voidable energy drain on accelerators and designed storage rings to minimize it. Early research at the SPEAR storage ring soon showed it to be an extremely intense, tunable source of useful x-rays that cannot be duplicated elsewhere.

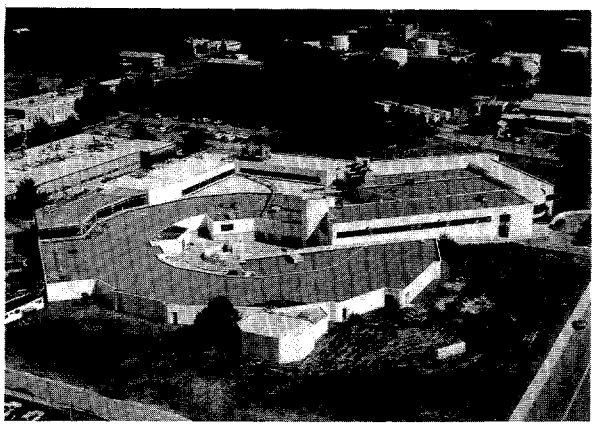

Figure 25. Aerial view of the National Synchrotron Light Source at Brookhaven.

This method of producing short wavelength x-rays has proved so important for research in crystallography, chemistry, biology, and materials science that the DOE funded storage rings dedicated to producing it, such as the National Synchrotron Light Source at Brookhaven. Others are in planning or currently under construction in the U.S., Europe, Japan, and the Soviet Union. These facilities, some costing hundreds of millions of dollars, are designed and operated by accelerator specialists who received their training in the field of high-energy physics. New techniques using devices called *wigglers* and *undulators* that surround the circulating beam have increased x-ray intensities a million fold over the past decade.

At these particle accelerators, industrial researchers have used intense beams of x-rays to make chips with tiny features less than a micron (a millionth of a meter) across. The goal of x-ray lithography, as the technique is known, is to etch finer semiconductor circuits than ever before. If manufacturing techniques being developed by IBM and other companies are perfected, the process would cram far more components onto fingernail-sized chips. While the best chips today bristle with a million or so circuit elements, future ones created with x-rays conceivably might hold up to a billion.

In recent years, accelerators have become increasingly important sources of radioisotopes for clinical and research medicine. Commercial production of radioisotopes was pioneered by New England Nuclear, now part of DuPont Chemical. It now operates four cyclotrons and a 45 MeV linear accelerator for commercial production of isotopes for both industrial and medical purposes. Industrial isotopes are used to measure wear on surfaces in motion, for thickness gauges, and other specialized applications. Other private radioisotope producers using cyclotrons include Mallinkrodt (a subsidiary of Avon) and Medi Physics.

High-energy physics often requires a significant fraction of the outputs of such high technology industries as very low temperature refrigeration equipment, high vacuum equipment, and superconducting magnets. Purchases of equipment for research reduces production costs through learning. Costs of additional units are lowered by incremental improvements in production technology, a process that may be further aided by researcher assistance in solving production problems. When these products are offered for sale in commercial markets their prices are lower, their quality is higher and their markets are likely to be larger.

Over a thousand electromagnets are used at Fermilab to confine the high-energy beams of protons within a slender tube 4 miles in circumference. The original magnets were tremendous consumers of electric power, soaking up a fair fraction of the laboratory's total operating cost. During the late 1970's, in an ambitious attempt to slash these costs and double the proton energy, Fermilab scientists began an extensive project to install magnets with windings made of superconducting materials throughout the entire ring. Because a superconductor offers no resistance to an electric current, its use can cut power consumption drastically.

There were many technological hurdles to overcome before this dream could become reality. Cable made from wires of just the right superconductor had to be developed to withstand the extreme stresses involved, and new methods were required to bind the magnet windings about their cores. Otherwise, the tremendous magnetic forces would have literally torn the magnets apart. Refrigeration systems of unprecedented scale and reliability were needed to cool and keep the superconducting elements at the temperature of liquid helium. But the challenges were met, and by 1983 the Tevatron was completed—the world's most powerful accelerator.

The construction of the Tevatron—with its 650 miles of superconducting cable—represents the first