Bandgap
5.0	±0.2%	LT1019C-5	20ppm (max)	1.2mA	N/A	Precision Bandgap
	±1%	LT1021BC-5	5ppm (max)	1.2mA	0.1	Very Low Drift
	±0.05%	LT1021CC-5	20ppm (max)	1.2mA	0.1	Very Tight Initial Tolerance
	±1%	LT1021DC-5	20ppm (max)	1.2mA	0.1	Low Cost, High Performance
	±1%	LT1021CS8	20ppm (max)	1.2mA	0.1	Low Cost, High Performance
	±0.02%	LT1027A	2ppm (max)	2.0mA	N/A	Low Drift, Tight Tolerance
	±0.05%	LT1027B	2ppm (max)	2.0mA	N/A	Low Drift, Tight Tolerance
	±0.05%	LT1027C	3ppm (max)	2.0mA	N/A	Low Drift, Tight Tolerance
	±0.05%	LT1027D	5ppm (max)	2.0mA	N/A	Low Drift, Tight Tolerance
	±0.1%	LT1027E	7.5ppm (max)	2.0mA	N/A	Low Drift, Tight Tolerance
	±0.2%	LT1029AC	20ppm (max)	700µA to 10mA	0.6	Precision Bandgap
	±1%	LT1029C	34ppm (max)	700µA to 10mA	0.6	Precision Bandgap
	±0.3%	REF02E	8.5ppm (max)	1.4mA	N/A	Precision Bandgap
	±0.5%	REF02H	25ppm (max)	1.4mA	N/A	Precision Bandgap
	±1%	REF02C	6.5ppm (max)	1.6mA	N/A	Precision Bandgap
	±2%	REF02E	250ppm (max)	2.0mA	N/A	Bandgap
6.9	±3%	LM329A	10ppm (max)	600µA to 15mA	1.0 (typ)	Low Drift
	±5%	LM329B	20ppm (max)	600µA to 15mA	1.0 (typ)	Low Drift
	±5%	LM329C	50ppm (max)	600µA to 15mA	1.0 (typ)	General Purpose
	±5%	LM329D	100ppm (max)	600µA to 15mA	1.0 (typ)	General Purpose
	±4%	LTZ1000	0.1ppm/°C	4mA	20.0	Ultra Low Drift, 2ppm Long Term Stability**
6.95	±5%	LM399	2ppm (max)	500µA to 10mA	1.5	Ultra Low Drift
	±5%	LM399A	1ppm (max)	500µA to 10mA	1.5	Ultra Low Drift
7.0	±0.7%	LT1021BC-7	5ppm (max)	1.0mA	0.2	Low Drift/Noise, Exc. Stability
	±0.7%	LT1021DC-7	20ppm (max)	1.0mA	0.2	Low Cost, High Performance
10.0	±0.2%	LT1019C-10	20ppm (max)	1.2mA	N/A	Precision Bandgap
	±0.5%	LT1021BC-10	5ppm (max)	1.7mA	0.25	Very Low Drift
	±0.05%	LT1021CC-10	20ppm (max)	1.7mA	0.25	Very Tight Initial Tolerance
	±0.5%	LT1021DC-10	20ppm (max)	1.7mA	0.25	Low Cost, High Performance
	±0.5%	LT1031BC	5ppm (max)	1.7mA	0.25	Very Low Drift
	±0.1%	LT1031CC	15ppm (max)	1.7mA	0.25	Very Tight Initial Tolerance
	±0.2%	LT1031DC	25ppm (max)	1.7mA	0.25	Low Cost, High Performance
	±0.3%	LT581J	30ppm (max)	1.0mA	N/A	3 Terminal Low Drift
	±0.1%	LT581K	15ppm (max)	1.0mA	N/A	3 Terminal Low Drift
	±0.3%	REF01E	8.5ppm (max)	1.4mA	N/A	Precision Bandgap
	±0.5%	REF01H	25ppm (max)	1.4mA	N/A	Precision Bandgap
	±1%	REF01C	65ppm (max)	1.6mA	N/A	Precision Bandgap

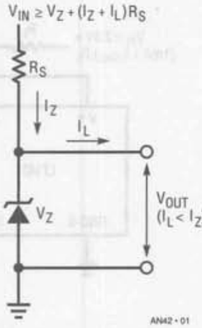
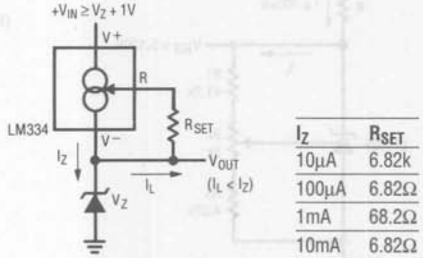
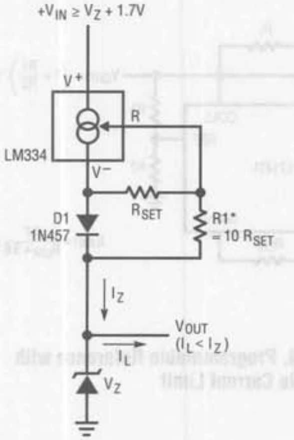


Figure 1. Basic Operation of Shunt Reference Family



I_Z	R_{SET}
10µA	6.82k
100µA	6.82Ω
1mA	68.2Ω
10mA	6.82Ω

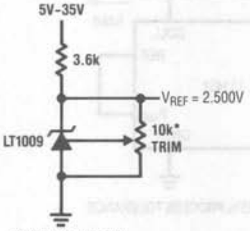
Figure 2. Current Source Stabilized Reference



$$I_Z \equiv \frac{67mV}{R_{SET}} + \frac{667mV}{R1}$$

* TRIM R1 FOR MIN T_C OF I_Z (IF NECESSARY)

Figure 3. Low TC Current Stabilized Reference



*DOES NOT AFFECT TEMPERATURE COEFFICIENT
±5% TRIM RANGE

Figure 4. 2.5V Output Reference, ±5% Trim Range

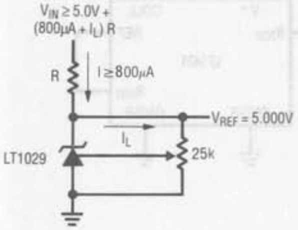
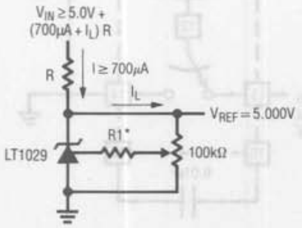
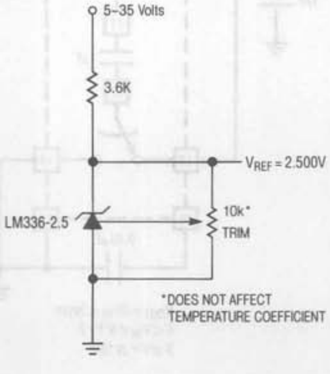


Figure 5. 5V Output Reference, +5%, –13% Trim Range



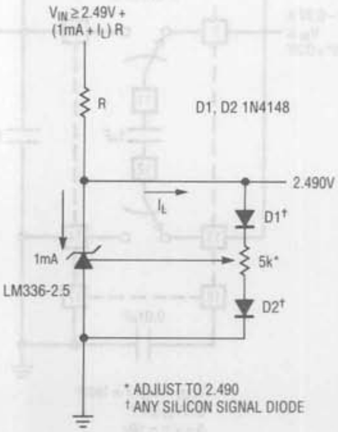
TRIM RANGE
0.4% — LT1029A, R1 = 750k
1.2% — LT1029, R1 = 250k

Figure 6. 5V Output Reference, Narrow Trim Range



*DOES NOT AFFECT TEMPERATURE COEFFICIENT

Figure 7. 2.5V Output, Temperature Independent Trim



* ADJUST TO 2.490
† ANY SILICON SIGNAL DIODE

Figure 8. 2.490V Output, Trim for Minimum TC

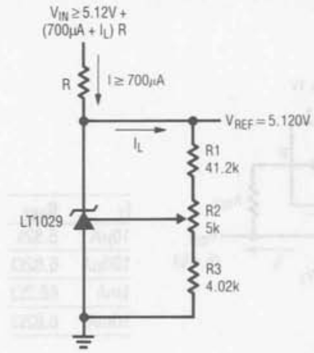


Figure 9. 5.120V Output, Trimmed Reference

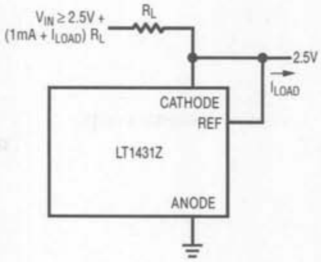


Figure 10. 2.5V Reference

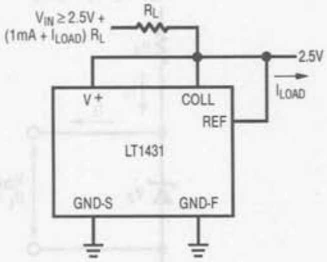


Figure 11. 2.5V Reference

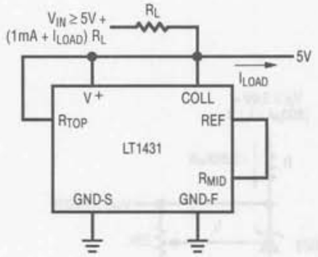
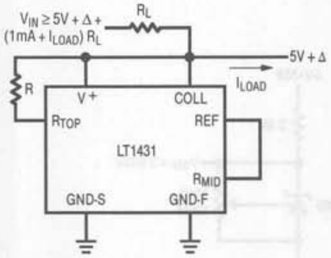


Figure 12. 5V Reference



$\Delta = R \times (0.5mA) \pm 25\%$ PROCESS TOLERANCE
$\Delta \leq 500mV$

Figure 13. Increasing 5V Reference

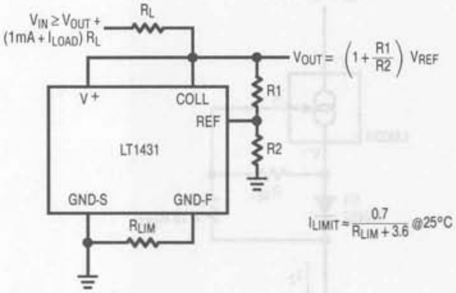
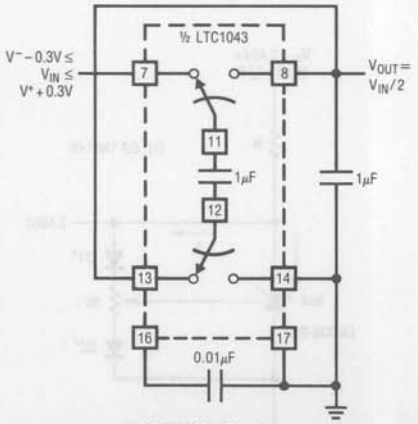
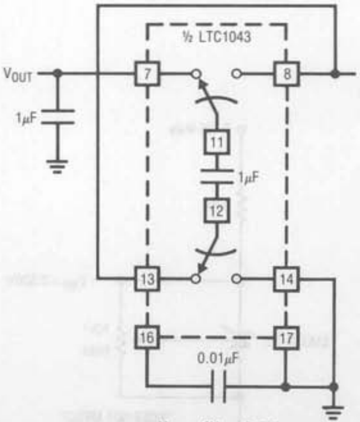


Figure 14. Programmable Reference with Adjustable Current Limit



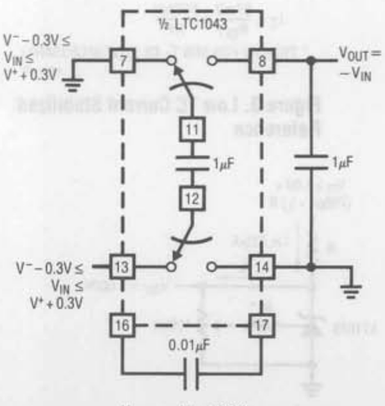
$V_{OUT} = V_{IN}/2 \pm 1ppm$
$0 \leq V_{IN} \leq V^+$
$3 \leq V^+ \leq 18V$

Figure 15. Precision Divide by Two



$V_{OUT} = 2V_{IN} \pm 5ppm$
$0 \leq V_{IN} < V^+/2$
$3 \leq V^+ \leq 18V$

Figure 16. Precision Multiply by Two



$V_{OUT} = -V_{IN} \pm 2ppm$
$V^- < V_{IN} < V^+$
$V^+ = +5V, V^- = -5V$

Figure 17. Ultra-Precision Voltage Inverter

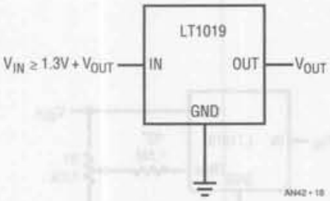


Figure 18. Basic Hookup for LT1019 Series Reference

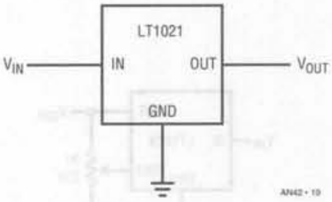


Figure 19. Basic Hookup for LT1021 Series Reference

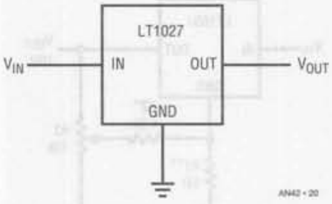


Figure 20. Basic Hookup for LT1027 Series Reference

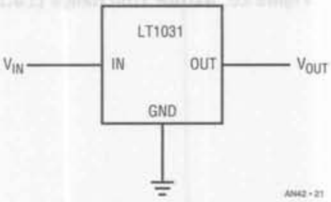
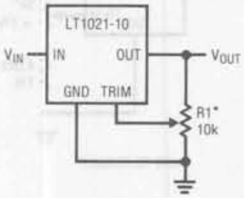
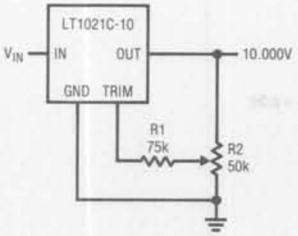


Figure 21. Basic Hookup for LT1031 Series Reference



* LOW TC CERMET
(CAN BE RAISED TO 20kΩ FOR
LESS CRITICAL APPLICATIONS)

Figure 22. 10V Output, Full Trim Range (±0.7%)



TRIM RANGE ≈ ±10mV

Figure 23. 10V Output, Restricted Trim Range for Improved Resolution

LT1031 PERFORMANCE

DEVICE	V_{OUT}	TC IN ppm/°C (TYP/MAX)
LT1031B	10V ±5mV	3/5
LT1031C	10V ±10mV	6/15
LT1031D	10V ±20mV	10/25

LT1021 PERFORMANCE

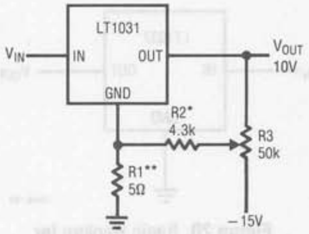
DEVICE	V_{OUT}	TC IN ppm/°C (TYP/MAX)
LT1021C-5	5V ±2.5mV	3/20
LT1021B-5	5V ±50mV	2/5
LT1021B-7	7V ±50mV	2/5
LT1021D-7	7V ±50mV	3/20
LT1021C-10	10V ±5mV	5/20
LT1021B-10	10V ±50mV	2/5

LT1019 PERFORMANCE

DEVICE	V_{OUT}	TC IN ppm/°C (TYP/MAX); C = COM, M = MIL
LT1019A-2.5	2.5V ±1.25mV	3/5 (C), 5/10 (M)
LT1019-2.5	2.5V ±5mV	5/20 (C), 8/25 (M)
LT1019A-5	5V ±2.5mV	3/5 (C), 5/10 (M)
LT1019-5	5V ±10mV	5/20 (C), 8/25 (M)
LT1019A-10	10V ±5mV	3/5 (C), 5/10 (M)
LT1019-10	10V ±20mV	5/20 (C), 8/25 (M)

LT1027 PERFORMANCE

DEVICE	V_{OUT}	TC IN ppm/°C (TYP/MAX)
LT1027A	5V ±1mV	1/2
LT1027B	5V ±2.5mV	1/2
LT1027C	5V ±2.5mV	2/3
LT1027D	5V ±2.5mV	3/5
LT1027E	5V ±5mV	5/7.5



*CAN BE INCREASED TO 5.6k FOR LT1031B AND LH0070-2

**INCREASE TO 10Ω FOR LT1031D

Figure 24. 10V Output, Trimmed Reference

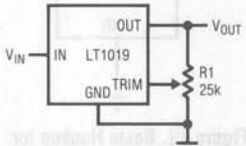
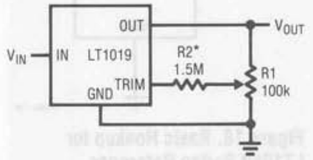
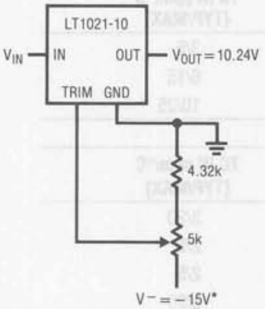


Figure 25. Wide Trim Range (±5%)



*INCREASE TO 4.7MΩ FOR LT1019A (±0.05%)

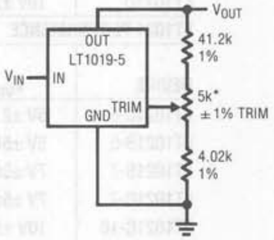
Figure 26. Narrow Trim Range (±0.2%)



*MUST BE WELL REGULATED

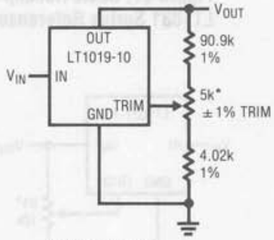
$$\frac{dV_{OUT}}{dV^-} = \frac{15mV}{V}$$

Figure 27. 10V Output, Trimmed to 10.24V



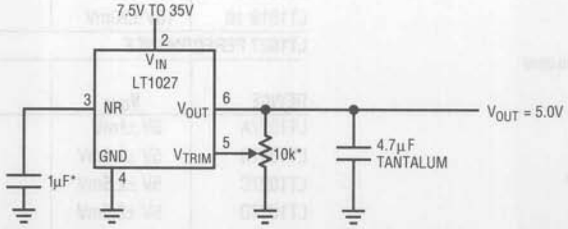
*LOW TC CERMET

Figure 28. 5V Output, Trimmed to 5.120V



*LOW TC CERMET

Figure 29. 10V Output, Trimmed to 10.240V



* NOISE REDUCTION CAP AND TRIM POTENTIOMETER OPTIONAL.

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Figure 30. 5V Output, Fast Settling, Trimmed Reference

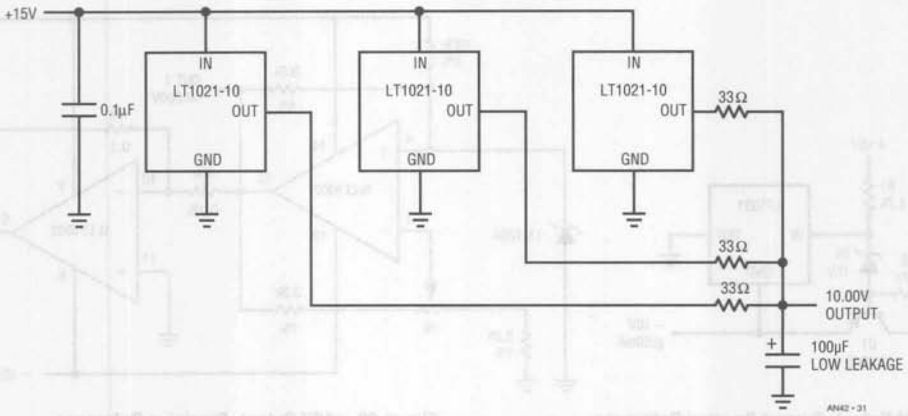


Figure 31. Low Noise Statistical Voltage Standard

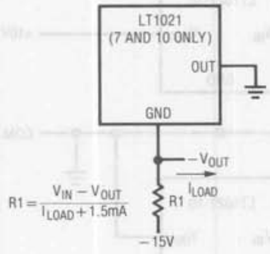


Figure 32. Shunt Mode Operation of a Series Device (LT1021-7, -10)

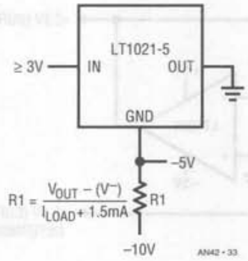


Figure 33. −5V Output Reference (LT1021-5)

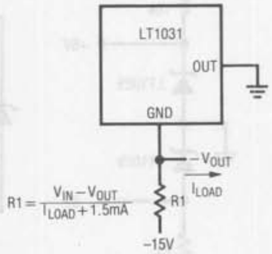


Figure 34. −10V Output for a Series Device

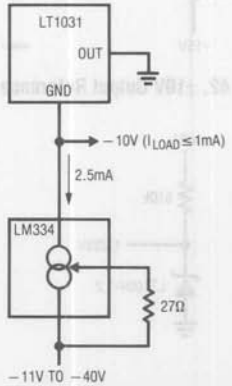


Figure 35. −10V Output, Wide Input Range

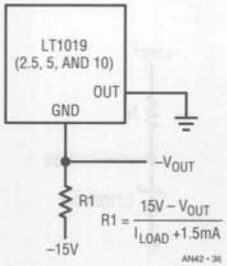


Figure 36. Shunt Operation of a Series Device (LT1019-2.5, -5, -10)

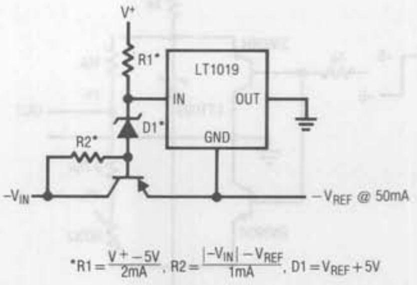


Figure 37. Current Boost Negative Reference (LT1019-2.5, -5, -10)

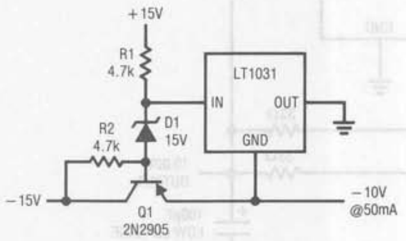


Figure 38. –10V Output, Current Boosted Reference

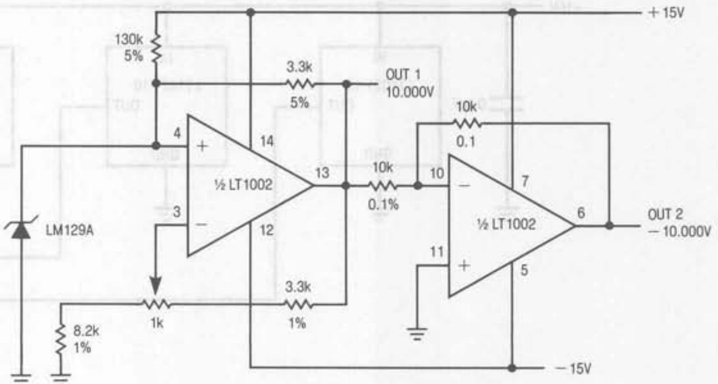


Figure 39. ±10V Output, Precision Reference

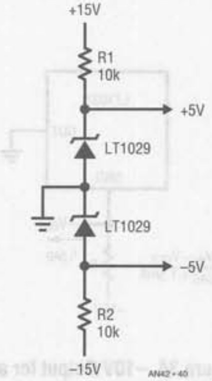


Figure 40. ±5V Output Reference

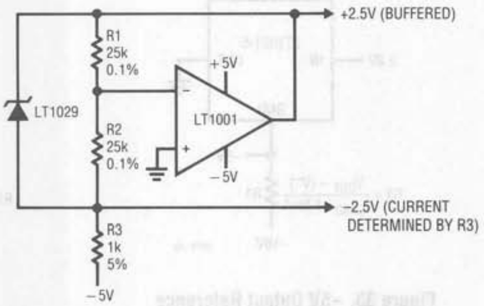


Figure 41. ±2.5V Output Reference

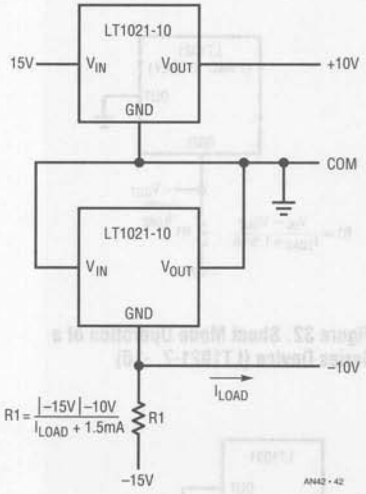


Figure 42. ±10V Output Reference

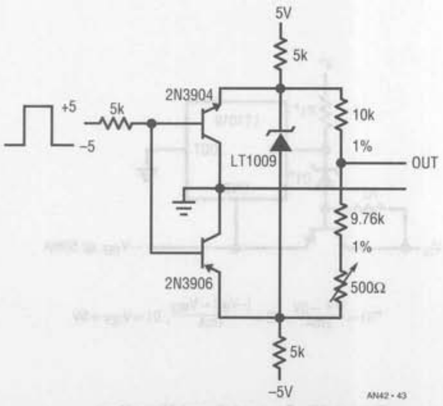
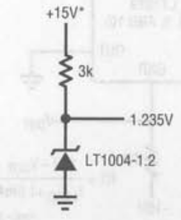


Figure 43. ±1.25V Output, Logic Programmable Reference



*OUTPUT REGULATES DOWN TO 1.285V FOR $I_{OUT} = 0$

Figure 44. 1.2V Output, Micropower Reference from 1.5V Battery

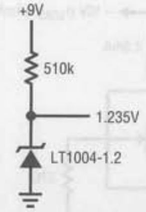


Figure 45. 1.2V Output, Micropower Reference from 9V Battery

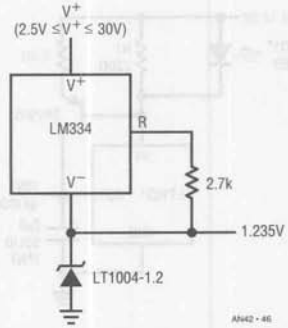


Figure 46. 1.2V Output, Micropower Reference with Wide Input Voltage Range

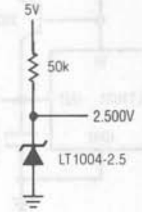


Figure 47. 2.5V Output, Micropower Reference

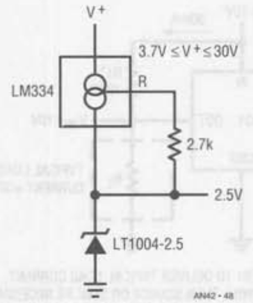


Figure 48. 2.5V Output, Micropower Reference with Wide Input Voltage Range

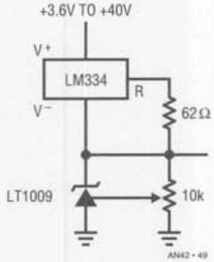


Figure 49. 2.5V Output with Wide Input Range

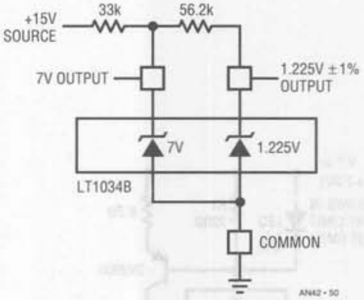
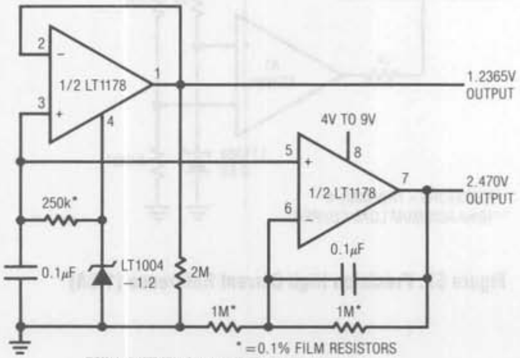


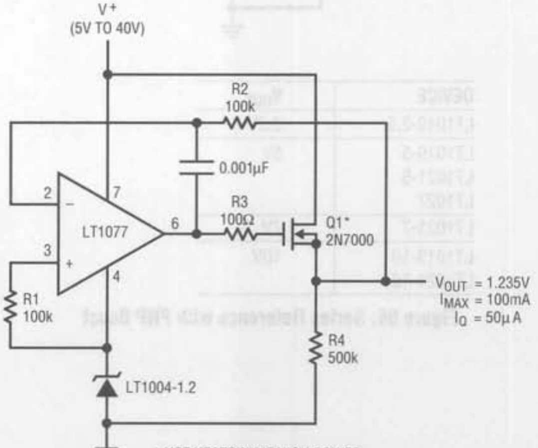
Figure 50. +1.2V, +7V Output, Pre-Regulated Reference



* = 0.1% FILM RESISTORS

TOTAL BATTERY CURRENT = 28µA
OUTPUT ACCURACY = ±0.4% MAX
TEMPERATURE COEFFICIENT = 20ppm/°C
LOAD REGULATION = 25ppm/mA, $I_L \le 5mA$, $V+ \ge 5V$
LINE REGULATION = 10ppm/V

Figure 51. +1.227V, +2.45V Output, Self-Buffered, Micropower Reference



* USE HEATSINK IF HIGH POWER DISSIPATION IS REQUIRED

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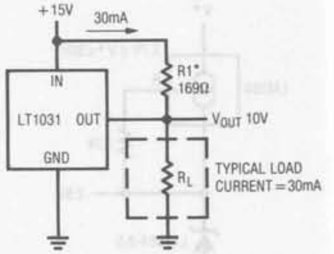
Figure 52. 1.24V Output, Micropower, Current Boosted Reference (100mA)



*SELECT R1 TO DELIVER TYPICAL LOAD CURRENT. LT1031 WILL THEN SOURCE OR SINK AS NECESSARY TO MAINTAIN PROPER OUTPUT. DO NOT REMOVE LOAD AS OUTPUT WILL BE DRIVEN UNREGULATED HIGH. LINE REGULATION IS DEGRADED IN THIS APPLICATION.

Figure 53. 10V Output with V_{IN}–V_{OUT} Shunt Resistor for Greater Current

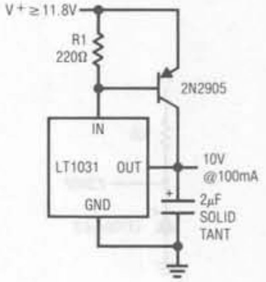
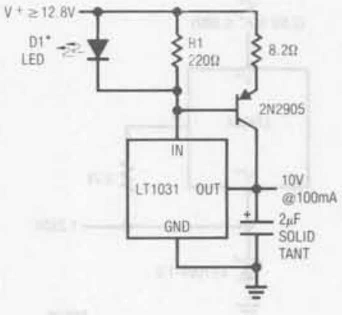
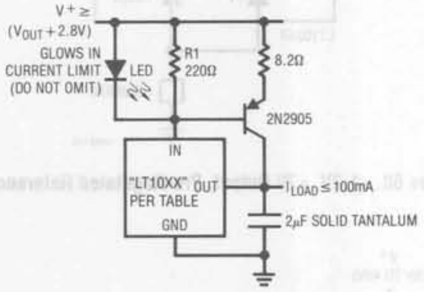


Figure 54. 10V Output with External PNP for Boosted Output (100mA)



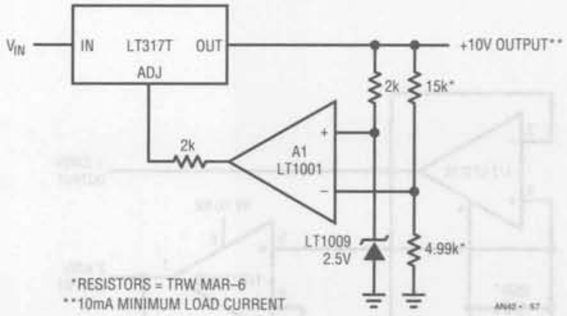
*GLOWS IN CURRENT LIMIT. DO NOT OMIT.

Figure 55. 10V Boosted Output with Current Limit (100mA)



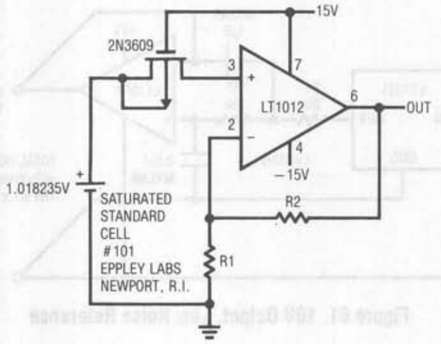
DEVICE	V_{OUT}
LT1019-2.5	2.5V
LT1019-5 LT1021-5 LT1027	5V
LT1021-7	7V
LT1019-10 LT1021-10	10V

Figure 56. Series Reference with PNP Boost



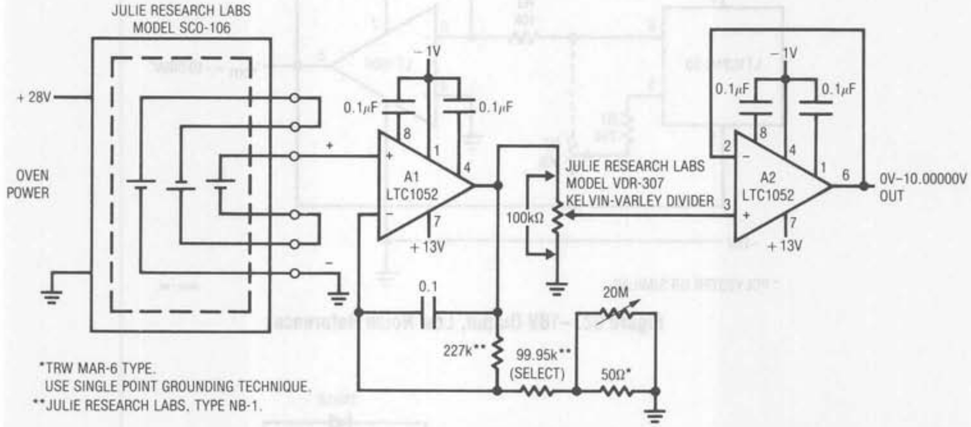
*RESISTORS = TRW MAR-6
**10mA MINIMUM LOAD CURRENT

Figure 57. Precision High Current Reference (1.5A)



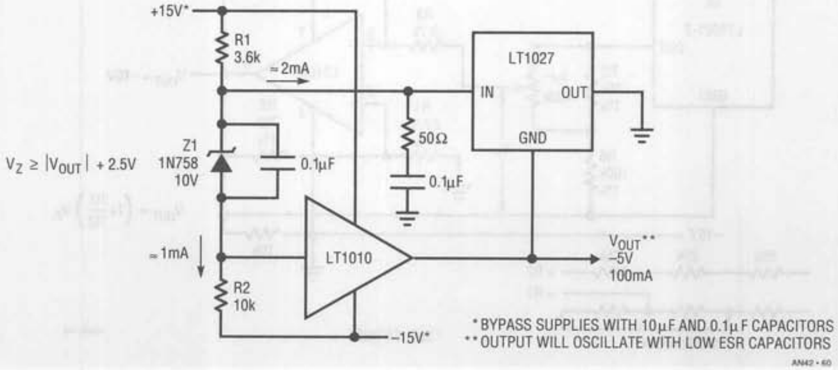
THE TYPICAL 30pA BIAS CURRENT OF THE LT1012 WILL DEGRADE THE STANDARD CELL BY ONLY 1ppm/YEAR. NOISE IS A FRACTION OF A ppm. UNPROTECTED GATE MOSFET ISOLATES STANDARD CELL ON POWER DOWN.

Figure 58. Buffered Standard Cell



*TRW MAR-6 TYPE.
USE SINGLE POINT GROUNDING TECHNIQUE.
**JULIE RESEARCH LABS. TYPE NB-1.

Figure 59. Standard Grade Variable Voltage Reference



*BYPASS SUPPLIES WITH 10μF AND 0.1μF CAPACITORS
**OUTPUT WILL OSCILLATE WITH LOW ESR CAPACITORS

Figure 60. −5V Output, Current Boosted Negative Reference with Overload Protection

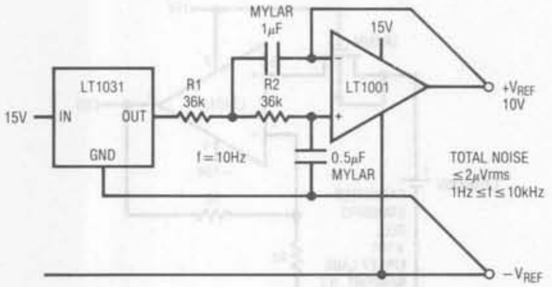
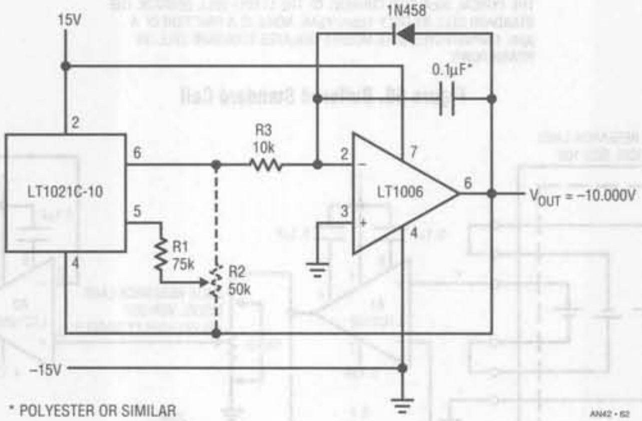
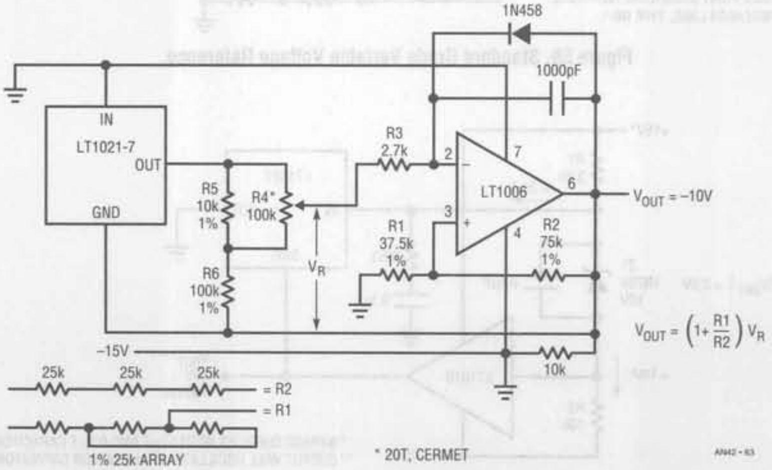


Figure 61. 10V Output, Low Noise Reference



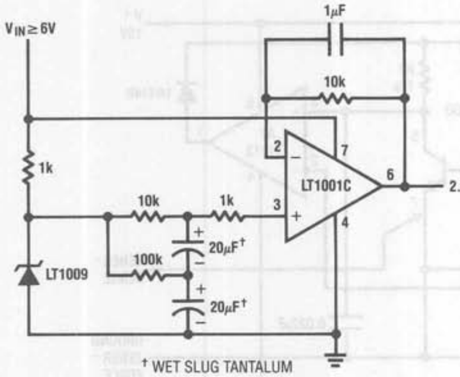
* POLYESTER OR SIMILAR

Figure 62. –10V Output, Low Noise Reference



* 20T, CERMET

Figure 63. Single Supply, –10V Output, Trimmed Low Noise, Low TC Reference



† WET SLUG TANTALUM

Figure 64. 2.5V Output, Low Noise Reference

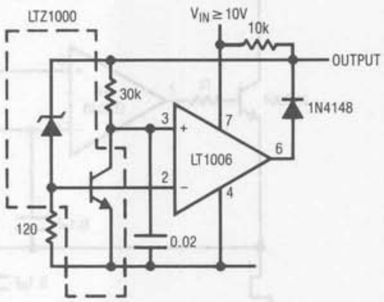
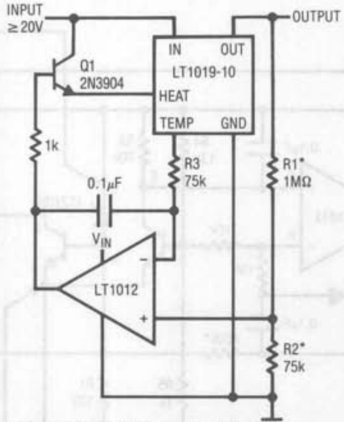
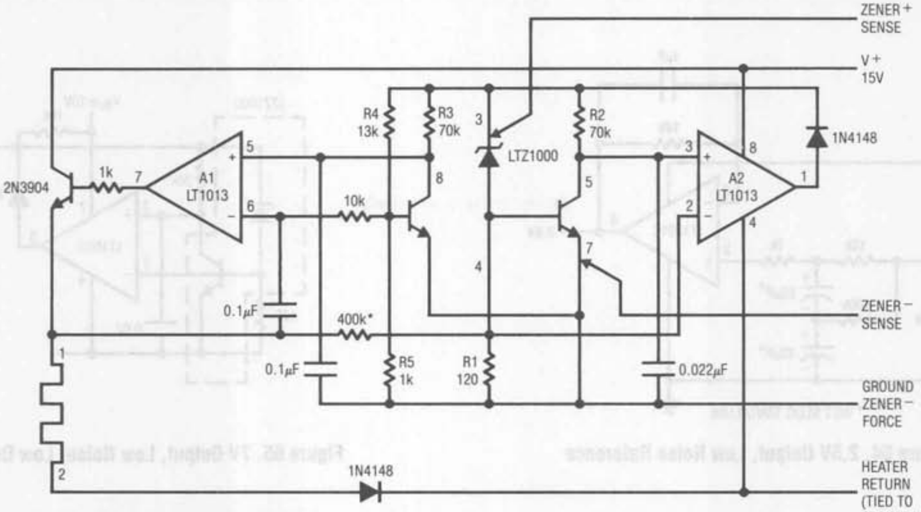


Figure 65. 7V Output, Low Noise, Low Drift Reference



*SELECT FOR DESIRED TEMPERATURE. VALUES GIVEN SET CHIP TEMPERATURE TO ≃70°C WITH $V_{OUT} = 10V$.

Figure 66. 10V Output, Temperature Stabilized Reference



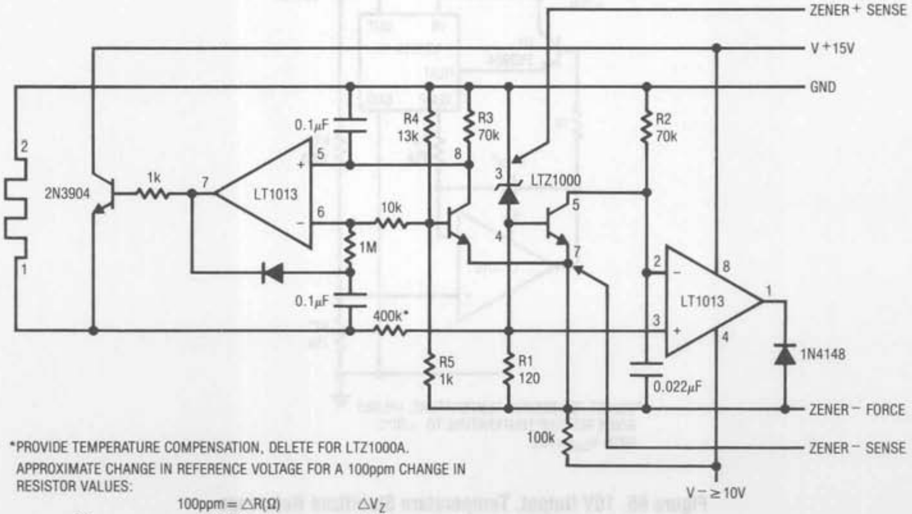
*PROVIDES TC COMPENSATION, DELETE FOR LTZ1000A.

APPROXIMATE CHANGE IN REFERENCE VOLTAGE FOR A 100ppm (0.01%) CHANGE IN RESISTOR VALUES:

	$\Delta R(\Omega)$	ΔV_Z
R1	0.012Ω	1ppm
R2	7Ω	0.3ppm
R3	7Ω	0.2ppm
R4/R5 RATIO	$\Delta R = 0.01\%$	1ppm

BOTH A1 AND A2 CONTRIBUTE LESS THAN 2μV OF OUTPUT DRIFT OVER A 50°C RANGE.

Figure 67. Low Noise, Ultra Low Drift, Long Term Stable 7V Positive Reference



*PROVIDE TEMPERATURE COMPENSATION, DELETE FOR LTZ1000A.

APPROXIMATE CHANGE IN REFERENCE VOLTAGE FOR A 100ppm CHANGE IN RESISTOR VALUES:

	$100ppm = \Delta R(\Omega)$	ΔV_Z
R1	0.012Ω	1ppm
R2	7Ω	0.3ppm
R3	7Ω	0.2ppm
R4/R5 RATIO	$\Delta R = 0.01\%$	1ppm

BOTH A1 AND A2 CONTRIBUTE LESS THAN 2μV OF OUTPUT DRIFT OVER A 50°C RANGE.

Figure 68. Low Noise, Ultra Low Drift, Long Term Stable Negative Voltage Reference

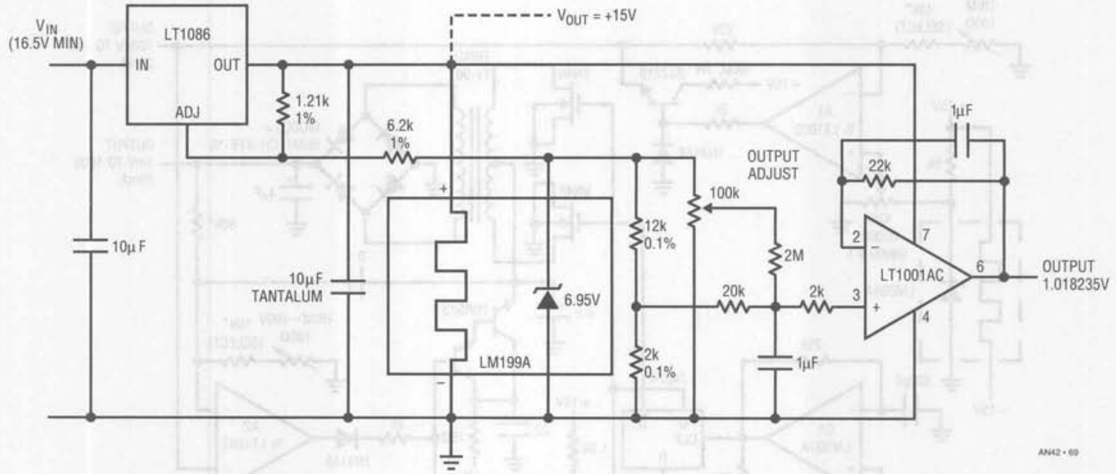


Figure 69. Buffered Standard Cell Replacement

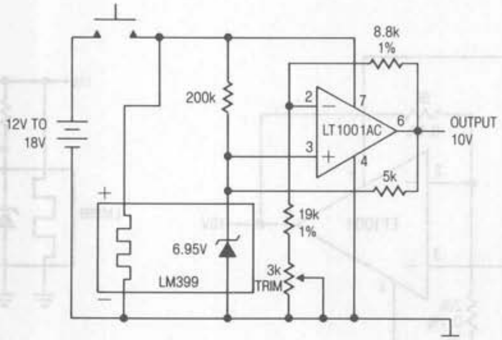
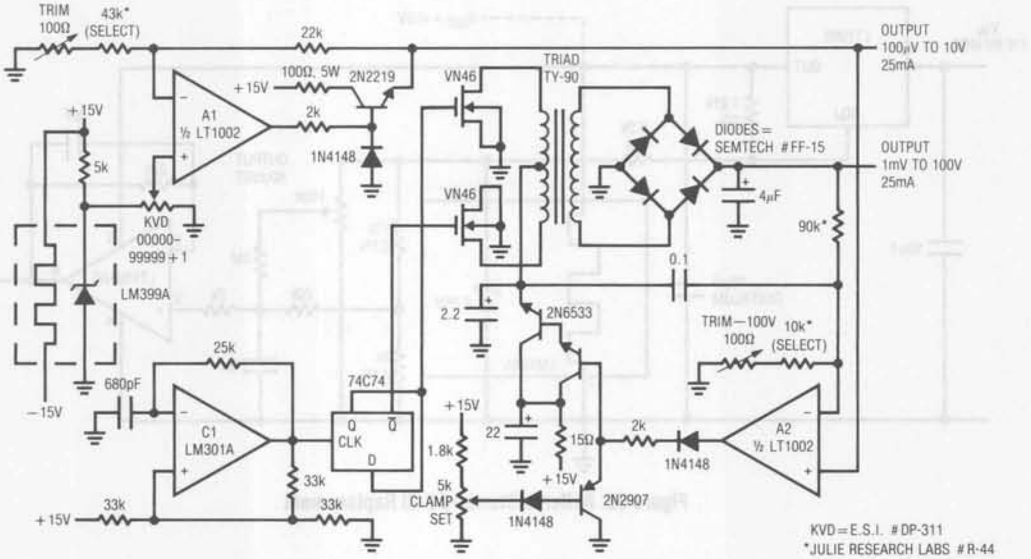


Figure 70. 10V Output, Self-Biased Temperature Stabilized Reference



KVD = E.S.I. #DP-311
*JULIE RESEARCH LABS #R-44

Figure 71. Ultra-Precision Variable Voltage Reference

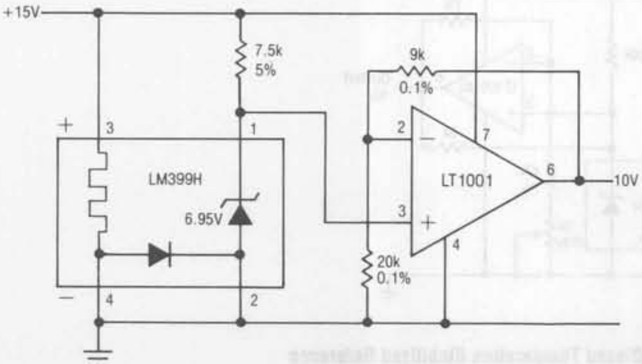
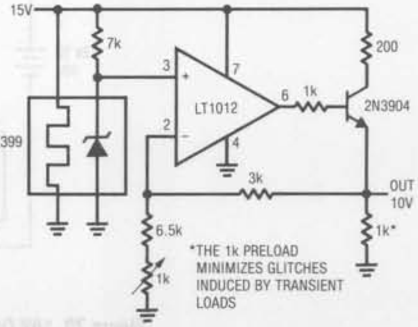


Figure 72. 10V Output, Temperature Stabilized Reference



*THE 1k PRELOAD MINIMIZES GLITCHES INDUCED BY TRANSIENT LOADS

Figure 73. Temperature Stabilized 10V Buffered Reference

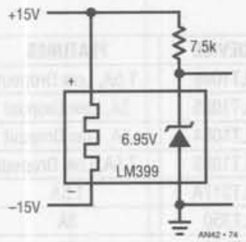


Figure 74. 6.95V Output, Temperature Stabilized Reference

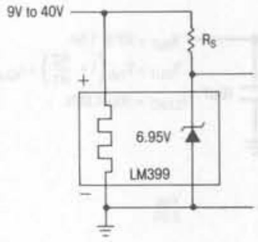


Figure 75. 6.95V Output, Temperature Stabilized Reference

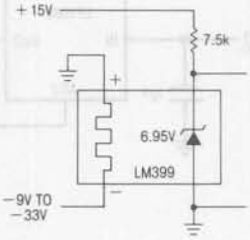


Figure 76. 6.95V Output, Temperature Stabilized Reference

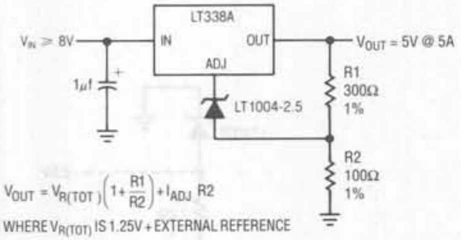


Figure 77. Simple High Stability Regulator

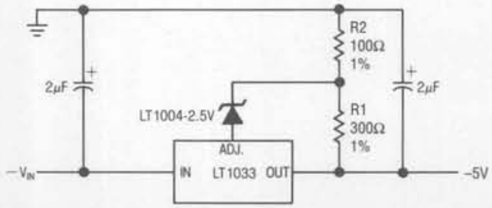
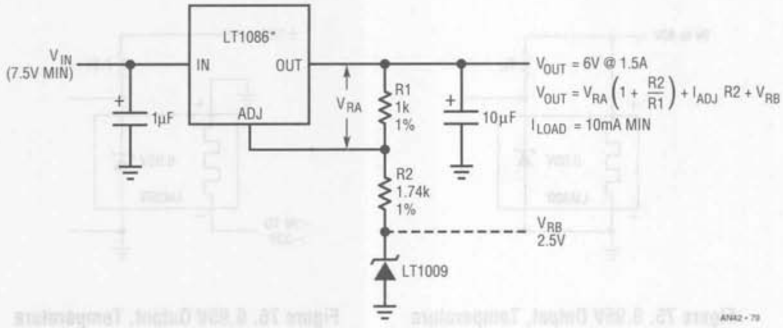


Figure 78. High Stability Negative Regulator



DEVICE	FEATURES
LT1086	1.5A, Low Dropout
LT1085	3A, Low Dropout
LT1084	5A, Low Dropout
LT1083	7.5A, Low Dropout
LT317A	1.5A
LT350	3A
LT338A	5A
LT1038	10A

Figure 79. Regulator with Reference

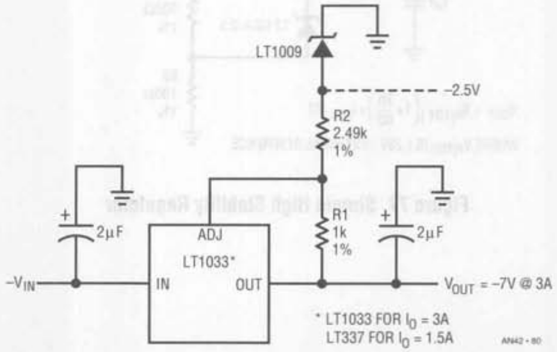
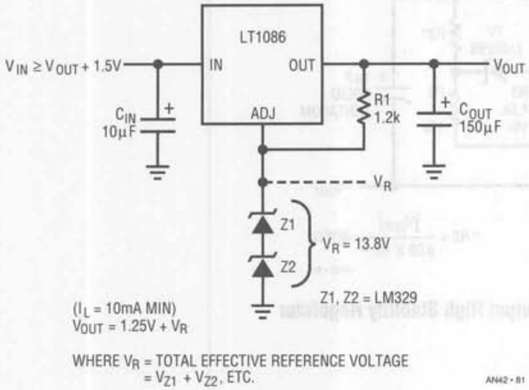


Figure 80. Negative Output Regulator with Reference



Z1/Z2	V_Z	V_R	V_{OUT}
LT1034	1.225	1.225	2.475
LT1004	1.235	1.235	2.485
LT1009	2.500	2.500	3.750
LT1034 + LT1009	1.225 + 2.5	3.725	4.975
LT1004 + LT1009	1.235 + 2.5	3.735	4.985
LT1029	5	5	6.250
LT1034 + LT1029	6.225	6.225	7.475
LT1004 + LT1029	6.235	6.235	7.485
LM329	6.9	6.9	8.150
LT1009 + LT1029	2.5 + 5.0	7.500	8.750
LT1034 + LM329	1.225 + 6.9	8.125	9.375
LT1004 + LM329	1.235 + 6.9	8.135	9.385
LT1009 + LM329	2.5 + 6.9	9.400	10.650
2 × LT1029	5 + 5	10.000	11.250
LT1029 + LM329	5 + 6.9	11.900	13.250
2 × LM329	6.9 + 6.9	13.800	15.050

Figure 81. Simple Stacked Reference/Regulator

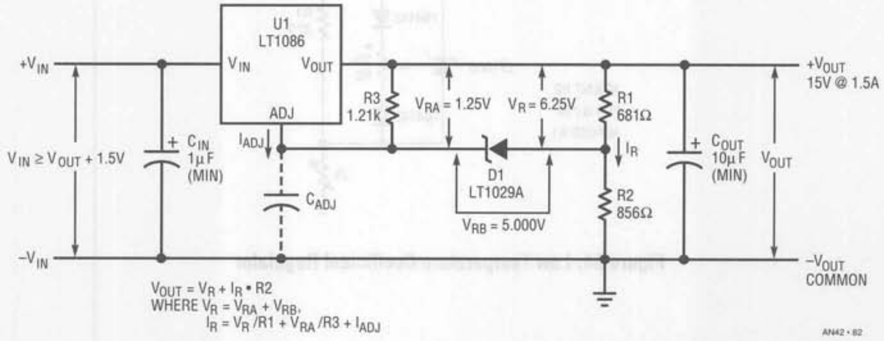
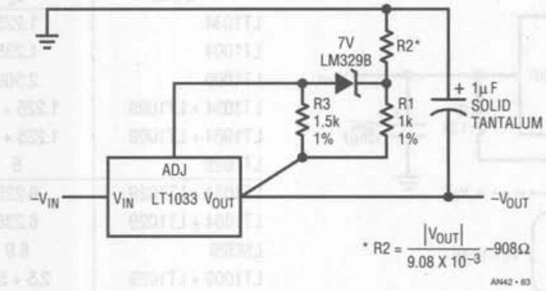


Figure 82. Programmable High Stability Regulator



$$* \; R2 = \frac{|V_{OUT}|}{9.08 \times 10^{-3}} - 908\Omega$$

Figure 83. Programmable Negative Output High Stability Regulator

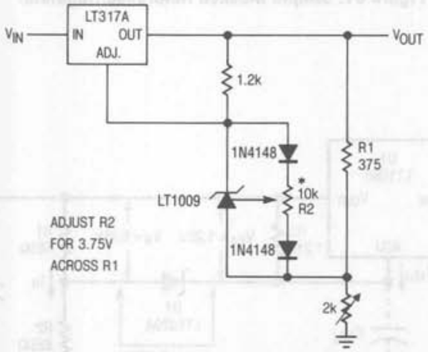


Figure 84. Low Temperature Coefficient Regulator

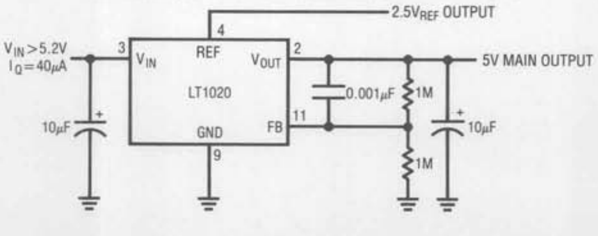


Figure 85. 5V Output, Low Dropout, Micropower Regulator with 2.5V Reference

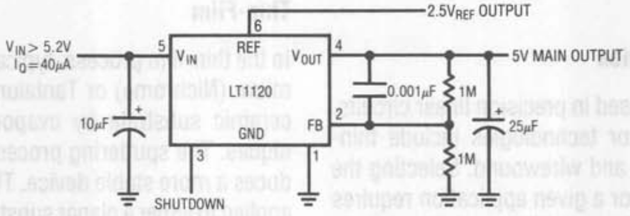
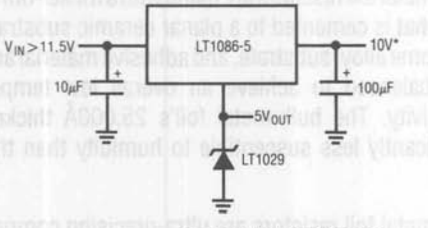


Figure 86. 5V Output, Low Dropout, Micropower Regulator with 2.5V Reference and Shutdown



* 10mA MINIMUM LOAD CURRENT

Figure 87. High Current Regulator with Reference

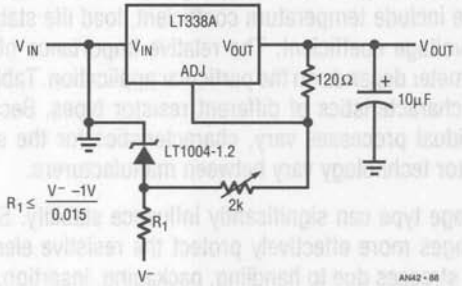


Figure 88. High Current Variable Output Supply

APPENDIX A

Precision Resistor Selection

Resistors are commonly used in precision linear circuits. Common precision resistor technologies include thin-film, thick-film, metal foil, and wirewound. Selecting the appropriate resistor type for a given application requires some understanding of the capabilities of the various devices available.

In many applications resistor selection depends on resistance value, absolute accuracy, and power dissipation. However, when designing precision linear circuits other performance parameters usually must be considered. These include temperature coefficient, load life stability, and voltage coefficient. The relative importance of any parameter depends on the particular application. Table A1 lists characteristics of different resistor types. Because individual processes vary, characteristics for the same resistor technology vary between manufacturers.

Package type can significantly influence stability. Some packages more effectively protect the resistive element from stresses due to handling, packaging, insertion, and lead forming. Also, manufacturing conditions including solder baths, cleaning solutions, and humidity can cause shifts in a resistor's value. Common package choices include conformal coating, molded and hermetic types. Conformal coated parts are the most common types in semi-precision applications. Hermetic sealing offers substantial stability improvements, regardless of resistor technology. Hermetically sealed metal cases also provide electrostatic shielding and isolation from humidity and other environmental effects.

Ultra-stable time and temperature characteristics become an issue when circuitry must hold calibration over extended ranges of time and temperature. In these applications an oil filled package may be required. The oil integrates ambient temperature variations, preventing thermal gradients across the resistor.

Various technologies available offer a spectrum of price-performance tradeoffs. Because of this, a summary of resistor types is useful.

Thin-Film

In the thin-film process, typically metal film, Nickel-Chromium (Nichrome) or Tantalum-Nitride is deposited on a ceramic substrate by evaporation or sputtering techniques. The sputtering process is preferred since it produces a more stable device. The 750Å-1500Å film can be applied to either a planar substrate or a ceramic cylindrical core. Resistor networks use the planar substrate with discrete thin-film resistors utilizing the familiar cylindrical shape. Nichrome parts have typical temperature coefficient of resistance (TCR) of 25ppm/°C for a planar substrate and 50ppm/°C for a ceramic core substrate. Tantalum-Nitride resistors tend to be slightly higher.

Bulk-Metal Foil

Bulk-metal foil resistors are made with a Nickel-Chromium alloy that is cemented to a planar ceramic substrate. The Nichrome alloy, substrate, and adhesive material are carefully balanced to achieve an overall low temperature sensitivity. The bulk-metal foil's 25,000Å thickness is significantly less susceptible to humidity than thin-film types.

Bulk-metal foil resistors are ultra-precision components. Generally, they offer tighter tolerance, better stability, and lower TCR's than their thin-film counterparts. Their high stability and uniformity makes them a good candidate for precision networks. The networks use hybrid type construction and offer extraordinary ratio stabilities (0.5ppm/°C). Unfortunately, bulk-metal technologies may cost two to five times that of film resistors.

Wirewound

Wirewound resistors are usually made by winding resistive wire of a specific diameter and characteristic around a core or card. Performance depends on the alloy used, wire lengths, diameter, and annealing process. Wirewound resistors can be ultra-precision components and are best suited in applications that require absolute accuracy, stability, power, or low resistance value. Wirewounds have excellent overload handling capability, but are poor candidates for high speed work due to inductive effects. Special winding schemes can greatly reduce this parasitic inductance, but never entirely eliminate it.

Table A1. Typical Resistor Characteristics

CHARACTERISTIC		CARBON COMPOSITION	THIN-FILM CARBON FILM	THICK-FILM CERMET	THIN-FILM NiCr FILM	WIREWOUND	METAL FOIL (MOLDED)	METAL FOIL (HERMETIC)
Ohmic Range		2.7M-100M	1M-4.7M	1M-3M	10M-3M	20k-468k	1k-250k	1k-250k
Absolute Accuracy*	Standard Available	5% 20%-5%	5.0%	1.0% 5.0%-0.1%	0.1% 1.0%-0.01%	0.01% 1.0%-0.005%	0.01% 1.0%-0.005%	0.01% 1.0%-0.001%
Temperature Coefficient*	Standard Available	– 5000ppm/°C	– 200ppm/°C – 100ppm/°C-–1500ppm/°C	100ppm/°C 25ppm/°C-200ppm/°C	10ppm/°C 5ppm/°C-25ppm/°C	5ppm/°C 1.0ppm/°C-20ppm/°C	2.5ppm/°C-8ppm/°C	0.6ppm°C
TCR Tracking*					1: (1-9), 1.0ppm/°C 1: (10-100), 2.0ppm/°C 1: (100-1000), 4.0ppm/°C	1: (1-4), 0.5ppm/°C 1: (5-10), 2.0ppm/°C	1: (1-4), 0.5ppm/°C 1: (5-10), 1.0ppm/°C	1: (1-4), 0.5ppm/°C 1: (5-10), 1.0ppm/°C
Ratio Matching*					1: (1-9), 0.005% 1: (10-100), 0.01% 1: (100-1000), 0.02%	1: (1-4), 0.005% 1: (5-10), 0.1%	1:(1-4), 0.005% 1: (5-10), 0.01%	1: (1-4), 0.005% 1: (5-10), 0.01%
Load-Life Stability*		1kHRS, 6% – 4%	3.0%	1.0%	1kHRS, 0.02%	10kHRS, 0.2%	2kHRS, 0.015% 10kHRS, 0.05%	2kHRS, 0.015%
Shelf-Life*		2.0%	0.1%	30ppm/YR	100ppm/YR	25ppm/YR	5ppm/YR	
Voltage Coefficient Of Resistance		– 0.02%/V		0.05ppm/V	0.1ppm/V	0.1ppm/V	0.1ppm/V	
Resistor Classification		General Purpose	General Purpose	Semi-Precision	Precision	Precision	Ultra-Precision	Ultra-Precision
Manufacturer's Part Number		Allen-Bradley** CB Series	International** Resistive Co.	International** Resistive Co.	International** Resistive Co. MAR5	Vishay/Ultronix** 105A	Vishay** S102 Series	Vishay** VHP1000

* ± Unless otherwise stated

** Parameters may vary between manufacturers

% = ppm × 0.0001
0.0001% = 1ppm
0.001% = 10ppm
0.01% = 100ppm
0.1% = 1000ppm
1% = 10000ppm

Thick-Film

Thick-film resistors are made from a paste mixture of Metal-Oxide (cermet) and binder particles, screen printed onto a ceramic substrate and fired at high temperatures. They are semi-precision components, with standard 1% tolerance and typical TC's of 100ppm/°C to 200ppm/°C.

Carbon Composition/Carbon Film

Carbon composition resistors are made from a large chunk of resistive material. They can handle large overloads for a short period of time. This is their main advantage over the other resistor technologies. They are general purpose components, not precision. Carbon composition resistors do not have constant TC's. TC's can vary anywhere between –2000ppm/°C to –8,000ppm/°C and have shelf-life stabilities of 2% to 5% of resistance value (20,000ppm/Yr to 50,000ppm/Yr).

Carbon film resistors are manufactured using a thin-film process. Initial tolerance and TC are similar to carbon composition. However, they do not have the high overload capability. The sole advantage is their low cost.

Resistor Manufacturers

1. Vishay/Ultronix
   461 North 22nd Street
   P.O. Box 1090
   Grand Junction, CO 81502
   (303) 242-0810

2. Vishay Resistive Systems Group
   63 Lincoln Highway
   Malvern, PA 19355
   (215) 644-1300

3. International Resistive Company
   P.O. Box 1860
   Boone, NC 28607
   (704) 264-8861

4. Julie Research Laboratories
   508 West 26th Street
   New York, NY 10001
   (212) 633-6625

5. Allen-Bradley Company, Inc.
   Electronic Components Division
   1414 Allen-Bradley Drive
   El Paso, TX 79936-4888
   (800) 592-4888

APPENDIX B

Capacitor Selection

Capacitor selection for voltage reference circuitry requires care. Capacitor parasitics can introduce errors. Typical capacitors found in reference circuitry include aluminum and tantalum electrolytics, ceramic, and polyester. Table B1 summarizes characteristics pertinent to reference applications. It reveals that equivalent value capacitors have electical characteristics that vary widely between different capacitor technologies.

Leakage current becomes an issue when an RC network filters a reference voltage. The leakage combines with the resistor to shift the output voltage. Leakage varies with time and temperature and varies from device to device. A low leakage capacitor must be used in these applications. The problem is illustrated by considering Figure B1. With R = 1M, a $1\text{x}10^{-12}$ leakage path in a capacitor creates a 1ppm error. Figure B2 is another approach to minimizing leakage induced errors. Here, the voltage across C1 is reduced to zero by bootstrapping via R1. Under these conditions C1's leakage current is effectively zero since there is 0V across it. C2's leakage appears in series with R1, rendering it harmless.

Output capacitors provide low output impedance at high frequencies. Large capacitors at the output of some references may cause oscillations. The capacitor introduces a feedback pole which reduces phase margin of the reference. Phase shift can be excessive with low effective series resistance (ESR) capacitors. The phase shift can be reduced by placing a small value resistor in series with the capacitor. If the phase shift is significant the reference will ring during transient conditions or simply oscillate. This condition is particularly significant for SAR type A/D converter applications. Here, the reference output must settle quickly or conversion errors will result. Consult manufacturers data sheet for recommended output bypassing techniques. Also, all references are not stable with all capacitive loads.

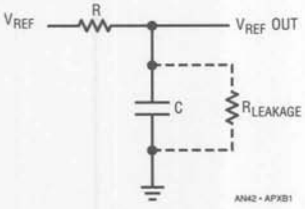


Figure B1. Leakage in the Capacitor Divides V_{REF}'s Output, Introducing Error

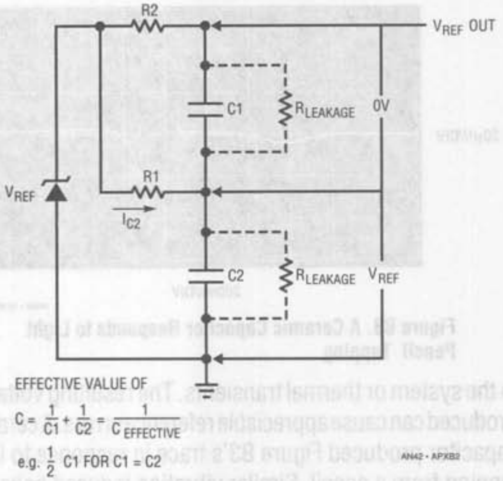


Figure B2. Bootstrapping Technique Minimizes Leakage Effects

Leakage and AC effects are not the only sources of problems. Some ceramic capacitors have a piezoelectric response. A piezoelectric device generates a voltage across it's terminals due to mechanical stress, similar to the way a piezoelectric accelerometer or microphone works. For a ceramic capacitor the stress can be induced by vibrations

Table B1. Typical Capacitor Characteristics

CHARACTERISTIC	ALUMINUM SOLID ELECTROLYTIC	POLYESTER FILM	SOLID TANTALUM ELECTROLYTIC	MULTILAYER CERAMIC	ALUMINUM ELECTROLYTIC	UNIT
Capacitance	0.47	0.47	0.47	0.47	0.47	μF
ESR* 100kHz	0.198	0.456	4.5	0.062	5.4	Ω
Leakage Current* @ 5V	20	0.03	30	0.16	175	nA
Manufacturer's	SANYO	SANYO	KEMET	KEMET	SANYO	

*Typical

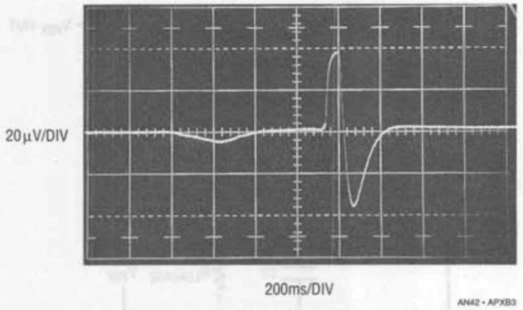


Figure B3. A Ceramic Capacitor Responds to Light Pencil Tapping

in the system or thermal transients. The resulting voltages produced can cause appreciable reference errors. A ceramic capacitor produced Figure B3's trace in response to light tapping from a pencil. Similar vibration induced behavior can masquerade as reference instabilities.

Capacitor Manufacturers

1. Nichicon (America) Corporation
   927 East State Parkway
   Schaumburg, IL 60195
   (708) 843-7500
2. Sanyo Video Components (USA) Corporation
   1201 Sanyo Avenue
   San Diego, CA 92073
   (619) 661-6322
3. United Chemi-Con, Inc.
   9801 West Higgins Road
   Rosemount, IL 60018
   (312) 696-2000
4. Illinois Capacitor, Inc.
   3757 West Touhy Avenue
   Lincolnwood, IL 60645
   (312) 675-1760
5. Kemet Electronics
   P. O. Box 5928
   Greenville, SC 29606
   (803) 963-6300

APPENDIX C

Trimming Techniques

It is often necessary to adjust a resistor's value in precision circuits. The desired value may not be available or readily predictable. Either case necessitates a trim.

For optimum stability and adjustability, always use the smallest value of trim resistance that gives the required range of adjustment. This reduces the stability and drift due to the poor matching characteristics between the fixed resistor and trim resistor. There seems to be a tendency for designers to use a 0.01% resistor with a 1% trim adjustment. Don't pay for accuracy that isn't needed.

Avoid the extremes of resistance range when using a trimmer. Although the entire range will meet the stated specifications, mid-range values tend to perform (TC, tracking, etc.) better than low and high values.

Typical resistor trimming techniques are shown in Figure C1. Selecting the appropriate method depends on various factors including trim range, temperature stability, long term stability, manufacturing processes, and calibration procedures. Figure C1(A) is a general purpose trim. This technique has an extremely wide range. Equation 1 represents the percentage change in the desired resistor value, R_{EQ}, for a change in trim resistance. This equation is useful when determining the optimum trimmer resistance and is provided for the various trimming schemes. If increased stability is required, the circuit in Figure C1(B) can be used. In this case, increased stability is achieved at the expense of a narrower trim range. R1 must have a tighter absolute tolerance than in the previous circuit for this technique to be useful. For improved resolution, a resistor can be placed in series with this network, see Figure C1(C). This approach is best suited for ultra-precision applications, since it has the highest resolution.

In some applications potentiometers may be unreliable. In these cases, resistor value can be trimmed by selecting the appropriate series resistor value, see Figure C1(D). However, this requires numerous resistors that must be hand picked in production. An alternative approach is to use a binary weighted trim as in Figure C1(E). The resistance is trimmed by opening various links. With just four resistors there are 16 different resistor values possible. With this method, the need for a bin of resistors on the production floor is eliminated.

Often, the best solution is to have coarse and fine adjustments. This can provide a more stable resistor value. Figure C1(F) illustrates various ways to implement this approach.

In many voltage reference circuits it is necessary to scale and buffer the output of a reference to some calibrated voltage. The trim sets the output voltage to the desired degree of accuracy. Figure C2 shows various techniques for trimming the buffered output. These examples utilize various resistor trimming techniques to set output voltage.

Figure C2 (B) shows a simple voltage reference circuit. The reference is connected to the non-inverting input of an op amp. The feedback resistors around the op amp scale the output voltage to the approximate output voltage. The potentiometer fine tunes the output to the desired value.

The temperature coefficient (TC) of the op amps gain setting resistors can add significant error to the reference output due to ambient temperature changes. The circuits temperature coefficient is primarily set by the ratio matching characteristics of the resistors, as opposed to their absolute tolerance. Matched resistor sets provide a decade or greater improvement in tempco performance than individually specified resistors. Therefore, resistors that have relatively high TC's can be used if they track.

Another interesting characteristic of this circuit is the magnitude of output voltage drift with temperature caused by the gain setting resistors. The drift error contributed by the resistors is determined by multiplying their ratio (R1/R2) by their TCR tracking tolerance. For example, to obtain a 10V output from a 6.9V reference the gain setting resistors ratio needs to be about 0.45. This means that 10ppm/°C resistor TCR tracking effects output voltage by only 4.5ppm/°C. Therefore, for minimum effect of the resistor's TCR tracking, it is desirable to have the reference voltage be a large percentage of the output voltage.

The remaining circuits in Figure C2 show some alternatives for trimming a reference voltage. The particular circuit selected depends upon the required performance specifications and manufacturing processes.

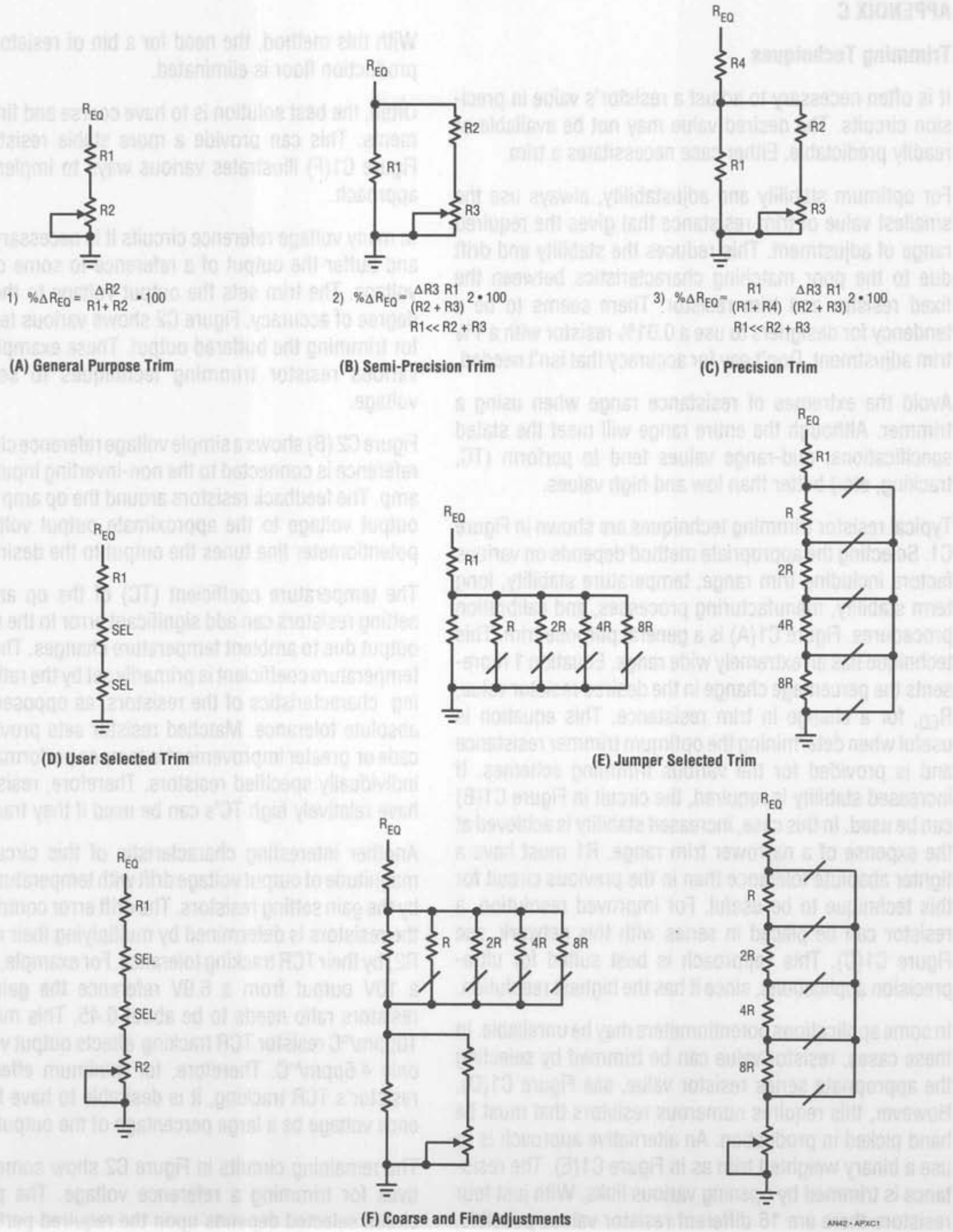


Figure C1. Resistor Trimming Techniques

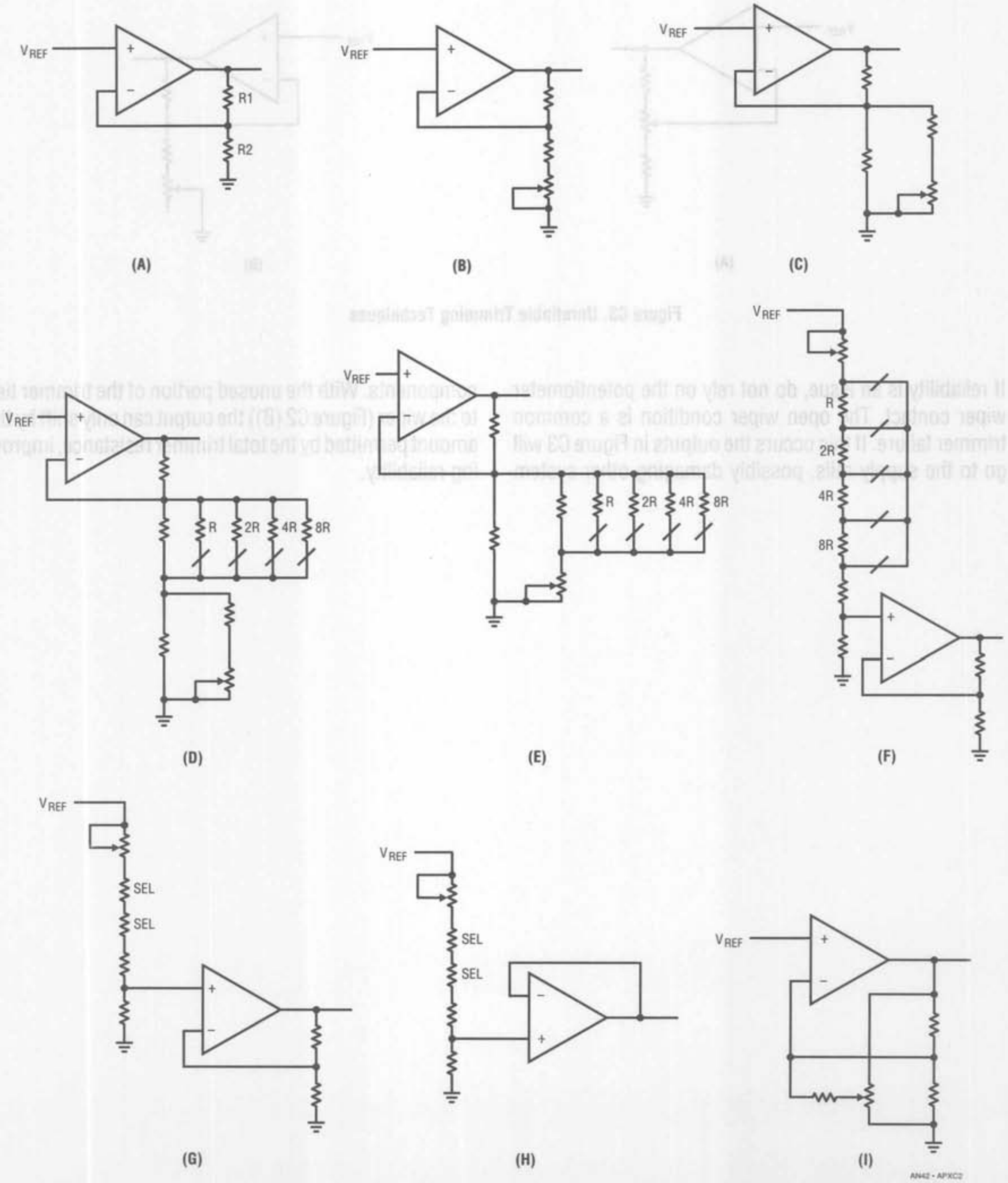
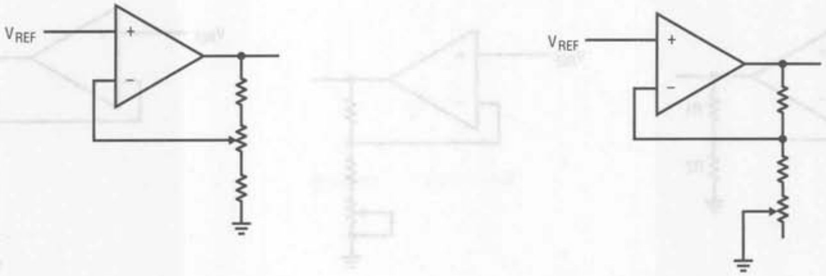


Figure C2. Output Voltage Trimming Techniques



(A)

(B)

Figure C3. Unreliable Trimming Techniques

If reliability is an issue, do not rely on the potentiometer wiper contact. The open wiper condition is a common trimmer failure. If this occurs the outputs in Figure C3 will go to the supply rails, possibly damaging other system components. With the unused portion of the trimmer tied to the wiper (Figure C2 (B)) the output can only shift by the amount permitted by the total trimmer resistance, improving reliability.