

July 22, 1969

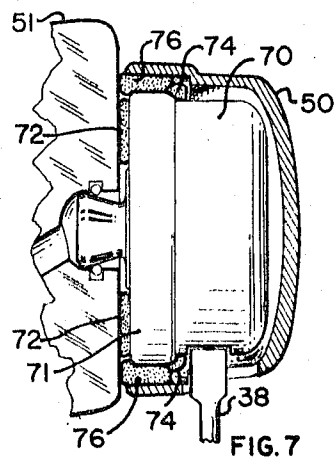
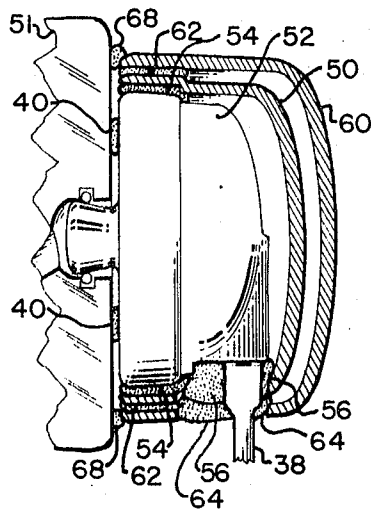
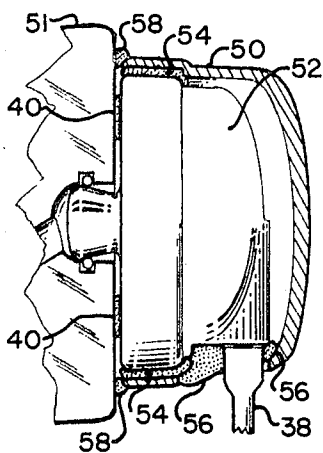
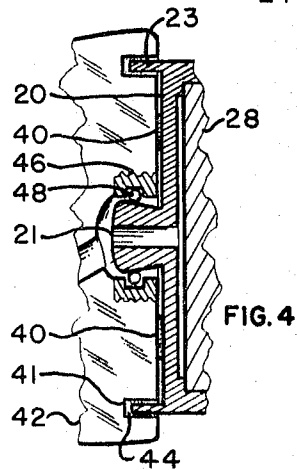
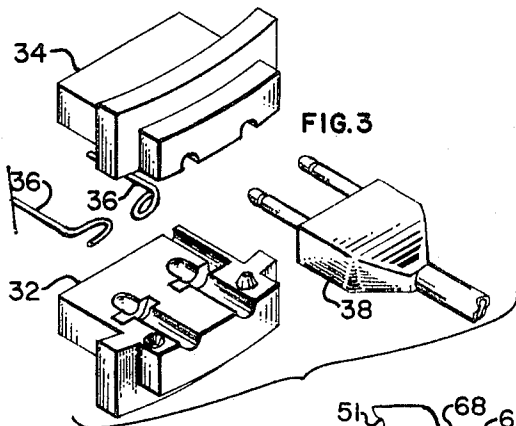
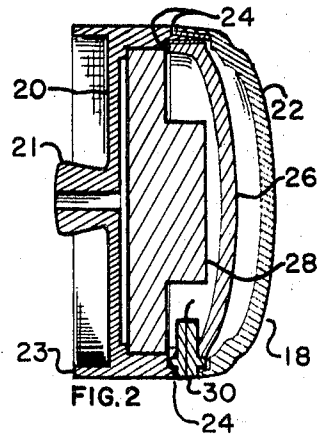
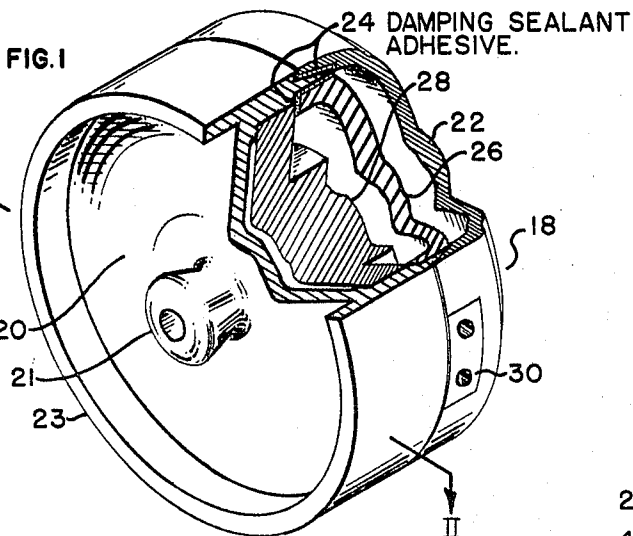
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3,457,375

HEARING AID MECHANISMS THAT ARE LARGELY IMPERVIOUS TO THE
LEAKAGE OF SOUND ENERGY AT AUDIO FREQUENCIES

Filed Oct. 1, 1965

3 Sheets-Sheet 1



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3 Sheets-Sheet 2

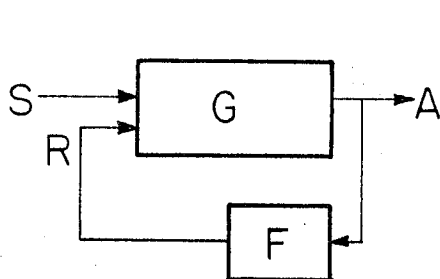


FIG. 8

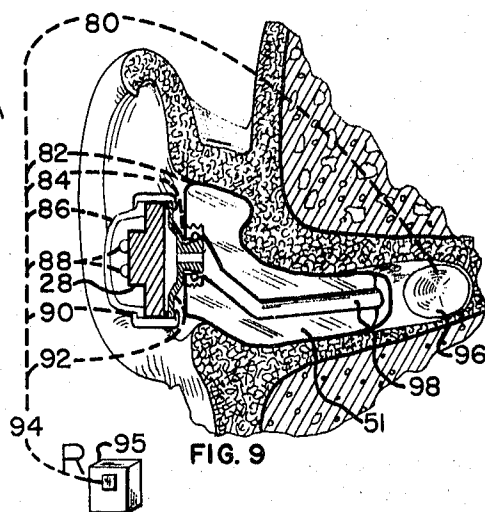
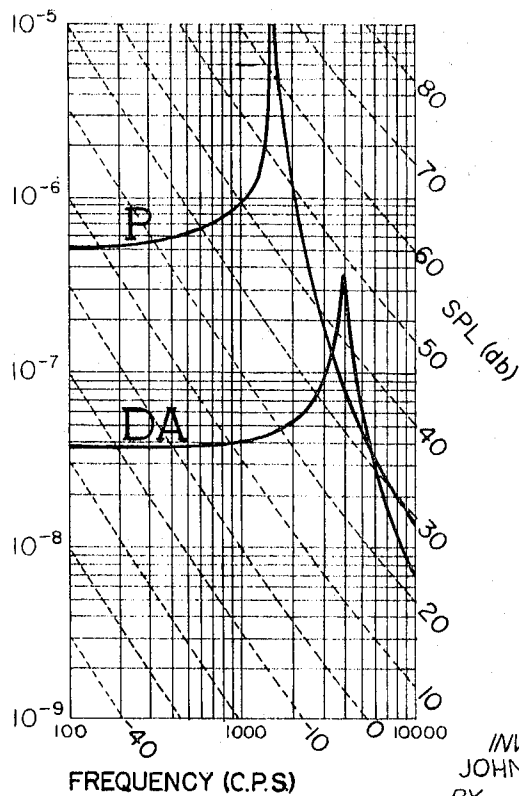


FIG. 9

FIG. 10

RADIAL
VIBRATION
(R.M.S. CM.)



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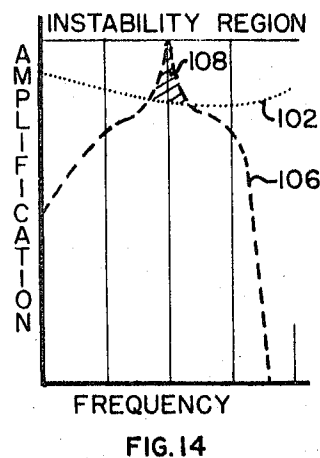
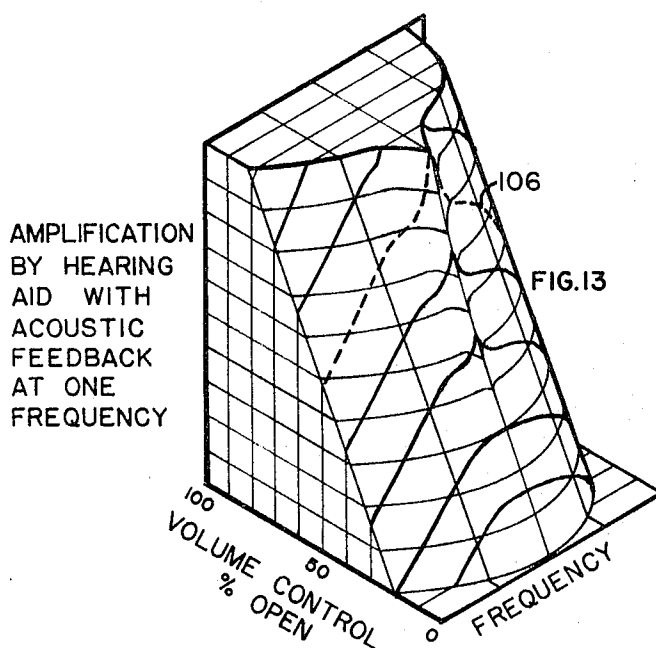
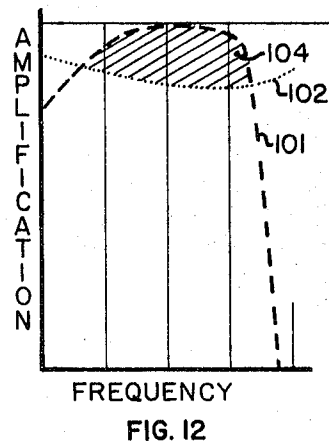
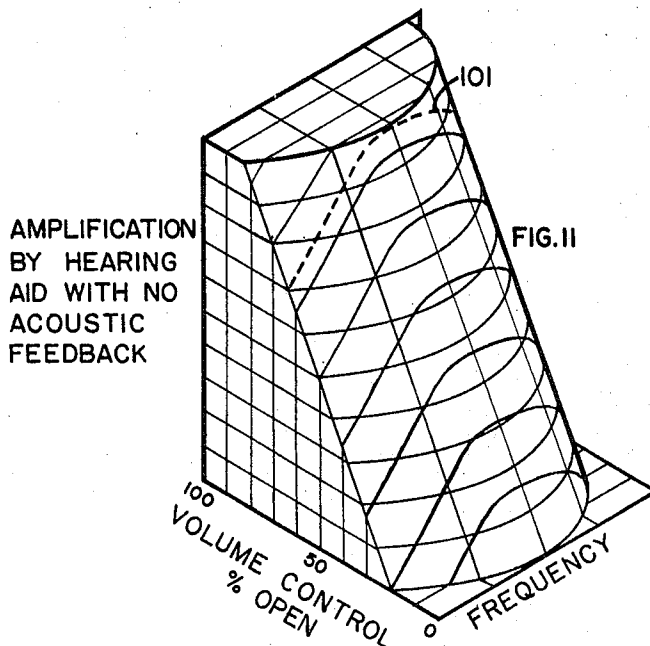
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3 Sheets-Sheet 3



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HEARING AID MECHANISMS THAT ARE LARGELY IMPERVIOUS TO THE LEAK- AGE OF SOUND ENERGY AT AUDIO FREQUENCIES

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Filed Oct. 1, 1965, Ser. No. 491,958

Int. Cl. H04r 25/02

U.S. Cl. 179—107

16 Claims

ABSTRACT OF THE DISCLOSURE

A lightweight stiff housing structure which is largely impervious to the leakage of sound energy at audio frequencies. The unavoidable structural resonances of this stiff housing's concentric shells are mutually de-tuned and individually damped to reduce those acoustic energy leakages which are greatest at those structural resonances. The structure may be in the form of a hearing aid device or significant portions of the structure may be added onto hearing aid ear receiver housings of existing design.

This invention relates to improved hearing aid systems, and relates particularly to improved housings for hearing aid ear receivers and their connection to earmolds.

The hearing aid industry trend toward amplifiers having higher reserve power potential has not affected the basic limitation of acoustical feedback on hearing aid system amplification stability and bandwidth-amplitude product. Unless this limitation is modified, the percentage of deaf persons who can benefit from hearing aids will not increase. It has long been recognized that with increasing amplification there is a growing need for control of hearing aid feedback howl and whistling which both annoy the wearer of a hearing aid system and prevent him from employing his hearing aid to its full amplification power capability. This recognition is so universal that many powerful hearing aid systems are sold with custom fitted earmolds whose primary function is to seal against leakages contributing to acoustical feedback at the same time as minimizing the air volume between the eardrum and the transducer. Custom fitted earmolds do not, however, eliminate all acoustical feedback. In fact it is not at all uncommon for a person with normal hearing when conversing with a wearer of a properly fitted hearing aid to hear small portions of his speech being rebroadcast as a result of the acoustic leakage from the hearing aid system, even though the system is not howling or whistling. As hearing aid systems are required to deliver higher and higher amplification for the increasingly deaf, they almost invariably oscillate (become unstable) at some audio frequency. For such persons, hearing aid benefits are limited to a delicate amplification setting at which feedback oscillation is a continuous incipient tendency. Hearing aid operation at this setting thus has a "ringing" characteristic which stops and starts with various head angles and positions. The frequency of ringing and howling depends on and varies with the hearing aid equipment in use, as well as its placement on the wearer.

To reduce loss of human potential among the profoundly deaf there has been active mutual interest and cooperation among hearing aid manufacturers, dealers, and educators of the deaf. Powerful body-worn conventional style hearing aids are being employed at the limits of their amplification capability in increasingly successful speech training of the nearly totally deaf. But this speech training becomes more difficult and less satisfactory when the hearing loss of a trainee exceeds 60 or 70 decibels. For persons with over 90 decibels hearing loss, speech

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training time is exceedingly long and the resulting speech quality is far from normal.

Delivery of large amounts of acoustical amplification for speech training purposes with present hearing aid equipment now requires large earmuffs to be worn over ear receivers. These large sound-containment devices conflict with the cosmetic needs of the handicapped deaf. Understandably the higher amplification enabled by the large earmuffs is limited to the classroom and some home situations.

As is well known, the speech of persons deaf from birth is an accurate imitation of what these handicapped persons perceive through their diminished sense of hearing. The lower the residual hearing capacity of a person, the more the hearing aid is relied upon. That the best of powerful hearing aid systems are not equal to the task of amplifying for persons with 80 decibels or more hearing loss is demonstrated by the indistinct speech of these persons as mentioned above. The sounds mouthed by this class of handicapped persons create a profound social barrier which causes predictable emotional and economic damage. The process by which hearing aids deliver increasingly unintelligible sounds to the increasingly deaf is explained in this specification.

An object of this invention is to provide a practical ear receiver housing and earmold connection construction which effectively contains acoustical energy within hearing aid ear receivers over the complete audible frequency range for the highest sound pressure levels deliverable by hearing aid amplifiers coupled with ear receiver transducers.

A further object is an improved hearing aid system capable of providing greater acoustical amplification over a greater audio frequency range than now possible in the arts of cosmetically acceptable hearing aids.

Another object is the provision of adaptation devices for existing conventional body-worn hearing aid systems providing substantial improvements in these systems at modest cost, weight, and cosmetic penalty.

A further object is the improvement of volume compression functions in volume compression type hearing aid systems.

The present invention provides an especially effective containment device for vibro-acoustic energy leakage at its source (the ear receiver and earmold assembly), for all audio frequencies and amplitudes. Any sound energy which travels through sound insulation shall herein be termed leakage. In one form, the invention comprises a lightweight housing structure which is largely impervious to the passage of sound energy at audio frequencies. The unavoidable structural resonances of this stiff housing's concentric shells are mutually de-tuned and individually damped to reduce those acoustic energy leakages which are greatest at those structural resonances. This structure provides improved hearing aid ear receiver devices, or significant portions of this structure may be incorporated by addition onto hearing aid ear receiver housings of existing design. Further features of devices in accordance with the invention are that the mechanical connection of the ear receiver to the earmold as well as the electrical connection of the ear receiver to the amplifier are made more secure against the passage of sound energy to the air. Each decibel of acoustic energy leakage reduction enables another decibel of wide-band amplification by hearing aids, and the present invention enables over 15 decibels improvement beyond present hearing aid amplification stability limits.

In accordance with the invention, the following features are employed in ear receivers and ear receiver housings, singly or in combination:

(A) The housing portions are made stiff (over 500,000

p.s.i./inch radial stiffness calculated as a pressure vessel) and preferably constructed of materials whose bulk specific acoustic impedance exceeds 7,000,000 kg./second \times meter². Three-dimensional curvatures as on a sphere are useful to increase wall radial stiffness with minimum weight penalty.

(B) The housing portions are made gas-leak-tight to prevent airborne acoustic energy waves from bypassing the mechanical containment barriers. Rolled compression joints are avoided and housing joints are more effectively sealed by other permanent means.

(C) The walls of the housing portions are preferably damped as much as possible to reduce their inevitable mechanical resonance effects in the audio frequency range. It is desirable to reduce wall thickness when in contact with damping materials, to facilitate transmission of any vibration energy into the damping materials by mechanical transformer action.

(D) The housing portions are alternatively made of multiple-wall construction. Preferably, each such wall has a fundamental mechanical resonance frequency differing by a substantial amount, and at least by $\frac{1}{3}$ octave, from that of any other wall. Coupling between these resonant elements is minimized by individual acoustical damping of each wall which tends to vibrate and by providing the greatest acoustical impedance mismatch at their interfaces. This mismatch is made usefully large by an airspace between the multiple walls.

(E) The physical size of all housing surfaces exposed to the external air is minimized. This acoustic radiation surface is significantly reduced by sealing leakage from the front surface of ear receivers at the periphery of the housing abutment with the earmold.

Suitable physical arrangements embodying the above construction practices are shown in FIGS. 1 through 7 of the accompanying drawings in which:

FIG. 1 is a perspective, partly cut away view of an ear receiver housing incorporating a preferred exemplification of the invention;

FIG. 2 is a sectional view of the housing drawn in FIG. 1;

FIG. 3 is an exposed view of an electrical connector assembly constructed in accordance with the invention;

FIG. 4 is a sectional view similar to FIG. 2, showing connection of the preferred ear receiver housing to an adjoining earmold which is specially configured in cross section;

FIG. 5 is a view partly in section of a modification unit in accordance with the invention for a conventional hearing aid ear receiver whose construction includes a plastic back housing shell;

FIG. 6 is a view partly in section showing a different modification unit coupled to the hearing aid ear receiver of FIG. 5;

FIG. 7 is a view partly in section showing a modification to another commercially available hearing aid ear receiver whose construction includes a metal back housing shell;

FIG. 8 is an acoustical energy flow diagram useful in explaining the invention and representing a hearing aid system as an amplifying servomechanism;

FIG. 9 is a simplified sectional view through the auditory canal of a human left ear when fitted with earmold and ear receiver, looking upwards, and is useful in understanding many of the major acoustic energy leakages in hearing aids and their total contribution to acoustical feedback to the hearing aid microphone;

FIG. 10 is a log-log plot of sound pressure level on the surface of variously constructed one-inch diameter hemispheres as a function of their radial vibration amplitude as driven by a uniform internal sound pressure amplitude whose frequency is adjusted over the specified range;

FIG. 11 is a three dimensional plot of the response surface of an idealized hearing aid system which is free

of any acoustical feedback, the scale units being arbitrary with amplification limited to that level established in FIG. 13;

FIG. 12 is a two dimensional plot of a section through the response surface of FIG. 11 at the position indicated by dashed lines;

FIG. 13 like FIG. 11 is a three dimensional plot of the response surface of an idealized hearing aid system, but which system includes acoustic feedback at one frequency only; and whose amplification is limited to that level above which the hearing aid oscillates;

FIG. 14 is a two dimensional plot of a section through the response surface of FIG. 13 at the position indicated by dashed lines.

An example of a hearing aid device in accordance with the invention is shown in FIGS. 1 through 4. These figures are not drawn to scale. The device is an exterior housing 18 with electrical socket connector 30 which together with an electroacoustic transducer 28 comprise an ear receiver worn by a person as part of a conventional body-worn style hearing aid. The ear receiver is normally connected into a custom fitted earmold 42 (FIG. 4 only) by a standard snap-fitting consisting of a hollow plug shape 21 and surrounding garter spring 48 seating in a standard socket fitting 46 in the earmold 42. The skin-side surface of the earmold 42 is molded to be closely complementary to the central convoluted manifolds of the wearer's outer ear and ear canal, while the snap-fitting side of the earmold 42 is substantially flat. The standard hollow plug 21 is on the central axis of the ear receiver, and also defines a substantially coaxial hole which channels the full sound intensity from the transducer 28 to the eardrum by means of a matching sound port in the earmold 42.

The ear receiver is also connected in conventional fashion to a portable microphone and audio amplifier (not shown) by means of an electrical cord whose plug end 38 only is shown. Because the portable audio amplifier is usually worn on the chest, the electrical cord spanning the distance between ear and chest is usually no longer than two feet. The ear receiver assembly functions to transform amplified electrical audio energy into acoustical energy immediately adjacent to the earmold. Ear receiver sizes are a compromise between cosmetic demands and the demands of generating high acoustic intensities, and ear receivers from commercial hearing aid manufacturers are now fairly uniform in size.

The housing 18 for the ear receiver must (for reasons to be related later) contain sounds of all audio frequencies and magnitudes within the limits of the housing and within the connection of said housing 18 to the adjoining earmold 42. To this end wall stiffness, resonances and leakage paths are, individually or in combination, selected or minimized in accordance with consideration now to be given.

There is no limit to the degree of sound containment and insulation desirable in a hearing aid ear receiver assembly with an earmold. However, referring to FIG. 9, the upper limit to the practical degree of sound insulation is set by the leakage path 80 from the inner ear at eardrum 96 via skull bones and flesh to the air. Measurements by von Bekesy (published in 1960) of sound leakage by the path 80 indicate that about 40 decibels (fairly uniform with frequency) of sound insulation is the magnitude of this upper practical sound insulation limit.

It is well known and easily calculated that in series with any sound leaking from the ear receiver and earmold assembly is about 30 decibels of sound insulation caused by spatial separation 94 of these leakages from the hearing aid microphone 95. This spatial insulation effect is largely independent of frequency.

Measurements by the inventor of sound leakages from most types of commercially available conventional ear receiver disclosed that the sound insulation values drop invariably to only 10 decibels or less at some frequency

dependent upon the particular ear receiver housing. Measurements of insulation effectiveness against leakage through these ear receiver types was made by cyclically plugging and unplugging the sound output port 21 of the ear receiver which was energized at many various steady frequencies. The decibel difference (indicated on a sound intensity measurement system) between the plugged and unplugged condition of the ear receiver was the inventor's measure of sound insulation by the ear receiver housing at a particular frequency. As will be explained later, the worst insulation frequency profoundly and adversely affects the hearing aid system behavior. The design of housings for ear receivers becomes one of the most critical elements of high-power hearing aid system operation, capable (as is now prevalent in the industry) of largely incapacitating the usually high quality electronic components of such systems by high frequency instability or howl.

Still referring to FIG. 9, the leakage paths through the said ear receiver types can be identified as rear housing shell resonance flexure 86; electrical socket hairline crack air passages 88; rolled compression joint hairline crack air passages 90; and front housing resonance flexure 92. The mechanical resonance flexure leakages are fairly sharply tuned (very dependent on excitation frequency). Because properly fitted earmolds 42 seal leakage 82 from the ear canal and leakage 84 from the snap fitting far better than ten decibels, the ear receiver housing leakages listed above comprise the present largest sources of acoustic feedback in hearing aids.

I have explained that the insulation performance of ear receiver housings can theoretically and usefully be improved from the present sub-10 decibel level to the 40 decibel limit imposed by skull leakage 80 or the lesser limit imposed by earmold leakage 82. Later I shall discuss why this improvement is a necessary and valid objective. As stated before, the present invention enables over 15 decibels improvement in acoustic energy leakage reduction, to a minimum insulation level about 25 decibels from the present 10 decibels, still beneath the theoretical objective of insulation of 40 decibels, but still within the limits of cosmetically acceptable sizes and weights. By extension of the design directions indicated in this specification, it is possible to achieve the 40 decibels acoustic insulation objective, but such assemblies are thought by the inventor to be excessively heavy and large; although many persons may not be able to hear satisfactorily without such large and heavy devices. Furthermore at about 25 to 30 decibels insulation, the fit of an earmold becomes more critical than now required in the hearing aid industry; earmold leakage path 82 must be as free of leakage as is the ear receiver.

To explain partially how the present invention achieves its high degree of sound insulation at small size and weight penalties, refer to FIG. 10. This graph of vibration, frequency, and sound pressure level (SPL) applied to one-inch diameter hemispheres vibrating radially. Sound pressure level (SPL) is measured at the outer surface of the vibrating hemispherical shells, with SPL (decibel) scale referred to some arbitrary reference pressure level. Curve P applies to a plastic hemispherical shell with damping .01 of critical; and curve DA applies to a similarly dimensioned aluminum shell with damping .05 of critical. Each shell is vibrating as forced by the same uniform SPL inside the shell. The difference of resonance frequencies is primarily the result of the differences of density and stiffness of the respective materials. In FIG. 10 is shown the combined effect of a material substitution and damping differences. Notice that at the low frequencies (below the resonance peaks) the wall vibration amplitude is essentially that same bulge amplitude resulting from a static internal pressure. At resonance, curve P peaks at 75 decibels SPL while curve DA peaks at 47 decibels SPL, a difference in this example of 28 db of which 23 db is assignable to stiffness difference and 5 db

assignable to the damping increase and its dissipation of resonance magnification effects. Because .01 is a rather high value of internal hysteresis damping for homogeneous thermosetting plastic, and because .05 is a conservative amount of damping obtainable from available techniques, then the calculated 28 decibels improvement in this example is conservative. It is apparent from this example that the greatest acoustic leakage through such hemispheres occurs at their mechanical resonances; and so it tends to be with ear receiver housing walls. FIG. 10 also illustrates that stiffness is an immediate way to achieve sound containment; and if it were possible to avoid resonances, another 20 decibels insulation would be possible.

Of course the curves of FIG. 10 are simplified representations (showing only a single resonance) of real non-spherical housing wall vibrations and the contribution of these vibrations to acoustic feedback in hearing aid systems. But overtone resonances are usually of smaller magnitude than fundamental resonances and are usually easily damped with the same means as the fundamental resonances are damped.

Note also that by limiting all amplified frequencies to those below the fundamental vibratory resonance of the ear receiver housing, it is possible to obtain vastly higher sound insulation values from even the plastic material. This enables (as will be shown later) vastly higher amplification levels within the limited frequency band by a hearing aid. Powerful aids whose frequency is limited to under about 500 cycles per second are known, but these are essentially sound magnitude indicator devices not speech transmission devices. The limited frequency response amplification so achieved does not satisfy the speech amplification requirements of the profoundly deaf whose needs quite often increase or at least remain constant up to over 8000 cycles per second.

These considerations enable better appreciation of the unique elements and relationships of combinations in accordance with the invention as shown in FIGS. 1 through 4.

The transducer 28 generates waves of acoustical pressure within the housing structure made of elements 20, 22, 24, and 26. Housing front case 20 is of a cylindrical shape with a circular disc spanning its internal diameter at about its mid-length. It is made of material whose specific acoustic impedance exceeds 7,000,000 kg./second \times meter², in this case aluminum suitable for anodizing. Centrally located on the circular disc and coaxial with the cylindrical case 23 is the hollow-sound-port and earmold-snap-fitting 21. On the opposite side of the circular disc is a circumferential positioning ledge which spaces transducer 28 slightly away from the disc surface. The volume defined between the disc and the transducer is employed for transducer diaphragm vibratory motions and resonant chamber tuning in the standard manner. It is difficult to construct a lightweight flat disc element in 20 which is over 500,000 p.s.i. per inch bulge stiffness; relatively large thicknesses or heavy materials are required. Instead of such expedients, vibratory transmission leakage 92 by the flat disc element of 20 is contained by the unique structure described immediately below.

Referring again to FIG. 9, acoustical leakage 84 from the snap connector joint as well as mechanical resonance leakage 92 from the housing front case disc are reduced by a damping pad 40 (see FIG. 4) disposed in a continuous generally circular pattern surrounding the snap connector 21. The exterior section 23 of the housing front case cylinder forms a skirt extending from the perimeter of the housing.

When the housing is fitted to an earmold as seen in FIG. 4, this skirt extends into and nearly fills a circular groove 41 in earmold 42 while the damping pad 40 abuts the flat surface of the earmold 42. A peripheral labyrinth seal is completed between the earmold and the ear receiver by caulking material 44 filling the clearance

voids between the skirt 23 and the groove 41. The caulking material 44 seals gas-tight the acoustic leakage path around the skirt 23 in groove 41. Pastes, waxes, thixotropic greases, etc. are suitable for the caulking agent 44. This caulked seal must be easily broken apart and reassembled during periodic cleaning of the earmold 42. The peripheral labyrinth seal made by 23, 41, and 44 can assume many alternate shapes such as screw threads, annular corrugations, concentric skirts, and the like.

The rearward extending cylindrical element of the housing front case 20 surrounds the periphery of the transducer 23 in a snug fit. Extending further rearward is a skirt which serves to locate the housing rear walls 22 and 26. The thickness of this locating skirt tapers from about .030 inch at its base to about .008 at its end. This taper is complementary to the thinning of peripheral edge sections of the rear housing walls 22 and 26. The tapering and thinning of the wall sections functions as a mechanical transformer for housing wall vibrations tending to couple the wall vibrations more effectively into damping materials 24 located interstitially between the tapers of 20 and 22 and between 20 and 26. Thixotropic viscous compounds or mixtures as well as solids and rubbers with high internal mechanical hysteresis can serve as the damping materials 24. Because it is convenient in this particular design to combine air leakage sealing and structural joining with damping functions, the damping element 24 can be a thin rubber bond cured in place with small proportions of foaming additive and other fillers to enhance the internal mechanical hysteresis of the rubber at normal room temperature, such as RTV108 adhesive sealant silicone rubber sold by General Electric Co. Note that there is a separate bonding and damping element 24 for each wall bonded to the housing front case 20, and that both of these bonding-damping elements are peripherally continuous around the circumferential joints of the housing, including a leak-tight bond to and around electrical connector assembly 30. All joints of the ear receiver housing must be gas-leak-tight, except of course sound port 21. The thickness of the damping element 24 should preferentially be no more than one-tenth of the axial plus radial length of one of the damping elements 24. The length and thickness of the joint are proportioned to preserve the pressure vessel stiffness of the housing.

The rear walls 22 and 26 of this ear receiver housing are configured as a cup-within-a-cup with an intervening airspace. Each rear wall has a fundamental mechanical resonant frequency differing from the other by preferably at least $\frac{1}{3}$ octave. The function of these separately damped, plural, and mutually detuned walls is the effective containment of acoustic leakage which occurs at unavoidable wall resonances. Damping at the periphery of such cup shapes is effective particularly when the peripheral edges are thinned to a significantly narrower section as discussed above. The compound or 3-dimensional curvatures of the cup shapes are each chosen to achieve the pressure vessel radial stiffness of at least 500,000 p.s.i. per inch for each cup. The material for the rear wall cups, like housing front case 20, should have a specific acoustic impedance in excess of 7,000,000 kg. per second \times meter². Aluminum suitable for anodizing serves well for this purpose.

Because of the requirements for detuning, the thickness for the internal rear wall 26 usually but not necessarily exceeds the thickness of the outer wall 22. The airspace between walls 22 and 26 serves to uncouple the free mechanical vibrations of the said walls by a substantial acoustical impedance mismatch. A vacuum would be superior to air in acoustical impedance mismatch, but permanent maintenance of a vacuum in lightweight structures subject to droppage impacts is not generally justified by the additional benefit achieved.

By electrical network analogy, each concentric wall is a tuned filter in series with another filter tuned to another frequency; and coupling between filters is minimized to

further reduce through-flowing energy. In the case of this invention, vibro-acoustic energy is mechanically filtered by tuning relationships drawn in FIG. 10. It is recognized that overtone resonances of cup shapes like bells are not in general integral multiples of the fundamental resonance. Because the outer rear wall 22 is proportioned differently from the inner rear wall 26, the overtones of the two walls will not in general be in the same musical interval relationship to their respective fundamentals. The outer rear wall 22 features a narrow annular impression near to its outer diameter which serves to reduce visually the apparent size of the housing structure.

In the electrical connector assembly (FIG. 3) an insulating block 32 is configured to mate with another insulating block 34, and at the same time to retain and position by mechanical recess means, the electrical spring contacts 36. The surface between the insulating blocks 32 and 34 is made gas-leak-tight by means of a permanent rigid cement which also seals the hairline air passage around the shanks of electrical spring contacts 36 where they protrude into the interior of the ear receiver housing. The cemented assembly of insulation blocks 32 and 34 together with electrical spring contacts 36 accepts by guide holes and spring action the prongs of the amplifier connection cord plug 38. Jumper leads (not shown) connect the transducer 28 to spring contacts 36.

The exterior surfaces of insulating blocks 32 and 34 are made to lock securely into the elements 20, 22, and 26 by means of damping-sealant 24. Thus in this design air cannot leak from the housing through the connector 30 or the damping seams 24 under small static pressures, say under ten pounds per square inch.

In addition to the preferred arrangement of this invention as drawn in FIGS. 1 through 4, adaptation devices in accordance with the invention may improve existing styles of hearing aid ear receivers. FIGS. 5, 6, and 7 illustrate the ways in which the two major styles 52 and 70 of hearing aid ear receiver are adapted in accordance with the invention.

The receiver 52 (FIGS. 5 and 6) is the standard and most common style of ear receiver; a plastic rear housing shell is joined, by rolling, to an aluminum front wall. In FIG. 5, a stiff (as specified above) small cup-like housing 50 is attached to plastic-backed ear receiver 52 by means of adhesive-sealant-damping material 54, thus adding a second rear wall to the housing of the ear receiver. The electrical plug 38 is coated with a release agent prior to insertion and sealing into the assembly via a port in the housing 50. The release agent allows removal of the plug 38 for periodic cord replacement after sealing. After insertion of the plug 38, the adhesive-sealant 56 shuts off leakage radiated from inside the metal shell 50. Front wall damping 40, of mechanical damping material as described above encircles and seals the void between the earmold 51 and the stiff housing 50. A release agent between 58 and 51 and between 50 and 51 allows removal of the earmold for periodic maintenance. The plastic back of the ear receiver and housing 50 each can have a different fundamental resonant frequency.

The device of FIG. 6 is similar to that of FIG. 5; but a larger over-housing-cap 60 is connected to small housing cap 50 by means of adhesive-sealant-damping material 62. Adhesive-sealant-damping material 68 encircles and seals the void between the earmold 51 and the over-housing 60. Adhesive-sealant-damping material 64 seals off the leakage from within overhousing 60, completing the second air-tight housing wall. The plastic back of the ear receiver, cap 50, and over-housing-cap 60 can each have a different fundamental resonant frequency in this triple-wall housing.

The ear receiver 70 (FIG. 7) is the type in which a thick aluminum back shell is joined to a thin steel front wall by a rolled ferrule rim 71. Leakage from this type of ear receiver is primarily through the thin front plate at its mechanical resonance, and secondarily through

hairline cracks under the ferrule 71. In the arrangement of FIG. 7, the modification kit is applied to the stiff-backed type of ear receiver 70. Damping material 72 reduces resonance effects in the thin front plate of this ear receiver. Adhesive sealant 74 seals leakages through hairline cracks at the rear of the ferrule 71, and adhesive sealant 76 attaches a small housing cap 50 to the ear receiver 70 while sealing leakage around the periphery of the joint with the earmold 51. If desired, the electrical plug 38 in FIG. 7 may be caulked by material such as 56 in FIG. 5.

It is seen by FIGS. 5, 6 and 7 that it is possible to apply design criteria A, B, C, D, and E above to ear receivers now being built and used throughout the world, by means of over-fitting housings like designated 50 and 60 together with adhesive-sealant-damping materials such as room temperature vulcanizing silicone rubber, and release agents. It is moreover possible to supply housings 50 and 60 in colors to match more closely the skin tone of the wearer, making the ear receiver less noticeable on the person.

Although not commonly thought of as such, a hearing aid operating close to the point of howling feedback is an amplifying servo system with positive feedback or regeneration. When viewed in this manner, further understanding of the invention is possible. Referring to the servo system diagram of FIG. 8, environmental sound S enters the microphone (transmitter)-amplifier-transducer box G to create amplified sound A from which some acoustic energy crosses the acoustic leakage path-filter F to sustain regenerative acoustic energy R which reenters G. Notice that all symbols in FIG. 8 are complex vector quantities, and that F particularly contains a significantly time delay. Because of the geometric flexibility of feedback path F together with its time delay and standing waves, it is guaranteed that some positive in-phase acoustic regeneration energy R will occur at some frequencies and negative out-of-phase energy will occur simultaneously at other frequencies. The combination of positive and negative feedback operating simultaneously at different frequencies tends to destroy any linearity of the frequency amplitude profile of the hearing aid system. And of course any leakage R from an ear receiver is the closest continuous sound source in a hearing aid system.

Output A of hearing aid systems can be expressed in terms of other system elements as

$$A = G(S + R) = G(S + A/F)$$

where G is complex gain intensity ratio and is loosely interchangeable with the word "amplification" and where F is complex insulation intensity ratio,

which by rearrangement:

$$\frac{A}{S} = \frac{\text{output}}{\text{input}} = \frac{G}{1 - G/F} = \text{system amplitude gain behavior}$$

Notice that whenever the G/F complex ratio approaches plus unity a volume expansion occurs at those frequencies preferentially selected by feedback path filter F. If G equals or exceeds F at any frequency, the system amplification is on the threshold of becoming unstable, contingent upon the vagaries of shifting phase relationships in F. Of course during system instability, the output of the system runs away to its power capacity saturation limits, and amplification by the system of other frequencies is distorted by the saturating oscillation at feedback selected frequencies.

After a hearing aid system has begun howling, it is possible to change the howl frequencies by changing the distance and/or orientation of the ear receiver and microphone. The howl frequencies usually jump from pitch to pitch rather than slide smoothly during this spacing change, confirming that feedback path F is not uniform with respect to frequency. Acoustic standing waves and

tuned leakages 86 and 92 all contribute to feedback path non-linearity with respect to frequency.

Just as the gain of a hearing aid system is increased at selected frequencies by the regeneration factor

$$1/(1 - G/F)$$

the time for the hearing aid system to reach this amplitude is increased by the same factor. A few cycles of the feedback frequency can be amplified by G without distortion. But in a few milliseconds, when acoustic feedback R arrives at the hearing aid input, the emphasizing amplification or degeneration occurs spontaneously. This feedback action then is a rapid-acting volume expander for some specific frequencies passed by path F. Distorted dynamic ranges of amplified sounds, making of non-expanded or perhaps cancelled frequencies, and extreme harmonic distortion and intermodulation distortions are only some of the system defects caused by acoustic feedback, regardless of the quality of the system's electronics, even without system howling. The worst system defects arise because of the concurrence of the above volume expansion effects with the high threshold of deafened sound perception to be explained more fully below. At this stage of the explanation it is fully understandable why many hearing aid wearers prefer to adjust their amplification volume control to slightly below the incipient feedback level and so obtain a broader frequency range of response with less distortion at the cost of overall amplitude. Only the partially deaf can waste amplification G to obtain better quality hearing.

Some hearing aids have been constructed to function as volume compressors. The object of the volume compressor type of hearing aid being that full natural dynamic power (volume) ranges of sound can be compressed into the smaller dynamic hearing range between the deafened perception threshold and the upper limits of sound pressure endurance (painfully loud sounds). But notice that the volume expansion effects of acoustical feedback largely accounts for the disappointing performance results obtained from volume compressor types of hearing aids for the deaf. The slower volume compression by electronics has been largely cancelled by the very fast acoustic regeneration effects by feedback. Those very persons who most need volume compression are those most harmfully affected by feedback. Cruder volume compression action by saturation of output circuitry with consequent truncation of waveform is a common distorting characteristic of hearing aid amplifiers which serves as a safety device against injury to an ear.

The above rationalization of hearing aid feedback yields further insights. FIGS. 11 and 13 depict hearing aid system amplification behavior, given uniform input sound intensity (e.g.—white noise), as a function of frequency and volume control setting respectively without and with acoustical feedback. Curve 101 shows the maximum amplification obtainable within the upper limit imposed in FIGS. 13 and 14. The same limit is used for system comparisons. FIG. 12 again plots curve 101 as a slice through the surface of FIG. 11. The sound perception threshold 102 of a very deaf person is dotted across FIGS. 12 and 14. The area 104 enclosed by curves 101 and 102 represents the deaf person's audio intelligence window with area measurable in decibel times octave product.

As the gain of a hearing aid is advanced toward the incipient instability or "ringing" condition, large peaks of time-delayed amplification arise on the frequency versus amplification profile. Curve 106 on FIGS. 13 and 14 shows the maximum amplification obtainable without reaching the instability amplification level which is drawn as the flat upper plane truncating the amplification surface at all other frequencies. Of course, the curves of FIGS. 13 and 14 are simplified to show only a single resonance frequency peak representations of real feedback's multiple peaks and valleys in hearing aid systems.

The area 108 enclosed by curves 102 and 106 in FIG. 14 represents the deaf person's perception window as provided by an aid set at the "ringing" condition; very little intelligence can be transmitted through such a frequency and volume range limited window. Of course as the deaf person's hearing diminishes, curve 102 rises; and the person's hearing perceptions (through hearing aids necessarily operating near incipient howl) is increasingly limited to the power peaks of volume-expanded, time-delayed sounds restricted moreover to the frequencies of incipient feedback. This selective emphasis of any one frequency of incipient feedback is the same as losing all the other frequencies and destroying any prescribed frequency/amplitude profile.

If sound leakage in the feedback path F (elements 80, 82, 84, 86, 90, 92, and 94) could be made uniform with respect to frequency, then less electrical gain G would be required for pure continuous tone perception; but the volume expansion effects of this acoustic regeneration would destroy the dynamic realism of the reproduced sound. Sharp percussive sounds would be distorted into grunts at the perception power level of the very deaf people. Realizing the above, it is easy to understand why the nearly totally deaf speak indistinctly in grunts (lacking clean cut consonant sounds) yet in faithful reproduction of what they perceive through their body-worn hearing aid equipment. The above is also a caution in interpreting pure continuous tone (or tones that are slowly swept or warbled across a small frequency range centered on the frequency of interest) audiometry with hearing aids as worn. To the extent of volume expansion, such audiometry probably indicates an optimistic degree of hearing assistance. Widely spaced "ping" or "dit" 20 millisecond or less tones are better.

Therefore all sound leakage must be minimized as those audio frequencies being amplified. Acoustic amplification is uniquely distorted by acoustic feedback prior to system howling. Insulation against feedback is meaningfully measured at its most leaky frequency. Hearing aid maximum amplification can be no better or greater than its least insulation against feedback.

It should be understood that it is not desired to limit the invention to the exact details of construction and configuration herein shown and described because many modifications within the scope of the claims may occur to persons skilled in the art. Having now particularly described and ascertained the nature of this invention, and in what manner this invention may be physically realized, I claim and desire to secure by Letters Patent:

1. An acoustic feedback resisting cap mechanism for hearing aid ear receiver housings comprising a cup shaped wall element with radial stiffness in excess of 500,000 p.s.i. per inch computed as a pressure vessel superimposed upon the housing of the hearing aid ear receiver, and means for providing a gas-leak-tight joint between the wall element and the housing.

2. The invention as set forth in claim 1 above, wherein the ear receiver housing front face abuts an earmold, and wherein in addition damping means providing a seal is disposed between the housing front face and the earmold.

3. An acoustic feedback resisting cap for commercially available hearing aid ear receiver housings comprising at least a pair of concentric cup shaped wall elements whose resonant frequencies differ and sealant means coupling the wall elements to a hearing aid ear receiver on the side of the ear receiver opposite the ear of the wearer.

4. An acoustic feedback resisting cap mechanism for commercially available hearing aid ear receiver housings, said housings having a measurable resonance characteristic and an electrical plug connection for receiving an external plug, the mechanism comprising at least one cup shaped wall element with radial stiffness in excess of 500,000 p.s.i. per inch computed as a pressure vessel superimposed upon and encompassing the housing at the side spaced furthest from the ear, and defining an in-

terior space having a substantially lower acoustic impedance than the housing and the wall element, the wall element including an aperture exposing the electrical plug connection, means disposed on the wall element providing acoustic damping thereof, and means disposed on the periphery of the housing and between the housing and the wall element for providing a gas-leak-tight joint therebetween about the housing and the electrical plug connection, means disposed on the wall element providing acoustic damping thereof, and means disposed on the periphery of the housing and between the housing and the wall element for providing a gas-leak-tight joint therebetween about the housing and the electrical plug connection.

5. A hearing aid ear receiver housing comprising a wall element disposed on the opposite side of the transducer within the receiver from the ear with radial stiffness in excess of 500,000 p.s.i. per inch computed as a pressure vessel, the wall element partially encompassing the ear receiver, and means disposed about the inner periphery of the wall element providing gas-leak-tight coupling to the ear receiver.

6. A housing for a hearing aid ear receiver comprising in combination generally hemispherical cap means disposed about and spaced apart from the transducer, the cap means having a wall radial stiffness in excess of 500,000 p.s.i. per inch computed as a pressure vessel, and sealing means disposed about the cap means and coupling the cap means to the transducer about its periphery and providing a substantially gas-leak-tight joint.

7. A hearing aid ear receiver housing comprising in combination at least a pair of substantially concentric wall elements whose resonant frequencies differ and including gas-leak-tight joint means coupling the walls elements to the housing.

8. An ear receiver housing having in combination wall means disposed about the transducer of the ear receiver and electrical connector assembly therefor with radial stiffness in excess of 500,000 p.s.i. per inch computed as a pressure vessel, housing joint means resistant to gas pressure leakage from the interior of aid housing to its exterior and disposed about the wall means, and stiff and gas leakage resistant means sealing the wall means about the electrical connection assembly.

9. The invention as set forth in claim 8 above, wherein the ear receiver is seated in an earmold, and wherein a front face labyrinth seal is provided between the earmold and the ear receiver portions.

10. In a hearing aid ear receiver, a housing to contain acoustic leakage, the receiver including a transducer and normally attached to an associated earmold, and the housing comprising: a pair of rear walls disposed on the opposite side of the transducer from the earmold, at least one of the walls being of a radial stiffness in excess of approximately 500,000 p.s.i. per inch radial bulge computed as a pressure vessel and comprising material having an acoustic impedance in excess of approximately 7,000,000 kg./sec.².m.², the walls having other than the same resonance frequency.

11. In a hearing aid receiver, a housing mechanism to contain acoustic leakage in undesired directions from the receiver, the receiver including a transducer and normally attached to an associated earmold, the housing mechanism comprising wall means disposed to at least partially encompass the receiver and to form plural walls relative to the transducer, at least one of the plural walls being generally hemispherical and having a radial stiffness in excess of approximately 500,000 p.s.i. per inch radial bulge when computed by the pressure vessel stiffness criterion, said wall also being of a material having an acoustic impedance specification in excess of approximately 7,000,000 kg./sec.².m.², and being gas-leak-tight, said walls also having different fundamental mechanical resonant frequencies; the acoustic impedance of said wall means being substantially higher than the spaced apart portions therebetween;

and acoustic damping means disposed individually on at least one of said walls.

12. The invention as set forth in claim 11 above, wherein the wall closer to the earmold includes means sealing the wall means to the earmold at the periphery of the wall, thus to contain acoustic leakage from front base vibrations and leakage from the sound port joint of the earmold.

13. For hearing aid ear receivers of the type including a circular receiver base having a transducer mounted on one side and fitting into an earmold on the other, an annulus on the receiver base fitting into a matching groove in the earmold, the receiver including a cover cap joined to the receiver base on the side on which the transducer is mounted, and further including a connector socket for receiving contact pins of an external connector plug, the combination comprising an external arcuate cap member having a periphery disposed about the periphery of the receiver base member, at least partially encompassing the cover cap, and spaced apart from the cover cap, the cap member having a radial stiffness in excess of approximately 500,000 p.s.i. per inch radial bulge computed as a pressure vessel, and both the cover cap and the cap member being of a material having an acoustic impedance specification in excess of approximately 7,000,000 kg./sec. \cdot m.², and including an aperture for receiving the connector plug, the cap member further tapering at its periphery to provide a mechanical transformer action, the resonance frequency of the cap member differing by in excess of $\frac{1}{2}$ octave from that of the cover cap; first sealant means providing a gas-leak-tight joint between the cap member and the receiver base about the periphery thereof; second sealant means disposed between the receiver base and the cap member and providing a gas-leak-tight joint about the connector socket; third sealant means providing a gas-leak-tight joint between the earmold and the receiver base and interposed within the groove between the earmold and the annulus of the receiver base; and acoustic damping means disposed between the broad faces of the receiver base and the earmold.

14. For hearing aid ear receiver type including an earmold and part metal part plastic cover combination, a transducer being disposed within the part metal, part plastic cover, and the plastic rear cover also including an electrical socket connection for receiving an external plug, the combination comprising: an external metallic cap member of generally hemispherical form configured to receive the plastic cover with an intervening air space generally therebetween, the cap member having a radial stiffness in excess of approximately 500,000 p.s.i. per inch radial bulge computed as a pressure vessel, and the material having an acoustic impedance in excess of approximately 7,000,000 kg./sec. \cdot m.², and the cap member material and attachment means being gas-leak-tight; acoustic damping means joining and sealing the opposing faces of the metal front base cover and the earmold to contain acoustic leakage from front base vibrations and leakage from the sound port of the receiver; first sealant means disposed between the cover and the cap member about the periphery thereof and providing a gas-leak-tight joint; second sealant means disposed between the cap member and the earmold about the periphery thereof and provid-

ing a gas-leak-tight joint; and third sealant means disposed about the electrical socket connection of the plastic cover and coupling the metallic cap member to the plastic cover and providing a gas-leak-tight joint about the electrical socket connection, all of said sealant means being readily separable for maintenance without destruction of any of the principal members of the hearing aid receiver or the metallic member.

15. A hearing aid ear receiver including in combination an earmold having a sound port; a hearing aid ear receiver member mechanically coupled to and disposed adjacent to the earmold and including a transducer within a metal-plastic cover, the rear portion being plastic and also including an electrical connector socket for receiving an external connector plug; acoustic damping means disposed between the earmold and the metal front cover; a first cap member generally hemispherical in form encompassing the plastic cover on the side opposite from the earmold and providing an air space therebetween, the first cap member having a radial stiffness in excess of 500,000 p.s.i. per inch radial bulge computed as a pressure vessel and being made of a material having in excess of approximately 7,000,000 kg./sec. \cdot m.²; first sealant means being disposed between the plastic cover and the first cap member and providing a gas-leak-tight joint; a second cap member of generally hemispherical form disposed about the first cap member and the second cap member and providing a gas-leak-tight joint about the periphery thereof on the side adjacent the earmold; third sealant means disposed between the second cap member and the earmold about the periphery thereof and providing a gas-leak-tight joint; the cap members also including apertures for receiving on the plastic cover within the apertures defined by the first and second cap members in the vicinity of the connector plug entry for providing a gas-leak-tight joint.

16. For a hearing aid receiver of the type including a transducer within a metal rear housing shell having a rolled ferrule rim, and an earmold, the combination comprising an additional generally hemispherical cap member disposed about the metal rear housing shell and providing an intervening airspace therebetween, the cap member made of material with an acoustic impedance in excess of 7,000,000 kg./sec. \cdot m.², acoustic damping means disposed between opposing faces of the metal cap and earmold; first sealant means disposed between the metal cap and the cap member at the peripheries thereof; and second sealant means disposed about the joiner line between the ferrule rim and the metal cap, each sealant means providing a gas-leak-tight joint.

References Cited

UNITED STATES PATENTS

2,344,023	3/1944	Carlisle	179—107
2,863,005	12/1958	Knauert	179—107
2,950,357	8/1960	Mitchell	179—107

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,457,375

July 22, 1969

John W. Haggerty

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, lines 22 and 23, "increasingly" should read -- increasingly --. Column 3, line 42, "exposed" should read -- exploded --. Column 4, line 15, "accordane" should read -- accordance --; line 52, "stiffness" should read -- stiffnesses --. Column 9, line 38, after "energy" insert -- R --; line 39, "simultanaeously" should read -- simultaneously --. Column 10, line 8, "incerased" should read -- increased --; line 15, "making" should read -- masking --; line 51, "depice" should read -- depict --; line 73, after "simplified" insert -- (--. Column 11, line 35, "as" should read -- at --. Column 12, line 41, "aid" should read -- said --.

Signed and sealed this 31st day of March 1970.

(SEAL)

Attest:

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Commissioner of Patents