passageways,[9,12] and through mufflers[10] are related topics and may be pursued in the literature.

III. The Ear and the Measurement of Hearing

Any discussion of industrial noise would be incomplete without a description of how it affects human beings. The physical aspects of noise can be measured in many ways, but this information would be useless without knowledge of human responses to noise. First, the operation of the auditory system will be reviewed quite briefly.

A. THE EAR

The ear may be divided into three parts called the external, middle, and inner ear (Figure 22). Sound waves enter the external ear and pass along the auditory

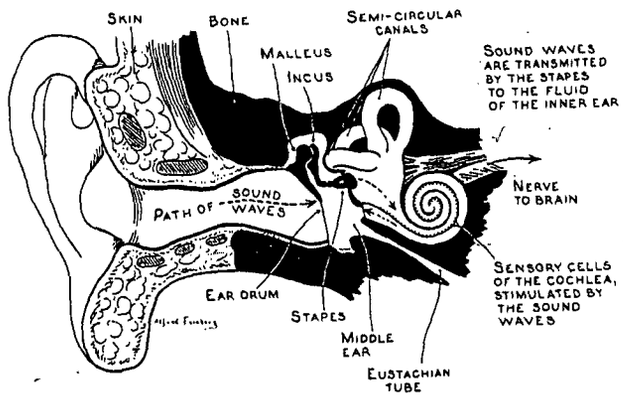

Figure 22. A schematic drawing of the ear.

canal, which is terminated by the ear drum membrane. This is the boundary between the external and the middle ear. Variations in the sound pressure at the drum membrane cause it to vibrate back and forth, and its displacement from normal is very nearly proportional to the sound pressure. The motion of the drum membrane is transmitted across the middle ear through a system of three small bones called the ossicles. The first of the three small bones is the malleus (hammer), which is attached to the inside of the drum membrane. The stapes (stirrup) carries the sound into the inner ear. The incus (anvil) connects the malleus to the stapes. The inner ear, or cochlea, is filled with fluid that moves

[9] R. H. Bolt, L. L. Beranek, and R. B. Newman, Handbook of acoustic noise control. Physical acoustics, Supplement 1, *Wright Air Development Center Tech. Rept.* 52-204, Wright-Patterson Air Force Base, Ohio, 1, 1955.

back and forth as a result of the vibration of the footplate of the stapes. In this manner, air-pressure variations produced by the sound source are changed into motion of the ossicles by the drum membrane and then into motion of the fluid in the cochlea. Finally, the motion of the fluid excites many thousands of tiny sensory units called hair cells. After excessive exposure to intense noise, these microscopic cells may not perform properly or may even show physical damage.

The middle ear cavity, which contains the three ossicles, has an opening in the back wall that goes to the mastoid area behind the ear, and an opening in the front wall that connects by way of a tube with the back of the nose above the soft palate. This connection is called the Eustachian tube, and one of its functions is to equalize the atmospheric pressure on the opposite sides of the drum membrane.

The cochlea is a spiral channel in the skull. It may be visualized as a tube divided lengthwise into three compartments, all filled with fluid. The wall separating two of the compartments is called the cochlear partition, and embedded in it are about 20,000 hair cells that serve to transform the mechanical motion into electrical signals. Nerve endings located at the base of the hair cells are stimulated by these electrical signals and initiate neural impulses that travel along the auditory nerve to higher nervous centers.

The hair cells nearest the middle ear are stimulated most effectively by sounds containing the highest audible frequencies. Sounds with low frequency components stimulate most effectively the hair cells in the area near the tip of the cochlea and farthest from the middle ear. The extremes of the audible frequency range are not sharply defined, but are related to the intensity of the sound. In young normal ears these extremes are approximately 30 and 15,000 c.p.s. for intensities which in the middle frequency range would correspond to that of the ordinary speaking voice. At greater intensities many listeners can hear sounds from 20 to 20,000 c.p.s.

Since the cochlea is set in the skull, intense vibration of the head at audible frequencies will agitate the fluid in the cochlea and cause the sensation of sound. This process is called hearing by "bone conduction." By contrast, the usual method, utilizing the drum membrane and ossicles, is called hearing by "air conduction."

B. THE MEASUREMENT OF HEARING

The device used today to measure hearing is called an audiometer. Years ago tuning forks, watch ticks, coin clicks, whispers, and voice tests were used exclusively. With the advent of the vacuum tube more exact methods of measurement became available. In the early 1930's the electronic audiometer developed rapidly and soon reached a state closely resembling today's models. The photographs in Figure 23 show five of the commercially available models that have been designed to meet the specifications of the American Standards Association and the American Medical Association. Those shown are adequate for most in-