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PREFACE

The 1988 *McGraw-Hill Yearbook of Science and Technology,* continuing in the tradition of its predecessors, presents the outstanding recent achievements in science and technology. Thus it serves as an annual review and also as a supplement to the *McGraw-Hill Encyclopedia of Science and Technology,* updating the basic information in the sixth edition (1987) of the Encyclopedia.

The Yearbook contains articles reporting on those topics that were judged by the consulting editors and the editorial staff as being among the most significant recent developments. Each article is written by one or more authorities who are actively pursuing research or are specialists on the subject being discussed.

The *McGraw-Hill Yearbook of Science and Technology* provides librarians, students, teachers, the scientific community, and the general public with information needed to keep pace with scientific and technological progress throughout the world. The Yearbook has long served this need through the ideas and efforts of the consulting editors and the contributions of eminent international specialists.

SYBIL P. PARKER
EDITOR IN CHIEF

A-Z 1988

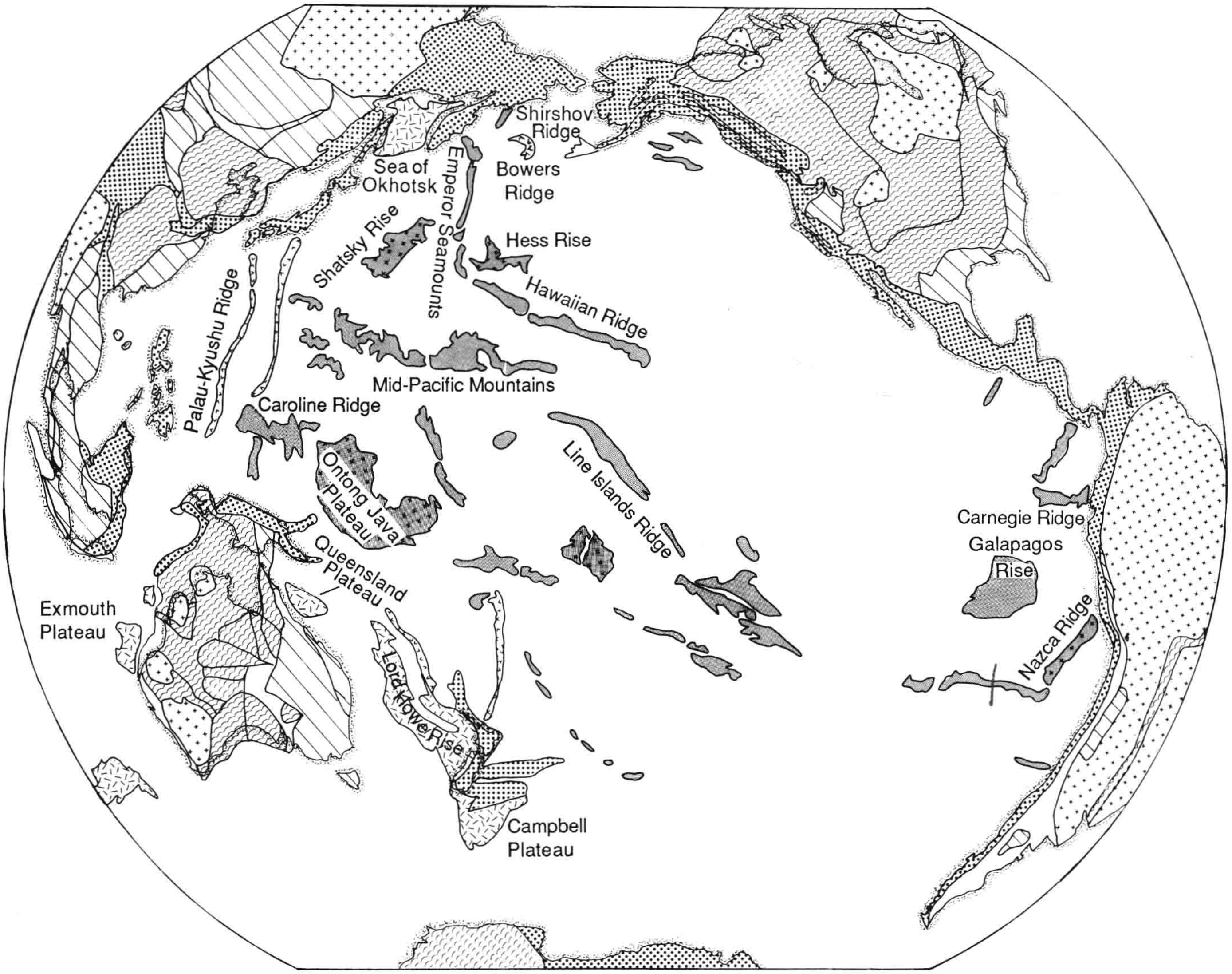
Accretion tectonics

Tectonics is the subdiscipline in geology that is concerned with fundamental earth forces and the effects these have on the distribution and configuration of rocks and strata. Movement along faults, uplifting of mountains, and folding of strata are common phenomena that traditionally have been the subject of tectonic studies. With the advent of plate tectonics in the mid-1960s, geologists began to grasp the full extent of the mobility of the Earth's outer layer of rock. This outer layer is composed of plates, each 60 to 90 mi (100 to 150 km) thick. The relative motion between adjoining plates produces most landforms and crustal configurations. On a global scale, oceanic crust is relatively young, averaging only 55 million years (m.y.) in age, with no ocean floor older than 200 m.y. The age range of continental rocks, however, is quite different, extending from the present age to an age of 3.8 billion years (b.y.). Exactly how all these rocks of diverse ages and compositions gathered to form continents is the concern of accretion tectonics.

Ocean crust forms as plates move away from each other. A 34,000-mi-long (55,000-km) ridge system, which defines the axis along which spreading and crustal generation are taking place, wanders across the modern ocean floor. Because the Earth maintains a constant volume, the spreading motion along oceanic ridges must be compensated by regions of crustal convergence where crust is subducted. In these regions, called subduction zones, one plate passes beneath another plate. A complex series of chemical reactions that results in explosive volcanism is assumed to be associated with subduction zones. The "ring of fire" surrounding the Pacific Ocean is the best-known segment of the 22,000-mi-long (35,000-km) volcanic ring that lies above the world's subduction zones. A plate does not always move directly away from or toward an adjoining plate. Motion ranging from oblique to perfectly tangential is also common. Here, plates slide past one another, defining earthquake faults such as the San Andreas Fault of California or the Alpine Fault of New Zealand.

Terranes. This mobility of the Earth's outer layer is manifested also by the juxtapositioning of rock bodies that formed apart from one another but have subsequently been amalgamated as a consequence of collision forces between two or more plates. The study of these phenomena is called accretion tectonics. With this concept, geologists assert that much of the cordillera of North and South America, the Himalayas of Asia, or the Alpine system of Europe is best represented as an agglomeration of discrete rock packages known as tectonostratigraphic terranes (commonly abbreviated to terranes; see **Fig. 1**). Continents therefore represent long-term effects of numerous accretion episodes. Some continents, for example North America, possess a crude radial symmetry, with the oldest rocks in the interior and successively younger belts of rocks that ring the older core. Australia, however, displays a west-to-east succession, with 3- to 4-b.y.-old rocks cropping out along the west coast. The rocks become progressively younger toward the east. This trend continues all the way to New Zealand, interrupted only by the superposed crustal spreading in the Tasman Sea that has had the effect of partially disrupting the accretion symmetry (see Fig. 1). The symmetric pair to this succession may exist on another continent (or parts of it may appear on several continents) which has been rifted from the west coast of Australia. In a similar fashion, the breakup of Gondwana 100 million years ago (m.y.a.) fractured the accretion symmetry that surrounded the previously amalgamated continents of Australia, Antarctica, India, Africa, and South America.

The symmetry in Asia is particularly difficult to discern because the region from India to Malaysia



- Archean cratonal blocks (> 2.5 billion years ago)
- Proterozoic orogenic belts and cratonal blocks consolidated during the Proterozoic (600 million to 2.5 billion years ago)
- Paleozoic orogenic belts, composed of terranes accreted during the Paleozoic (250-600 million years ago)
- Mesozoic - Cenozoic orogenic belts and accreted terranes (0-250 million years ago)
- continental fragments
- remnant volcanic arcs
- oceanic islands and seamounts, including hotspot tracks
- mixed orgin-oceanic with anomalously thick, continental-like structure

Fig. 1. Generalized map of circum-Pacific tectonostratigraphic terranes.

and northward across China to the Siberian Platform composes as many as five discrete older continental fragments, Tarim, Sino-Korea, Yangtze, Indochina, and India, each with some vestige of an accretionary rim formed somewhere other than in their current setting (see **Fig. 2**). The Siberian Platform has acted as a geologic backstop against which large crustal fragments have swept in from the south. In this way, the belts of accretion have become progressively younger toward the south, with India being the last to arrive, and Australia and the smaller crustal fragments of Indonesia soon to follow. Furthermore, within each accretionary zone the rocks often have a complex history inherited from previous episodes of crustal accretion and dispersion.

The geometry of individual terranes as well as assemblages of terranes in a tectonic collage is the product of the history of plate movements and associated tectonic interactions. Terranes that form on an oceanic plate (for example, basaltic seamounts or volcanic island arcs) generally retain their shape until they collide and accrete. The process of tectonic accretion and the events that follow commonly result in crustal movements that modify the shapes of the terranes. In Asia the direction of accretion has been mostly northward head-on with the Siberian Platform. The shapes of the microcontinental terranes retain the configuration inherited from an earlier continental rifting episode and do not reflect contortions as a result of the accretion tectonics; however, 42 m.y.a. India began to collide with Asia. The resulting north-south compression is causing the previously accreted terranes to the north to extend east and west, absorbing the crustal strain. The terranes of the cordillera of North America reflect an elongation oriented toward the northwest, the principal motion vector between the North American Plate and oceanic plates to the west. These oceanic plates have carried the terranes to the cordillera and also exerted stresses that act to reshape previously accreted terranes or extant portions of the North American craton.

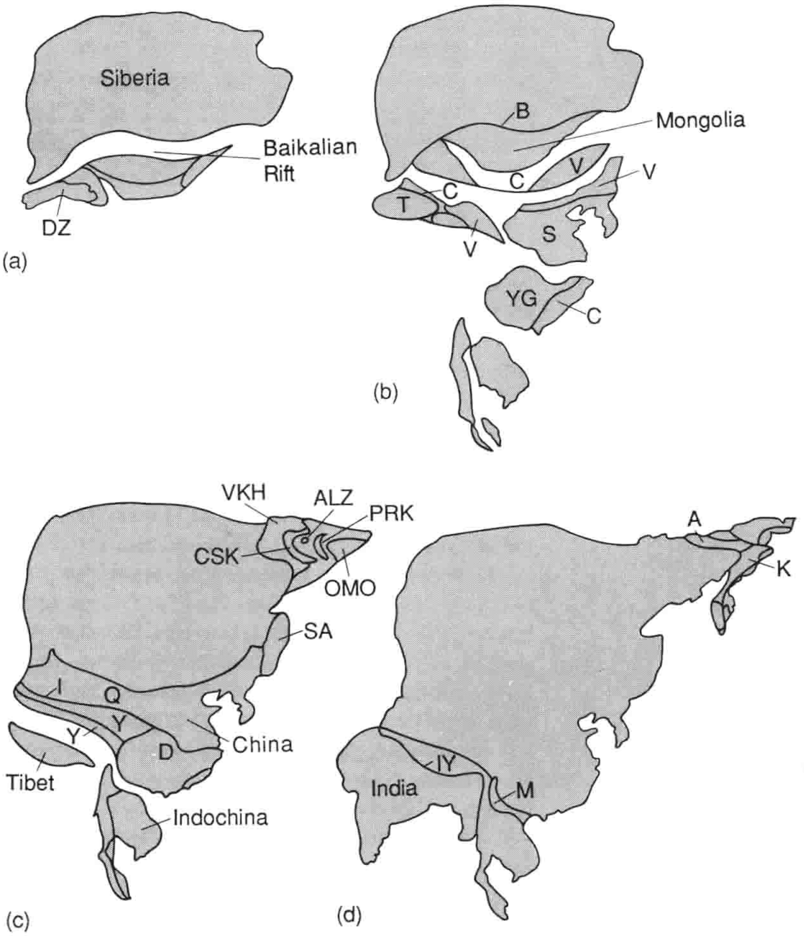


Fig. 2. Schematic representation of accretionary evolution of Siberia and Asia. (*a*) About 550 million years ago. (*b*) About 300 m.y.a. (*c*) About 200 m.y.a. (*d*) About 35 m.y.a. DZ = Dzungaria; C = Caledonian fold belts; B = Baikalian suture; V = Variscan fold belts; T = Tarim; S = Sino-Korea; YG = Yangtze; CSK = Cherskiy terrane; ALZ = Alazeya; PRK = Prikolymsk; VKH = Verkhoyansk fold belt; OMO = Omolon terrane; SA = Sikhote Alin; I = Indosinides sutures; Q-D = Qilian-Dabie Shan suture; Y = Yenshanides fold belts; A = South Anyui; K = Koryak Highlands; M = Mekong fold belt; IY = Indus-Yaluzangbu suture. (*After E. R. Schermer, D. G. Howell, and D. L. Jones, The origin of allochthonous terranes: Perspectives on the shaping of continents, Annu. Rev. Earth Planet. Sci., 12:107–131, 1984*)

Crustal movements. The movement history or kinematics of individual terranes is not always known. The study of fossils to establish ancient paleogeographic settings may provide evidence for the displacement. Also, for some rocks the preserved paleomagnetic signal can specify the latitude at which a rock was deposited. (The Earth's magnetic field can be modeled as a dipole or bar magnet coincident with the Earth's spin axis. The force lines of this field steepen with respect to the Earth's surface as given reference points approach the North and South poles. Thus, for rocks deposited at the Equator, the magnetic inclinations are zero, tangential to the surface, while rocks in the Arctic possess magnetic orientations of nearly 90°, perpendicular to the Earth's surface.)

Despite the uncertainty involving the specific kinematic history of an individual terrane or an assemblage of terranes, plate tectonics provides a means and a necessity for both small and large amounts of crustal movements. The average modern plate speed is approximately 1.6 in. (4 cm) per year, plate speeds up to 6.2 in. (16 cm) per year are known from the South Pacific, and some paleomagnetic data suggest that speeds up to 12 in. (30 cm) per year may have occurred in the past. At the rate of 1.6 in. (4 cm) per year, a 4-b.y.-old rock would have moved 99,000 mi (160,000 km) or a distance equivalent to four circumglobal transits. Transoceanic travel should not be a surprise, because in 200 m.y., which is the longevity of most ocean basins, a terrane traveling at 1.6 in. (4 cm) per year could move 5000 mi (8000 km).

Terrane classification. The composition and stratigraphy of a terrane are the key factors for identifying its spatial limits as well as for inferring possible kinematic histories for a given terrane. A host of terrane classifications is possible. A simple scheme which clearly displays the accretionary tectonic aspects on a global scale classifies terranes into the five categories described below:

Oceanic rocks such as ocean crust or seamounts. Even though ocean crust represents nearly 70% of the rock covering the surface of the globe and is constantly being created along the ocean-ridge spreading centers, ocean crust is rarely preserved as a terrane. These rocks seem to be too dense to become accreted; alternatively, in the process of subduction the ocean crust is the conveyor belt that continues to flow into the deeper parts of the mantle. As many as 25 global ocean floors have been created and destroyed (subducted) since plate tectonic processes began, but all of this material represents only 4% of the volume of the mantle that lies above and around the liquid core. Seamounts, on the other hand, are more buoyant. On a global basis they are growing at approximately 0.05 mi^3 (0.2 km^3) per year. Because they protrude above the sea floor, the accretion process is facilitated once a seamount enters into a subduction zone.

Oceanic rocks mixed with continentally derived sediments. The world's river systems carry large volumes of detritus to the ocean. Much of this material is deposited in the deltas and on the shelves of the submerged parts of the continents. The volume of sediment that lies wholly on the oceanic crust is approximately 34,000,000 mi^3 (142,000,000 km^3). This volume includes an amount resulting from the porosity of the sediment, but if this amount is subtracted the equivalent is 23,000,000 mi^3 (94,000,000 km^3) of sedimentary rock on the sea floor. Because the oceanic crust averages 55 m.y. in age, a continental denudation of 0.396 mi^3 (1.65 km^3) per year is represented by this material. Accretion tectonics, in effect, transfers this material back into the continental domain, though the sediment may be drastically altered in the process; for example, some is melted and becomes igneous rock that intrudes the continental framework, some is offscraped at the toe of a subduction zone and piles up in great masses, and other portions may be partially subducted and plated onto the underside of the leading edge of a continent. Subsequent vertical Earth motions reveal these rocks in an altered or metamorphic state as schists and gneisses. Exactly how much sediment is subducted into the mantle along with the ocean crust is not known; this is an important question regarding the budget for continental growth.

Oceanic volcanic arcs. These explosive volcanic edifices grow above subduction zones (for example, the arcs of Sumatra, New Hebrides, Marianas, Aleutian, and Lesser Antilles). The global production of these volcanic arcs is approximately 0.26 mi^3 (1.1 km^3) per year. Because they stand high and are composed of relatively light material, they are readily accreted once they have entered into a subduction zone or have obliquely converged against a continental margin.

Volcanic arcs with continental basement. These types of terranes represent areas where a subduction zone lies along the edge of a continent (for example, the Andes of South America or the Cascade volcanoes of the western United States). The volume of new crustal material isincluded in the global production figure of 0.26 mi^3 (1.1 km^3). This new continental material is incorporated initially as an igneous event (liquid magma intruding into the host rock), but because of the spatial proximity to the dynamic motions of an active continental margin these kinds of volcanic arcs are unstable. They commonly are translated along the margin and ultimately become incorporated into the terrane collage as a result of accretion tectonics.

Continental fragments. The pieces of old continental blocks in Asia admixed with the other types of terranes is an example. Many such terranes, however, are much smaller flakes that have been ripped off a continental margin elsewhere. The repositioning of continental material dramatically changes the shapes of continents, but it is essentially a zero-sum proposition with regard to total continental growth.

Summary. Thus accretion tectonics is a corollary to the plate tectonic paradigm. The outer layer of the Earth is composed of mobile plates. The continuous movement of these plates shifts the continents and results in the creation of new ocean crust along the axes of the globe-girdling system of spreading ridges. In zones where a component of collision exists between two or three plates, crustal fragments may amalgamate to form a collage of accreted terranes. In this way the debris that is constantly being eroded from the continents and deposited in the deep ocean is returned to the continental framework. Newly created volcanic rock in the form of seamounts and volcanic ridges or arcs may also accrete to the continents. This has the effect of increasing the overall mass of continents. Preliminary estimates of the rates of these phenomena suggest denudation of the continents at about 0.396 mi^3 (1.65 km^3) per year, whereas newly created volcanic rock is produced at about 0.31 mi^3 (1.3 km^3) per year. Depending upon the efficacy of accretion tectonics, continents will grow or shrink.

For background information SEE CONTINENTAL DRIFT; MARINE GEOLOGY; PLATE TECTONICS in the McGraw-Hill Encyclopedia of Science and Technology.

David G. Howell

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Acoustic noise

Antinoise or antisound refers to noise deliberately created to mimic an existing noise field in antiphase so that the two fields cancel each other, resulting in silence. Antinoise, heard on its own, would be the same as noise. The idea of mutual destruction of interfering wave fields originated over 100 years ago; however, practical realization has been made possible only recently by high-speed electronic technology. Research is in progress to develop the ability to silence the low-frequency rumble from jet engines as well as other unwanted noise sources. In a few years, many such applications will be commonplace.

Principles of antinoise. The idea of making silence by adding a secondary, antiphase wave field to cancel an existing one was first patented in 1934. In fact, the phenomenon of destructive interference has long been appreciated for its effect on acoustic fields. It also plays a central role in James Lighthill's theory of aerodynamic sound production, formulated in 1952. According to this theory, aerodynamic sources are naturally arranged in a closely packed quadrupole array in which only a small fraction of the acoustic potential available from any single element of the array escapes destructive interference. But the term antinoise is used only for those deliberately created waves that are produced by a controlled source that is superposed on an existing noise field for the purpose of artificially creating a destructive interference.

Source ambiguity. The source of sound waves is largely a question of a point of view. For example, just as the light field reconstituted in a region through a hologram is indistinguishable from that of the real event, so does the ambiguity carry over to sound; perfectly silent source fields are possible. For this reason the definition of a sound source is rather arbitrary. However, the wave field written in terms of ϕ, the velocity potential, produced by a particular source field q is unambiguously calculated from the equation below,

$$\frac{\delta^2\phi}{\delta t^2} - c^2\nabla^2\phi = q$$

where ∇^2 is the laplacian operator and c is the speed of sound, together with the radiation condition stating that a source cannot anticipate the field it produces. There are many physical processes, described by this equation, which have a nonzero q in some region. This is the source region, and q describes the source distribution.

The significance of this observation about source ambiguity in the context of active noise control is that, if two different source distributions can generate the same wave field, and one of the source distributions is under human control, then a simple change in sign makes the primary noise field subject to extinction by the presence of the secondary field. Furthermore, even though the source of antinoise can be of a completely different construction from that of the primary field, the silence is, in principle, achievable everywhere outside the source distribution.

Requirements for canceling wave fields. In order to achieve complete silence, the two canceling wave fields must match exactly, not only continuously for all time, but also everywhere in space. Any degree of mismatch will result in some residual sound. But the closer the match is made, the more sound attenuation can be achieved.

It follows from the fundamentals of acoustics that the reproduction of a sound beam would require sources spaced closer than half a wavelength apart and distributed over the entire cross section of the beam. This is essentially the spatial form of the Nyquist frequency criterion. In fact, the closer the sources are spaced, the better the matching. Sounds in the audible frequency range, from 20 to 20,000 Hz, have wavelengths from 60 ft (20 m) to 0.8 in. (2 cm). Current transducer technology limits active sound control to the low-frequency (long-wavelength) regime.

The control system that generates the signals for the secondary sources which create the antisound must respond to the temporal variation of the source or wave field being controlled. Thus the higher the frequency of the sound, the faster the processing required. It is here that recent advances in high-speed electronic processing have allowed the technology to progress rapidly. Current systems of simple geometry now operate up to frequencies of a few kilohertz.

Operation of antinoise system. In order to ascertain what sound the control system must produce, it is necessary to have some knowledge of the source process, that is, of how the source fluctuates in time. This information is found from a transducer located near the source which responds to the source activity. Most commonly used are microphones that respond to the sound's air-pressure fluctuations, or accelerometers that sense the vibrations induced by the action of the source. The signal from the transducer or, for more complex spatial source distributions, the signals from an array of transducers are sampled by the digital control system to produce a continuous high-speed stream of numbers. Complex real-time processing algorithms are used to simulate the effects of the above equation for the wave field within the complex geometrical constraints of the particular spatial environment. This simulation requires extremely fast numerical calculations, and most systems use computational units in parallel to speed up the process. Typical multiplications, the basis of calculations, are carried out in less than 100 nanoseconds. New advances in emitter coupled logic (ECL) technology will allow calculations to proceed at 10 times this rate. However, the possible frequency bandwidth of the active sound control system will increase by only a factor of 3, since the number of calculations that must be accomplished increases in proportion to the frequency bandwidth, and the rate at which they must be undertaken is proportional to the highest frequency.

The results of the calculations, again a set of streams of numbers, are converted into analog electrical signals, which are used to drive the

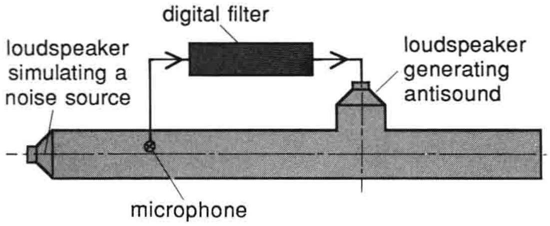

Fig. 1. System for testing sound control in ducts through antinoise. One loudspeaker simulates a source of noise in the duct, and the microphone senses noise in the duct. The other loudspeaker generates antisound to cancel the noise from the source.

secondary sources. Up to now, these sources have usually been specially adapted forms of conventional loudspeakers, but as the sources under control have become larger, with a consequent increase in the sound levels, research has been increasingly directed toward developing alternative sources of sound. Some of the most interesting alternatives come from deliberately causing the flow of a jet to fluctuate by introducing a modulating mechanism. The modulation produces a fluctuating volume of sound, the essence of the simplest source form. Devices of this kind can produce intense sound fields, and have been used to communicate over many miles. A variant of this source mechanism causes the rate of burning of a flame to fluctuate by modulating the fuel supply rate. Experiments in 1984 showed that this device can produce sound levels much more intense than those of the gas modulation process itself.

Applications of antinoise. The antinoise technique has been used to control acoustic noise generated in the cockpits of fighter aircraft, in long narrow ducts, in the exhaust of a gas turbine, and in various forms of rotating machinery.

Cockpit noise. One of the simplest geometries, where the technique is highly advanced, is that of so-called active ear defenders, which the crew members of some modern fighter aircraft now wear. The cockpit noise levels can be so high as to cause fatigue and interfere with communication among the crew members. Good communication can be achieved only if the signals are substantially above the noise; thus reduction of the noise is essential if crew members are not to be harmed by the high level of these signals. Lightweight ear defenders employ active sound control to maintain the small cavity of the ear at constant pressure by using the earphones themselves. The sound that penetrates the headset from outside creates pressure fluctuations in the cavity which are matched, in antiphase, by sound from the earphones. The communication signal can then be fed at a low level into this relatively quiet environment.

Duct noise. Another relatively simple situation where sound can be controlled actively is in long narrow ducts, such as air-conditioning ducts or pipework (**Fig. 1**). The sound wave, traveling down the duct from a distant noise source, is monitored by a microphone which measures its pressure fluctuations. The digital filter processes this signal to produce the loudspeaker drive signal. The sound from the loudspeaker and the propagating wave combine beyond the loudspeaker to produce silence.

Exhaust control. The first major antisound suppressor was installed in 1981 in the exhaust of a gas turbine which drives a compressor to pump gas through underground gas pipelines (**Fig. 2**). The gas turbine engine is housed in a sound-deadening enclosure, and the hot, spent gases are exhausted through the stack. The low-frequency rumbling noise that escapes from the stack may be heard in the neighborhood around the gas compressor site. The antisound system is very similar to that of the duct controller. It has microphones near the bottom of the stack where the sound is generated, but it uses 72 large loudspeakers driven by a microprocessor-based controller to reduce the noise exhaust rumble by 15 dB.

Periodic noise. Special control systems can be used to reduce the noise generated by rotating machinery of all forms, such as diesel and gasoline engines, gearboxes, fans, compressors, pumps, and propellers. The signals used to drive the loudspeakers for periodic noise are generated in a very simple way. Since the same waveform is required for each cycle of the machine, it can be stored in electronic memory and a microprocessor used to recall and send it to the loudspeaker in synchronism with the machine. The synchronization is maintained by an electrical signal taken from a tachometer. The system can adapt to changes and, typically, noise reductions in excess of 20 dB can be maintained. The next generation of propeller-driven aircraft will have the internal cabin noise field controlled in this manner.

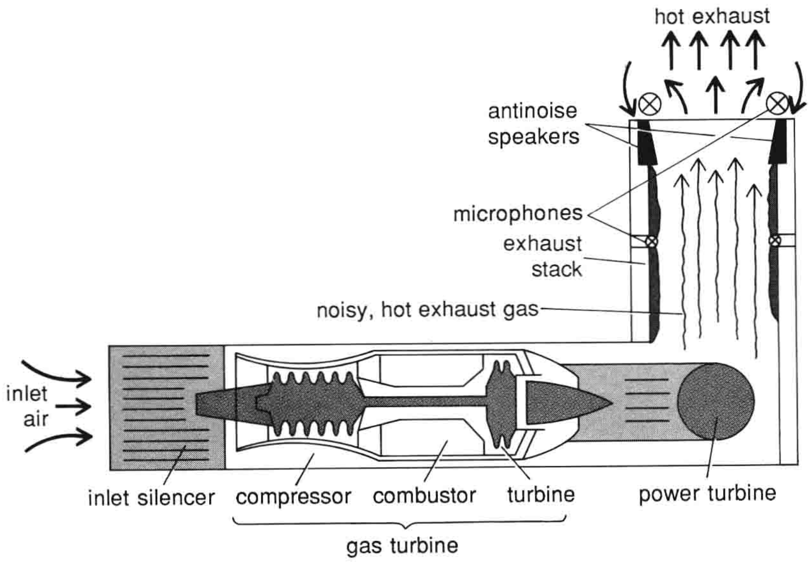

Fig. 2. Antinoise system at gas compressor station. The exhaust stack has a conventional, sound-absorbent surface. Antinoise speakers prevent the escape of rumbling noises.

For background information SEE ACOUSTIC NOISE; INTERFERENCE OF WAVES; SOUND in the McGraw-Hill Encyclopedia of Science and Technology.

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Adhesive bonding

Adhesive bonding may be defined as the holding of materials together by surface attachment. This technique of attachment is very ancient. The original glues were based on naturally occurring materials such as coal and pine tars, animal protein, and blood albumin. From the bonding of papyrus in ancient Egypt for use in writing to the bonding of elastomers to metal for tanks in World War II, these same materials were of primary importance to the adhesive technologist.

Not until the mid-1930s did the chemistry and technology of polymer and resins based primarily on principles of organic chemistry begin to yield new raw materials for new generations of adhesives. The adhesive industry continued to develop new theories of adhesion and appropriate raw materials, based on phenolic resins, urethanes, polyvinyl esters, and, in the 1950s, the epoxy resins.

Formation of adhesive bond. Among the parameters that must be considered for an adhesive product to have practical applications are contact and transition.

Contact. The adhesive must be brought into intimate, continuous contact with the substrate or surface that is to be joined. To accommodate this requirement, the adhesive at some point must be liquid during the formation of the bond in order to wet, spread, and form a continuous film. This requirement is generally fulfilled by application of a solution of solid polymer in a volatile solvent, by subjection of a solid polymer to sufficient heat or pressure, or both, during contact with the substrate to cause a liquid flow, and by application of liquid reactive components that can be made to react chemically in place to form a solid adhesive polymer after wetting and spreading.

Transition. Once the adhesive has been brought into intimate, continuous contact with the substrate and has at some point been in a liquid state during contact with the two adherends, the adhesive must pass through a transition to a tough, nonflowing, nonliquid, load-bearing interlayer in the bonded assembly.

In the case of permeable or porous substrates the assembly can be made while the adhesive is still wet with solvent. The transition from liquid to solid may then be realized via simple evaporation of solvent through the porous substrate. This process is used in many adhesive areas such as wood bonding, fabric bonding, and carton sealing. In some cases these techniques can also be used to advantage with essentially nonporous substrates.

In the case of nonporous or nonpermeable substrates the transition of the adhesive interlayer from liquid to solid must be accomplished via techniques other than solvent evaporation. There are two methods most commonly used. The method involving heat to flow–cool to set is best represented by thermoplastic adhesives or hot-melt adhesives. The solid adhesives are heated to their flow temperature, the substrates are joined and held in contact with the molten system, and the assembly is then allowed to cool to form the bond. The other technique utilizes an in-place chemical reaction. Normally liquid coreactive moieties are placed on the substrate, the substrates are joined, and the adhesive passes from a liquid to a solid via a chemical reaction in place. Representative adhesive systems are epoxy-amines, isocyanate-polyols, anaerobic dimethacrylates, acrylic-peroxides, and alpha-cyanoacrylates.

A technique that may also be considered in this respect is the slow crystallization of certain polymers that progress from liquids to solids via a crystallization phenomenon; this is surely at work in the case of neoprene-phenolic contact cements.

Other attributes. The adhesive products themselves must necessarily have additional attributes to be commercially practical. Some of these additional attributes are measurable shelf or can stability, reasonable cure times and temperatures, relatively nontoxic and nonenvironmentally polluting constituents, relative versatility in substrate affinity, and in many cases ability to gap-fill (to tolerate the bonding of imperfect mating surfaces).

Theoretical considerations. There are many different theories of adhesion. The original theories suggested that a true chemical bond between the adhesive and adherend was necessary and responsible for the formation of the bond. At about the same time, it was theorized that the bond was a result of intermolecular attraction between molecules in close proximity or between the adherend and adhesive. These forces are known as van der Waals or London forces of intermolecular attraction. Most adhesive technologists conjectured that probably combinations of both true chemical bonds (ionic, covalent, or coordinate) and van der Waals forces come into play during the bonding operation.

These theories gave rise to considerable controversy and additional research since the actual bond strengths accomplished in practice did not approach the theoretically calculated strengths possible through van der Waals forces alone—let alone a true chemical bond.

One view held that the adhesive polymers were not properly selected to wet and spread on the substrate to allow the intimate contact for van der Waals forces to come into play. Via measurement of contact angles and bond strengths, W. A. Zisman developed his theory of critical surface polarity. In simplified form, it states that if the molecular polarity (or surface tension) of the liquid adhesive is less than the surface polarity of the substrate, wetting and spreading will occur and a superior bond will be formed; and conversely, if the liquid adhesive polarity is higher than the polarity of the substrate surface, wetting and spreading will not occur and therefore a weak bond is formed.

Metals are considered to have a high surface polarity, and also strongly bonded molecular layers of water on their surfaces. A molecular model of a metal surface is shown in **Fig. 1**.

The bonding of metals has been approached with some success by using reactive ingredients to react with chemisorbed water layers as depicted in Fig. 1. Metals are considered to be high-energy surfaces, while at the other end of the spectrum polyethylene is not wet by water and seems to abide by Zisman's theory as applied to adhesive bonding. The surface of polyethylene has an extremely low surface polarity.

Low-energy surfaces have been effectively bonded when the surface is converted by oxidation techniques to offer greater polarity to the substrate in order to allow the adhesives to wet and spread effectively.

A similar technique of modifying polymeric substrates, such as cured elastomers via subjecting the cured elastomer surface to chlorination prior to bonding with adhesive systems, has proved to be of practical utility in improving the bond strength by allowing more effective wetting and spreading of the adhesive constituents.

It is reasonable to conclude that the practical application of this theory has been essentially substantiated. However, research has offered evidence that some cases of adhesive bonding tend to refute the teachings of critical surface polarity under closely controlled laboratory conditions that indicate surface morphology of a polyethylene surface may be a greater factor than surface polarity. Still, the actual bond strength, while abiding by Zisman's theory, although improved, did not approach the theoretical levels calculated via van der Waals forces.

Another theory by J. J. Bikerman suggests that a weak boundary layer is the reason that bond strengths are below the theoretical level. Again, in simplified terms, this theory states that the probability that an adhesive-adherend failure will propagate across a heterogeneous interface is practically zero; essentially, there is no such thing as adhesive failure; all failures are cohesive within a single phase; and this single phase is labeled as a weak boundary layer. Research to substantiate or refute the practicality of this hypothesis has generally proven the validity of the theory.

The CASING (crosslinking at surfaces in inert gases) technique developed from studies on polyethylene lends credence to the presence of a weak low-molecular-weight layer on the surface as perhaps more detrimental than the actual surface polarity in obtaining acceptable bond strengths. The formation or presence of weak boundary layers on substrate surfaces has been recognized in adhesive bonding, as well as the less obvious formation of weak boundary layers on the adhesive side of the adhesive–adherend interface via migration of weak layers from constituents in the adhesive to the interface.

Other recent research on theories of adhesion considers the subject of fracture mechanics. It is suggested that during the formation of an adhesive bond, points of stress are formed and concentrated in proximity to the interface because of the essential heterogeneous nature of the adhesive and the adherend in most cases. When an exterior force is applied to the bonded assembly, a failure initiates at a point or several points of high stress concentration. A fracture or fractures can therefore initiate (or are already present) at these built-in, concentrated points of stress far below the force value expected by theoretical calculation. The fracture then propagates via stress relief along a path of points of concentrated stress in close proximity to the adhesive–adherend interface.

In the field of vulcanization bonding of elastomers and elastoplastics, an important theory has

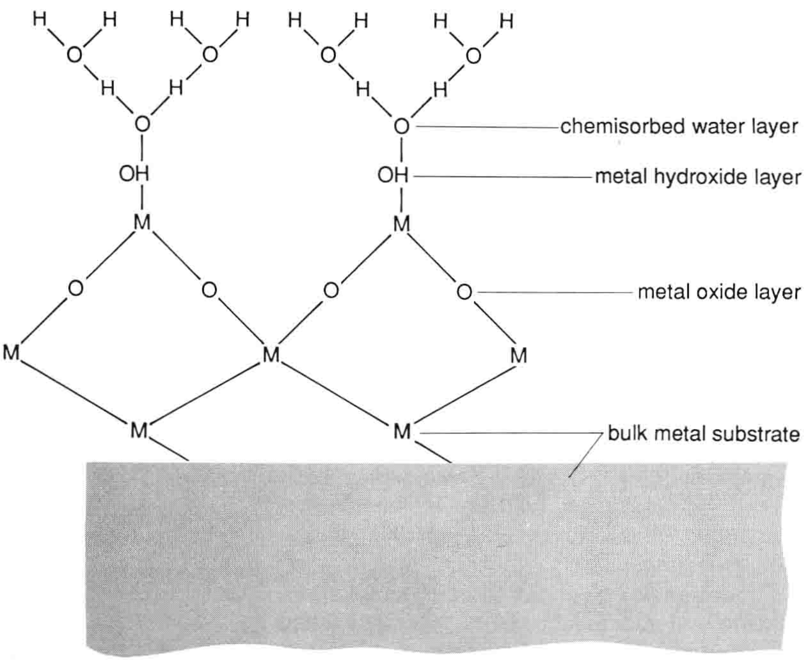

Fig. 1. Molecular model of a metal surface. M = metal.