Some Experiments With Miniature Power Triodes

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The author's experiments with miniature-tube amplifiers yield one circuit with push-pull 6AQ5's and—more interesting—a single-ended 6S4 unit with even better performance, along with a noteworthy set of conclusions on the all-but-forgotten single-ended vs. push-pull controversy.

SOME TIME AGO, being rather bored by the limited possibilities of the old but unreplaced 2A3 family, and not especially impressed with the 6AS7 (mainly because of the unreasonably low amplification factor), the author decided to try out a few ideas on the uses of miniature tubes as power-amplifier triodes.

Until very recently there were no really satisfactory miniature power triodes—none which could properly be called power tubes, that is—and the best possibilities seemed to lie amongst the pentodes. Of these, unfortunately, there were very few, and only two types, the 50B5 and the 6AQ5, appeared to be worthy of test. The former was distrusted because of the a.c.-d.c. aroma—heater troubles, etc.—and the latter was chosen for use as a triode.

Examination of curves for the 6V6, an equivalent, showed a triode-connected amplification factor of 9, a transconductance of 3000 μmhos, and a plate resistance of 3000 ohms (approximate figures), for a 320-volt plate supply and 25 ma of cathode current. The corresponding bias, −24 volts, indicates a drive problem about half as bad as that of a 2A3 and a fifth of that of a 6AS7.

The official plate dissipation of the 6AQ5 is 12 watts, while the screen is rated at 2 watts or the same as for a 6V6. However, and very wisely, the manufacturers recommend using the miniature tube at lower ratings than the GT version. In practice, it has been found that for normal audio use and construction, 8 watts (triode-connected) was about as much as one could reasonably expect to dissipate. Even at this level the shields, which are used for mechanical reasons, get very hot indeed, while at 10 watts they turn brown. No trouble has ever been experienced by the author, on this and other jobs, with 6AQ5's operated at 8 watts dissipation.

The expected efficiency of 25 per cent meant that each tube would yield 2 watts of useful power, and four tubes would thus provide the 8 watts which was deemed suitable, on the basis of experience, for the speakers, the room, and the music. The obvious circuit to use, since this was merely a tube-testing project, was the rather unimaginative but thoroughly reliable push-pull-parallel, so that the power-stage input requirements became 320 volts at 100 ma.

The purpose of the experiment was to try out the tubes on a long-term, living-room basis, and not to display ingenuity in circuitry. Part of the purpose included economy. An interstage and an output transformer were on hand from previous adventures, and the design accordingly settled into the familiar pattern of single-ended driver, phase splitting by transformer, and push-pull power stage. While lacking many features generally held in esteem, such as feedback around the power stage, the amplifier was intended to be built without much test equipment and yet offer stable, long-lived performance of satisfactory quality in small rooms and at medium power levels.

The finished amplifier, diagrammed in *Fig.* 1, uses 6S4's as voltage amplifiers, which is somewhat unusual (they are really power tubes, of which more later). 12AU7's were originally used, but were removed when it was decided to use only two stages of voltage gain. An attempt was made to build a good driver by using a feedback loop (roughly 20 db in the midband controlled by R_1) around both 6S4's, in view of previous troubles with driver distortion when dealing with the lower-mu tubes.

Loading the interstage transformer (R_2 and R_3) to flatten the response at the high end, helps control of the feedback system, and the customary resistors in the grid and screen circuits of the paralleled power tubes also aid in the avoidance of oscillation.

To permit good balancing of the power stage, both milliammeter jacks and precision resistors R_4 and R_5 (for null readings) were provided. All important circuit junctions were made at small pin jacks which serve as test points and tie points alike, so that there is no need to take the unit out of its rack for inspection. The finished amplifier is pictured in *Fig.* 2.

Performance is quite satisfactory for such a standard circuit. The frequency response at 4 watts output as about that of the output transformer alone, or substantially better than ±1 db from 20 to 20,000 cps. At the primary of the interstage transformer the response was down only 1 db at 60 kc, which shows how the power stage and its transformer limit the high-frequency performance. The voltage gain is 5.0 from input line to voice coil at 1000 cps, when accompanied by 20 db of distortion re-

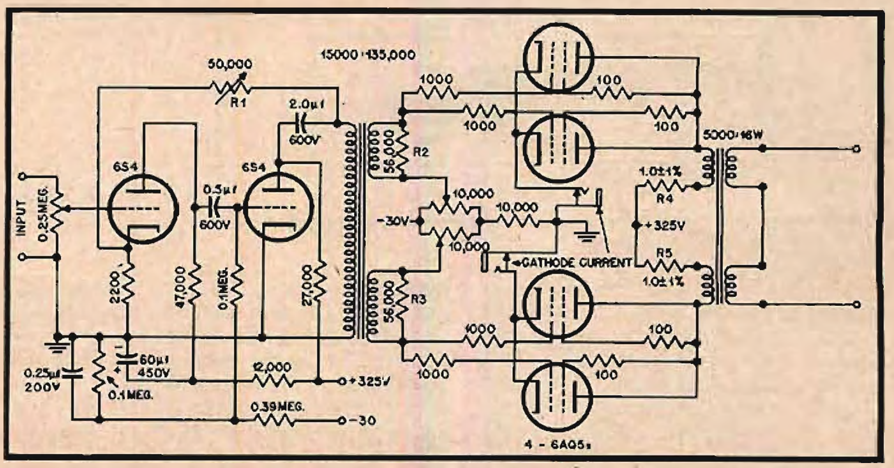

Fig. 1. This push-pull-parallel 6AQ5 amplifier proves that good performance can be secured from miniature tubes.

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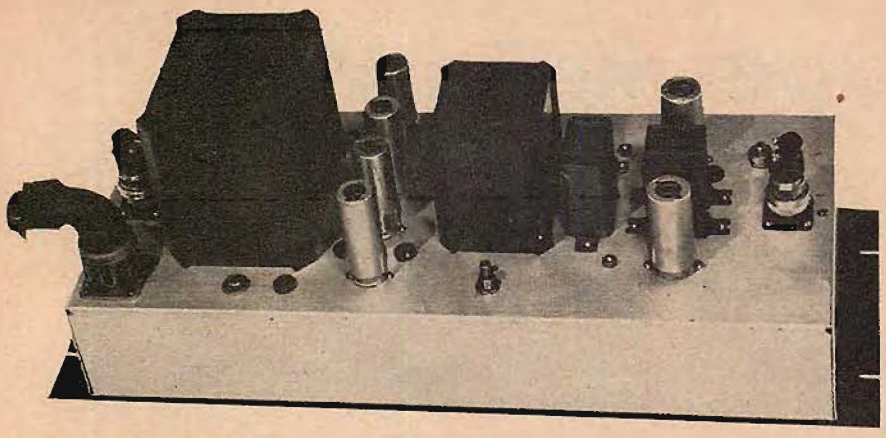

Fig. 2. The 6AQ5 amplifier, dish-mounted on a rack panel. Some of the pin jacks giving measurement access to important circuit points are visible.

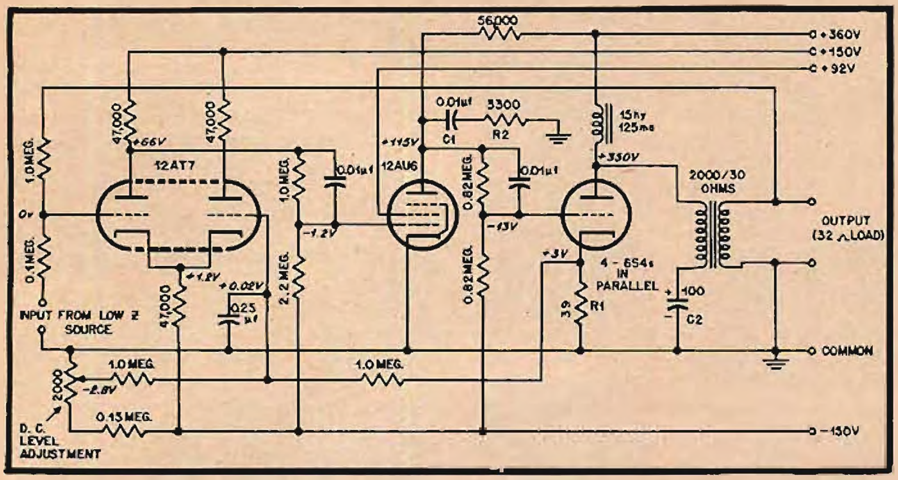

Fig. 3. The single-ended amplifier is direct-coupled and contains simple but ingenious d.c. and a.c. stabilization provisions.

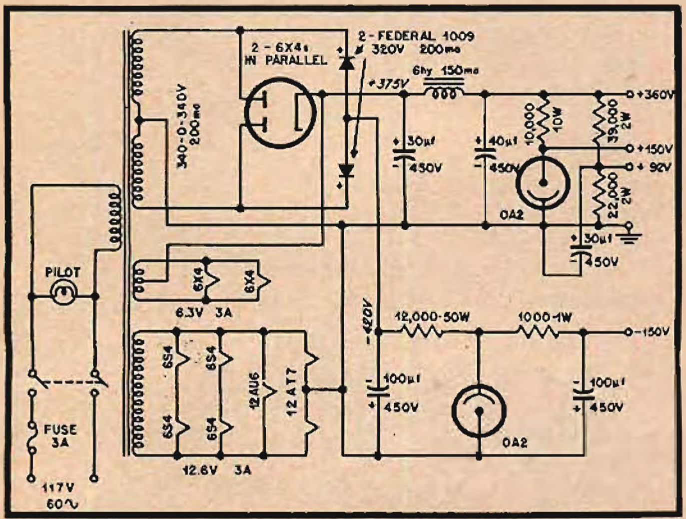

Fig. 4. This simple power supply is adequate for the 6S4 amplifier, despite the fact that electronic regulation is commonly supposed to be essential.

duction in the part of the circuit encompassed by the feedback loop. The overload characteristic is symmetrical and indicates that the power stage overloads first at 8 watts output.

Lastly, before dismissing this design, and moving on to better things, it is necessary to mention the output impedance. This is rather disappointing, being 70 per cent of rated load at 1000 cps. High damping factor is not the strong point of this particular design, since there is no feedback around the power stage; it requires some care and skill to put any useful amount of feedback around the output transformer even if it is very good, and the use of an interstage transformer makes the problem far worse. Notwithstanding this lack of the "Williamson touch," the amplifier has proven to be a successful and pleasant-sounding device.

Encouraged by the stability and freedom from tube failures (or other signs of glaringly poor design) experienced with the triode-connected 6AQ5, the field was again scanned for likely small triodes. The appearance of the 6S4 during the first experiment made the next step inevitable. Although not possessed of a spectacular plate power rating (better, however, in point of a larger structure, than the 6AQ5), the 6S4 looked very good indeed. After the 300-volt ratings of most earlier tubes, the 500-volt d.c. plate potential rating (2 kv peak allowable for television uses) was especially pleasing. The tube also has a 7.5 watt plate dissipation rating and reasonable characteristics.

Why Not A Single-Ended Amplifier?

While high-mu tubes are not commonly thought of as making good power triodes for audio use (the mu of the 6S4 is 16) the drive problems one has with the super-low-mu tubes had produced something of a movement in the other direction. In defense of the decision to use the 6S4 there is the fact that the final efficiency turned out to be about the same as (and certainly not less than) one would have obtained with other tubes of lower amplification factor operated in the same manner.

At about the same time as the 6S4 project began, there was a revival of discussion in certain circles of the single-ended power stage. Since the invention of the push-pull circuit, which permitted operation in class B and therefore made possible increased efficiency, the single-ended stage has been a lost cause for high-quality audio power amplifiers. There has been almost no discussion of really good single-ended power amplifiers in print since the war. Many people who might build, with distinction, a fine single-ended amplifier, fall prey to the lure of even-harmonic cancellation, and end by having an amplifier rich in *all* kinds of distortion.

The defects of the push-pull system are very plain. It depends for its proper operation on a precise balancing of tubes, resistors, capacitors, and (worst) transformers, and upon phase splitting which is both balanced as to amplitude (at all levels) and insensitive to frequency. The advantages are well-known: even-harmonic cancellation, avoidance of net d.c. magnetization in the transformer, and the permissibility of discontinuity of the individual plate currents (so that the added efficiency of class AB or B operation can be had with minimum penalty).

Even-harmonic cancellation is, of course, a very fine thing. It is to be seriously questioned, however, whether in practice it is anything like completely realized in units built with ordinary components and ordinary pains and skill.

The application of substantial amounts of inverse feedback to push-pull, transformer-coupled amplifiers is not easy, and it involves work, test equipment, and skill. The usual dilemma is this: you either have to run a single-ended loop around too many stages for comfort, or run a balanced, push-pull loop around too few stages, so that there just isn't enough gain inside the loop.

The single-ended amplifier confronts its builder with fewer decisions of this sort, and a single-ended (of course) loop from input to output (or, if you like, *vice versa*) is the normal, inevitable, and easy way to apply the feedback. For the same amount of pains, it is possible to get a great deal more feedback with a single-ended amplifier, although there is no theoretical argument which makes this inevitable; it is just a working rule.

It is not unusual to find single-ended power amplifiers which are stable with 80 to 100 db of feedback at low audio frequencies, but it is not common to find push-pull amplifiers with such large degeneration. It has been the author's experience that it is possible to put perhaps 20 more db of feedback around a single-ended amplifier than would have been possible with a push-pull amplifier of the same type or purpose, for the same amount of effort and skill. Generalizations are difficult in matters of this sort. It is not hard, though, to use amounts of distortion reduction due to feedback which greatly overshadow those likely to be realized by the even harmonic cancellation of the push-pull system. It is just that it seems hardly worthwhile to worry about a few per cent less even-harmonic distortion in the basic amplifier at the expense of a more complicated circuit when you are planning to reduce the even *and* odd distortion by, say, 100 to 1.

One can argue for the push-pull system by saying that it is not possible to get an actual 60 db, say, of feedback at 10,000 cps even with a single-ended amplifier, and that even 40 db is very tough (especially with a transformer), while 10 to 20 db is the more usual figure. This is very true. In order to have 20 db of feedback at 10,000 cps while maintaining the low-frequency performance as usual, a very fine transformer is necessary. However, it is questionable how much distortion cancellation actually occurs at the higher frequencies with the push-pull system. There is such a thing as capacitive unbalance and phase splitters are often full of it. When one considers that the odd harmonics are still with us when we use the push-pull system, so that feedback is necessary in virtually the same proportions for equal over-all results with either a single-ended or double-ended amplifier, the advantages of the more complex arrangement look dubious.

Elimination of the direct current from the primary of the output transformer may be accomplished in a variety of ways. In this particular case it was decided to use the old-fashioned choke and capacitor shunt-feed system. There are three or four better ways to do it.

The push-pull circuit is, naturally, required for class B work. It is only class A which is being discussed here, as it is felt that except for purposes where economy and, therefore, efficiency are essential and dominate the design, class A is the proper way to build good-quality audio equipment. There is something very disturbing about the thought of discontinuities in the plate current of the power tubes for a real musical amplifier, even in the light of some notable advances in the minimization of the difficulties of these discontinuities. A really good system for reproducing sound will be very heavy and expensive, and the small economies one achieves by the use of class B—or AB—are not worthwhile in non-commercial equipment.

The 6S4 Amplifier

To test the 6S4 and to try out some single-ended ideas the amplifier of *Fig.* 3 was constructed. It is entirely single-ended, using 10 tubes in all including the power supply shown in *Fig.* 4, and was built with permanence of performance in mind. The finished job appears in *Fig.* 5.

The central idea governing the design of the circuit as a whole is the direct coupling of all stages, save only for the plate circuit of the power stage, which involves a shunt-fed transformer. Only in this manner was it possible to avoid trouble with the large amounts of feedback used, since the loop is from voice coil to input grid. By building the voltage amplifiers in direct-coupled form it is possible to reserve most of one's time and ingenuity for the really taxing problems which are often to be found at the high end of the audio spectrum, leaving the low end as "solved." (This is an oversimplification, of course, since it is only in the more elementary and less demanding circuits that one can toss off the low-frequency problem so blithely. It is not implied that this instrument has optimum very-low-frequency response, but simply that it is, in this respect, quite satisfactory for its purpose.) By direct coupling of all or most of the stages, it is possible to greatly simplify one's problems, although it is sometimes at the expense of an elaborate power supply that one does.

With a multistage d.c. amplifier it is necessary to provide some means of controlling the various tubes so that they always operate at the proper potentials and currents. In this case it was found that the power stage remained either saturated or cut off unless substantial d.c. feedback was employed. A resistor R_f was placed in the cathode lead of the power stage and the voltage appearing across it sampled, filtered to subtract a.c. components, compared with a reference voltage, and the result applied to the grid of a differential amplifier, the second 12AT7 triode. Any tendency on the part of the output stage to depart from a certain optimum quiescent plate current is fed back to the differential grid in degenerative fashion. Another way of looking at this is to say that there is roughly speaking no voltage gain for d.c. from input grid to output transformer primary so that there is very little d.c. drift in the output tube plate potentials. All that is required in this type of amplifier is that the d.c. drift be small enough not to limit significantly the maximum a.c. power output. Unless drastic damage occurs, such as tube failure, the large amount of d.c. feedback ensures that each tube is, if capable of even poor performance, doing as well as it can in the circumstances. The amplifier will go on working reasonably well under very adverse circumstances, such as failure of most of the power stage tubes. When dealing with the usual a.c. power amplifier, one is never too sure without meters that all is well, while with this method of de-

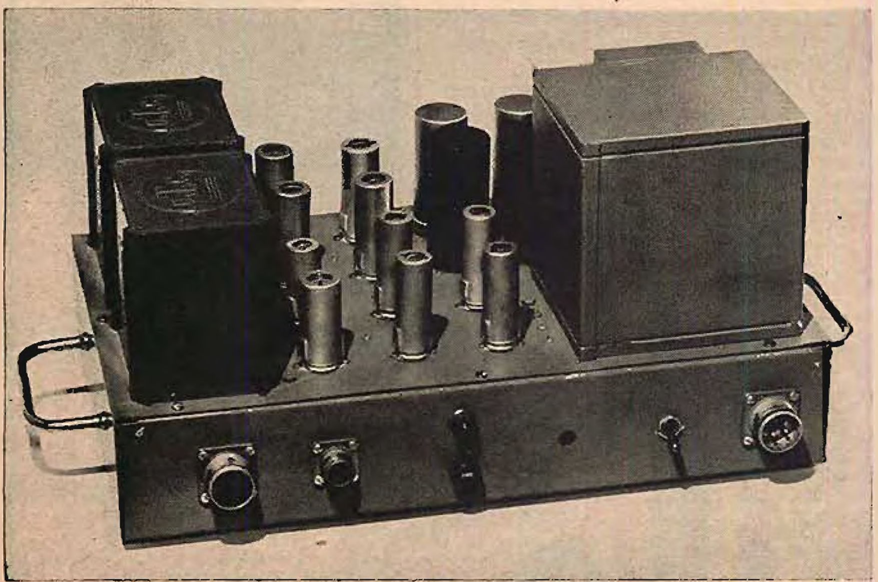

Fig. 5. The 10 tubes and other components of the 6S4 amplifier are mounted on this not-oversize chassis without crowding, sacrificing neat appearance and good separation of tubes for heat dissipation.

sign reassurance may be had—if needed —by a single meter reading. If the output tubes are operating with, say, the proper quiescent cathode current, then the whole of the rest of the circuit is very probably all right.

The first stage of this particular design uses a 12AT7 as a symmetrical differential amplifier. The differential amplifier is convenient as an input stage, since it provides a high-impedance point—the differential grid—to which d.c. feedback can be applied. It was expedient in this case to use the main input grid for a.c. feedback, and the differential grid for d.c. feedback, in this way obtaining and input circuit at d.c. ground potential, and avoiding problems of mixing a.c. and d.c. feedback voltages.

Symmetry of this differential stage is important. There is a possibility of 6 db more stage gain and hence that much more feedback, if the differential plate is returned to a well-regulated source of +60 volts or even to the +150 v. from the 0A2. It was not possible, however, to do this, without trouble with d.c. regeneration. The power supply, not being regulated, has a finite output resistance, and common to four stages (counting the differential stages as two), in spite of assistance from the upper 0A2 (*Fig.* 4). Full electronic regulators are, of course, almost a necessity with multistage d.c. amplifiers, and it was only a firm desire for simplicity, economy, and compactness which dictated the simple—but effective—supply used here. No trouble with d.c. instability has been experienced when reasonable symmetry of the 12AT7 circuit was attained, and commercial tolerances of parts have proven to be quite adequate. There are no selected, matched, or premium-quality components.

The driver stage was made a pentode for reasons of gain, at least 40 db of a.c. feedback being sought. A 12AU6, one of the higher-performance 12-volt tubes, was chosen. (A heater winding of that voltage happened to be the most convenient to use of the windings available on the transformer.)

The 12AU6 is operated at a screen potential of about 100 volts, which is a fair compromise between the higher gains obtained at lower voltages, and the larger output swings made possible with higher voltages. The screen was run at +150 volts for some time and the only difference was a little less feedback.

The network in the plate circuit of this tube (R_6-C_1) is designed to reduce the gain of the stage at a 6 db-per-octave rate, from 300 to 5000 cps, so that the driver is not contributing to the rolloff in the critical 10–100-kc region where the transformer is letting down. High-frequency oscillation is thus avoided.

The final stage is made up of four 6S4's in parallel, using a 15-hy (nominal at 125 ma d.c.) shunt-feed choke, and a 100-µf coupling capacitor. A stock transformer, not of the largest size (which does control low-frequency results), was used to present the 32-ohm speaker load to the power tubes, so that they see 2000 ohms total, or 8000 ohms per tube, which seems about right. The 6S4 has a stated plate resistance of 4000 ohms at typical operating conditions, and the load here used is probably not too far from optimum. Tests at other loads have not contradicted this. More power might have been had with special components more exactly suited to the job, but a compromise was nessary, and without, it is felt, too great a penalty.

The interstage networks are designed to pass d.c. voltages with 3 to 6 db loss, and to pass a.c. (above 20 cps or so) with negligible loss. Feedback, of course, produces a flat over-all response.

The measured value of feedback, at its maximum, was 47 db at 250 cps. It is reduced at a 6-db-per-octave rate beyond this frequency, due to the network in the 12AU6 plate circuit. Less and less feedback is required for musical reproduction as frequency increases, for amplitudes become less and distortion is generally less serious, even without feedback. The average speaker system will not pass harmonics of (fundamental) frequencies over 6,000 cps, although it may generate its own distortion signals anywhere in its spectrum.

The a.c. feedback path is dependent on having a low-impedance source—a cathode-follower of the usual sort seems adequate—to drive the amplifier. Since it is usual to terminate preamplifiers in cathode-follower output stages or their feedback "equivalents," this is not a great disadvantage. Under this stipulation, the over-all gain of the amplifier is set by the ratio of the 1-megohm and 100,000-ohm resistors at 10.

The large value, 100 µf, of coupling capacitor C_2 was used because it was a convenient and readily available size, and more important, because it was intended to avoid resonating with the choke. The reactance of the capacitor remains low while the choke begins to let down at the low end of the spectrum, so that low-frequency stability is obtained.

The power supply of *Fig.* 4 is of the simplest kind. As rectifiers 6X4's are used on the positive side and selenium rectifiers, for instant starting, on the negative. By the use of an instantaneous negative supply we ensure longer life for the power-stage tubes. Except for a sharp, short transient, there is no chance for the power stage to draw excessive current on warm-up.

Performance Data

Performance of this unit was quite satisfactory for its size. Square-wave tests showed a slope down of 40 per cent at the 10-cps repetition rate, and there was the usual set of dips and peaks amounting to 15 per cent of the total amplitude in the 10,000-cps square wave (due to transformer resonances, which are inevitable).

Sine-wave response was down 0.1 db at 20 cps, and 0.5 db at 20 kc. (Unless a special transformer is wound it is extremely difficult to do much better than this, with tolerable stability and reasonable lack of care in construction, when about 50 db of feedback is involved.)

Phase shift was less than 10 deg. at 8 cps and at 10,000 cps, and less than 1 deg. from 40 to 1000 cps. (Frequency response runs, as to both phase and amplitude, were run at about 1 watt output.)

Maximum power was 7.5 watts from 100 to 10,000 cps, and 2.7 watts at 20 cps. The low-frequency power was limited by the iron-cored components.

Hum and noise amounted to 4 mv, referred to the output, or 72 db below full power, quite a reasonable figure.

Comparison of the two amplifiers (both of them highly experimental in the sense that they were not intended to be the constructor's last word on the subject) shows a clear superiority of performance and of ease of construction (with a reasonable amount of equipment) for the single-ended 6S4's. Better results were more easily obtained with the "unorthodox" circuit, even though performance was limited by the use of small sizes of iron-core components.

Acknowledgment must be made of the many arguments in favor of single-ended, direct-coupled amplifiers for audio use presented by Mr. George W. Downs, which led to the construction of the 6S4 amplifier described. As a result of the confirmation of these arguments in this and other projects the author is unlikely to build a push-pull amplifier again unless paid to do so!