getter films. Building on the getter concept, titanium getter pumps were developed (in the 1960's) to handle hydrogen loads in pulsed and non-tritium machines for the next two decades. Titanium getter pumping has since been used in many of the large fusion experiments whenever clean high speed pumping for hydrogen or other chemically active gases is required.

Auxiliary Plasma Heating Technologies

Progress in plasma heating has resulted both from technological advances and greatly improved understanding of the microscopic processes underlying propagation and deposition of energy in non-uniform plasmas. Until the early 1970's, the primary technologies for heating plasmas to high temperatures were magnetic compression and resistance heating; but new technologies were needed to attain plasma temperatures for energy break-even. With new technologies such as neutral beams and radiofrequency heating developed in the 1970's and improved in the 1980's, the heating of plasmas to break-even temperatures has become reality.

The development of neutral beam particle accelerators, high power radiofrequency systems, and microwave sources at high power and high frequency have enabled researchers to reach plasma temperatures of 200 million degrees—more than three times what had previously been possible without auxiliary heating.

Neutral Beam Particle Injectors – Neutral beam heating using particle injectors is the method now used to heat plasmas to fusion temperatures. It involves the injection of high energy atoms of deuterium into the confined plasma. Before they are injected, they must be accelerated to very high energy. This is done in the following manner. Positive-charged deuterium ions or nuclei (both are the atoms stripped of its electrons) are first generated and then passed through a series of electrical grids which focuses the ions into a beam and accelerates the beam. Before the high energy ion beam passes into the fusion chamber and penetrates the confining magnetic field, the positive-charged ions are neutralized by putting a negative-charge, an electron, back on each of them.

The resulting super high energy atoms in the beam then collide with ions (nuclei) and electrons which are already present within the confined plasma. When these collisions occur, the extremely high energy of the atoms from the beam is transferred to the plasma nuclei and electrons; and their temperature rises accordingly. In the heat of the fuel chamber, the injected deuterium atoms themselves ionize into plasma, thus enriching the plasma fuel.

The research on neutral beam technology in the fusion program has precipitated qualitative advances in the understanding and manufacture of neutral beam systems. Beam performance has grown from tens of kilowatts of beam power for 10-20 thousandths of a second to tens of thousands of kilowatts of power for as long as 30 seconds. The development of large area sources of ions, essential to the broad uniform ion beams used by the thin film industry, materials modification industry, and semiconductor industry has been heavily influenced by the "bucket source," which was invented in the fusion program in 1975. Technology for fabricating key components—novel cathodes to cause ionization, multiaperture grids to control and focus beams, and cooling channels—have all matured significantly. Computer programs to describe beam behavior and response to focusing have also been augmented. Diagnostic instruments, such as the pinhole camera developed by the Oak Ridge National Laboratory and infrared grid scanner developed by the Princeton Plasma Physics Laboratory, lead the state-of-the-art.

Radiofrequency Plasma Heating – Radiofrequency wave heating uses a steady beam of electromagnetic waves and radar waves, which are directed into the confined plasma with a special antenna. Heat energy is transferred as in a microwave oven; those particles moving at the same frequency as the beam have their temperature increased, and the temperature of the plasma goes up accordingly.

The principal engineering advantage of radiofrequency heating is the ability to locate the bulk of the equipment in an area remote from the reactor core, thus adding to reliability, simplifying maintenance, and reducing the size of the reactor hall. Other advantages include more efficient utilization of power supply, increased component life, and reduced complexity of required support equipment. In addition, radiofrequency heating offers the ability to direct the heat to specific locations in the plasma such as the center or edge, and thereby control the distribution of heat in the plasma.

The MFE Technology Development Program has led in the development of high-power gyrotrons, a class of high power microwave tubes a million times more powerful than previous ones of the same frequency. Similar technological advances have been made in components for carrying the microwave signal to the reactor hall and in high power antenna systems to send the waves into the plasma fuel. To make it possible to direct the waves from an antenna housed outside the vacuum chamber, new ceramic windows have been developed. These windows, installed in the vacuum wall, allow the waves to enter the chamber without disturbing the vacuum inside. Keeping the antenna outside the vacuum simplifies construction and maintenance of a reactor system.

Still under development, radiofrequency heating has already been used in a tokamak to attain plasma temperatures in the 50–60 million degree Celsius range.