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Precision Electro-Acoustic Research Laboratory. Hand-Builders of Fine Music-Reproduction Equipment

Notes on a Work in Progress

The PEARL SC 280—March, '90.

IT SEEMS TO ME that somewhere along the way almost everyone who considers himself an audiophile has dreamed of owning fabulous-sounding, high-power amplification. Unfortunately the retail cost of such amps is so high that only a very few people are ever able to realize such aspirations. As with anything worth owning, the cost to design and build good electronics is unavoidably high. Add to that the profit margin that a retailer must secure in order to make his business worthwhile and the cost of great amps is in the vicinity of a decent car or a down payment on a house.

During the 1950s and the early 60s there were all kinds of kits available to the home builder and although none of them was particularly high powered by today's standards, a few were then considered to be monsters. They were eagerly purchased, constructed and enjoyed by the literal thousand. How many Dynaco Stereo 70s are out there, giving pleasure to this day?

With the demise of the tube in mainstream audio during the late 60s, the rise of the transistor and the onslaught of inexpensively produced, aggressively marketed and heavily hyped Japanese equipment, the needs of the hobbyist were somehow forgotten. Marketing became the name of the game… well, you know the rest.

The fact that many capable people would much prefer to build a thing with their own hands than buy it at retail seems to have been obscured almost to the point of obliteration by self-interested manufacturers and their wallet-hovering marketeers.

The high-end audio-market has matured to a state where superb products are sold for enormous sums but not a single high-end kit is to be found.

In spite of the considerable cost of the parts required to build it, I believe there is a real market for an honest-to-God, high-power amplifier kit. My plan is to make available all of the unique and difficult-to-source parts required, such as the transformer set, painted and silk-screened chassis, pc-boards, power supply caps, tubes, Iso-sockets, Iso-mounts for the output tubes, etc. The sourcing of the more usual parts such as resistors and capacitors will be left to the individual builder. To make life as easy as possible we will supply pre-printed order forms made out to certain suppliers such as Digi-Key, Sonic Frontiers and others so that all that is required to get the common parts is to send the form to the supplier along with the necessary funds.

I would like to form an SC280 Builders Club and publish a newsletter every so often containing information, tips, mods and different circuit ideas. I fully expect that some of these kits will be bought by people with design ideas quite different from mine, it should be truly interesting to see what other people come up with. With enough people building these amps and tinkering away at them, it should be possible to offer a kit and associated circuitry that is simply the best available.

Having invested several years work in the development of the circuitry presented in this Audio Note, I think the current design is a well-balanced approach to the many inter-related problems such an amplifier presents. The power supplies in particular are well tried and sonically proven not only by myself, but by other designers who arrived at the same design conclusions independently and in a couple of cases, several years before I did.

This effort has received input from many people and is by no means solely my work. The part for which I am responsible is the way in which all of the various ideas have been assembled, the electrical layout and the mechanical, thermal and aesthetic design.

While I was working on this and several other tube-related projects, I undertook a massive and thorough-going literature search that now runs to something on the order of about a nine hundred articles. Many times I'd be thinking about this amp and dream up what was *sure* to be a new idea only to later find that someone had done it in 1956 or some such!

Prior art notwithstanding, I can say with a reasonable amount of confidence that no one has produced a commercial offering that uses quite the same topology presented here. Given the cost of this circuit and the fact that high-end audio is only really about ten years old, it's not too surprising that this could be the case. There was essentially no market in 1955 for a $1000.00 amplifier.

I have invested hundreds of hours of work into this project so far and have tried to design the circuits to be as simple, reliable and trouble-free as possible. Tube-aging effects are essentially nullified in the phase-inverter/driver stages by the use of a form of feedback known as “active error-correction”[4] whereby the differential amplifiers are made permanently self-balancing. The output stage uses two, manual bias-balance controls that operate in conjunction with a third control that allows the operating point of the amplifier to be continuously varied over a wide range.

The tube types have been chosen on the basis of linearity, sonics and on-going availability. The output stage uses EL34s, while the front-end uses 3 – 6CG7s, 1- 5687, and two FETs. The EL34, a pure pentode, is renown for its sweet upper registers and good, if not overpowering bottom end response. Unlike the 6550, this tube is not a high perveance—high current-output— device and so must be run at a fairly high plate voltage and rather lower plate current for a given amount of power output. While the 6550 certainly belts out the bottom end, the treble is often a little edgy and this being a distortion form I cannot stand, I’ve chosen to run more EL34s at higher plate voltage. The EL34 has been produced in some European plants for at least 30 years and one can reasonably suppose that the bugs are out of the production processes by now. The 6550 is presently made only in China. With the recent demise of the Sylvania plant in Emporium, Pa. and the GE (MPD) plant in Owensboro, Ky., there isn’t really a source of what I consider to be good sounding, consistent and reliable 6550s. I’m told that while the Chinese items are sonically quite acceptable, reliability can be an issue. There are apparently about 30-odd plants in China, all of which market through the same agency, so one never really knows the origin of a given lot of tubes. I am not out to belittle the Chinese tubes, so if anyone has more accurate information than the info I have, please fill me in!

I hope that this offering strikes a responsive chord within some of you as I feel that building and listening to a pair of these amps will be a richly rewarding experience in every way. I’d like to give credit to some of the people who have helped with the design of this amp because without their assistance and encouragement this project would not likely have been undertaken. In no particular order, thanks to:

- Norman Crowhurst, for 20 years of the best technical writing from which its been my pleasure to learn.
- Jack Senecal, ex of Precision Fidelity presently consultant to Krell. We have enjoyed many discussions relating to tube equipment design over the years.
- Chris Paul, for much help with circuit analysis and for putting before me the active plate load circuit used in this amplifier.
- Ed Logan, Logan Labs, for telling me how to build a tube, power-output stage, and providing many useful and hard-to-come-by tidbits of information.
- Bruce DePalma, ex of Dynaco during the PAS, Stereo 70 and MkIII era. Bruce pointed out the value of running EL34s at high plate voltage and low current and provided some very timely encouragement.
- Ken Stevens, Convergent Audio Technology: we’ve enjoyed hours of lively and enlivening discussion relating to tube audio in general and to the operation of triode output stages in particular.
- Ed Meitner, Museatex and Meitner. Ed provided me with a lot of insight into dielectrics and many of other peculiar phenomena, he also coined the unforgettable phrase *“Inca Firebottles”*.
- the hundreds of people who wrote the articles that constitute archive library I have built up over the course of my literature search.

THE SINGLE CHANNEL 280

Perhaps the single most daunting aspect of owning a large tube amplifier is the near inevitability of ongoing and costly tube replacement. Hand in glove with this is the steadily diminishing sonic quality shown by aging tubes. The reason for owning tube gear in the first place is that it sounds better than anything else and this fact makes tube deterioration doubly frustrating.

I own and use an enormous amount of equipment of many types; a complete and well-equipped woodworking facility with a large table saw, jointer, thickness planer, wood lathe, radial saws, polishing lathe, veneer press and a large tool-room metal-working lathe; an equally complete and well-equipped electronics-acoustics laboratory with dual channel fast Fourier analyser, scopes, voltmeters, microphones, oscillators, anechoic chamber, and lastly, an office/design room set up with a big, Macintosh desktop publishing system, a jillion megs of application software, back-up hard drive, CD ROM, scanner, printer, high-speed photocopier, Cerlox binding equipment, etc.

If the equipment I buy is not of extremely high quality and reliability I soon find myself in position where I am constantly repairing one thing or another and chewing up a lot of time doing so.

The design of this amplifier meant that I had to solve the reliability problem if I was ever going to be able to tolerate owning it. I worked this problem over in my mind for several years and intuitively it always seemed to me that the very high temperatures at which tubes typically operate had to be a factor in the short working-life so often observed.

Through several bits of good fortune and a couple of co-incidences I found conformation that high bulb temperature was definitely a problem and went ahead to develop the line of tube coolers that PEARL now markets. Working on the basis that whatever I developed had to be readily and simply retro-fittable to all kinds of existing equipment without resorting to forced air cooling, a number of effective products have been developed. See our Audio Note 1.3, "*Tube Coolers and Equipment Reliability*" for the full scoop on this.

In any convective cooling system there is only so much "power" available to move air. The effectiveness of most such cooling or heating arrangements can generally be increased by forcing air through the system with a fan. In a tube amp the trick is to provide a balanced flow of air over all the tubes so that they operate at very nearly the same temperature. This has been accomplished in the SC280 by the use of a "pressurized" pan-type chassis. It is basically a 25″ wide x 14″ front-to-back x 4″ deep chassis with the tubes and transformers mounted on the 25″ x 14″ top surface. See Fig. 2 for a sketch of this. Low noise fans are compliantly mounted on the bottom, inside the chassis and quietly create a positive pressure within the chassis. This pressure finds relief through a number of clear acrylic plastic chimneys seated in suitably sized holes punched in the top deck of the chassis. With coolers fitted, the tubes, both front-end and output, reside within a directed air flow guided by the chimneys. In this manner, extremely reasonable bulb temperatures are achieved and very long tube life can be rightly anticipated. As an example of the effectiveness of this arrangement is as follows:

- If an EL34 is simply plugged into a socket, to which only filament power is supplied and allowed to come up to temperature, the bulb hot spot will run about 100°C. If the tube is

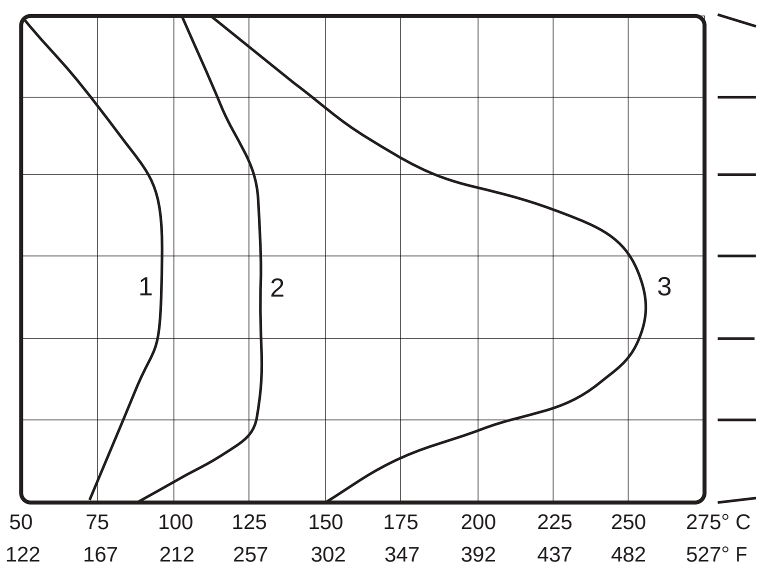
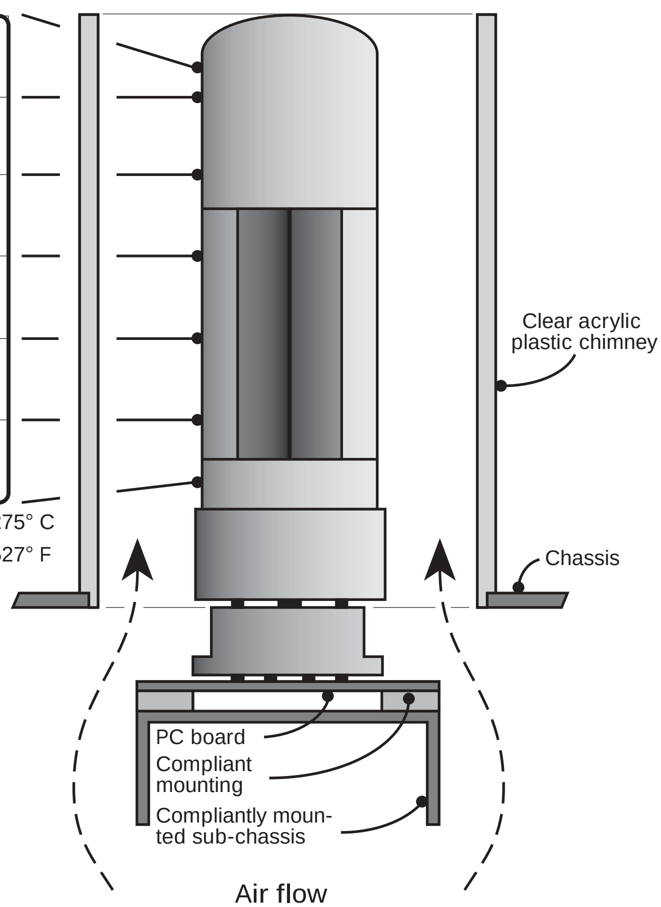


Fig. 1. The effectiveness of the cooling system used in the SC 280 is shown above.

Curve 1 illustrates the bulb temperature with only the filament running. The tube is dissipating 9 watts of power into free air and is not fitted with a cooler nor placed in a forced-air chimney.

Curve 3 shows the free-air bare-bulb temperature and substantial gradient when the tube is operated at its maximum rated plate+screen dissipation of 28 watts. The total power radiated by the envelope is 37 watts including the filament's contribution. Again, neither cooler nor chimney is used.

Curve 2 shows the bulb temperature and low gradient achieved with the fan-cooler-chimney arrangement used in the '280. Operating conditions are the same as for curve 3; for clarity the cooler is not shown in the illustration. The hot-spot temperature is reduced by a whopping 230° F.



> then triode connected and run at its maximum rated screen-plus-plate dissipation of 28 watts, it will be radiating an additional 9 watts from the filament, for a total of 37 watts of energy to be "sunk" into the atmosphere. The bulb hot-spot will then be about 250°C. and a temperature gradient of 100°C. will be present from the hot spot to either end. If the cooler-chimney-fan arrangement is then fitted, the bulb hot-spot temperature will drop, in about 5 minutes, to around 130°C. In other words the tube can be made to run nearly as cool under conditions of flatout-maximum dissipation as it does under conventional operation with nothing more than the filament lit! See Fig. 1

During the 50s and 60s the people at McIntosh produced thousands of amplifiers that ran with very low standing currents in the output tubes (essentially Class B) and consequently, low bulb-temperatures. These amps were famous for their incredibly long and reliable tube performance. Other instances of cooling vs. usable life exist by the hundred.

One situation that was instrumental in getting me going in the cooler business has to do with some tube-type acoustic analysis gear made by Messrs. Bruel & Kjaer during the 60s and 70s. I have a number of their level recorders that I bought for good prices because they wouldn't run reliably. It took me several years of fiddling to develop a series of mods that would solve the problems in such parts as capacitors and resistors. But it was not until I began to pay serious attention the operating temperature of the tubes that the problems really began to go away.

The gear was originally fitted with bright JAN tube shields (see Audio Note 1.3, Appendix 2: Figs. A & B) and one day I decided that these had to go. I removed not only the shields but the shiny-base retaining-sockets and installed a powerful but somewhat noisy fan to force an air blast of about 1000 ft/min directly onto the hottest running tubes. Being a maximum of 4″ from the fan, these tubes run at a far lower average temperature than was previously the case. Whereas I was getting about 1 year of intermittent use from a given level recorder before tube failure, I have units in the field that have been running at least 8 hrs a day, 5 days a week for over two years without so much as a hiccup. *Lowering bulb temperature extends tube life!*

I have talked with a few people who are under the mistaken impression that the cathode coating in a tube is somehow "used up" by the basic operation of the tube. While the coating is chemically quite fragile and subject poisoning by spurious gas within the tube, damage due to ion bombardment, stripping due to excessive demands for current or cold-cathode starts with full B+ applied; there is no fundamental reason why a tube cannot be made to run for years on end.

This was the thinking of the people at Bell Labs and Western Electric when they developed tubes of such high reliability that they were installed and permanently sealed into trans-Atlantic telephone cables as repeater amplifiers. One can't be fooling around replacing tubes in 2500′ of water! Admittedly these tubes were handbuilt laboratory specimens and subjected to the most rigorous QC procedures possible. The fact remains however, that with sufficient care in construction and use, cathodes can be made to last virtually indefinitely.

During my literature search, I came across some information regarding various life-extending measures taken by the folks who designed, built and ran the 18,800 tube Electronic Numerical Integrator and Computer. [1] Changes in operating procedures show results quite quickly with a machine of such size and complexity as a test bed.

Most people who have worked with tubes for any length of time have wondered about the effect of high-inrush-filament-current on tube life. The ENIAC people wondered about this too and did a good deal of work on the matter. Their conclusion was that a cycle of daily turn-on; turn-off had no effect on the frequency with which tubes failed. The following is a quote from ref. 1:

> "*A series of experiments was started, using 100 tube samples, to determine whether a graduated application of voltage would materially reduce the rate of failure when heaters were turned off and on. Such experiments showed no difference between the group of tubes to which full filament voltage was applied at once and those receiving a gradual application of voltage.*"

A number of measures were implemented that did show an increase in tube life:

- the operation of filaments rated for 6.3V at 6.0V. See Audio Note 1.3, "*Tube Coolers and Equipment Reliability*", Fig. 1 for further details.
- operation of plate circuitry so as to reduce plate dissipation to ⅛ of its design centre rating. Such low-power operation lowers bulb temperature dramatically
- the heater-to-cathode potential was limited to ±50V, with all heaters biased with respect to the cathode voltage. [2]

In the late 40s, the concept of bulb cooling hadn't been discovered and wasn't used in the ENIAC project.

As far as possible, the foregoing measures have been applied to the present amplifier although power tubes cannot be run at significantly lower filament voltages without a noticeable reduction in current-output capability.

It's quite unusual to see the output tubes run with DC filament supplies because—I guess—most people think of induced-hum as the problem and think that an output stage, with its large signals, will not be adversely effected.

The output-tube filaments in this amplifier run on DC for a very good reason: a distinct buzzing/tinkling sound can sometimes be heard from power-tubes when their filament are energized by AC yet when DC is applied the tube goes silent. This occurs because AC-current flow through the folded up length of insulated filament wire within the cathode initiates a motor action that causes the filament to contract, accordion-style, with every voltage swing away from zero, positive or negative. As the voltage returns to zero the filament expands to its original shape. Thereby, it acts as a little 120Hz. "shaker" within the cathode and almost certainly stimulates "guitar string" resonances within itself, cathode resonances and probably several grid resonances. This shaker mechanism gets things going within the tube to such an extent that plainly audible sounds are produced. With the internals of the tube set into resonance and thereby into relative motion, adverse effects upon any musical signal amplified by the tube can easily be imagined. This mechanism is silenced DC is used to energize the filaments.

The problems caused by acoustically induced microphonic output have been given a lot of thought and measures have been taken to ensure that such coloration is kept to a minimum. Iso-sockets and compliant pc-board mountings are used throughout and the output tubes are mounted in groups of three on separate, compliantly mounted sub-chassis.

All of the power supply circuitry is built on conventional PC boards while the signal-path circuitry is hard-wired using a specially developed ground-plane, hybrid construction. Normal double-sided pc-board material is etched on one side to carry the filament currents and on the other to provide a ground-plane grid in the usual manner. Provision is made for solder-type turret terminals, to which all signal path connections are made. The PC board acts as nothing more than a glorified terminal board and provides the convenience of PC board construction while maintaining the sonic superiority of point-to-point hard-wiring.

Basic Notes on the Circuitry

Referring to the block diagram, the amplifier is seen to be comprised of three sections of amplification. Three sorts of feedback are employed, local, loop and active common-mode error. True absolute phase switching is remotely selectable and the amplifier may be driven from single-ended or balanced sources. The output stage uses amply AC bypassed solid-state regulation of the standing current in each individual output tube, ensuring that the amplifier will hold its DC balance regardless of the match of the DC characteristics of the output tubes used. The front end is completely self-balancing—both AC and DC—and maintains its balance regardless of tube aging or match.

The Front End

All balanced, push-pull, tube-type output stages must be driven by a pair of antiphase signals. One of these drives the "push" side while the other drives the "pull" side of the output stage. The phase inverter's task is to provide such a signal pair and to be able to derive it from a single-ended source. It must do so in an accurately balanced fashion with regard to both amplitude and phase.

Amplifiers using only a single pair of tubes in the output stage often require that these signals be slightly unbalanced in amplitude while being exactly 180° antiphase. This is done to account for side-to-side gain variations in the output tubes and is usually necessary to achieve balanced currents in the half-primaries of the output transformer. With a push-pull–parallel output-tube configuration, reasonably careful matching will ensure that the "average-tubes" acting in the push and pull halves exhibit very similar transfer curves. Each half of the push-pull configuration can then be driven by a signal that is an exact "mirror-image" of the other. As long as Class A operation is maintained, local feedback in the output stage in combination with the high rejection of power-supply-induced common mode signals exhibited by a good output transformer, will effectively "mop-up" most of the residual, side-to-side imbalances.

Literally scores of circuits have been developed that are pretty much capable of "mirroring" a single-ended signal into a pair of equal amplitude, phase opposed signals. The great majority of these however, suffer from one defect or another and I have spent several years working on high-precision, phase-splitting techniques. The result of this effort is *The Actively Plate-Loaded, Self Balancing, Ultra-Linear, Differential Cascode, Phase-Inverter/Driver Stage.* This circuit solves virtually all of the problems encountered and does so using only four dual-triodes, two J-FETs, one positive and one negative power supply. It:

- is DC coupled from input to output.
- is exceptionally quiet.
- has very high common mode rejection from both input and feedback sources.

- exhibits very wide bandwidth, low distortion both harmonic and IM.
- treats even-order distortion as a common-mode signal and substantially reduces it.
- has a low output impedance.
- will easily swing 200V p-p.
- can be driven from any single-ended source-impedance up to 100KΩ with virtually no effect on output balance.

The application of feedback is always an issue that must be carefully considered. In this case, feedback applied to $V1_b$ and $V2_b$ has the interesting effect of linearizing the operation of the tubes ($V1_a$ and $V2_a$) that are "upstream" from the point at which feedback is applied. The mechanism by which this happens will be explained in Audio Note 15.0, "*The Cascode for Audio Amplification; New Developments.*"

The Output Stage

For purposes adequate to this brief introduction, the operation of the output stage is covered in Audio Note 2.1 & 2.1.1, "*A Little Input on Audio Output Transformers & Update.*" The subject will be dealt with in considerable depth in the following, upcoming Audio Notes:

3 - Basic Transformer Action.
16 - The Transformer-Coupled Output-Stage: The Basics of Push-Pull Operation.
17 - Cathode Coupling; Optimizing the Output-Stage.
18 - Class Distinctions; Modes of Amplifier Operation.
20 - Feedback From the Output-Stage; An Examination of the Options.
21 - Triode vs. Pentode; The Grass is Greener in the Middle!

Experienced builders will notice the unusual connection of the output-tube suppressor grids. I discovered that by swinging the suppressor in phase with the plate, but at a fraction of its peak voltage, a worthwhile quantity of secondary emission could be eliminated. A suppressor grid looses it effectiveness as the plate voltage swings towards the suppressor's zero potential and the grid must be swung negative to account for this. Sonically the result is quite gratifying.

It turns out that the grounded, center-tapped secondary provides an ideal source of dynamic bias for the suppressors. To achieve proper phasing the grids are tied to a point that—using negative cathode-feedback—is the cathode of the opposing tube of the push-pull pair.

This "cross coupling" effects *only* tubes that have a physical suppressor grid connected to pin 1 and does not effect the operation of beam power tubes such as KT66, 77, 88, 90, 6CA7, 6L6, 5881, 6550, 8417, etc. These tubes suppress secondary emission by the creation of a virtual cathode between the screen and plate and don't rely on a physical grid; more on this later.

May 1991 Addendum

There is some confusion regarding the 6CA7/EL34 as this tube is produced in both a two-grid, beam-tetrode and a three-grid pentode version. Yet, no distinction is made between them and either device can be found labeled with either number.

For those of us who concern ourselves with the sonic characteristics of tubes, this haphazard labelling presents a problem because a pure pentode and its beam-tetrode "equivalent" are not at all the same beast from a sonic standpoint. The tetrode exhibits significant grid-current problems in the –10 to 0 control-grid-volt region, whereas the pentode version does not and is therefore sonically superior in capacitively coupled, fixed-bias or self-biased output stages. Look for more on this in *Audio Note 23.2.*

The pentode can be distinguished from its beam-tetrode look-alike by counting the pairs of grid-support side-rods protruding through the top support mica and flanking the cathode tube—within which resides the filament. With one pair of side rods required per grid, it's a simple matter to count the rods and thereby derive the internal structure of the tube.

Two pairs of side rods are seen in the beam-tetrode, which I label a 6CA7. Three pairs are found in the pentode which I call an EL34. I have created this connotative nomenclature based on the following thinking:

- the pentode—EL34—has not, to my knowledge, ever been produced in North America so I have chosen to use the non-North American number to designate the non-North American tube
- the beam-tetrode—6CA7—is the version produced on this continent and others as well, so I have given it the number used in the American system.

References

1 Tube Failures in ENIAC, F.R.Micheal, *Electronics*, October 1947.
2 The Heater-Cathode Leakage Problem, M. Horowitz, *Radio TV News*, publication date unknown, copies available from PEARL.
3 Technical Reference Manual, *Lamptronix Co. Ltd.*, Crystal Lake, Ill, USA 60014.
4 The Application of Active Error-Feedback, J.R. Macdonald, *Proc. I.R.E.*, July 1955

SC 280 Power Amplifier

Fig. 2 - Mechanical Layout - Plan View

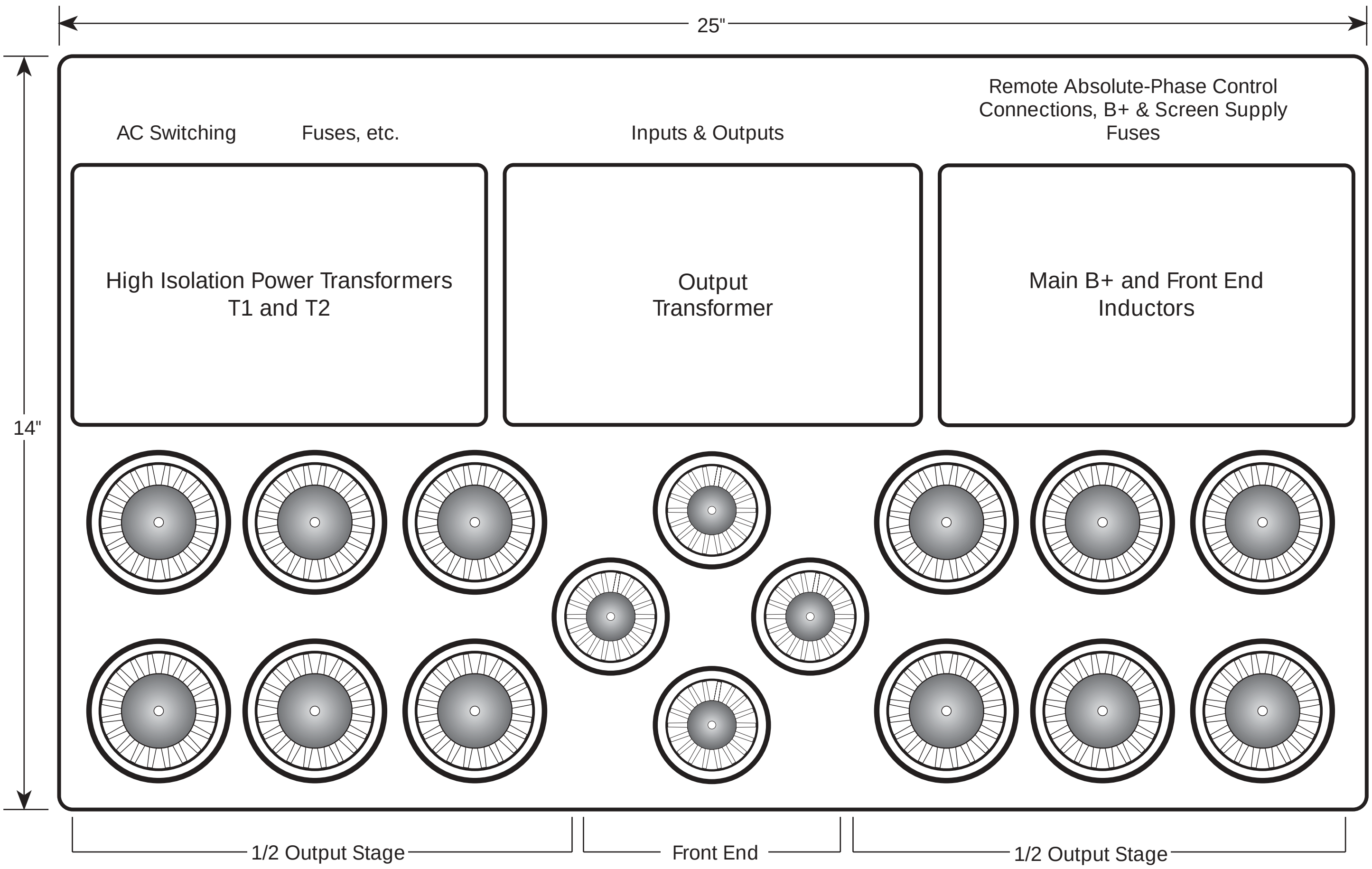
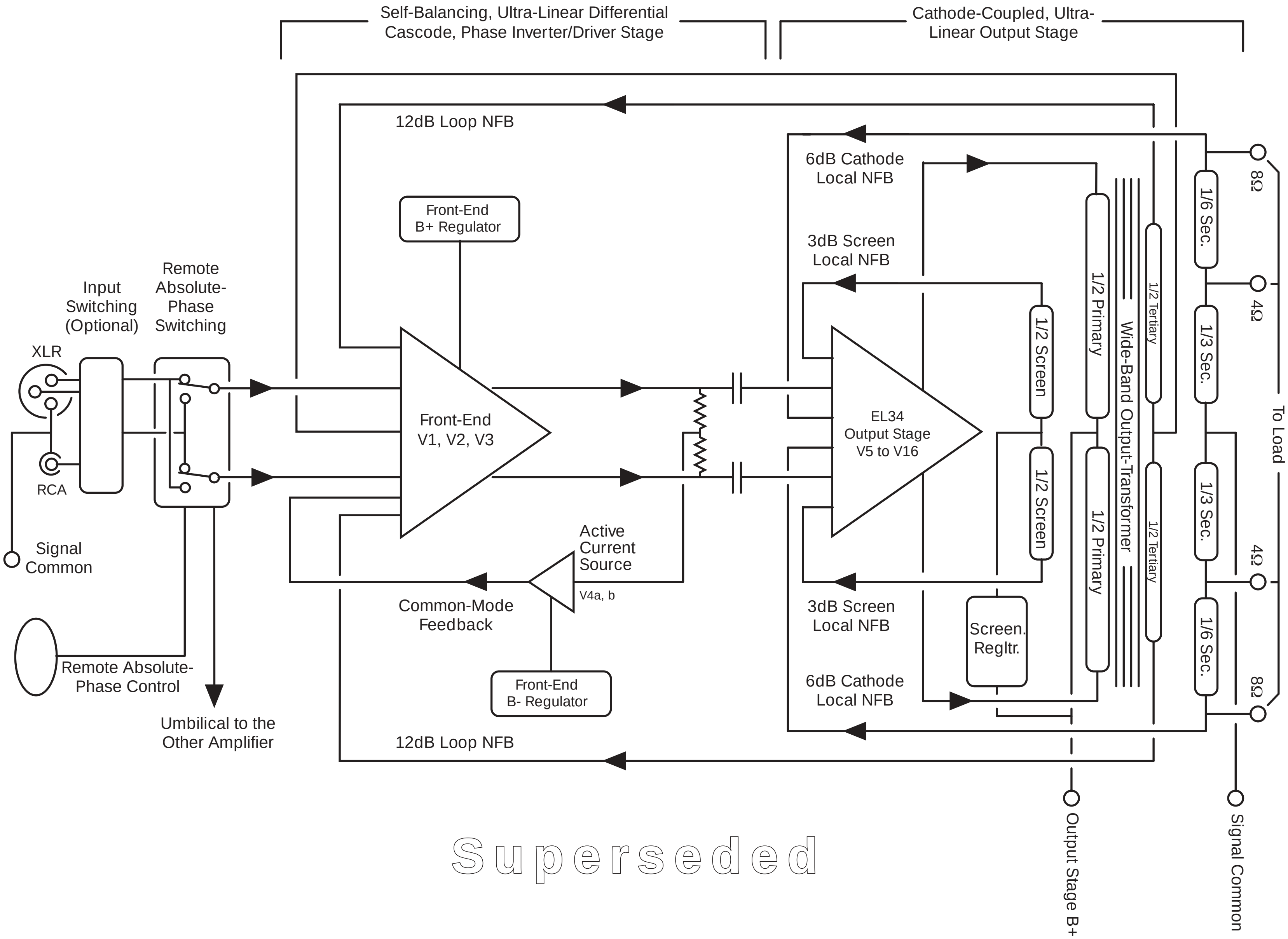


Fig. 2. The PEARL SC 280 MONOBLOCK is shown in plan view. Note the symmetry of the layout. Fans within the chassis force cooling air up through all of the cooler-chimneys resulting in the sort of tube cooling performance shown in Fig. 1. All power-utility AC is contained within a sealed, bulkheaded compartment directly below the high-isolation power transformer. Only isolated, filtered and initially rectified AC is allowed into the rest of the chassis.

The remotely-controlled absolute-phase-switching circuitry is operated from an umbilical that runs from the listening position back to either one of the amplifiers. The pair of amplifiers is connected by a second umbilical, ensuring that the absolute phase of both amps switches simultaneously with remote switch actuation.

SC 280 Power Amplifier

Fig. 3 - Block Diagram



SC 280.1 Power Amplifier Schematics

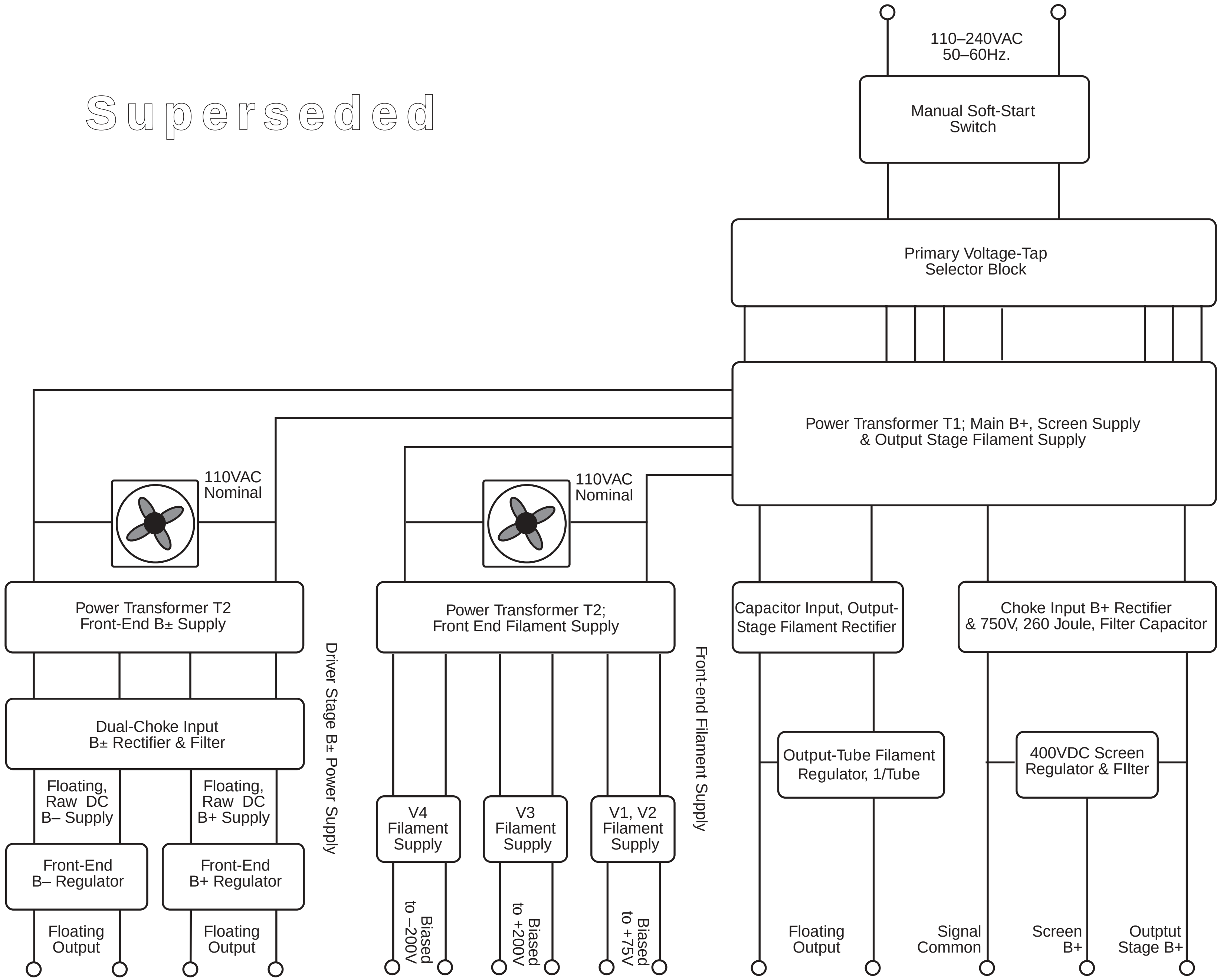
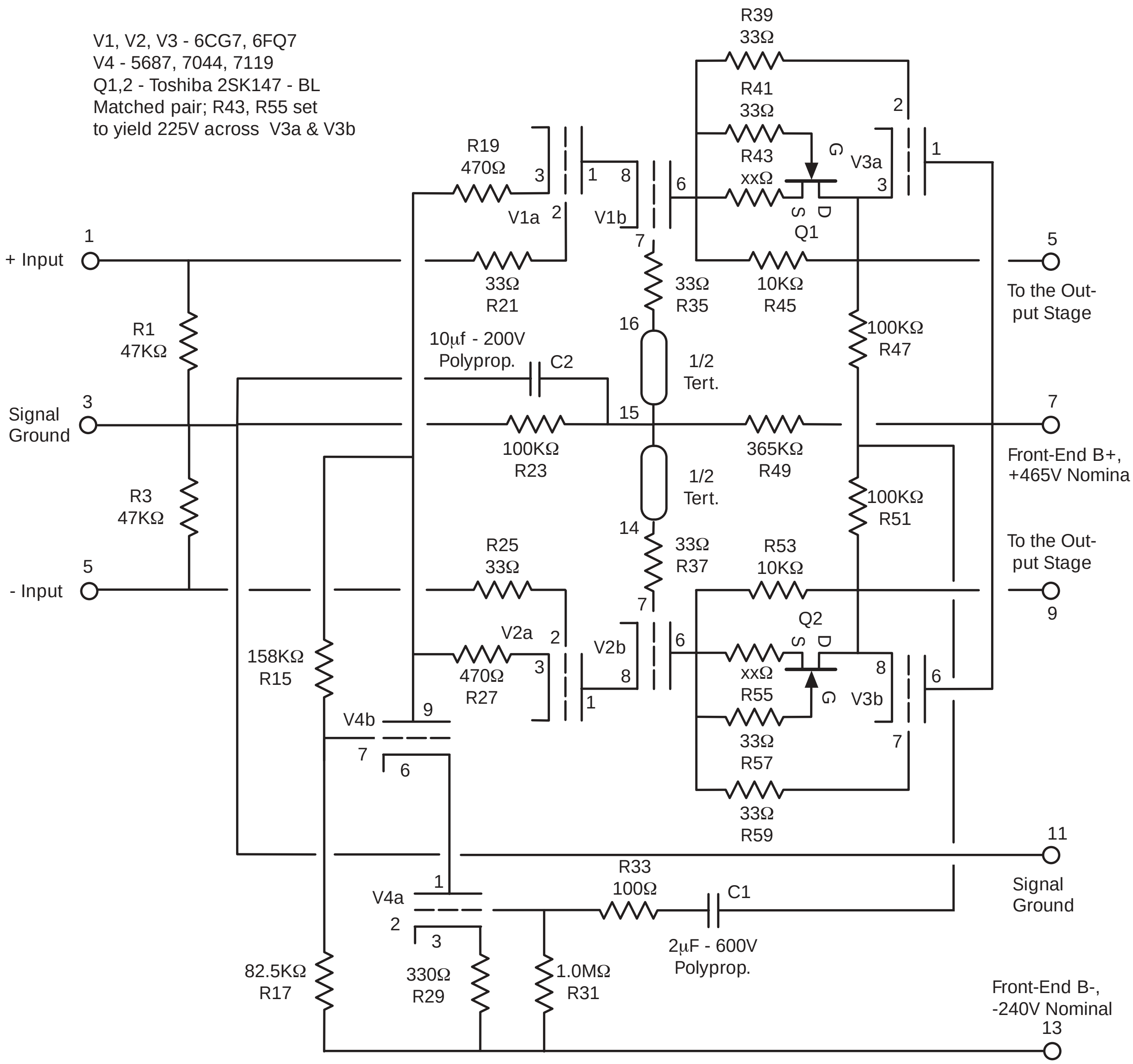


Fig. 4 - Power Supply Block Diagram

SC 280 Power Amplifier

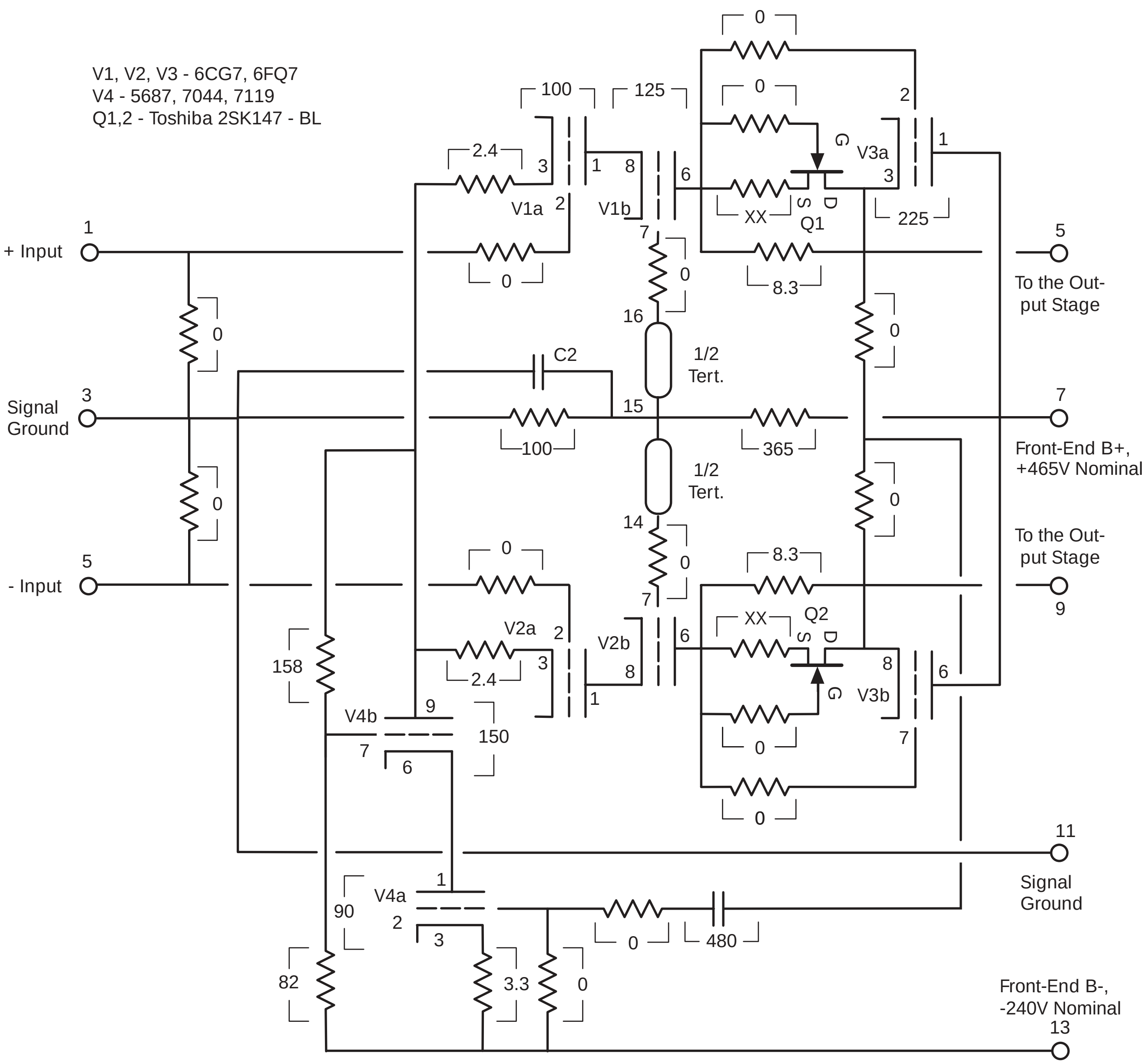
Fig. 5 - Front End - Component Values

Superseded



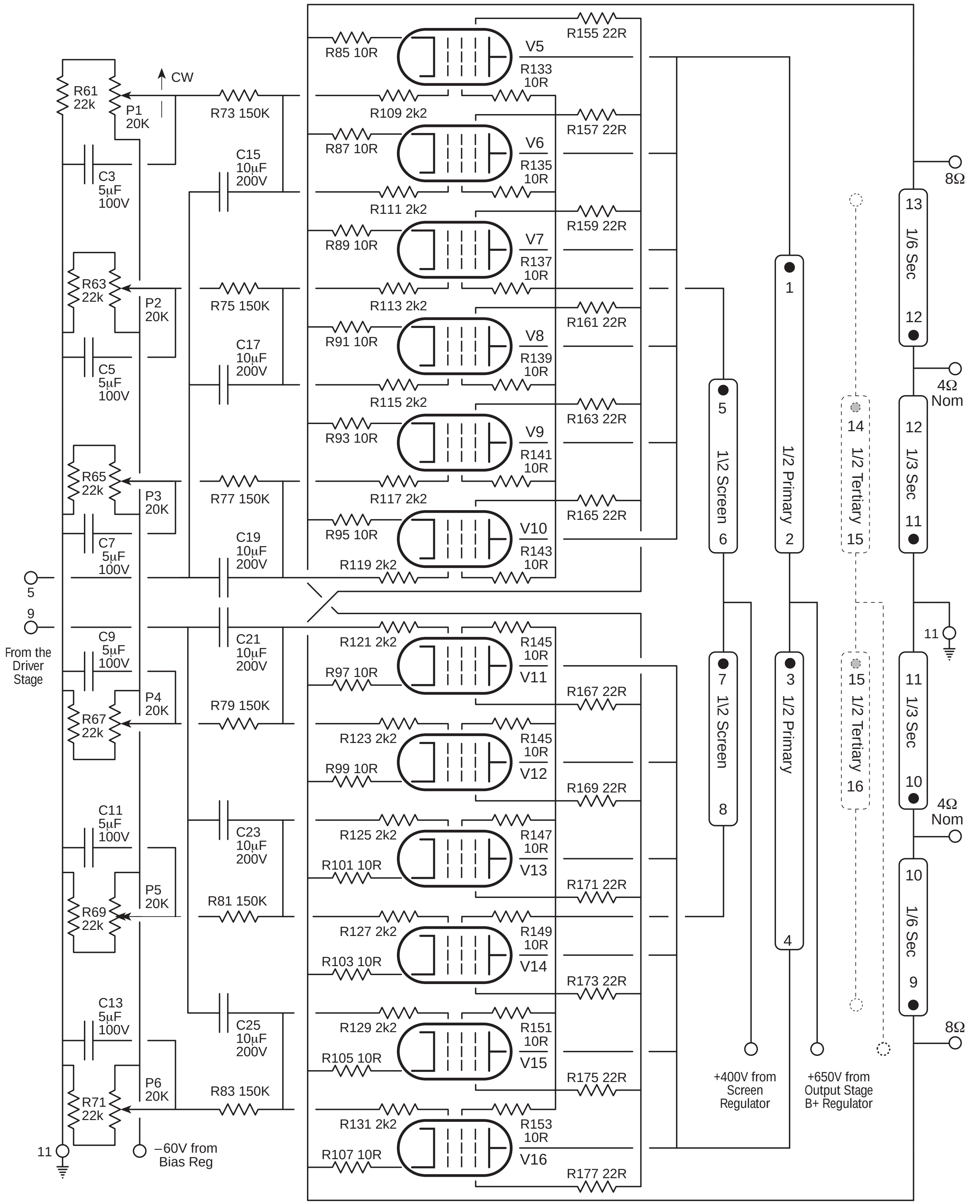
SC 280 Power Amplifier

Fig. 6 - Front End - DC voltages



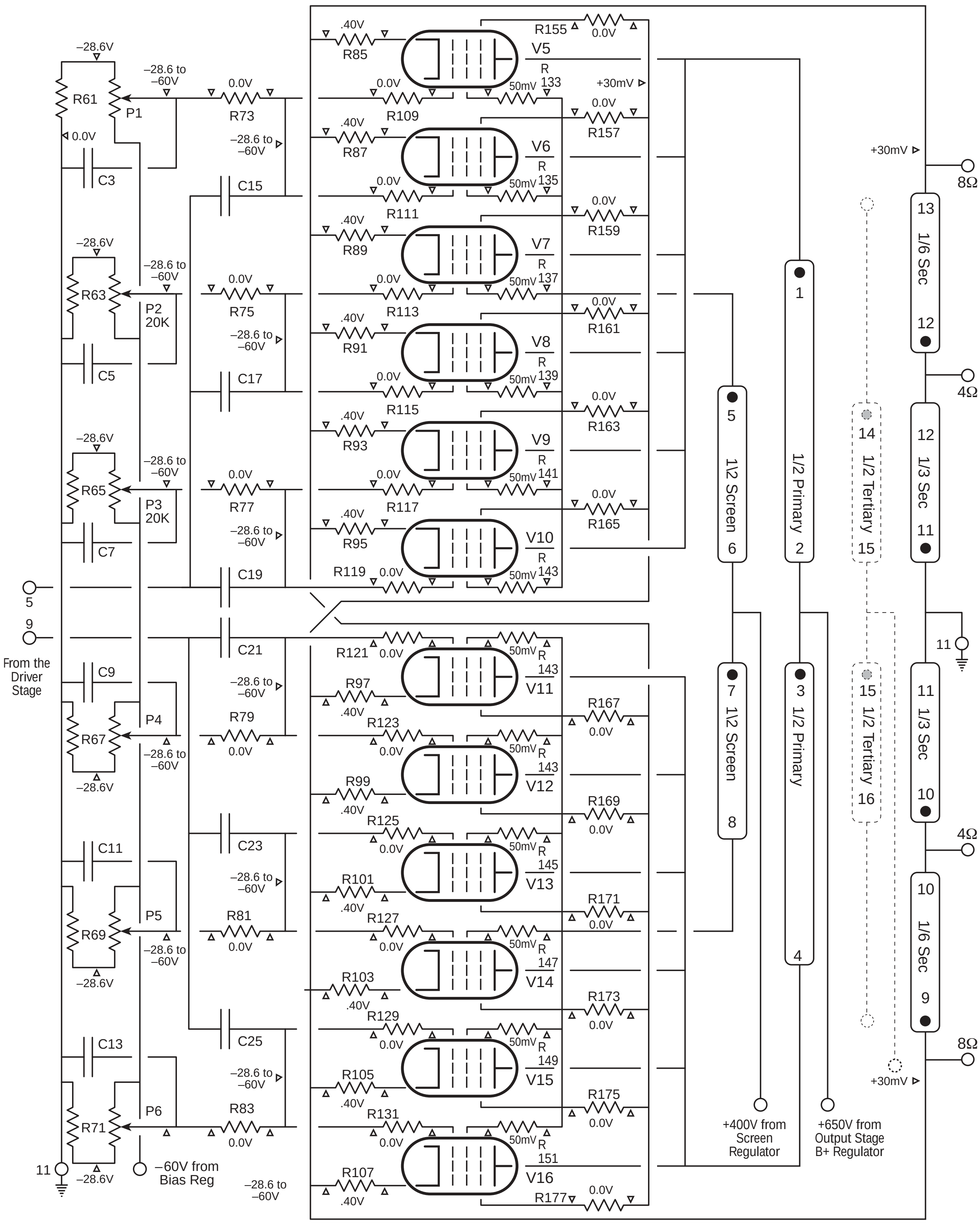
SC 280 Power Amplifier

Fig. 7 - EL 34 Output Stage - Component Values



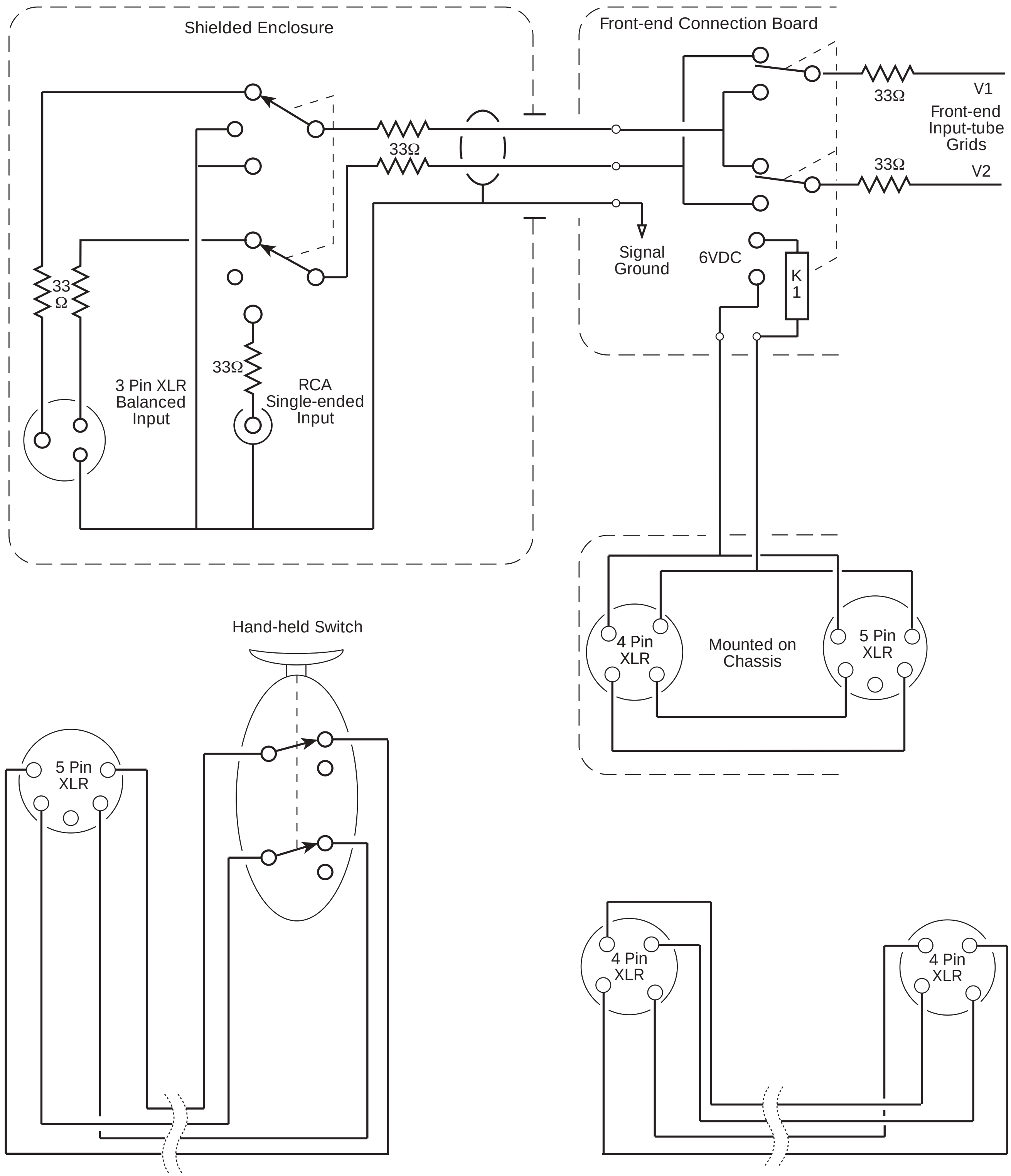
SC 280 Power Amplifier

Fig. 8 - EL 34 Output Stage - DC Voltages



SC 280.1 Power Amplifier Schematics

Fig. 9 - Input Switching & Remote-Absolute-Phase Inverting Control



Absolute Phase Remote Control Umbilical

Amplifier Inter-connecting Umbilical