Arecibo Ionospheric Observatory

Studies of the upper atmosphere and planets are made with the aid of a huge reflector in Puerto Rico.

William E. Gordon

The most striking feature of the recently completed Arecibo Ionospheric Observatory (*1*) is the antenna, which has the form of a large hemispherical reflector with an aperture whose diameter is 305 meters (1000 feet) (Fig. 1). This reflector serves the same purpose as a large mirror in an optical telescope; it collects the energy arriving over the aperture of the reflector and focuses it on a sensing device. A transmitter and a receiver are the two other major components of the radar at the observatory. With this equipment, studies are being made of the earth's upper atmosphere—its chemical composition, the electron and ion temperatures, the charge densities, and the regular and irregular motions, as well as the spacial and temporal variations in these characteristics. The facility is also a powerful tool for radar exploration of the solar system and for radio reception of signals originating in galaxies, planets, and probably stars.

When directed into the earth's atmosphere, a radar signal is scattered at heights above 60 kilometers by the natural irregularities in the charge density. The received signal is thus effected by the characteristics of the atmosphere, but because the effect observed is weak, an unusually powerful radar is required. The power of radar is increased by increasing the size of the antenna, the strength of the transmitter, or the sensitivity of the receiver. Since the transmitter and the receiver at Arecibo were to be the best available, the size of the antenna was designed by applying the theory of measuring the characteristics of the ionosphere by means of the weak scattering coefficient (*2*). Following the confirmation of the theory by Bowles (*3*), 305 meters was determined to be the diameter required for the aperture of the antenna.

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The Facility

In 1958, when the size required for the antenna was established, it was not clear that an antenna of such size could be built. The largest antenna at that time was the 76-meter (250-foot) reflector at Jodrell Bank. To achieve an economical construction, the ground, properly shaped, would have to be exploited to support the reflector. After some preliminary studies by McGuire and Winter at Cornell, the feasibility of the ground-supported reflector was established.

Besides the necessity for suitable ground on which the antenna could be constructed, there was a further criterion by which the site for the Arecibo observatory was to be chosen. The site was to be located in the tropics so that the planets would pass nearly overhead and therefore into the cone of view of the antenna. Puerto Rico was therefore chosen by Donald J. Belcher as the most suitable location, since it had, besides numerous limestone sinkholes (Karst topography), the advantages of a government friendly toward the United States, and professional scientists at the University of Puerto Rico. Potential sites were spotted by aerial photography, and the actual bowl was selected near Arecibo by a ground survey.

Interest in the antenna and its potentialities was expressed by members of the Advanced Research Projects Agency of the Department of Defense, who suggested that a way be sought to provide a means by which the antenna beam could be moved about in the sky. It was originally proposed that the reflector should be paraboloidal, with its radio beam pointed along the direction of the axis of the paraboloid and movable from that direction by about one degree. However, to increase the scanning angle of the beam a hemispherically shaped reflector with a complicated focal line was designed instead. A decade of research on spherical reflectors at the Antenna Laboratory of the Air Force Cambridge Research Laboratories provided the basis for the design of an appropriate "feed" for the reflector. The feed, a distribution of radiating (and receiving) elements along a line, must not only be held rigidly on a radius of the spherical reflector when the antenna beam is pointed in the direction of the radius, but must also be moved from one radius to another as the beam direction is changed, keeping the top of the feed at a distance of one-half the radius above the reflector. With these restrictions, and the known tolerances, McGuire and I established the feasibility of scanning the beam 20 degrees off the vertical axis in any azimuth. Thus, the beam formed by the reflector at Arecibo can be pointed in any direction within a 40-degree cone centered overhead.

When only the antenna and the receiver are used, the equipment is said to be operating as a radio telescope. When it is operated as a radar telescope—with the transmitter generating short pulses of radio waves—the pulses are distributed over the reflector by the feed. The reflector, now connected to the transmitter rather than the receiver, collimates the pulses into a beam that is directed at a target of interest. Thus, the reflector is used twice, in sending and in receiving.

A reflecting mirror, optical or radio, is of good quality if its departure from the desired shape and its surface imperfections are no larger than one-twentieth of a wavelength. The smooth, highly polished mirror of the optical telescope (wavelength about one-half micron) may be replaced in the radio case (wavelength about one meter) by a reflector made of wire mesh having openings less than about one-twentieth of a meter, and supported in the appropriate shape to within about a twentieth of a meter. Thus, the reflector shown in Fig. 2 is a highly polished mirror for radio waves, in the same sense that the 5 meter (200 inch) mirror at Palomar is for light waves. At Arecibo the reflector is constructed of wire mesh (Fig. 3) having openings of 1.3 cm; the measured departure from the desired spherical shape has a root mean square error of 2.5 cm. The smoothness achieved at Arecibo is a substantial accomplishment when one considers the area of the reflector, 7×10^4 m^2 (18 acres).

A reflecting mirror is only useful if the appropriate sensing elements, the feed, can be held rigidly at its focus. At Arecibo the feed (Fig. 4) consists of lines of sensing elements cut into the walls of a hollow pipe of square cross-section tapering from 100 cm at the top to 35 cm and measuring 29.3 m in length. The feed is supported rigidly along a radius of the spherical reflector and moved precisely from one radius to another by the structure shown in Fig. 5. The triangle, suspended by cables to the tops of towers held by more cables to massive anchors, is also tied by guys from each corner of the triangle down to anchors on the reflector rim. The structure is remarkably rigid and stable even in gusty winds. The motion of the feed is accomplished in azimuth by rotating the large arm on a circular track hung under the triangle, and in elevation by driving the feed along the circularly curved underside of the arm.

The transmitter is a versatile instrument and generates pulses of radio energy at 430 megacycles per second, having peak powers of 2.5 million watts and pulse lengths from 2 microseconds to 10 milliseconds. A second transmitter having similar specifications but operating at 40 megacycles per second is being added to the facility.

The sensitivity of a receiver depends on the amount of electrical noise in its circuits, since this will compete with the wanted signal, and on the receiver bandwidths being matched to the expected signal. A significant enhancement in sensitivity may be achieved by processing (usually averaging or correlating) the signal in the electronic circuits or in a computer or in both. The receivers at Arecibo are designed and operated for maximum sensitivity. The radar receivers operate at 40 and 430 megacycles per second, corresponding to the transmitter frequencies which are fixed, and the radio astronomy receivers will soon operate at the additional frequencies of 608 and 1420 megacycles per second, frequencies that are reserved internationally for use by radio astronomers.

The Upper Atmosphere

The thin atmosphere above a height of 60 kilometers contains free electrons that have been ripped from atoms or molecules of gas by solar effects. On a macroscopic basis the atmosphere is electrically neutral, but on a microscopic basis the electrons and positive ions exist in numbers that vary with height and with time. At some height, usually between 100 and 300 kilometers, there are normally a sufficient number of electrons to act as a reflector for waves at radio frequencies near 10 megacycles, and it is this property that permits long-distance radio communications by reflecting the radio signal back to the ground one or more times as it travels around the earth from transmitter to receiver. At the frequency of 430 megacycles per second, as used at Arecibo, the ionosphere is transparent. The radio waves travel through the ionosphere and continue into space without being reflected or attenuated. To a first-order this statement is correct. It is only when the problem is examined more closely that the electrons are observed to have a very weak second-order effect. That is to say, the electrons have a scattering cross section for radio waves that is so small that previously it had been neglected. Since each electron scatters a small amount of the power incident on it, and the electrons act independently of each other, the total power scattered in any direction is proportional to the number of scatterers and, therefore, to the number of electrons. Thus a powerful radar (see *4*) can measure the number of electrons in a volume determined by the cross section of the antenna beam and the length of the radio pulse along the beam. By recording the total power arriving at different times, one can measure the number of electrons at different heights and produce a profile of electron density. Such profiles are now being produced.

The charged particles are in thermal motion. While it is the electrons that scatter the radio waves, it is the positive ions that dominate the motions (through coulomb forces). A radio signal scattered by a particle with a component of motion along the line of sight will have its frequency shifted by an amount proportional to the line of sight velocity. The velocity will be higher for warmer, lighter ions. By comparing the frequencies contained in the signal scattered back from a volume of the upper atmosphere with the

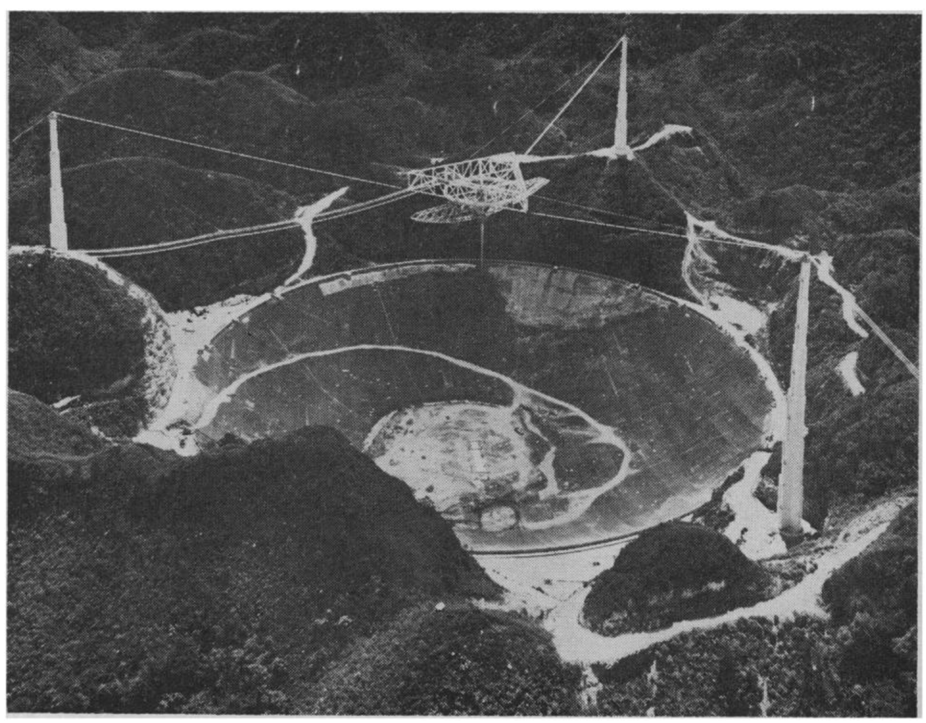

Fig. 1. The reflector at the Arecibo Ionospheric Observatory, with the feed system suspended 144 meters above.

Fig. 2. The reflector is suspended above the ground on a network of cables.

frequency transmitted, one may deduce the temperatures of the charged particles and the ionic species. Studies are now being made of temperature as a function of height, and attempts are being made to determine the ionic composition of the upper atmosphere.

The significance of the radar "backscatter" technique is that it allows density and temperature measurements to be made continuously in time and height over a range of heights from 100 to 1000 kilometers or more; for the major portion of this range, measurements could not previously be made with any continuity. Three-dimensional mapping of irregularities in electron density is revealing a type of structure that frequently represents a wave whose properties change markedly with height. The great promise of the back-scatter measurements is the potential for establishing ionic composition as a function of height and time.

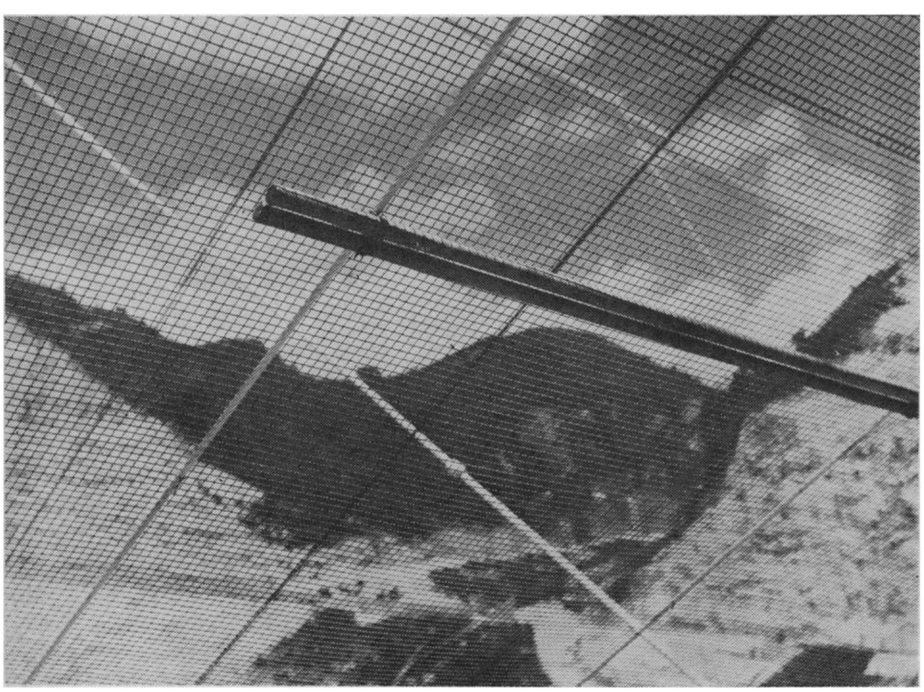

Fig. 3. The surface of the reflector is constructed of wire mesh tied to suspending cables. Ballast bars are attached to the cables to help the reflector hold its spherical shape.

Radar Astronomy

At the Arecibo observatory we are currently studying the moon, Venus, and Mercury. In the fall an attempt will be made to observe Jupiter, and Mars will be coming into range in December. For all these targets (except, possibly, Jupiter) it will be possible to obtain fairly precise values of echo delay, which is equivalent to a measurement of range. For the moon, Venus, and Mercury, it is also possible to measure precisely the Doppler shift in the frequency of the returned echo. A related technique, which may be used where signals are sufficiently strong, permits a determination of the target rotation rate. This work is under the direction of Gordon Pettengill.

The fine accuracy in angular measurement achieved by the optical astronomers is well complemented by the precision in range obtained by the radar astronomers. Thus the elements of the planetary orbits that depend directly on distance are now becoming known with greater accuracy. As an example, the Astronomical Unit, a measure of the size of the solar system, was known to an accuracy of about one in 10^8 prior to radar observations of the planets; the early radar observations increased the accuracy by two orders of magnitude and another order of magnitude is in prospect. Comparison of the positions of Venus and Mercury as observed at Arecibo with the best available predicted positions shows small discrepancies.

One of the predictions of Einstein's theory of general relativity is concerned with the rate of precession of Mercury's orbit. Precession and, therefore, the rate of precession are much more easily measured from range data than from angular data. In fact, a series of radar measurements on Mercury spread over about 2 years should achieve an accuracy in precession-rate equivalent to that obtained from the application of optical observation spread over the past 100 years.

If one surface feature of a planetary target scatters back to the radar more energy than a neighboring feature, then the location of the first feature will be indicated in two ways. First, the frequency shift associated with the enhanced signal indicates the displacement of the feature in a direction normal to the axis of rotation as seen on a projected picture of the planet's disk. Second, the time delay of the enhanced region measured with respect to the closest portion of the planet identifies a ring on the planet's surface, the axis of the ring being the line of sight. The use of these two coordinates from a single set of observations locates the feature on the surface with an ambiguity associated with the intersection of a frequency line and a range circle. Repeated observations may sometimes resolve the ambiguity. From this procedure will shortly emerge the first map of the cloud-hidden surface of the planet Venus.

Radio Astronomy

A variety of astronomical objects are under radio observation at Arecibo. Strong, discrete radio sources associated with known galaxies have provided a needed grid for calibration of the antenna pointing angles. Against the known grid weaker radio sources are detected and located; the distribution of the weaker sources bears on the questions of cosmology and the expanding universe. The occultation of radio sources by the moon provides precise positions and sizes of the sources. Flare stars are being checked for unbelievably strong bursts of radio radiation for comparison with the disturbed radiation from our nearest star, the sun. At Arecibo the work is under the direction of Marshall H. Cohen. Most of the observations are made at a frequency of 430 megacycles, although receivers and feeds at other frequencies are becoming available.

The temperatures observed for the planets present a puzzle. Observations made at radio frequencies of the temperatures of Venus and Jupiter provide a remarkable contrast. At Arecibo, the observed temperature of Jupiter is in agreement with other observations (also made at radio frequencies) which indicate that the temperature of 30,000°K originates from an equivalent black body at 30,000°K; this suggests that the radiation originates not at the surface, where the microwave radio and infrared temperatures are observed to be 150° and 135°K, respectively, but probably in a belt of energetic electrons surrounding the planet much as the Van Allen belts surround the earth. In contrast, Venus exhibits a temperature of 600°K when observed in the radio spectrum above about 1000 megacycles compared to 250°K in the infrared spectrum. At

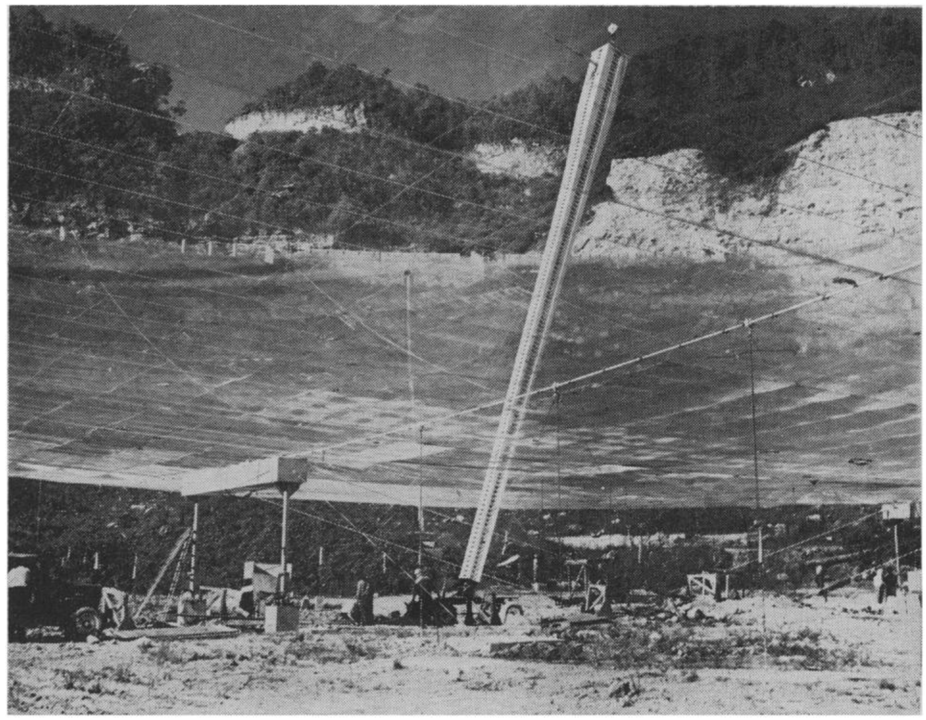

Fig. 4. The line feed (here being erected) has slotted sides to allow the radio energy to radiate out onto the reflector. The feed is 32 meters long, and at this point has four 2.7-meter sections yet to be attached before it is raised to the center structure.

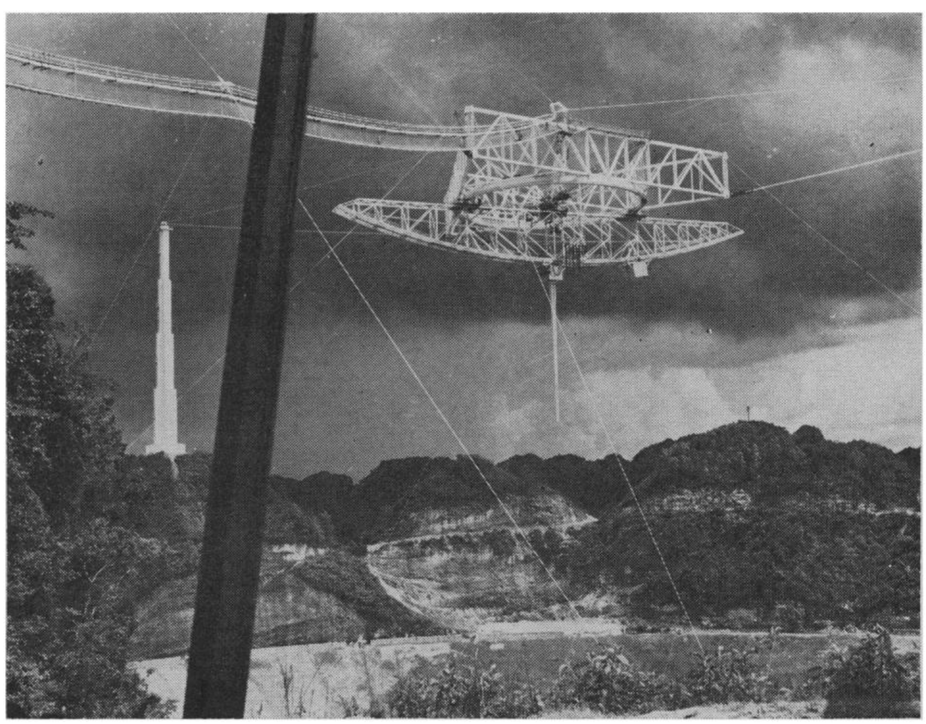

Fig. 5. The center structure is composed of four basic parts: (i) the triangular platform which is rigidly held by cable suspension; (ii) the circular azimuth track; (iii) the bow shaped feed arm which rotates on the azimuth track; and (iv) the line feed which travels along the lower side of the feed allows beam movement anywhere with a 40° scanning cone centered overhead.

750 megacycles Venus looks like a black body of about 450°K, and at Arecibo the radio spectrum is being extended downward to 430 megacycles where the temperature is 200 or 300 degrees. Interesting properties of both planets are being revealed by the radio observations, and it is clear that the dominant radio characteristics represent different phenomena.

Strong discrete sources of radio radiation are sometimes misnamed radio stars, although none of them are individual stars but should be identified with galaxies. Such sources provide an excellent grid against which the direction of the antenna can be checked. The internal consistency of the checking process shows that a few of the sources are incorrectly reported either in position or strength. Corrections will become available, but the real function of a survey is to locate the weaker, more remote sources. A catalogue of such sources in a limited portion of the sky is being prepared. Observations at radio frequencies help with the astronomical classification of the sources and bear on the theoretical problem of the formation of the universe.

By using the moon as a diffracting screen between distant radio sources and observers on the earth, Hazard (*5*) has demonstrated a powerful technique for the precise location and size estimation of radio sources that are occulted by the moon. The technique is being applied at Arecibo and results will soon be available.

Because of the great distances between the earth and even the nearby stars, signals originating in individual stars are too weak to be detected by techniques now available. If storms occur on stars, as they do on the sun, and if the radiation is enhanced markedly for brief periods, as occurs on the sun, then the enhanced radiation becomes detectable. Searches have been conducted for this type of radiation from promising stars at a number of radio astronomy observatories with some success. The sensitivity of the Arecibo facility is being brought to bear on this problem. Results are not yet available.

References and Notes

1. The Arecibo Ionospheric Observatory forms an integral part of the graduate program of Cornell University, and provides a unique facility for research in ionospheric physics, radar astronomy, and radio astronomy. Professors on campus and resident at the observatory guide the doctoral research of some fourteen graduate students, of whom four have conducted experiments at Arecibo. Two visiting staff members participate in the experimental program of the Observatory, and others use the facility to supplement their own research programs. Experiments are also conducted at the observatory by graduate students from other universities. The observatory is operated by Cornell University with the support of Advanced Research Projects Agency through a contract with the Air Force Office of Scientific Research.
2. W. E. Gordon, *Proc. I.R.E. Inst. Radio Engrs.* **46**, 1824 (1958).
3. K. L. Bowles, *Phys. Rev. Letters* **1**, 454 (1958).
4. ———, *Science* **139**, 389 (1963).
5. C. Hazard, *Monthly Notices Roy. Astron. Soc.* **134**, 27 (1962).
6. I thank Prof. M. H. Cohen and Dr. G. H. Pettengill for their helpful discussions during the preparation of this paper.

Radiation Chemistry of the Fixation of Nitrogen

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The fixation of nitrogen by ionizing radiation has such a tremendous potential for economic exploitation that a "breakthrough" would have a far-reaching impact on the world-wide chemical industry. A major consideration today is the possibility of using a nuclear reactor for the chemical synthesis—specifically, of using the kinetic energy of the nuclear-fission particles to produce the excited species, atoms and ions, to interact and fix nitrogen. This article presents the state of our knowledge, the unresolved problems, and some indications of possible solutions.

The term *fixation of nitrogen* denotes the chemical binding of nitrogen gas of the air to form a chemical compound. One of the simplest concepts in the fixation of nitrogen is the binding of the nitrogen gas of the air with the oxygen gas of the air. The final product is nitrogen dioxide, NO_2 or the dimer N_2O_4. Unfortunately, the intermediate reaction leading to NO_2 formation—namely,

$$N_2 + O_2 \rightarrow 2NO \qquad (1)$$

is endothermic by 42 kilocalories and does not proceed under normal conditions. To overcome this difficulty two major approaches have been used, one direct and the other indirect. In the direct approach, a very high temperature is used to overcome the endothermicity. This is exemplified in the Birkeland-Eyde flaming arc process and the thermal pebble bed process. Temperatures here lie in the region 2500° to 3000°C. The nitric oxide (5 to 10 percent) in thermal equilibrium at these high temperatures must be cooled immediately or it will decompose to nitrogen and oxygen. Thus a rapid chilling of the intensely hot air is required. Once the nitric oxide is cooled and in the presence of additional oxygen, the reaction

$$2NO + O_2 \rightarrow 2NO_2 \qquad (2)$$

will produce nitrogen dioxide. The further addition of oxygen and water to the NO_2 will produce nitric acid, HNO_3.

The indirect method is best exemplified by the Haber-Bosch process, in which nitrogen and hydrogen combine at high pressures (a few hundred atmospheres) over a hot iron catalyst to produce ammonia:

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad (3)$$

To form nitrogen dioxide, the ammonia is burned in air or oxygen by a catalytic process to form NO. As in the direct process, the addition of oxygen and water will produce nitric acid. For the indirect process large sources of hydrogen must be readily available. Even so, the economics of the more efficient Haber-Bosch process are better than any direct process, and it is universally used.

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