A3 INTERNAL CIRCUIT FEATURES

A3.1 Basic Regulator Operation

The basic circuit functions included in all of the three-terminal regulators are shown in Figure A3.1.

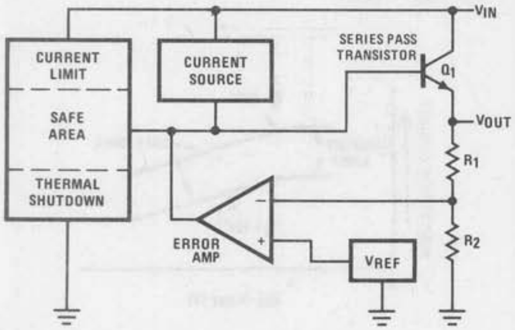


FIGURE A3.1. Basic Regulator

V_{REF} is a temperature-stabilized voltage developed from a zener or ΔV_{BE} circuit as discussed below. The error amplifier compares V_{REF} with a fraction of the output voltage determined by the feedback ratio of $R_2/(R_1 + R_2)$, and thereby controls the base drive of the series pass transistor to provide regulation.

All the regulator protection circuits, current limit, safe area and thermal shutdown, when activated, limit or turn off the base drive for the series pass transistor, so output current is either limited or the series pass transistor is turned completely off.

A3.2 The Voltage References

There are two types of references which are commonly used in the regulators. The first, known as a "band-gap" or ΔV_{BE} reference is shown in simplified form in Figure A3.2. Operation of this reference, which was first used in National's LM109, relies on the fact that two monolithic transistors operating at different current densities develop a predictable voltage, ΔV_{BE}, at the emitter of Q_2:

$$\Delta V_{BE} = \frac{kT}{q} \ln \frac{I_1}{I_2}$$

This voltage, which has a positive temperature coefficient (TC), is amplified and added to the base-emitter voltage of Q_3, which has a negative TC:

$$V_{REF} = \phi_3 + \frac{R_2}{R_1} \Delta V_{BE}$$

If the gain R_2/R_1 is properly chosen, the negative TC of ϕ_3 can be made to cancel the positive TC of ΔV_{BE} producing nearly zero temperature drift.

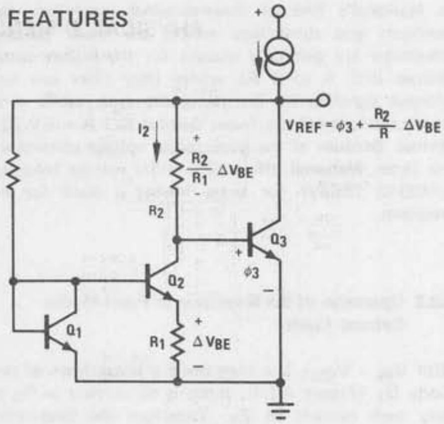


FIGURE A3.2. Simplified Schematic of Band Gap Reference

Advantages of the band-gap reference compared with a zener reference are: (1) low noise, since avalanche breakdown devices such as "zeners" are noisy, and (2) better long-term stability. This last property results since transistor V_{BE}'s are very stable and insensitive to surface effects. Disadvantages include: (1) it is more difficult to accurately control initial voltage tolerance since V_{BE} varies with transistor base width, (2) temperature drift is usually higher, and (3) thermal gradient effects (see below) are much more severe. The gradient effects arise because the band-gap reference consists of many components, each of which sees slightly different temperatures as heating occurs in the output transistor.

The major drawback of the zener reference, poor long-term stability, can be eliminated if the zener breakdown site is placed below the die surface where it is shielded from high field effects of mobile surface ions. It is difficult to achieve a controlled subsurface breakdown with normal diffusion techniques, but by using a new technology known as *ion implantation*, one can bury a highly doped region below the surface, thereby generating a stable and reproducible avalanche diode (see Figure A3.3).

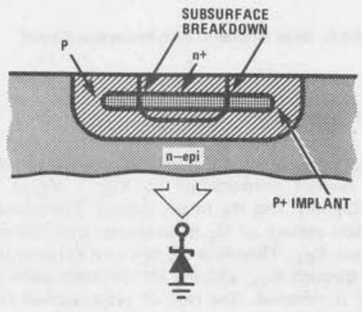


FIGURE A3.3. Zener (avalanche) Reference Employing Ion Implantation to Produce a Subsurface Breakdown

In National's line of three-terminal regulators, both band-gap and subsurface zeners are used. Band-gap references are generally chosen for the higher current devices (0.5 A to 3 A), where they offer low noise without significantly increasing die area, while zeners are chosen for small die, lower current (0.1 A and 0.25 A) devices. Because of the good initial voltage control with the zener, National offers ±2% initial voltage tolerances (LM3910 family) for users having a need for high precision.

A3.3 Operation of the Regulator in Fault Modes Current Limit

With V_{IN} - V_{OUT} less than the 6 V breakdown of zener diode D_1 (Figure A3.4), there is no current in R_3 and only base current in R_4. Therefore the base-emitter voltage on the current limit transistor Q_2 essentially equals the voltage developed across current limit sense resistor R_{CL}. As the regulator output current increases the voltage across R_{CL} and the base-emitter of Q_2 increases until Q_2 turns on, preventing additional base drive from reaching the series pass transistor Q_1 and thereby limiting the output current.

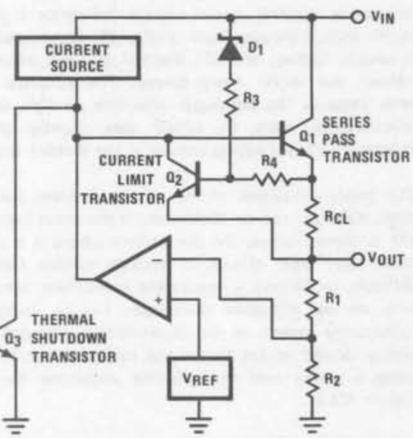


FIGURE A3.4. Basic Regulator with Protection Circuit

Safe Area Protection

With V_{IN} - V_{OUT} greater than the breakdown voltage of D_1, current proportional to V_{IN} - V_{OUT} flows through D_1, R_3, and R_4 to the output. This causes the base-emitter voltage of Q_2 to be greater than the voltage drop across R_{CL}. Therefore Q_2 turns on at lower output currents through R_{CL} and the current limit point of the regulator is reduced. The rate of reduction of current limit with increase in V_{IN} - V_{OUT} is equal to

$$\frac{\Delta I_{CL}}{\Delta(V_{IN} - V_O)} = -\frac{R_4}{R_3 R_{CL}}$$

amps per volt. This is the slope of the safe area curves in Figure A3.5. These curves also show a reduction in current limit with increased junction temperature, which results since a reduced base-emitter voltage is required to turn on the current limit transistor as its junction temperature increases. It is important to note in selecting a regulator that the safe area circuitry causes the maximum output current to drop significantly for large V_{IN} - V_{OUT}.

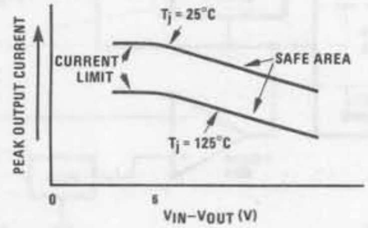


FIGURE A3.5. Peak Output Current Graph

Thermal Shutdown

The thermal shutdown transistor, Q_3 (Figure A3.4), is physically located next to Q_1, the major heat source on the die. The base of Q_3 is held at approximately 0.4 V, which is below its turn-on voltage at room temperature. As the die temperature increases, the voltage required to turn on Q_3 will decrease to 0.4 V. When Q_3 turns on it removes all base drive from Q_1 and turns off the output. Various regulators have thermal shutdown temperatures ranging from 150°C to 190°C. The regulators also have hysteresis built into their thermal shutdown circuits so that the shutdown temperature is several degrees above the temperature at which the regulator turns back on. This reduces the *chance* of high frequency thermal oscillations.

A3.4 Output Impedance, Line and Load Regulation: Thermal and Electronic Effects

Few people realize that many of the important specification limits of high power regulators are determined by thermal characteristics rather than electrical ones. To illustrate, suppose a high current step load is placed on a regulator and the output voltage is observed on a storage oscilloscope as shown in Figure A3.6. The response is due to both electronic and thermal effects.

a) Initially a large negative spike (not shown in Figure A3.6) can occur due to the presence of regulator and circuit lead inductance.

b) This is followed by the electronic response of the regulator loop which will consist of a small negative step of a few microseconds duration. Details of this response are effected by the load

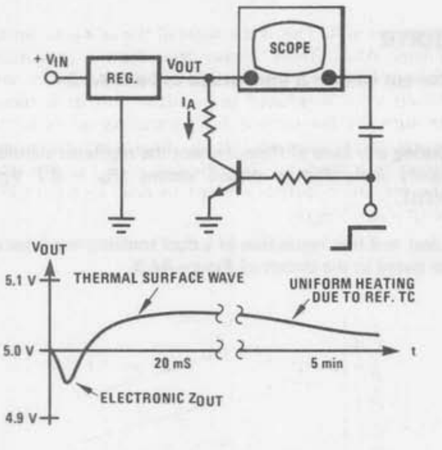


FIGURE A3.6. Thermal and Electronic Effects on Output Impedance for a Representative Regulator

capacitor used and by internal wirebond resistance in the regulator. Wirebond resistance ranges from approximately 150 milliohms in the 100 mA TO-92 regulators to 40 milliohms in the 1 A LM340. The 3 A regulators use electronic compensation to cancel effects of wire resistance, so this effect, which would otherwise dominate output impedance, is reduced.

c) As the electronic response decays, a third exponential response is observed with a time constant in the 20 mS to 40 mS region (see Figure A3.6). This is the major thermal response which results from the "thermal surface wave." A qualitative feel for this thermal effect can be obtained by studying the simplified thermal model of the IC die and package shown in Figure A3.7. Referring to Figure A3.7 (b), we see that the power transistor and reference circuitry can be visualized as being coupled thermally by a distributed RC transmission line. This line is, of course, the electrical analog of a thermal line, with temperature replacing voltage, thermal resistances replacing normal Rs, etc.

Applying this electrical analog for a step increase of power in the pass transistor, it is seen that there is an immediate increase in the power transistor temperature, T_P. Temperature gradients then begin to set up across the die as the heat propogates through the die (transmission line), see Figure A3.7 (a). The various components of the reference circuitry now are no longer at a single temperature, so small thermally-induced shifts occur in the reference voltage. These shifts then reflect to the output as a change in output voltage in response to a change in *dissipated power* in the pass transistor. We see, therefore, that changes in either load current or input voltage can cause a thermal response, so both load and line regulation have thermal components.

d) The last portion of the response in Figure A3.6 shows a long term (minutes) settling effect, which is due largely to uniform heating effects in the die, header and sink. Such heating gives rise to normal temperature drift effects in the voltage reference which then reflect as small output voltage changes.

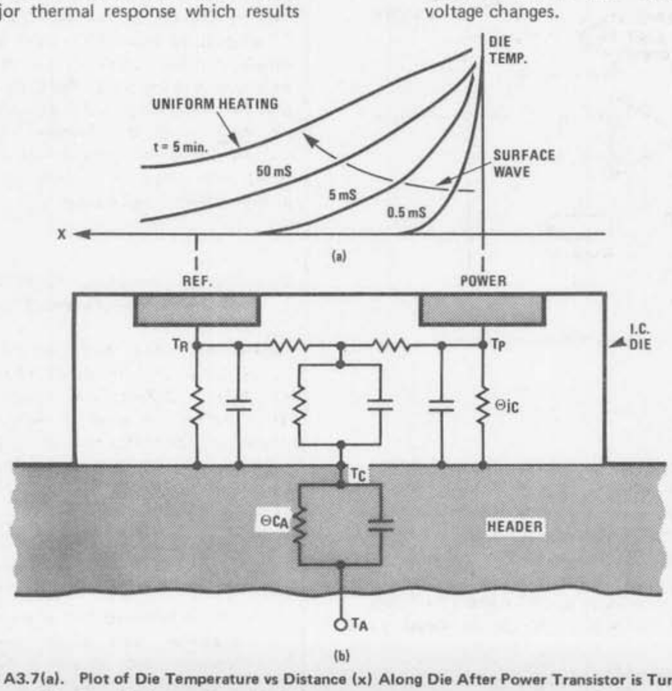


FIGURE A3.7(a). Plot of Die Temperature vs Distance (x) Along Die After Power Transistor is Turned On.
(b). Simplified thermal model of IC power regulator mounted to metal header.

A4 TEST CIRCUITS

Figure A4.1 illustrates a circuit for testing line and load regulation, I_Q variations and output voltage of a positive three-terminal regulator. For line and load regulation, a pulse technique is used. An LM555CN timer, connected as an astable multivibrator, is the pulse generator. Duty cycle and pulse width can be adjusted with R_A and R_B. The test method is summarized in Table A4.1.

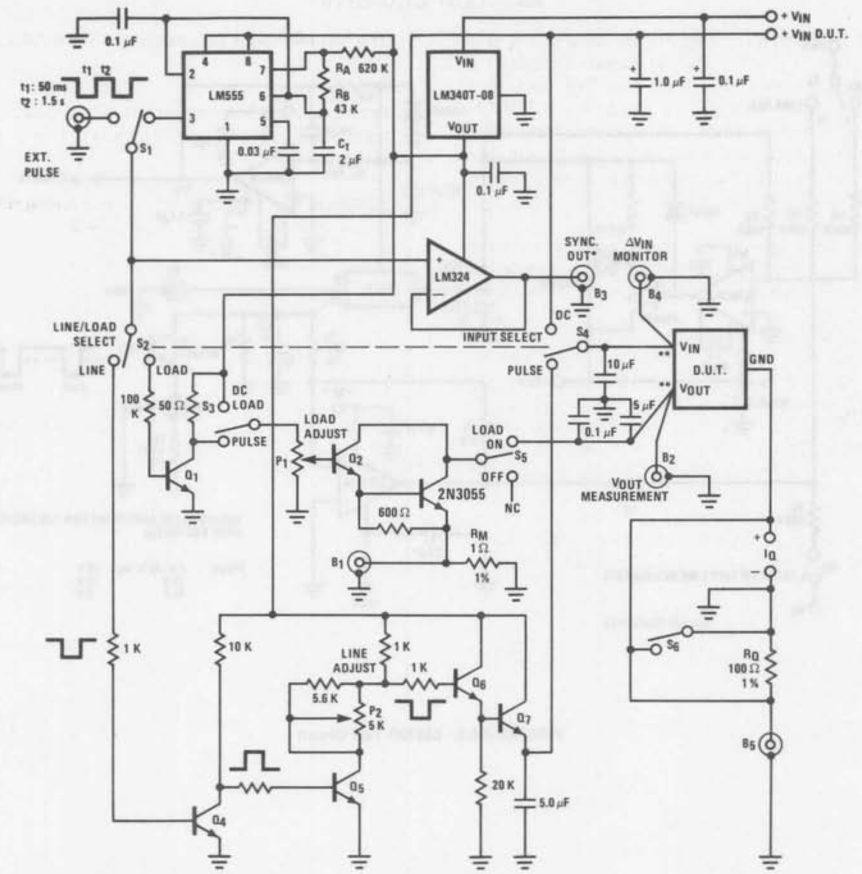
Notice that line regulation is measured with constant load and pulsed input voltage, whereas load regulation is measured with constant input voltage and pulsed load.

Figure A4.2 shows a similar test circuit for negative three-terminal regulators. The schematic does not include a pulse generator, but an LM555CN can be used for generating variable amplitude negative pulses to drive the PNP switch Q_3. The loop composed of the two LM101As insures that live voltage variation is within data sheet specifications for LM120, independent of the value of the fixed output voltages of the negative regulator. An LM101A converted as a current-to-voltage converter, is used to monitor quiescent current variations during the load and line regulation test.

The test method is summarized in Table A4.2.

During any kind of measurement the regulator should be lightly preloaded as already shown [R_P = 0.2 V_{OUT} (kΩ)].

Load and line regulation of a dual tracking regulator can be tested in the circuit of Figure A4.3.



NOTE: SELECT Q_3, Q_7 ACCORDING TO THE RATED POWER OF THE REGULATORS
HEAT SINK Q_3, Q_7
Q_2, Q_6, Q_1, Q_4, Q_5 : 2N5030
*OPTIONAL
**KELVIN CONTACTS

FIGURE A4.1. Test Circuit for Three Terminal Positive Regulators

TABLE A4.1.

TEST	SWITCH POSITIONS					Measurement at Connector
	S_2	S_3	S_4	S_5	S_6	
Load Regulation (pulsed mode)	LOAD	PULSE	DC	ON	CLOSED	B_2
Line Regulation (DC load ON)	LINE	DC	PULSE	ON	CLOSED	B_2
Quiescent current, I_Q	LOAD	DC	DC	ON	OPEN	B_5
I_Q change: 1) with load	LOAD	PULSE	DC	ON	OPEN	B_5
2) with line	LINE	DC	PULSE	ON	OPEN	B_5
Output Voltage	LOAD	DC	DC	ON	CLOSED	B_2

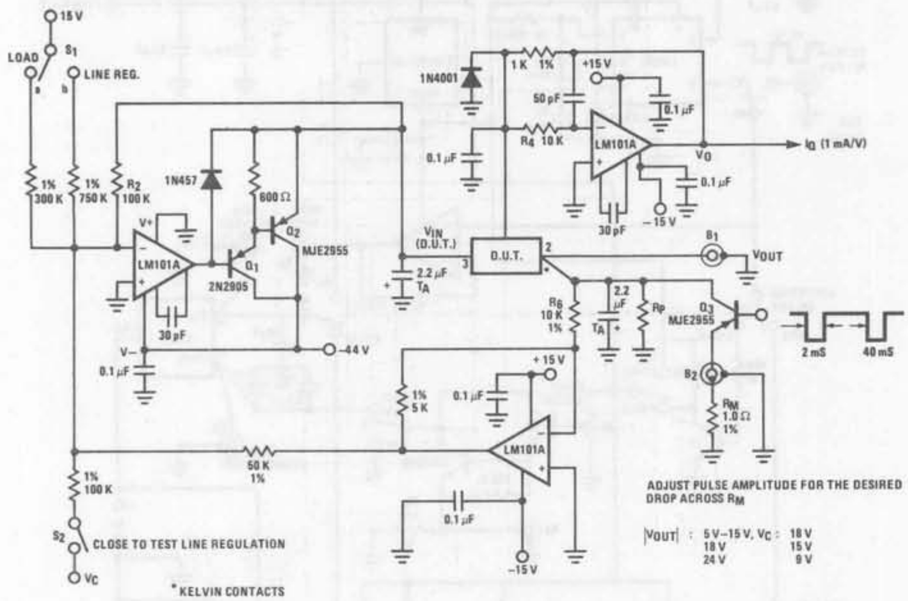


FIGURE A4.2. LM320 Test Circuit

TABLE A4.2

TEST	Q_3	S_1	S_2	Measurement at Connector
Load Regulation	ON-OFF	a	open	B_1
Line Regulation	OFF	b	open-close	B_1
Quiescent current, I_Q	OFF	a	open	V_O
I_Q change: 1) with load	ON-OFF	a	open	V_O
2) with line	OFF	b	open-closed	V_O

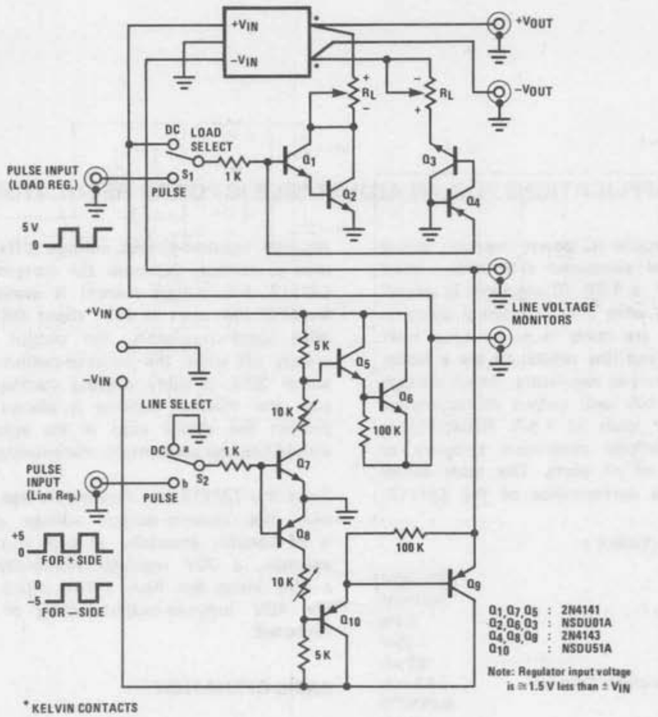


Figure A4.3. Line and Load Regulation Test Circuit for the Dual Tracking Regulators

TABLE A4.3.

TEST	S_1	S_2	Measure
Line regulation	DC	PULSE	$\pm V_{OUT}$
Load regulation	PULSE	DC	$\pm V_{OUT}$

A5 RELIABILITY

IMPROVING POWER SUPPLY RELIABILITY
AN182 DEVICE RELIABILITY

For steady state operation within the operating junction temperature range of the part, most failure modes are due to die surface related effects such as zener voltage drift due to field effect changes caused by movement of ions in the oxide. After extensive life testing, National Semiconductor has developed some average "acceleration factors" relating increased surface related failure rates to increased junction temperature. For example: an IC device operating steady state at $T_J = 125°C$ for 500 hours will experience approximately the same failure rate as if operated at $T_J = 70°C$ for 72,500 hours. The acceleration factor from 70°C to 125°C (T_J) would be 145. From 125°C to 150°C (T_J) the acceleration factor is 6.3. This indicates the greatly increased part lifetime the user can realize by maintaining the part at a low operating junction temperature.