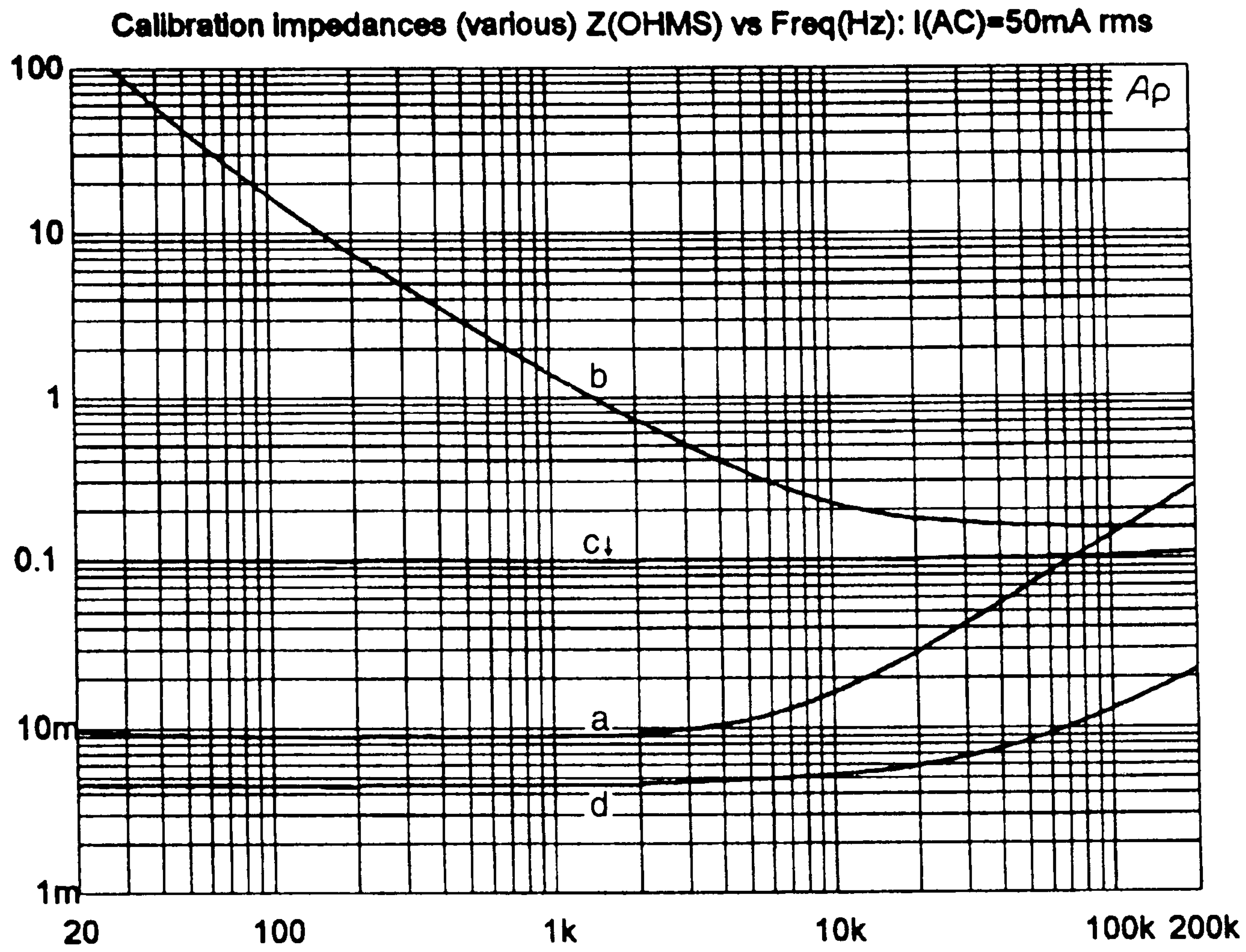

FIGURE 17: Z measurement calibration impedances, a) 12" loop of #18AWG spaced 1"; b) 120µF/25V HFQ; c) 0.1Ω±1%; d) ZEROHM jumper.

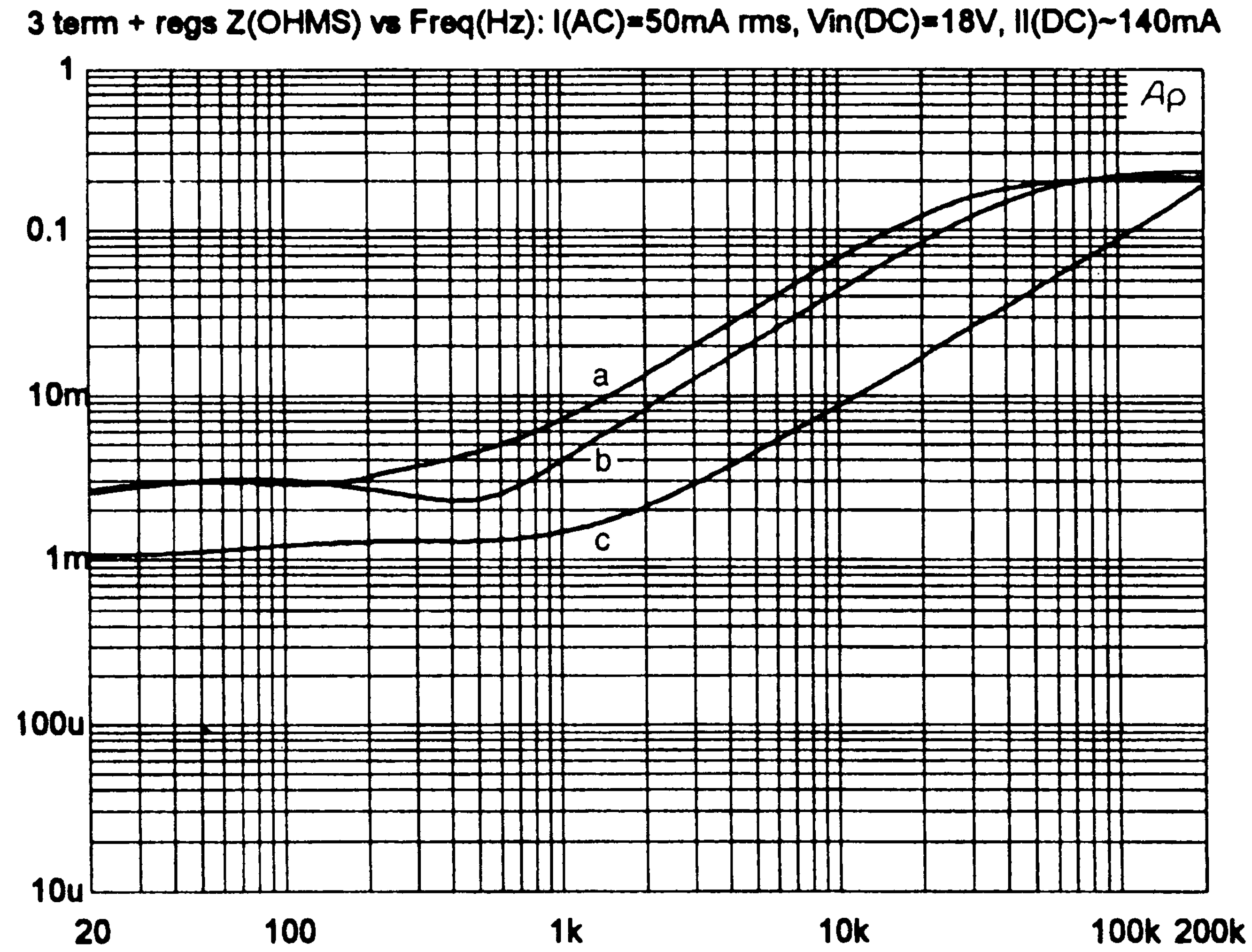

FIGURE 18a: Three-terminal positive regulator Z_O performance, a) 7815; b) 317; c) 1085.

ference mentioned above.

With C_{ADJ}, the regulator's AC gain is reduced essentially to unity, and the noise at the output consists of the basic bandgap reference cell within the device. This data amplifies the point that among the various three-terminal regulators the adjustable units offer best performance when the adjustment pin is bypassed. *Note that the scale of this plot also ranges from 1µV to 0.1V.*

High-Performance Topologies and Noise

A plot of high-performance negative regulator noise is shown in *Fig. 16a* (note scale change). Before comparing the various regulators, it is useful to explore how topology affects noise results. In this case the topology involves the specifics of how you choose the reference device and interface to the amplifier. These higher-performance regulators use as their basic reference the industry-standard 329 diode, a low-noise, *buried zener* IC, which offers the lowest self-generated noise among the various reference types.[6] For the typical 6–7V breakdown voltage, the noise is on the order of 100nV/√Hz.

This may sound like only a factor of two or so below popular 2.5V bandgap-based IC references such as the AD680, but as a percentage of full scale, the buried zener noise is closer to 6–7× lower and is thus an optimum choice from a noise standpoint. Further, by carefully controlling filtering and AC scaling within the regulator circuit, you can suppress the noise of the reference diode to negligible proportions.

Figure 16a shows the noise of an unbypassed 329 diode as operated within the Fig. 4 POOGE 5.51 regulator (a), which is roughly flat with frequency (considering the 3dB/octave upward slope). The 1kHz noise is just about 100nV/√Hz, which is typical. Bypassing can reduce the effective diode noise as it appears at a regulator's output, but the degree to which this may be possible depends upon the surrounding circuit impedances.

Since the basic 329 dynamic impedance is less than 1Ω, bypassing it directly requires rather heroic capacitance values, and even then it will only be effective at high frequencies. In Fig. 4 for example, the reference voltage appears at the error amplifier emitter, AC bypassed by the 560µF capacitance with a Z of ≅0.25Ω at 1kHz. As a result, bypassing reference noise in this configuration can only be effective above 1kHz, and limited in degree.

The noise output of the Fig. 4 POOGE 5.51 regulator (b), coincidentally, is also about 100nV/√Hz at 1kHz. While it may seem odd that the regulator shows a noise level the same as its (unbypassed) internal reference at 1kHz, in this case it is because of the filtering effects. Above 1kHz, the regulator noise output drops considerably due to filtering, while below, the noise rises above that of the reference, as you would expect. While the POOGE 5.51 design is quite effective for its simplicity, ultra-low noise is not its strongest suit. Nevertheless, the noise is still more than competitive with three-terminal regulators, particularly at high frequencies.

The high-performance op-amp-based negative regulators (c, d, e) reveal sequentially decreasing output noise. All of the op amp regulator designs can more effectively low-pass-filter the reference noise, because they use additional series resistance between the reference and the amplifier.

This noise filter, for example R1-C4 of Fig. 8b (or 8a), allows you to easily lower the filter corner frequency, in this case to 2.6Hz. It dramatically affects regulator noise, which you can appreciate by comparing any of the three op amp regulator curves to that of the unbypassed 329 curve. For frequencies below 100Hz, the low-pass filter is less effective, which shows up as the rise in low-frequency noise for all these regulators.

Other Performance Factors

Another topological detail which minimizes output noise is the connection of an AC feedback capacitor, such as C3 of Fig. 8a or 8b. This capacitor, used in the original Sulzer regulator to lower output impedance, also decidedly affects noise. Without it, the op amp amplifies its own noise and that of the filtered reference by the output gain factor (V_{OUT} equation of Fig. 1). With it, the op amp amplifies these noises by a factor of unity. For the 5–20V output range regulators, the net difference with/without this capacitor can be 6dB or more, which is important for high performance.

At frequencies of 1kHz or more, the differences in noise generally follow the basic voltage noise characteristic of the op amp under test. For example, the specified voltage noise of the AD848, 5534, and AD797 follows a decreasing

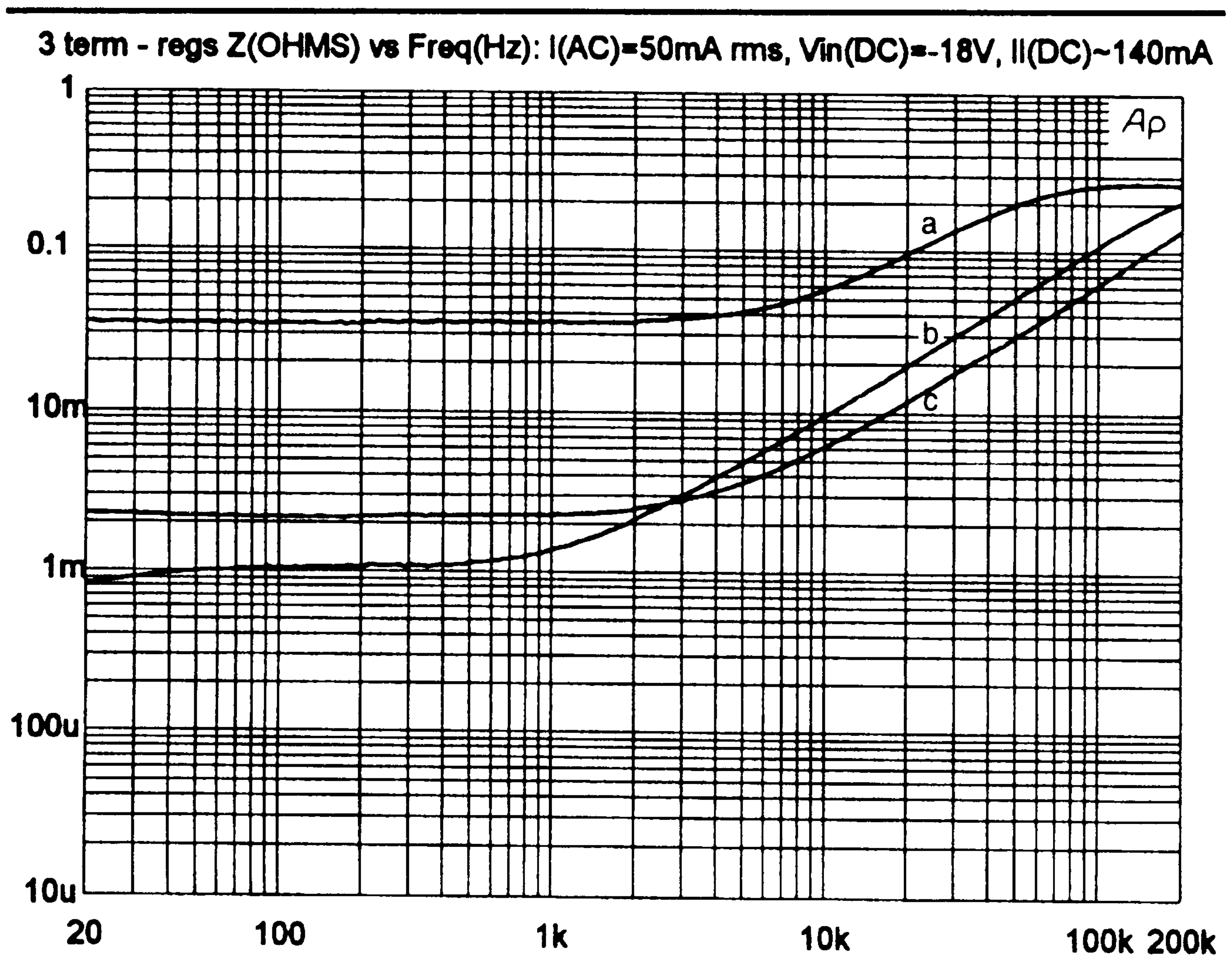

FIGURE 18b: Three-terminal negative regulator Z_O, a) 7915; b) 1033; c) 337.

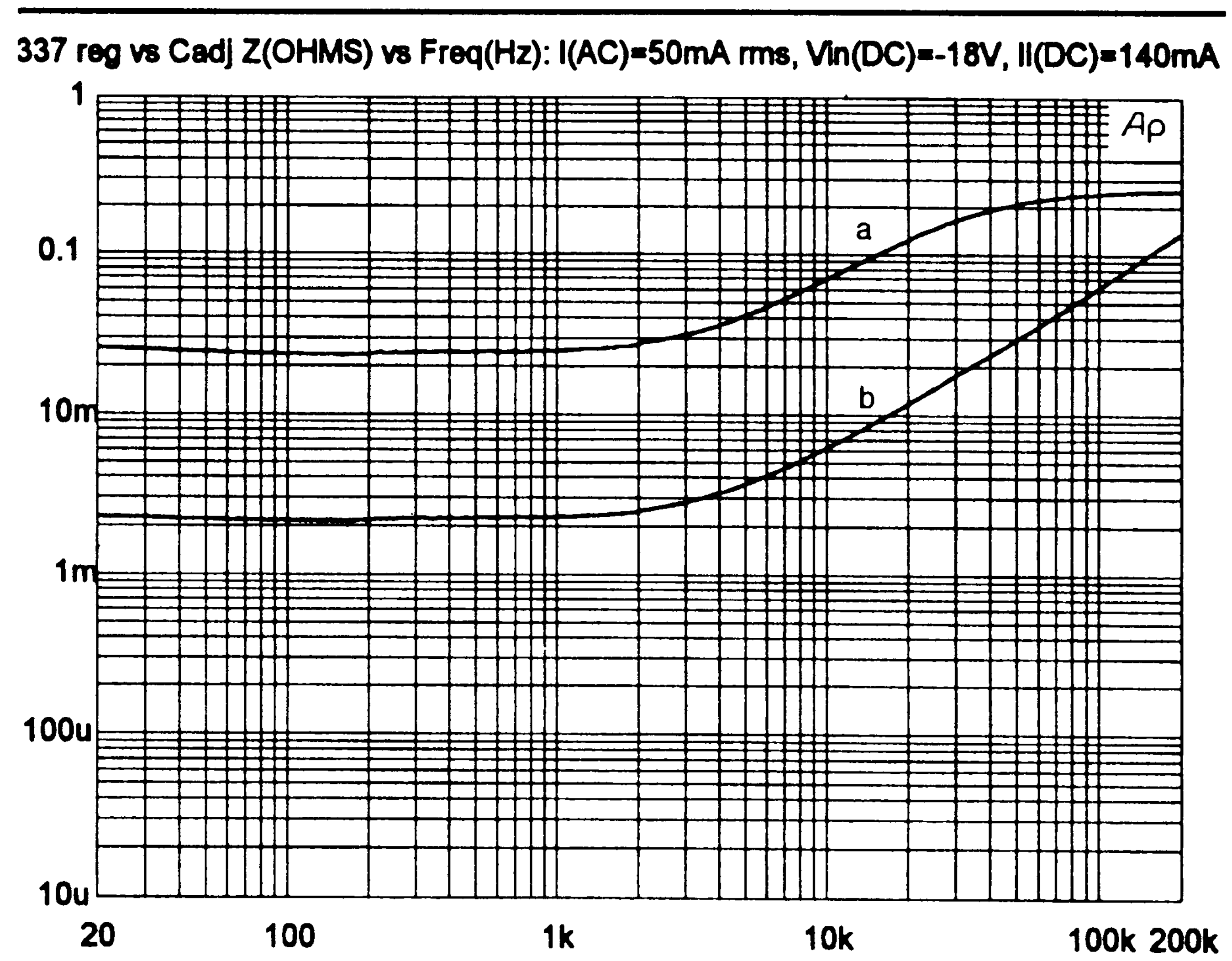

FIGURE 19: 337 regulator Z_O vs C_{ADJ}; a) C_{ADJ} = 0; b) C_{ADJ} = 100µF.

sequence, which is also depicted by the three noise curves, representing the noise outputs of Fig. 8b with the AD848 (c) and AD797 (e), and Fig. 7b with the 5534 (d).

However, since the 1kHz noise level for any of these regulator designs is below 10nV/√Hz, it begins to push the resolving power of the noise test preamp (*Fig. 13a*). As a result, the actual noise levels, which appear to be about 6, 4, and 2.8nV/√Hz, respectively, are even lower. This is due to the ≅2.6nV/√Hz preamp noise, which sets a lower limit to noise resolution. However, their *relative* order is valid as shown.

Figure 16b shows a plot of high-performance positive regulator noise, which generally follows the pattern established for the negative regulators of *Fig. 16a*, with some variations in the POOGE 5.51 regulator of Fig. 3 (a) and the Sulzer regulator of Fig. 7a (c). The two variations of the Fig. 8a circuit with the AD848 and AD797 (b and d) are a bit better than the Sulzer circuit of Fig. 7a below 100Hz.

In the sub-100Hz range, however, final noise performance of these op amp regulators can be a function of the filtering as well as the op amp (and the setup, of course). The Fig. 8a circuit at these frequencies is more limited by the filter than by the op amp, since the AD848 and AD797 curves tend to merge, even though the two devices have a roughly 5/1 different voltage noise.

Finally, a trace representing the setup residual noise (e) is added to this plot, which closely parallels the AD797's curve above 1kHz. This indicates that for the AD797 at least, the true regulator noise is less than this setup can resolve at the high frequencies.

5V Regulator

As I mentioned earlier, the reference device itself can limit noise, even in instances of low-pass filtering. While buried zener reference types offer the lowest inherent noise, they are not always available to an application, since they must operate from at least ≅7V. For a 5V regulator with low dropout, a low-voltage bandgap reference is therefore your only choice. The logic regulator of Fig. 9 has evolved from the regulator of reference 15 and operates with a three-terminal 2.5V bandgap reference at U2, either an AD780 or an AD680. The AD780 has the lower output noise, ≅100nV/√Hz versus ≅250nV/√Hz.

You can use either IC in U2 position of the Fig. 9 circuit, and *Fig. 16c* shows the noise output from this circuit as a function of the reference IC in (b) and (c). For this test the op amp is the AD848, and for frequencies above 1kHz, the noise is comparable to that of the AD848 in the regulators of Figs. 8a and 8b, independent of the reference. While below 100Hz the AD780 is the quieter of the two U2 devices, it is unlikely that low-level variations of 20Hz noise in a logic regulator will have serious audible consequences.

Figure 16c also shows the noise of the 7805CT 5V three-terminal regulator (a). The 1kHz measurement of the Fig. 9 circuit using the AD848 op amp is about 20× better than the @120nV/√Hz 1kHz reading of the 7805. When the noise of the measurement preamp is accounted for, the 1kHz of the Fig. 9 circuit is more like @5nV/√Hz with the AD848, and optionally lower yet with the AD797.

Z_O Tests

Output impedance tests for regulators are among the more important and identifiable. In general, the lower the Z_O the higher the regulator's quality. These

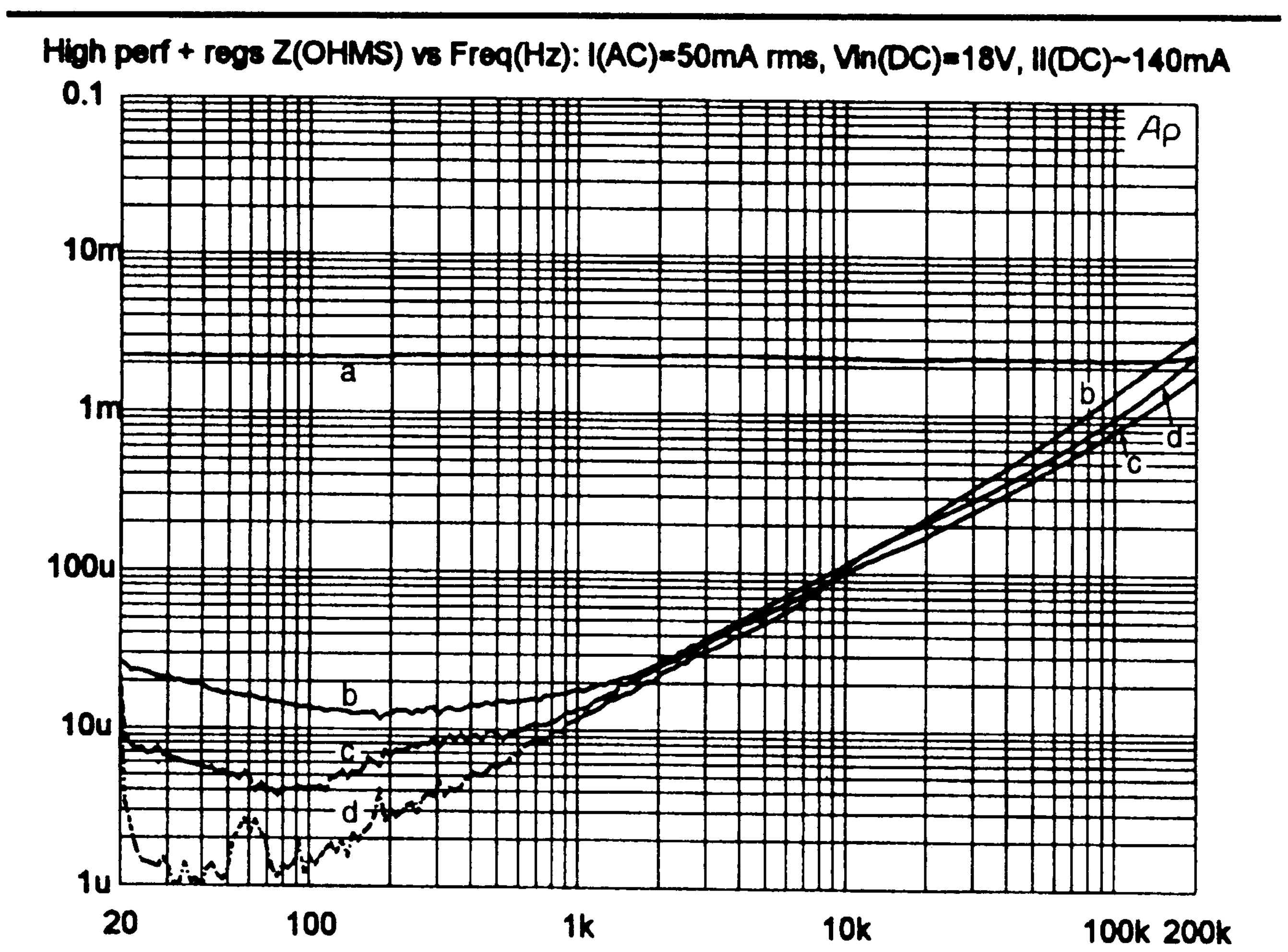

FIGURE 20a: High-performance positive regulator Z_O, a) POOGE 5.51 (Fig. 3); b) Sulzer (Fig. 7a); c) AD848 (Fig. 8a); d) AD797 (Fig. 8a).

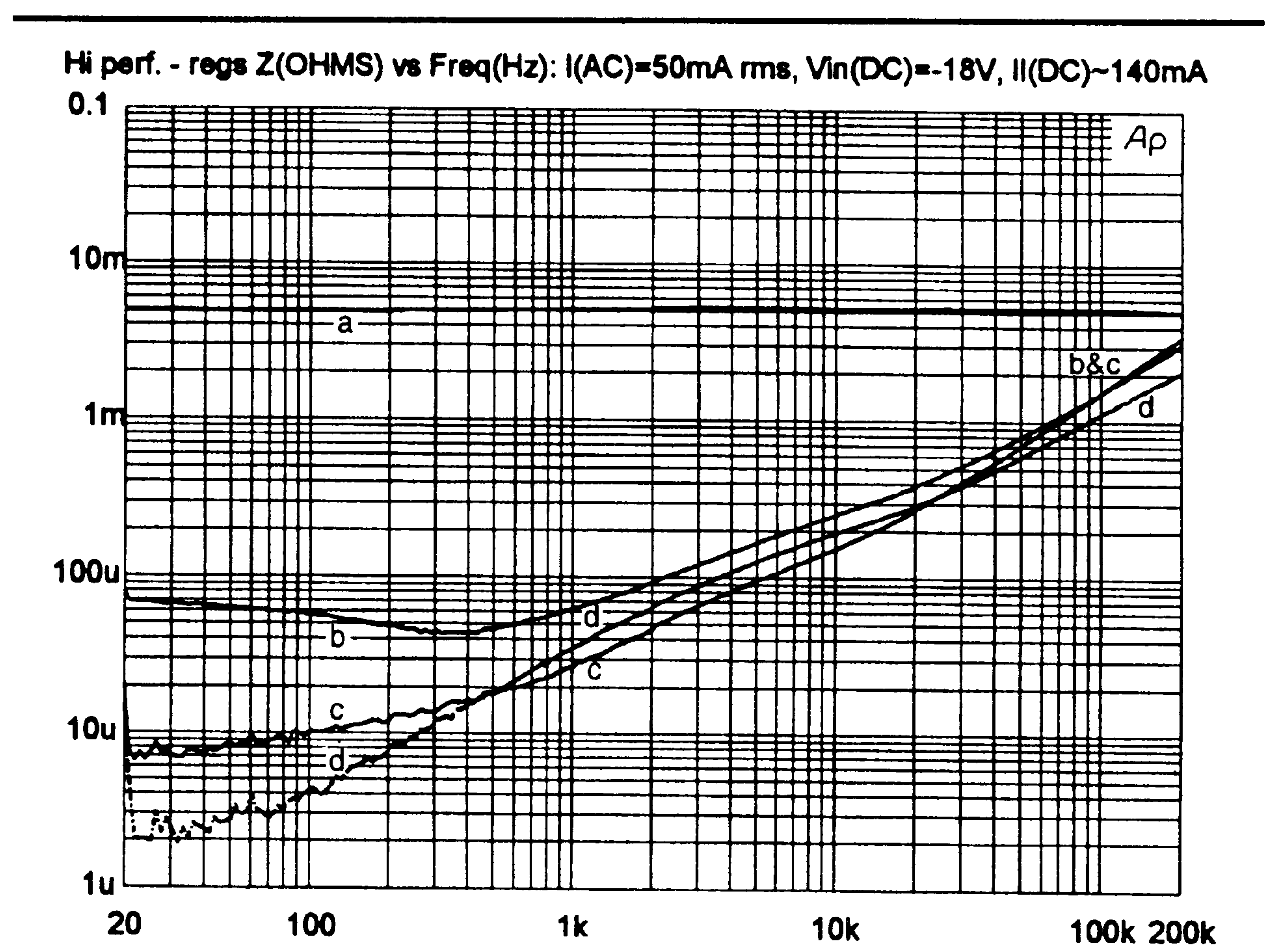

FIGURE 20b: High-performance negative regulator Z_O, a) POOGE 5.51 (Fig. 4); b) AD848 (Fig. 8b); c) Sulzer (Fig. 7b); d) AD797 (Fig. 8b).

tests generated Z_O data for easy comparison by regulator type.

Considerable effort was spent developing the test techniques and hardware to allow high-resolution Z_O measurement over a wide range of frequencies. In the interest of setup calibration and an overall Z_O sanity check, various component impedances were plotted (*Fig. 17*) and illustrate the sensitivity of the test setup over the working frequency range of 20Hz–200kHz.

First, a 0.1Ω±1% resistor is shown in the flat trace (c), which demonstrates just a hint of inductance towards 200kHz. A 120µF/25V-type HFQ capacitor (b) follows a capacitor-like Z fall until about 10kHz, where it then levels off, exhibiting an ESR-dominated Z of about 0.15Ω at 100kHz.

ACKNOWLEDGMENTS

Along the course of this project I was fortunate to have help in various forms from numerous parties, all much appreciated and gratefully acknowledged. Among those who replicated one or more of the regulator circuits were Paul Kelly, Rick Miller, Glenn Moore, Courtenay Osborne, Richard Pell, Phil Schniter, Don Spangler, Karl Youtsey, and Hank Zumbahlen. Hampton Childress's work on the POOGE 5 project and its regulator was also a meaningful early contribution. I received helpful comments on the manuscript and circuits from Erno Borbely, Hampton Childress, Clarke Greene, Bruce Hofer, Kal Rubinson, Phil Schniter, Scott Wurcer, and Karl Youtsey. For their detailed comments which improved the manuscript, special thanks to Jan Didden, Gary Galo, and Rick Miller.

I could not contact Mike Sulzer during the article's preparation, but I acknowledge his pioneering regulator work. Rick Miller worked very closely with me on many phases of these as well as earlier discrete regulator developments, and also identified the high current D4X series transistors first suggested in reference 9 and used here. I especially appreciate his many helpful comments and audio enthusiasm. Finally, it has been a pleasure working with Jan Didden and Gary Galo on this article series, and I hope the implementation of its concepts will also be a pleasure of yours.

The remaining two curves quite graphically illustrate the practicalities of low-Z wiring. The trace for the 12″ loop of #18AWG hookup wire spaced apart 1″ (a) shows a Z of about 10mΩ below 1kHz, rising to about 150mΩ at 100kHz. The fourth trace (d) represents a minimum-length ZEROHM jumper,[16] connected between the analyzer sensing points with a minimum lead length. As this data shows, even this *single* minimal-length conductor has about 4–5mΩ of DCR, and begins to show inductive effects above 10kHz.

This plot illustrates that, even within the audio band, just relatively short conductors of ordinary size show both resistive and inductive components. In other words, don't consider wire as simply DC resistance alone when placed in the context of practical regulation. For regulation impedances below a few milliohms, the distributed wiring can dominate impedance very quickly. This underscores the virtues of the star power distribution scheme outlined in Fig. 1, but more so, the value of remote sensing where applicable (a topic discussed in the next part of this series).

Low Impedance

In the following regulator Z_O data, most measurements fall below 100mΩ, and for display purposes the vertical scaling is 5 decades, with consistent scaling where possible (for ease of comparison). In the three-terminal positive regulator group's Z_O performance (*Fig. 18a*), an option for 4-wire load connection is not possible, so you should use short heavy leads for good regulation, particularly from the regulator's V_{OUT} pin to the load. In these tests, the measurement connects directly to the IC's output pin. All three ICs show a reasonably low 1–3mΩ Z_O at low frequencies, but impedance starts to rise around 1kHz. The broad flattening off in Z_O around 100kHz is likely due to the 100µF output capacitor.

In the three-terminal negative regulator group's Z_O performance (*Fig. 18b*), the two adjustable types (b) and (c) perform far superior to the 7915 fixed regulator (a) at all frequencies, achieving 1–2mΩ at low frequencies. However, they (like the positive three-terminal types) also show a rise in impedance above 1kHz.

As with noise and LR, you can optimize Z_O performance in three-terminal regulators by adjust pin bypassing. *Figure 19* shows Z_O data for the 337 adjustable regulator with/without a 100µF adjustment bypass capacitor. Without this measure, the device Z_O is more than an order of magnitude higher at low frequencies for these test conditions (a).

In the plot of high-performance positive regulator Z_O data (*Fig. 20a*), note the vertical scale shift, which now ranges 1µΩ–0.1Ω. You'll also see that the high-performance regulators, in particular the op-amp-based designs, can lower output impedance well below 1mΩ, or orders of magnitude below ordinary wire limited Z (*Fig. 17*).

This data, taken on carefully constructed layouts with measurements at the sensing divider, may appear overly optimistic, or even nonrelevant from a pessimistic viewpoint. But, the high sensitivity of the bandpass measurement Z_O technique allows such extremely low impedances to be resolved, sometimes revealing subtle differences between op amps applied in

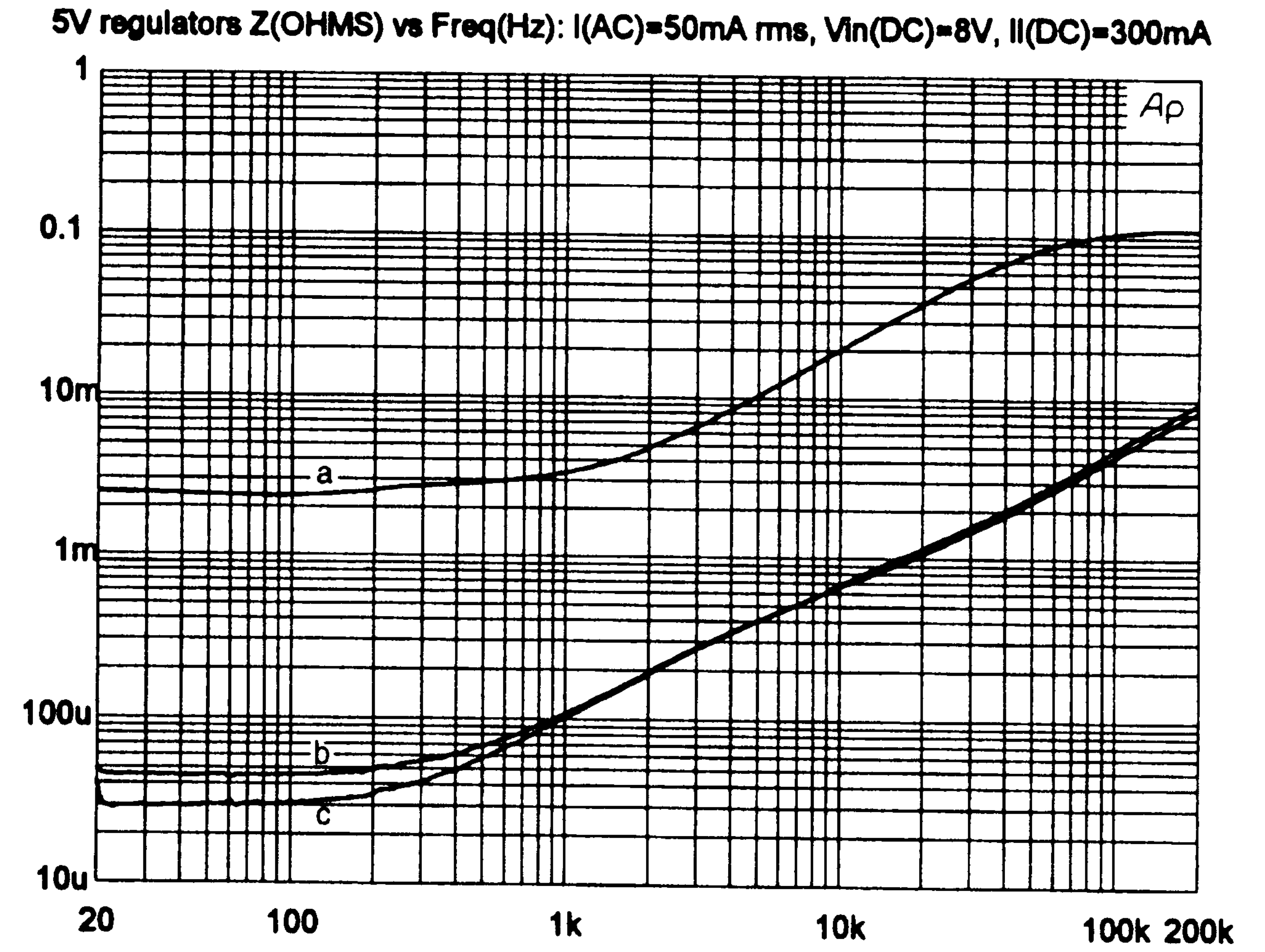

FIGURE 20c: 5V regulator Z_O, a) 7805; b) AD848 (Fig. 9); c) AD797 (Fig. 9).

TABLE 1

PROGRAMMING RESISTOR VALUES OF FIGURES 8A AND 8B FOR VARIOUS OUTPUT VOLTAGES

VOUT (V, nominal)	R4/R3 (ideal)	R1 (Ω)	R3(1) (Ω)	R4(1) (Ω)	R6 (Ω)	VOUT(2) (V, actual)
10	0.449	499	1.58k	715	2.21k	10.022
12	0.739	499	1.18k	866	3.65k	11.964
13.8 (as shown)	1	499	1k	1k	4.99k	13.800
15	1.174	499	931	1.1k	5.90k	15.053
16	1.319	499	866	1.15k	6.49k	16.063
18	1.609	499	806	1.3k	7.87k	18.029

(1) Closest 1% values.
(2) Assuming 6.9V reference.

the same circuit. More important, however, is the factor that the lower impedances *are* relevant, from a power distribution *quality* point-of-view.

Here quality implies both the magnitude of impedance, plus how well it is maintained over frequency. The lower the regulation impedance is at the sense point, the better a regulator can effectively short out current-proportional crosstalk from multiple load stages. This justification assumes that the power system has been wired with a star distribution scheme (Fig. 1). On the other hand, "daisy chain" power distribution may defeat virtually everything gained from high-quality regulation, by allowing the inevitable finite impedances of the power distribution system to build up crosstalk-related voltage drops at the power tap points.

More Data Analysis

It is interesting to note that the POOGE 5.51 regulator of Fig. 3 (a) has a virtually flat ≅2mΩ Z_O over the entire range, indicating its wide bandwidth. This modest regulator's Z_O is equal or superior to a ZEROHM jumper, suggesting that even a simple circuit can benefit from the star power distribution scheme.

With the Figs. 7a and 8a op-amp-based regulators, the low-frequency Z_O can go as low as 10μΩ or less, depending on the specific device and/or circuit. The extremely high gain AD797 operating in the Fig. 8a circuit can produce a low-frequency equivalent Z_O of close to 1μΩ (d), which, of course, in practice will be quite environment-dependent. The AD848 in the same circuit does nearly as well (c), with the Sulzer circuit of Fig. 7a not far behind (b).

As a practical matter, you should carefully consider impedances below about 100μΩ, making comparisons only under the most controlled conditions, i.e., changing only an op amp in an otherwise identical circuit. With regard to this data, for example, you can directly compare AD848 and AD797, since they both have been operated within the same circuit. Comparison with the data of the Sulzer Fig. 7a circuit is somewhat less precise, since it is physically and electrically different.

Under the stated measurement conditions, all of the op-amp-based regulators can achieve high-frequency Z_O performance on the order of 1mΩ at 100kHz, a feat which is by no means trivial. Key to this is a tight, compact, and low-inductance layout.

As with their positive counterparts, negative regulators (*Fig. 20b*) can also achieve output impedances well below 1mΩ. Also as before, the POOGE 5.51 regulator of Fig. 4 is quite flat in impedance (a), at about 5mΩ (albeit higher than the positive version, for reasons not obvious).

In the op-amp-based negative regulators, all circuits do very well at low frequencies, to below 100μΩ for frequencies below 1kHz, with the AD797 in the Fig. 8b circuit the lowest of all, again pushing 1μΩ (d). At high frequencies all three op amp regulators are again close to 1mΩ at 100kHz (b, c, d).

A plot of 5V logic regulator Z_O data (*Fig. 20c*) includes performance for the AD797 and AD848 in the Fig. 9 circuit, as well as that of a 7805CT for reference. *Note the vertical scale shift, which now ranges from 10μΩ to 1Ω.*

The op-amp-based 5V logic regulators in this circuit do not perform quite as well as in the Fig. 8a circuit. In the audio band the AD848 and AD797 traces (b and c) achieve a Z_O of 1mΩ or less, but at 100kHz they rise to 4–5mΩ.

REFERENCES

16. Digi-Key, PO Box 677, Thief River Falls, MN, 56701-0677, (800) 344-4539.

17. Gary Galo, "Ask TAA: Analog Devices Chips/Super Regulators," *TAA* 4/94, p. 43.

18. Karl Youtsey, Chris Youtsey, Phil Schniter, "Digital Audio Jitter: RIP? Part 1," *TAA* 4/94, p. 8.

19. Dick Marsh, "Power Up," *TAA* 3/83, p. 16.

20. Daniel Dufresne and Pierre Martel, "Make the Right Match," *TAA* 3/84, p. 14.

21. Ben Duncan, "Voltage Regulator Chips: Switch to Linear?" *Electronics World & Wireless World*, October 1994.

The standard 7805CT TO-220 regulator (a) achieves a low-frequency impedance of about 2–3mΩ, but at higher frequencies the Z_O rises to about 0.1Ω, and at all frequencies the 7805 Z_O is an order of magnitude or more higher than that of either Fig. 9 regulator variation.

Field Tests

Many people acknowledged below replicated the new ±14V or +5V logic regulator in one form or another, within various items of equipment. While in general these efforts were successful, an earlier circuit using a custom-compensated AD829 op amp exhibited some instances of instability. This factor was largely why I changed to the AD848 late in the project cycle. The AD848 is an uncompensated device, and, importantly, one which has shown none of the sometimes maverick tendencies of the AD829, either in the various equipment installations or in bench testing.

My experiences with the latest AD848-based Figs. 8a and 8b circuits have been positive, in both a preamp and DAC960 D/A converter, plus logic supply AD797 and AD848 circuits, also successfully applied in this same D/A. Earlier versions of the final Fig. 9 circuit using an AD829 were used in a logic application with the AD1890 evaluation board,[17] and in a modification to an Audio Alchemy D/A converter.[18] In addition, Hank Zumbahlen has used a version of the Fig. 8a/8b regulators in a D/A design for an upcoming application note.

"Successful" here means that the circuits installed without mishap and worked according to theory—in other words, they behaved as they should. My prototype tests all were "kludge-card" versions implemented on sections of Radio Shack general-purpose PC board #276-168 (one of these cards can support a pair of the regulators). I recommend the Jan Didden PC board design as the best implementation choice, since it has an integral ground plane and a good layout. See Jan's article (Part 3) and Gary Galo's follow-up on its practical installation and operation (Part 4).

Summary, Sundries, and Hints

Summarizing an article of this scope is a difficult task, but various highlights do emerge. One is the fact that, not unexpectedly, the more complex regulators of Figs. 8a, 8b, and 9 yield the highest overall performance. This article includes the performance data for all the various regulators, which allows ready comparisons of relative quality for the three measurement dimensions (along with a fourth already mentioned, complexity).

This information allows the designer to choose a circuit type appropriate to a given quality level. I hope to leave the reader with the impression that these more complex circuits deliver performance worth their price and the effort of implementation, as they certainly do. Some users have already reported so, as noted above.[17,18]

Proponents often prefer *shunt regulators* for audio applications, and might ask why these new regulators don't operate in a shunt mode. One reason given for using a shunt regulator is that it can both source and sink output current, whereas a series regulator (such as these) can only source current. Without getting into the pros and cons of the (major) efficiency and LR differences between series and shunt designs, it is true that a series type regulator can be optionally operated with a high bleed current.

Dick Marsh covered this factor and other worthwhile points on system aspects of power supplies.[19] This rather