Output Transformers in Transistor Power Amplifiers

by Sidney Corderman*

Output transformers can make transistor power amplifiers more reliable, more flexible, and more powerful. At the same time output transformers offer the best continuous protection to loudspeakers against the hazards of avalanche failure of output transistor devices.

Time has shown that output transformers make transistor amplifiers operate cool and safe. The output transformerless amplifier (OTL) becomes less exciting when amplifiers must give long, consistent and predictable operation.

Let's take a look at transformers in general - - - at their past and present use in amplifiers - - - and at why McIntosh Laboratory continues to be the leader in the amplifier field with the use of transformers.

Remember Vacuum Tube Amplifiers?

Until the early 1960's, McIntosh and just about everyone else in the high fidelity component manufacturing business produced vacuum tube power amplifiers exclusively. The familiar push-pull circuit of Fig. 1 reigned supreme. In that circuit we had a pair of tetrode or pentrode tubes with their high output impedance trying to deliver power to low impedance loudspeaker systems. A transformer was needed to provide the necessary impedance match between them. But there were problems in trying to achieve an optimum transfer of power between tubes and speakers. Typically, using a pair of 6L6 output tubes in push pull, we had a tube load impedance of 4000 ohms trying to deliver power to, say, an 8 ohm speaker load. The impedance ratio was 500 to 1, and the necessary transformer had to have a turns ratio of around 22 to 1 (turns ratio varies as the square root of the impedance ratio). The required turns ratio created problems at both ends of the audio frequency spectrum. Leakage inductance and shunt capacitance (represented as dashed lines in Fig. 1) caused high frequency roll-off. The primary inductance of the transformer together with its inherent nonlinear characteristics placed limits on low-frequency response. And the energy stored in the unwanted leakage inductance caused notch distortion, as illustrated in Fig. 2.

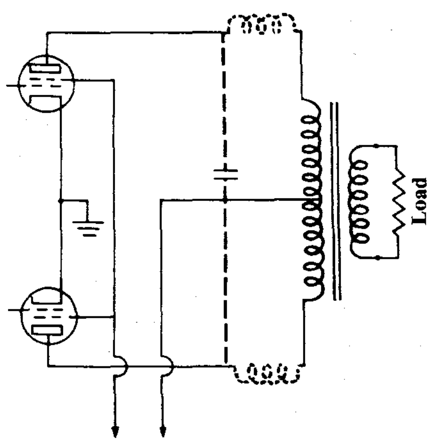

Fig. 1 — Typical push — pull output circuit (see story for dashed line information)

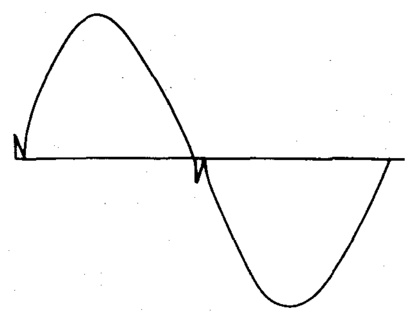
Fig. 2 — Notch distribution in a typical Class B output circuit

The McIntosh Unity Coupled Circuit

Long before the advent of transistorized power amplifiers, McIntosh found an effective way to solve these problems. We called it the Unity Coupled Circuit. The basic configuration is illustrated in the diagram of Fig. 3. The impedance ratio required between primary and secondary has been reduced by a factor of four-to-

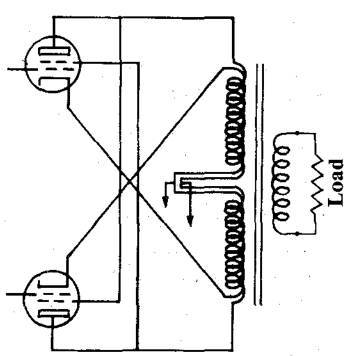

Fig. 3 — McIntosh "notch free" low distortion Unity Coupled Circuit

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one compared with the conventional arrangement. It is now 125 to 1 (1000/8). The turns ratio is therefore 11 to 1, only half of what it was before. Leakage inductance is therefore much lower, and so is the shunt capacitance across the windings. The use of a bifilar winding technique completely eliminates the leakage inductance problem of coupling between the sections of the primary windings. It was the development of the Unity Coupled Circuit by McIntosh (the circuit is patented) way back in 1947 that enabled us to produce amplifiers which were a whole order of magnitude lower in distortion than the competition of those days. Typically, we were able to produce power output circuits with total harmonic distortion of under 1.0% even before the distortion-reducing negative feedback loop was added. With just 20 dB of feedback applied, the THD was further reduced to under 0.1%!

What About Transistor Amplifiers

The audio industry welcomed the power output transistor as the solution to all its problems. After a few faltering starts (early germanium power output transistors were notoriously unreliable and easily destroyed by high operating temperatures), silicon power transistors became the standard power device in power amplifiers.

Since power output transistors can operate into a low output load impedance, it was possible to design output circuits to match 8-ohm loads directly-without the need for a matching audio output transformer. Indeed, most OTL amplifiers, when coupled to 8-ohm resistive loads for test purposes, can deliver full rated power to those loads for long periods of time without overheating or exceeding safe thermal dissipation limits. The trouble is that we don't listen to resistors-we listen to loudspeakers. It will come as no surprise to you to learn that speakers having a "nominal" impedance of 8 ohms often measure lower and higher impedance values at different audio frequencies. Then, too, consider the fact that many popular speaker systems have nominal impedances of 4 ohms, and the impedance of 4 ohm speakers can easily dip down to as low as 2 ohms at certain frequencies. What happens to an OTL amplifier with such low impedances connected to it? In theory, if an output stage is designed to match an 8 ohm impedance, its power output capability should double when it's connected to a 4 ohm impedance. But as this mismatch occurs, thermal dissipation increases rapidly. In fact, operating into a 4 ohm load, heat dissipation is double what it would be when operating at 8 ohms, as illustrated in Fig. 4. Unfortunately, if the amplifier was designed for 8-ohm operation, its thermal dissipation limits were designed with some safety factor for 8 ohm operation, so as to meet the FTC* preconditioning requirements. These call for the amplifier to be able to deliver one-third rated power at rated impedance for one hour. But, as you can see from Fig. 4, the safety margin is not nearly great enough to permit operation at 4-ohms-or 2-ohms-or 1-ohm impedances. Remember, too, that many amplifiers and receivers have provisions for connection of more than one pair of speakers for use in different listening rooms, so that even if 8-ohm speakers are selected, using double pairs of them results in a 4-ohm net nominal impedance even before allowing for downward variations in impedance at specific frequencies in the audio spectrum. So, unless manufacturers are willing to resort to disproportionately massive heat sinks, cooling fans or combinations of both, designing power amplifiers that can deliver their maximum powers continuously at both 8 ohms and impedances of 4 ohms and lower becomes physically impractical in the case of the OTL amplifiers.

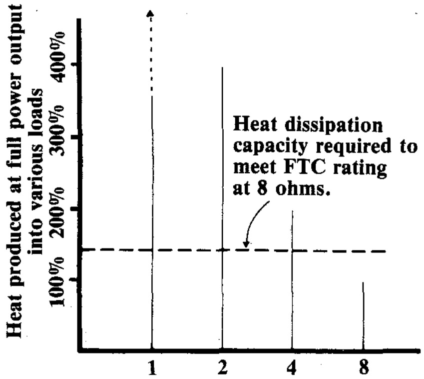


Fig. 4—Heat produced by transformerless amplifier at various load impedance

The Answer-Output Transformers!

If a transistorized amplifier were equipped with an output transformer, you could move up or down in load impedance and maintain full power ratings without over-dissipating anything, since the amplifier's output stages would always be working into an ideal load.

To many hi-fi enthusiasts, output transformers tend to create visions

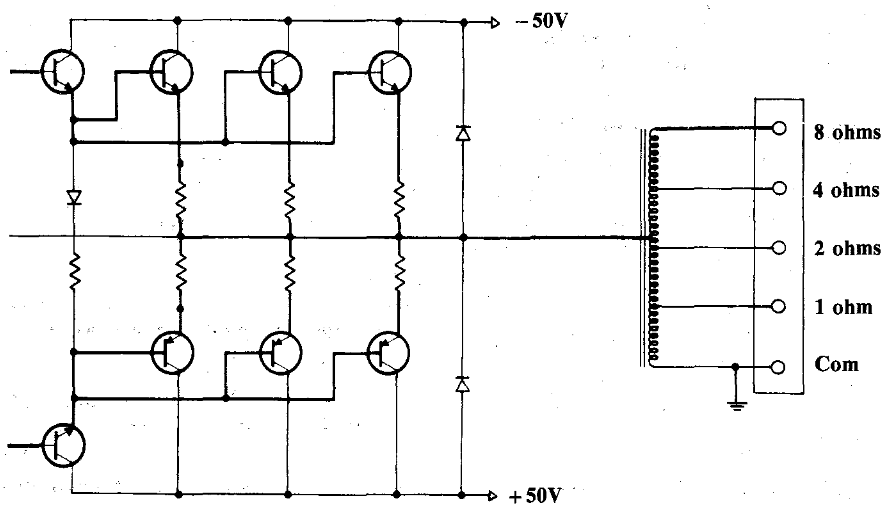


Fig. 5—McIntosh MC 2255 output stage and transformer

*Federal Trade Commision regulations of Nov. 4, 1974 concerning power output claims.

of compromised design. That is just not the case today. Technology in materials and transformer design methods have advanced significantly in recent years and, remember, we're dealing with low impedance devices-not tubes.

It's no longer necessary to translate impedances from a "plate circuit" to a speaker — a step down of several hundred to one. With transistor output stages, a ratio of only 4 to 1 or less is required. In tube amplifiers, extremely good balance in the push-pull primary was required if notch distortion was to be avoided. Now, using a single ended push-pull transistor output stage the transformer can be driven in a single ended fashion. One end of the winding is returned to ground potential. With the transformer at ground, no isolation is required between the input and output and therefore a simple autotransformer can be used.

Fig. 5 shows a typical arrangement used in our new MC 2255 amplifier. The output stages are designed to work optimally into a load impedance of 2.1 ohms and it becomes a simple matter to "tap into" the auto-transformer for precise impedance match. Taps for 1 ohm, 2 ohm, 4 ohm and 8 ohm operation are arranged so that the output transistors continue to work into their optimim impedance. The result: full power output at any of these impedances, with no possibility of thermal over-dissipation.

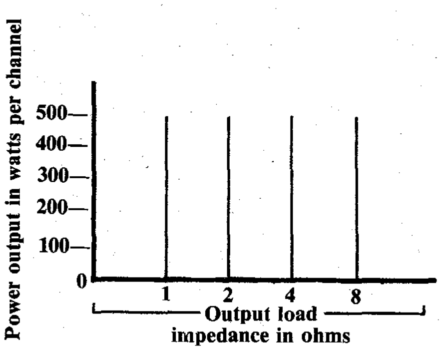
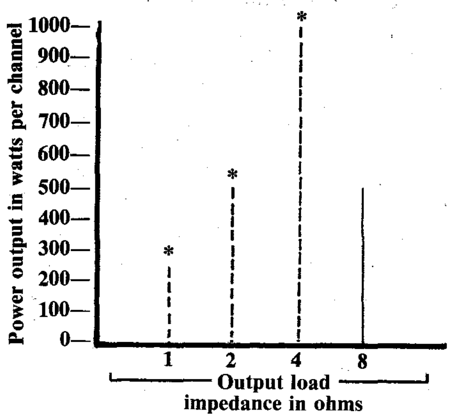


Fig. 6 - Performance of MC 2500

Our popular MC 2500 amplifier also uses an auto-transformer and Fig. 6 shows how that amplifier is able to deliver its full rated power (500 watts RMS per channel) into impedances of 1, 2, 4, and 8 ohms. If we compare these results with those obtained with similarly rated OTL amplifier (Fig. 7) we see that at all but 8 ohms, continuous opera-



(*- - - Continuous operation not possible due to overheating. Protection circuit is assumed to current limit when load falls below 4 ohms, in actuality the output into 4 ohms and lower impedances will fall below the values shown.)

Fig. 7—Performance of non McIntosh transformerless amplifier rated for 500 watts in 8 ohm load

tion at theoretical maximum power is impossible because of overheating and protection circuit limiting.

What About Phase Shift?

Critics opposed to the use of transformers in output circuits of audio amplifiers are quick to point out that "transformers introduce phase shift" at the low and high frequency extremes. As a matter of fact, a properly designed transformer (and we'll get into some of the factors that are involved in designing McIntosh output transformers in a moment) can introduce zero phase shift at 20 Hz and about 3 degrees of phase shift at 20 kHz (Fig. 8A), which is certainly in-

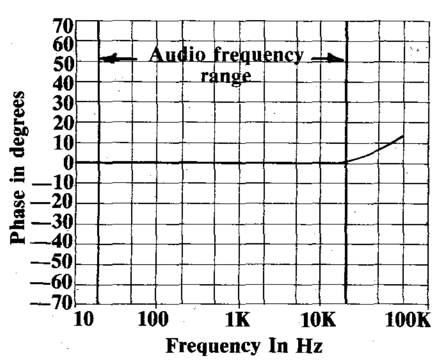
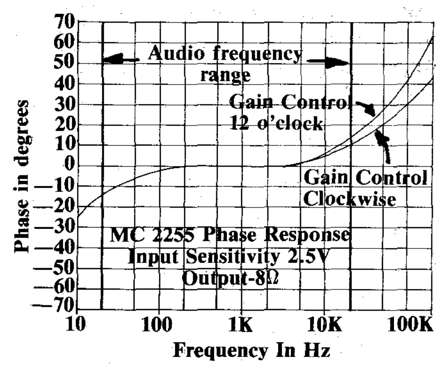


Fig. 8A—Typical of phase shift in McIntosh auto-transformer at 8 ohms

significant. The typical volume control used on amplifiers (both those that are OTL and those equipped with transformers) introduce more shift than that — about 15 degrees in fact (Fig. 8B). Since an output transformer is driven from an extremely low impedance, there is actually more low-frequency phase shift caused by the usual input coupling capacitor at these low frequencies than by the transformer. So, why haven't more manufacturers used output transformers on solid-state amplifiers? Possibly they are not aware of the technology, but more likely they don't want to spend the extra cost. A good transformer is an expensive component. It is heavy, takes up a fair amount of space and contradicts the audiophile's notion that transistorized equipment must be small and lightweight. Be that as it may, the FTC regulations suggest that output transformers are the only logical solution to rating audio amplifiers honestly at 1, 2, 4, 8 or any other impedance required.



1 watt, 8 ohms
— Volume Control Clockwise
----Volume Control 12 o'clock

Fig. 8B—Typical shift in a complete McIntosh amplifier

Not Just Any Transformer!

At McIntosh, we wind all our own output auto-transformers. Of course, we could purchase them from any one of a number of transformer companies who do nothing but wind transformers (our power transformers are, in fact, purchased from other suppliers), but we have long since found that transformers can't always be made successfully "according to the book". A great deal of experimentation is required before a new design of a transformer can be mated to a specific amplifier circuit. We went through dozens of developmental samples in the case of our new MC 2255 amplifier. What we ended up with is shown schematically in the diagram of Fig. 9. The transformer is trifilar wound to provide adequate coupling between windings. It takes 23 individual windings to make this output transformer. There are six different winding sections, five of which are connected in parallel. We use grain oriented silicon steel core laminations because that kind of core means less iron-and less iron in turn means tighter coupling. It also means lower winding resistance for a given size wire. The grain oriented silicon steel means that it has a higher magnetic saturation point-about 17 kilogauss versus 12 to 13 kilogausses for the non-oriented variety and higher permeability. There is therefore less core loss, or, to put it simply, we end up with a more efficient transformer—one which couples more of the available amplifier power to the speaker loads. To further improve coupling, we don't use any interlayer insulating paper. In a power transformer that might pose a voltage breakdown problem. But since our polyurethane insulated wire is rated at 4000 volts per mil (and since the highest voltage we're talking about for an audio transformer is about 100 volts), this really is no problem at all. All of our output transformers are potted with material which has especially high thermal conductivity. Besides helping to keep operating temperatures within the transformer down, this compound reduces lamination buzz to inaudible levels. We figure you'd rather listen to your speakers than to our transformers!

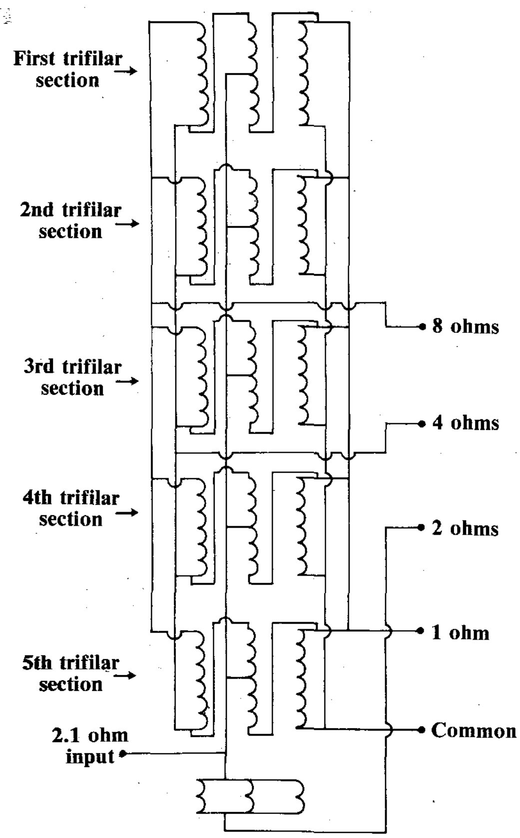


Fig. 9—MC 2255 output auto-transformer schematic diagram

Our Transformers Are Only Part Of The Story

Whether an amplifier uses an output transformer or not, its output devices must be designed to work into an optimum load so that maximum current delivered by the output transistors never exceeds the safe operating area specified for the transistor. Fig. 10 shows current versus voltage limitations for the epibase type of output transistor used in our MC 2255 amplifier. If all amplifier loads were purely resistive, staying within the safe operating area would be relatively simple, but the fact is that speakers often present highly reactive loads to amplifiers. In Fig. 11 we have combined the safe operating diagram of Fig. 10 with load and limiting characteristics at the 8-ohm tap of our MC 2255. As you can see, even when the load is highly reactive, every possible voltage and current condition falls within the safe operating area of the output devices used. Compare this diagram with Fig. 12 derived from data concerning the output transistors used in a currently available high-powered amplifier. Note that inadequate protection is provided for reactive loads.

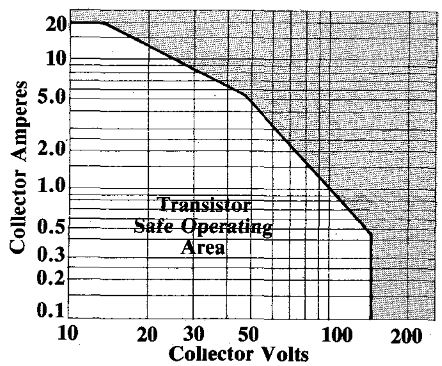


Fig. 10 - Current versus voltage limitation epibase type output transistor

To Sum It All Up

The points we've tried to make are relatively few, but they spell the difference between a McIntosh output transformer equipped amplifier and every other kind of amplifier around.

1. A transformer equipped amplifier will deliver rated power at any impedance for which a transformer tap is provided.

2. An OTL amplifier designed for 8-ohm operation cannot operate safely (according to the FTC rules) when driving lower impedances (4 ohms, 2 ohms, etc.), yet such loads commonly occur either because of speaker impedance variations with frequency or because of paralleling of multiple speaker systems across one channel of an amplifier.

3. The FTC power rule regarding audio amplifiers has forced many manufacturers to omit 4-ohm ratings-even though 4-ohm speakers are in common use. McIntosh transformers equipped audio amplifiers deliver full power at any impedance for which a transformer output tap is provided.

4. Because of their design, McIntosh transformers introduce less series leakage inductance than is commonly encountered with OTL amplifiers which require a series inductance between the output circuit and the speaker connection for amplifier stability. At the 8 ohm tap of our MC 2255, leakage inductance is a low 3.5 microhenries. This represents an impedance of only 2.2 ohms at a frequency of 100 kHz.

5. Properly designed output transformers impose no limitations on frequency response. At the 8-ohm tap of the MC 2255, response is down only 0.3 dB at 50 kHz. With a 4-ohm load connected, response is down but 0.1 dB at 50 kHz.

6. Phase response of the MC 2255 amplifier, contributed by its specially designed output transformer, is accurate to within 9 degrees at the 8 ohm tap at a frequency of 50 kHz and undergoes zero degrees of phase shift at 20 Hz. At the 4-ohm tap, phase shift at 50 kHz is only 7.2 degrees.

Next time anyone gets into an argument with you concerning the attributes of an OTL amplifier versus a McIntosh transformer-equipped amplifier, you might let your adversary read this story.

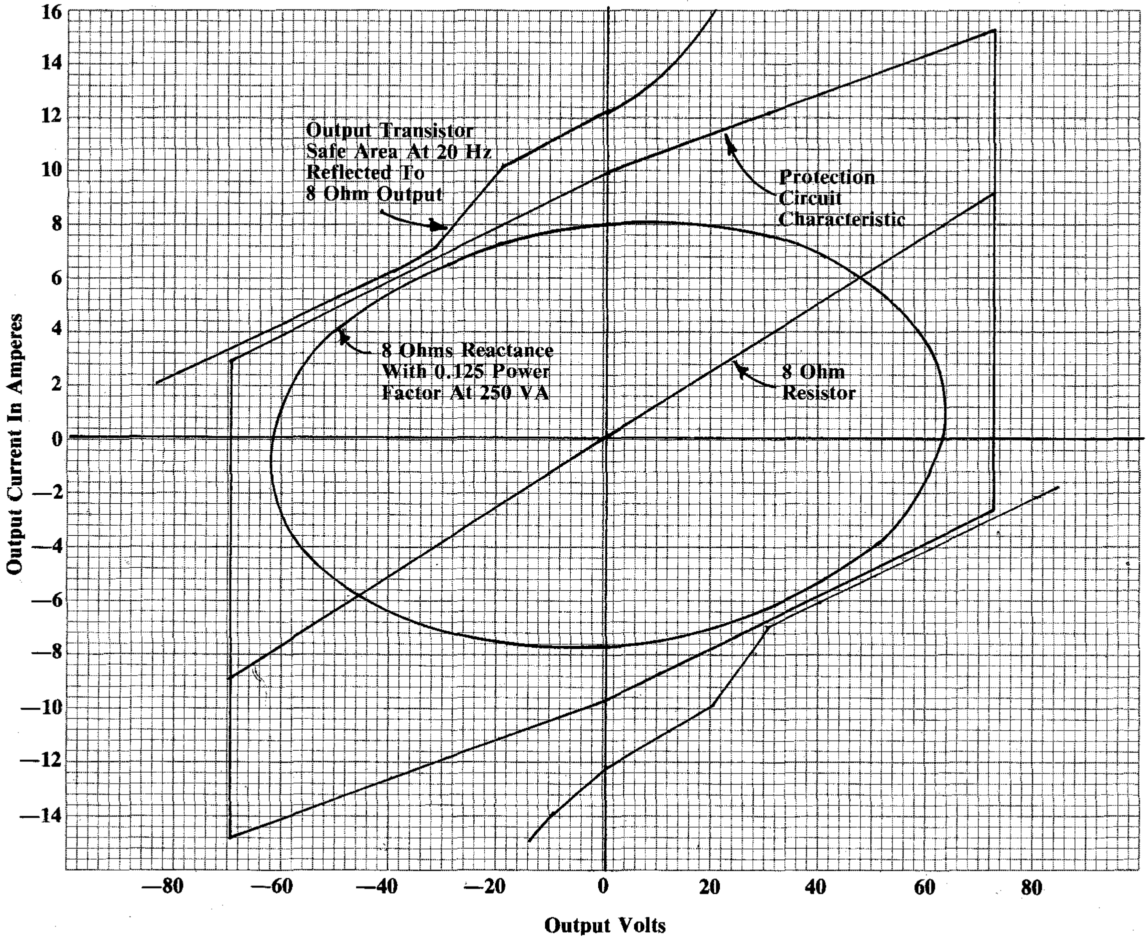


Fig. 11 - Load And Limiting Data of the McIntosh MC 2255 measured at 8 ohm output.

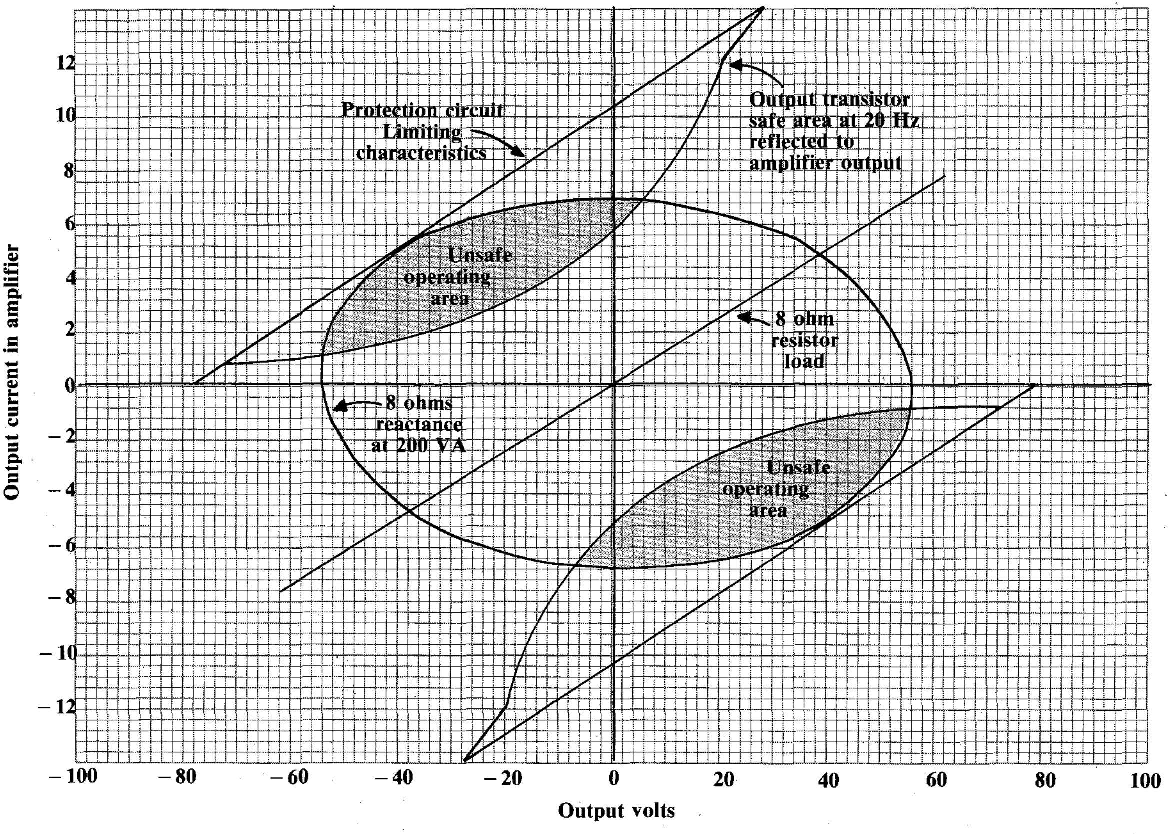


Fig. 12 — Load and limiting data of a non McIntosh high-powered transformerless amplifier measured at 8 ohms output.