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LEAK HUNTING PROBLEMS ASSOCIATED WITH CONTROLLED THERMONUCLEAR FUSION EXPERIMENTS

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Introduction

Vacuum technology has been intimately associated with the progress of controlled fusion research since its inception. Some of the first[1] large, ultra-high vacuum systems were developed for early experiments in magnetic confinement of energetic hydrogen plasmas. The changes in the character of CTR experiments as the plasma physics evolves ave continued to extend the state of the art in vacuum technology.

The basic phenomenon that creates the various vacuum problems is the contaminating effect of neutral gas on energetic plasmas. The surface of a magnetically confined plasma is determined roughly by the pressure equilibrium established between the diamagnetic plasma and the plasma displaced magnetic field. In other words, the plasma pressure is balanced by the magnetic pressure which gives the plasma the shape of the confining magnetic field. The rate at which neutral gas impinges upon the plasma surface is proportional to its pressure. When a cold neutral gas molecule encounters the energetic or hot plasma, it can either be ionized, thereby diluting the hot plasma or, worse, and more likely, charge exchange with the hot plasma ion thus neutralizing the hot ion which allows it to leave the confining magnetic field while the cold ion is trapped and confined. If the pressure is high enough, the plasma energy can be dissipated at a rate greater than it can be supplied. In general, the vacuum goal in CTR is to reduce the plasma losses due to charge exchange from the background gas or the walls to a level that is insignificant compared to the losses peculiar to the magnetic confinement system under study. Plasma chamber pressure less than 10^{-9} torr and wall coverage less than .1 monolayer provide tolerable vacuum conditions for most CTR experiments.

Achieving acceptable vacuum conditions in the present and next generation CTR experiments requires rigorous application of current techniques and continued development of new ones. The successful development of high energy (>10 Kev) high current (> 100 amperes) neutral beams to produce and feed magnetically confined plasmas has imposed demands on vacuum pumping that is on the ragged edge of the state of the art. For every ampere of energetic neutral beam produced three additional ampere equivalents of gas must be pumped due to the poor gas efficiency of the ion sources. This can result in gas loads on the order of 60 torr-liters/sec for a 100-amp beam which must be differentially pumped at pressures ranging from 10^{-4} torr to $<10^{-9}$ torr. Closely associated with the pumping problem, in the degree of difficulty, is the problem of locating and reducing the leakage to acceptable levels. The base pressure and plasma wall coverage limitations in CTR devices require that the total leakage rate be insignificant compared to the outgassing for the system as a whole.

2XIIB

The LLL 2XIIB experiment, shown in Fig. 1, is typical of the size and complexity of CTR systems. The high vacuum volume is 50,000 litres (1800 ft^3) with a surface area of about 2×10^6 cm^2. A pulsed Yin Yang coil set (Fig. 2) in combination with a D.C. guide field produces the magnetic field. The rise time of the pulsed field magnet is less than 500 μsec which precludes the use of any material within or in close proximity to the magnet that is electrically conductive. The magnet structure (Fig. 3) is fiberglass reinforced epoxy and the high vacuum plasma chamber (Fig. 4) is fabricated from architectural pyroceram plates supported by a fiberglass board structure (Fig. 5). Pyroceram plates of the size used cannot take a pressure differential in excess of .2 torr necessitating the use of a guard vacuum which is provided by the fiberglass magnet structure. Sealing of the pyroceram from the guard vacuum is accomplished with room-temperature-curing, silicone rubber. The two coaxial end tanks are aluminum and the two neutral beam tanks are stainless steel.

Very high shock loads are produced in the magnet when the field is pulsed requiring a shock isolating support for the pyroceram plasma chamber as well as very compliant silicone rubber sheet seals between the four openings of the plasma chamber and the four metal tanks, all of which comprise the high vacuum volume.

Pumping is provided by mercury diffusion pumps and titanium sublimation. The base pressure of the guard vacuum is about 10^{-5} torr and about 2×10^{-7} torr in the high vacuum space using the diffusion pumps only. After titanium sublimation, the high vacuum pressure drops into the 10^{-9} torr range. The very high gas load generated during the 10 msec pulse of the twelve 50-ampere sources is handled by the volume delay in the two large neutral beam tanks (Fig. 6). These tanks delay the arrival of the ion source gas in the plasma chamber for about 10 msec by which time the experimental shot is over and the gas is removed by the diffusion and titanium pumps in preparation for the next shot. Six retractable getters put a fresh layer of titanium on the plasma chamber after each shot. Because of the inability of the pyroceram chamber to withstand a pressure differential exceeding .2 torr there is crossover valving system (Fig. 7) between the guard and high vacuum space. The differential is monitored and the valve is actuated by a capacitance manometer. This somewhat detailed description of the 2XIIB system was intended to illustrate the difficulties such a device presents to successful leak hunting.

Leak Hunting 2XIIB

The total parasitic or residual gas load on 2XIIB under proper operating conditions is between 1 and 4 x 10^{-4} $\frac{\text{torr-liter}}{\text{sec}}$. The goal of leak hunting is to insure the leakage constitutes less than 1% of that total or less than 10^{-6} $\frac{\text{torr-liters}}{\text{sec}}$. While this leak rate is many orders of magnitude greater than the sensitivity of available leak detection equipment the design peculiarities make it very difficult to identify and locate leaks. The procedure used is as follows:

Starting from air, it takes about 3-4 hours to rough pump the system (Fig. 8). The crossover or equalizer valve between the high vacuum volume and the guard vacuum is open during roughing and both volumes are pumped through the high vacuum chamber. The pumping speed is varied through the sequential opening of valves ranging from 1/8 in. to 6 inches, while the differential pressure due to gas flow is monitored by the capacitance manometer. The first plateau in terms of leaks is attained when these chambers reach 50 microns or less. At this point, a preliminary check is made, before the equalizer valve is closed, by passing a portion of the roughing stream through a helium MS leak detector. The purpose of this is to locate any large leaks that would possibly generate a rate of rise in either chamber that might exceed the limiting .2 torr differential pressure before the equalizer valve could actuate. If there are no gross leaks apparent, the diffusion pumps are opened to the system, the equalizer valve is closed, and the pumpdown proceeds.

If there are no gross leaks, the guard vacuum quickly drops to 10^{-4} torr or even a few times 10^{-5} torr. The high vacuum chamber usually drops quickly to the 10^{-6} torr range. Both chambers are monitored with permanently installed mass spectrometers. The spectrums and pumpdown characteristics are well known through experience and quickly indicate trouble which may be from air leaks, internal leaks from the guard vacuum, cooling water leaks, or internal leaks from the maize of crossover valving from the various diffusion pumps and roughing systems.

If the spectrometer indicates an air leak, the procedure is conventional in that helium tracer gas is used externally. In this case, where the pressure is low enough or, conversely, if the leaks are small enough, the permanently installed quadrupole MS is monitored. This has the advantage of viewing a large part of the residual spectrum; also, changes in the helium peak height, indicating leaks, are easily determined regardless of a large helium background that often builds up in and around large systems. Probing 2XIIB is a very difficult and tedious procedure as there are over 600 linear feet of hard flange seals, 550 feet of elastomer seals, 6000 convolutions of welded bellows, 350 ceramic feed-throughs for getter power and about 150 water line feed-throughs. Further, deuterium is the plasma gas which creates background problems.

If no external air leak can be found, yet that is the indication on the quadrupole, it is most likely an internal leak from the guard vacuum. To determine this, the guard vacuum pump is "valve off" allowing the pressure to rise; an attendant rise in the high vacuum space indicates a leak. To find this leak is a major operation. Both chambers are let up-to-air and the guard vacuum is pressurized to 10^{-1} torr above atmosphere with tracer gas. A ping pong ball on a tube-to-atmosphere is used as a pressure relief valve for protection of the pyroceram plates. Once the .1 torr overpressure is set, the gas supply and the relief valve are closed and the pressure drop is monitored to determine the approximate size of the internal leak.

A special sniffer probe was developed that appears to be several orders of magnitude more sensitive and far more stable than those commercially available. Fig. 9 shows the sniffer which was made from a copper reducer, 1/8 in. thick sintered stainless sieve with a silastic film of rubber over it. The silastic film being selectively permeable to helium makes the sniffer very stable by preventing buildup of condensibles. The sniffer was connected through a large flexible metal hose to a 300 liter per second diffusion pumping system in which was mounted a quadrupole mass spectrometer, or to a standard He leak detector. The sniffer was sized to give a pressure in the quadrupole chamber between 5 x 10^{-5} and 10^{-4} torr. When other tracer gases such as neon or argon are used, a fixed orifice type of sniffer (Fig. 10) is used.

As previously mentioned, the ceramic plasma chamber is compliantly sealed to the four metal tanks with about 600 sq. in. of silastic rubber sheet. This rubber sheet and RTV comprise the seals between the plasma chamber and the guard vacuum system (Fig. 11). This is the area that is probed with the sniffer. The background due to helium permeation is very large, but the wide range of sensitivity on the quadrupole and the high pumping speed allows changes in peak height to be easily determined and the leaks to be located.

Internal water leaks are found in the usual way be selective evacuation of some 3000 ft. of plastic and copper cooling lines.

Internal crossover leaks are also found in the usual way by isolating and backfilling with tracer gas, although it is complicated by the roughly 100 valves in the high vacuum, fore vacuum, and rough vacuum systems.

Once the machine is on the air and in an operational mode, the high vacuum chamber rate of rise and the mass spectrum is taken twice daily and logged. Any deviation in what is known to be good conditions indicates trouble initiating corrective action.

Baseball II

The BBII (Fig. 12), and modification BBIIT (Fig. 13), is fairly conventional except for two aspects. One, it contains a 15 ton superconducting magnet and a 500 liter liquid helium dewar and, two, it has a base pressure in the low 10^{-11} torr range.

Leak hunting this system is conventional with the exception of the problems presented by the liquid helium and the magnet. The magnet (Fig. 14) contains 44,000 ft. of 1/4 in. sq. N_bT_i superconductor in a copper matrix. The conductor bundle, with insulation, is about 1 ft. square and is enclosed in a welded stainless steel case two inches thick. The liquid helium and the magnet leads are fed through 1 in. dia. tubes to the overhead 500 liter dewar. The tubes are joined with aluminum foil sealed flanges (Fig. 15). The coil case and dewar must be vacuum tight. The problem is to leak check it.

The coil case cannot be evacuated and leak checked in the normal manner because of the conductor bundle and the great quantities of fiberglass insulation. The alternative is to pressurize it to two atmospheres of helium and externally probe with a sniffer. The probability of getting such a system tight is poor for two reasons. One, the rate at which a fluid leaks in the molecular flow regime is proportional to the density difference across the leak. The density ratio between 30 psia of helium and liquid is about 300. Two, the best sensitivity one can expect with a sniffer is about $10^{-8}\ \frac{\text{atm cc}}{\text{sec}}$. Thus, a leak on the threshold of detectability at room temperature could leak at the rate of $3 \times 10^{-6}\ \frac{\text{atm cc}}{\text{sec}}$ at liquid helium temperature.

Our procedure was to shroud the magnet with plastic over the support stand and with a large blower and duct bring in outdoor air to minimize helium background buildup. The sniffer, previously mentioned, was used to probe the 600 linear feet of weld and the gasketed flanges. With some skill and a lot of luck, we have been operating BBII with an insignificant helium peak.

REFERENCE

1) T. R. Ullman, A Large Metal System Permitting Low Base Pressure, 1957 Vacuum Society Symposium Transactions, pp. 95

Work performed under the auspices of the U.S. Energy Research and Development Administration

2XIIB

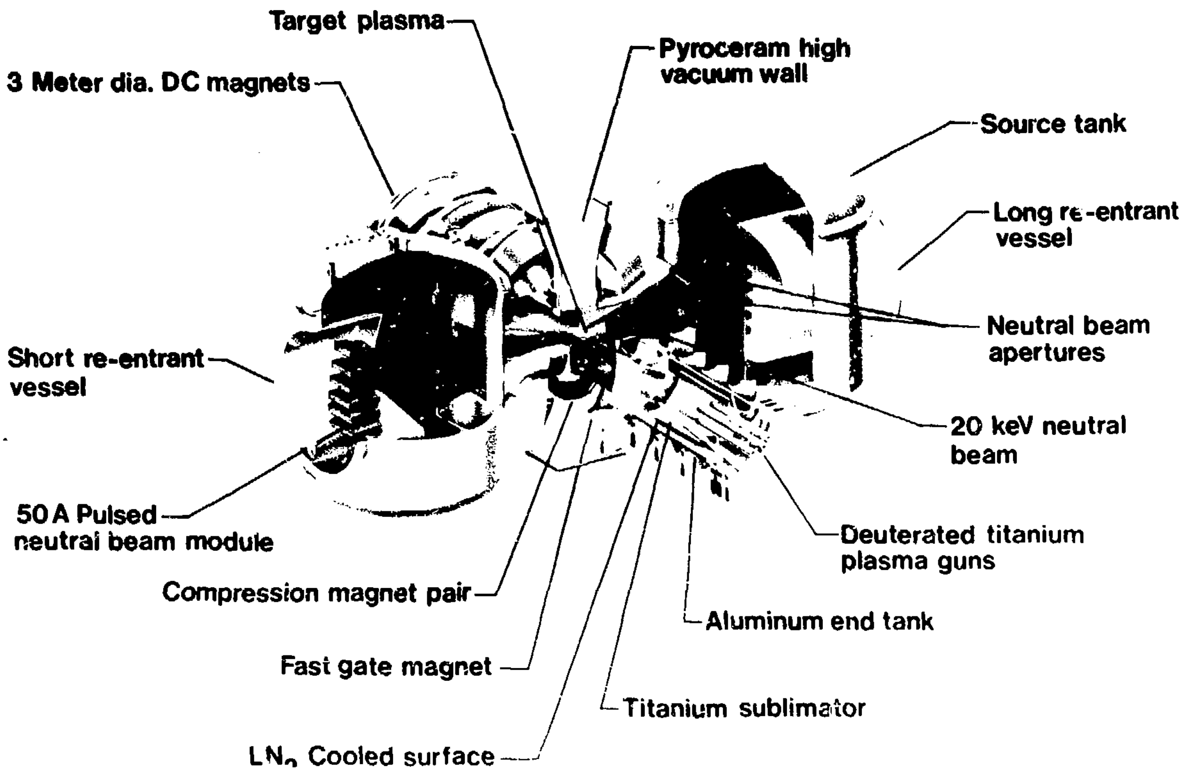

Target plasma
Pyroceram high vacuum wall
3 Meter dia. DC magnets
Source tank
Long re-entrant vessel
Neutral beam apertures
Short re-entrant vessel
20 keV neutral beam
50 A Pulsed neutral beam module
Deuterated titanium plasma guns
Compression magnet pair
Aluminum end tank
Fast gate magnet
Titanium sublimator
LN$_2$ Cooled surface

Fig. 1

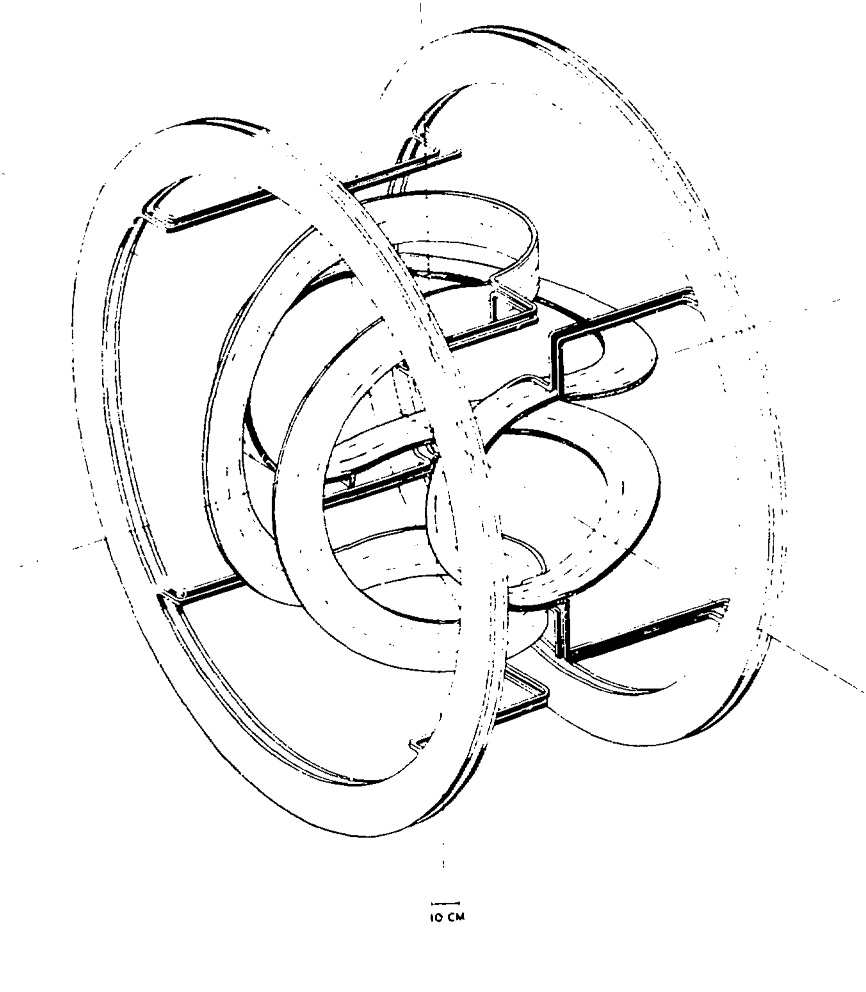


Fig. 2

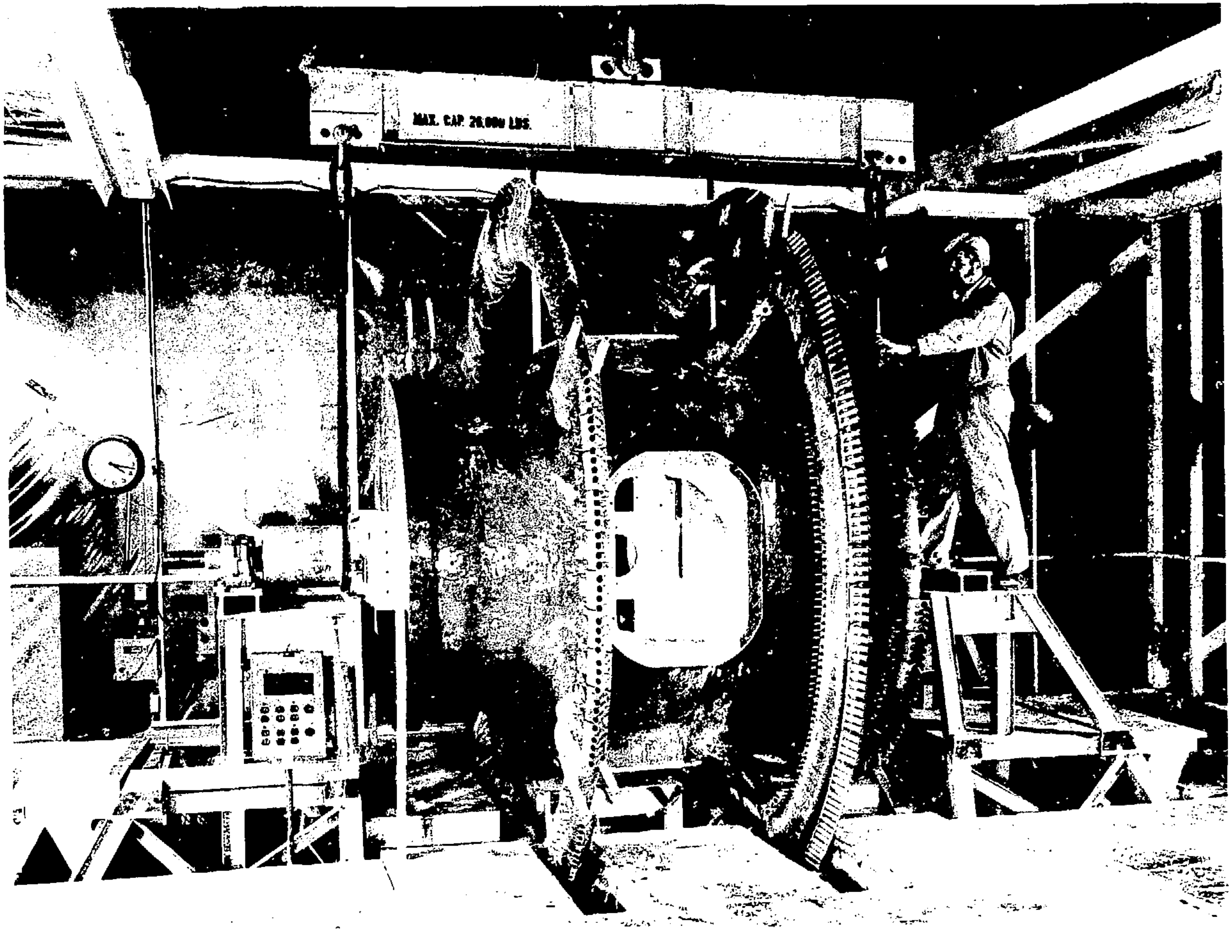


Fig. 3

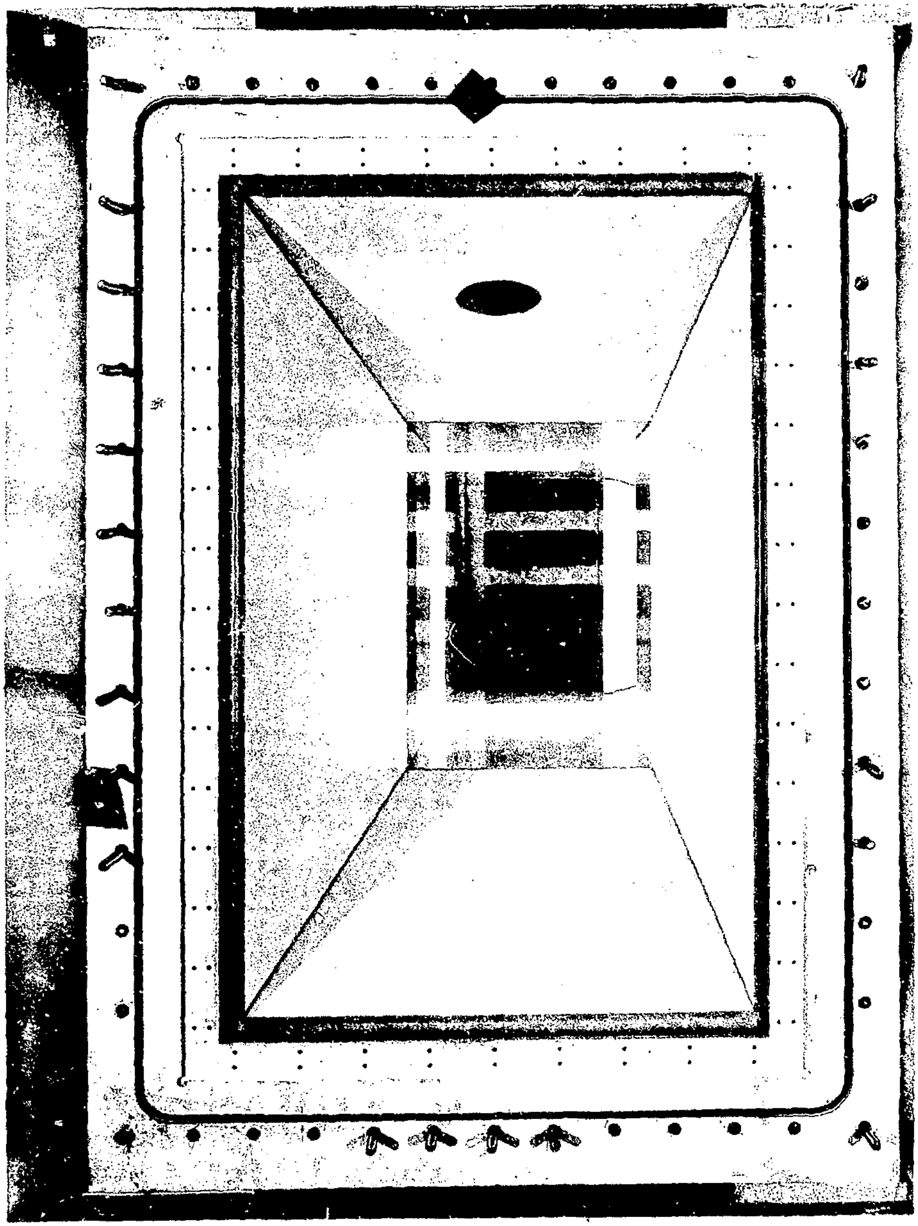
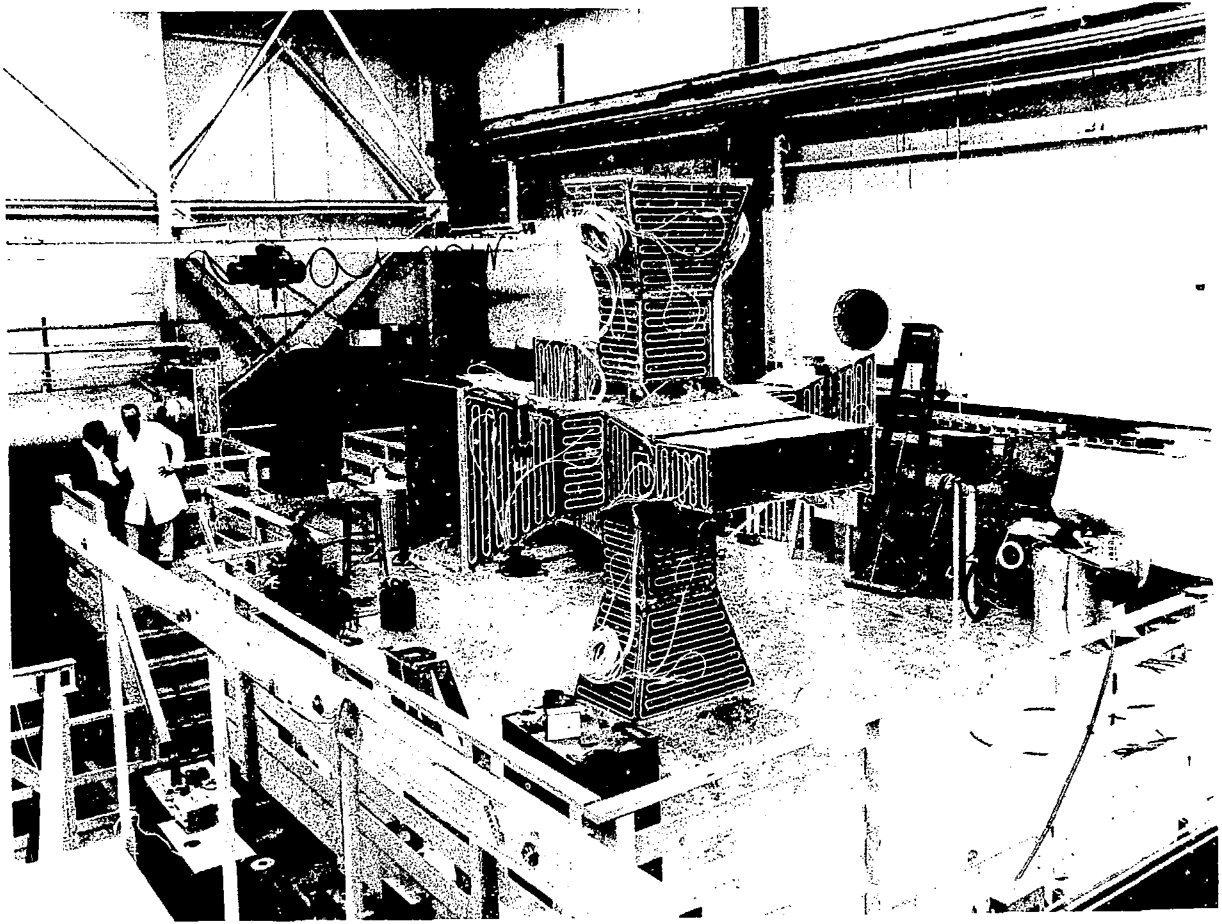


Fig. 4



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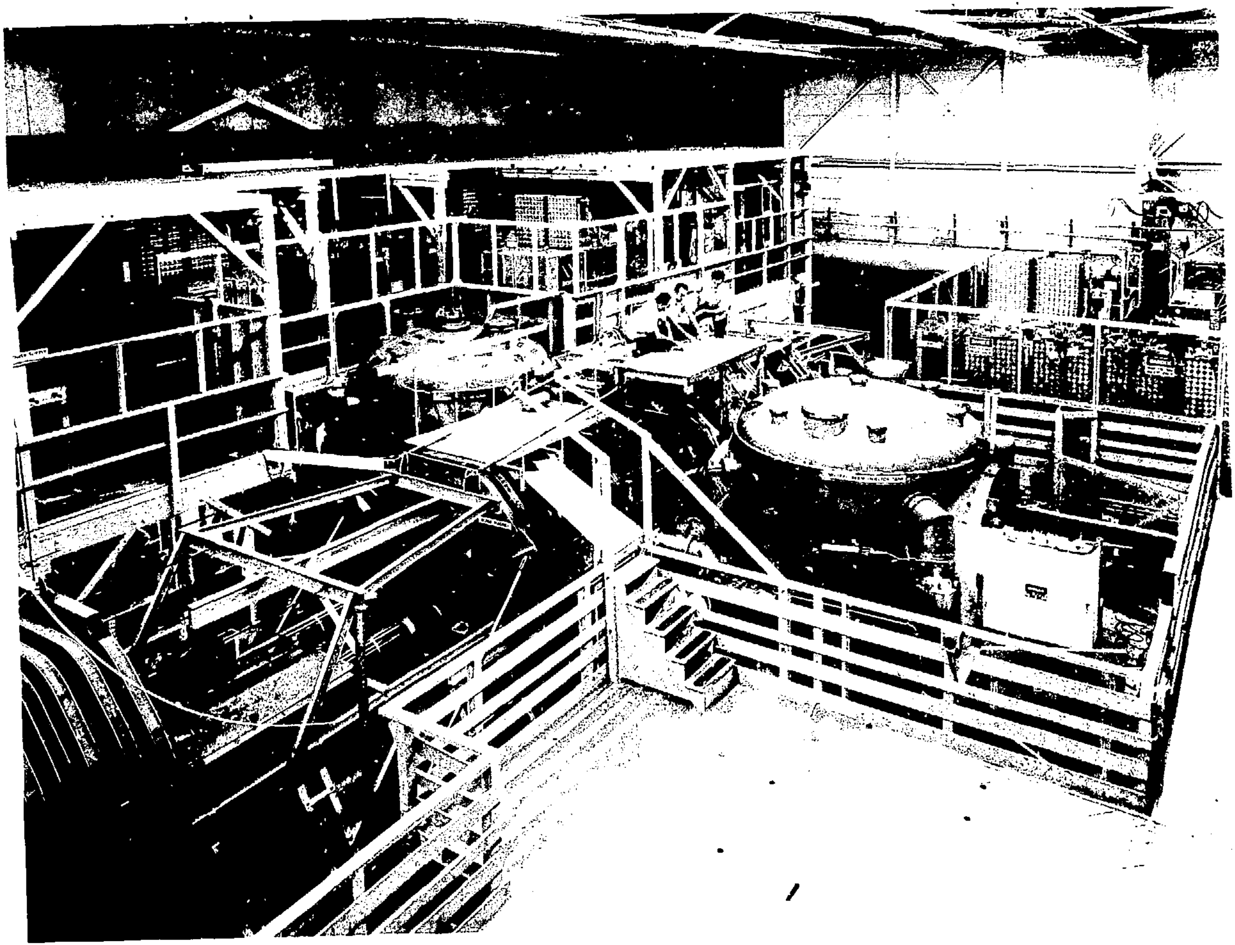


Fig. 6

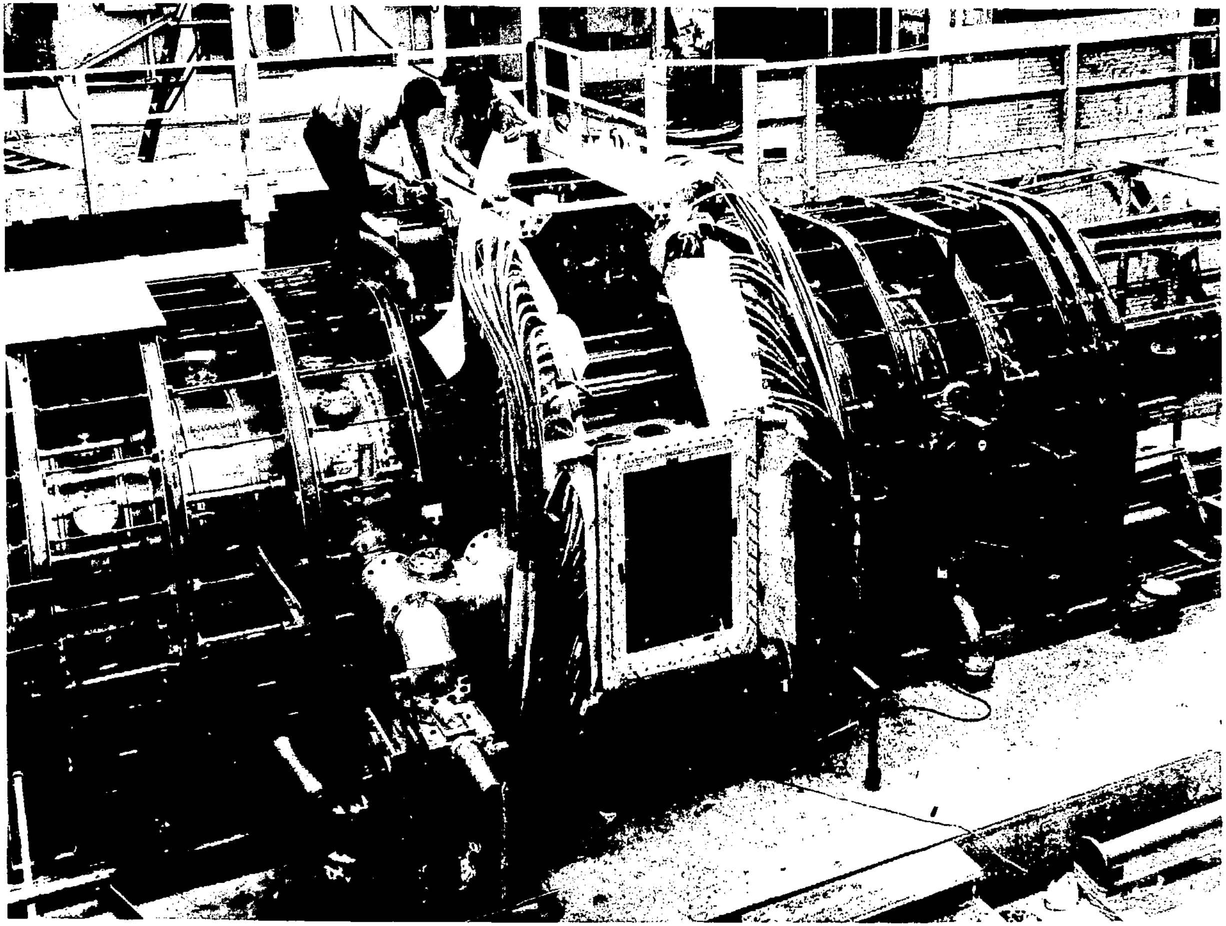


Fig. 7

2XIIB VACUUM SYSTEM

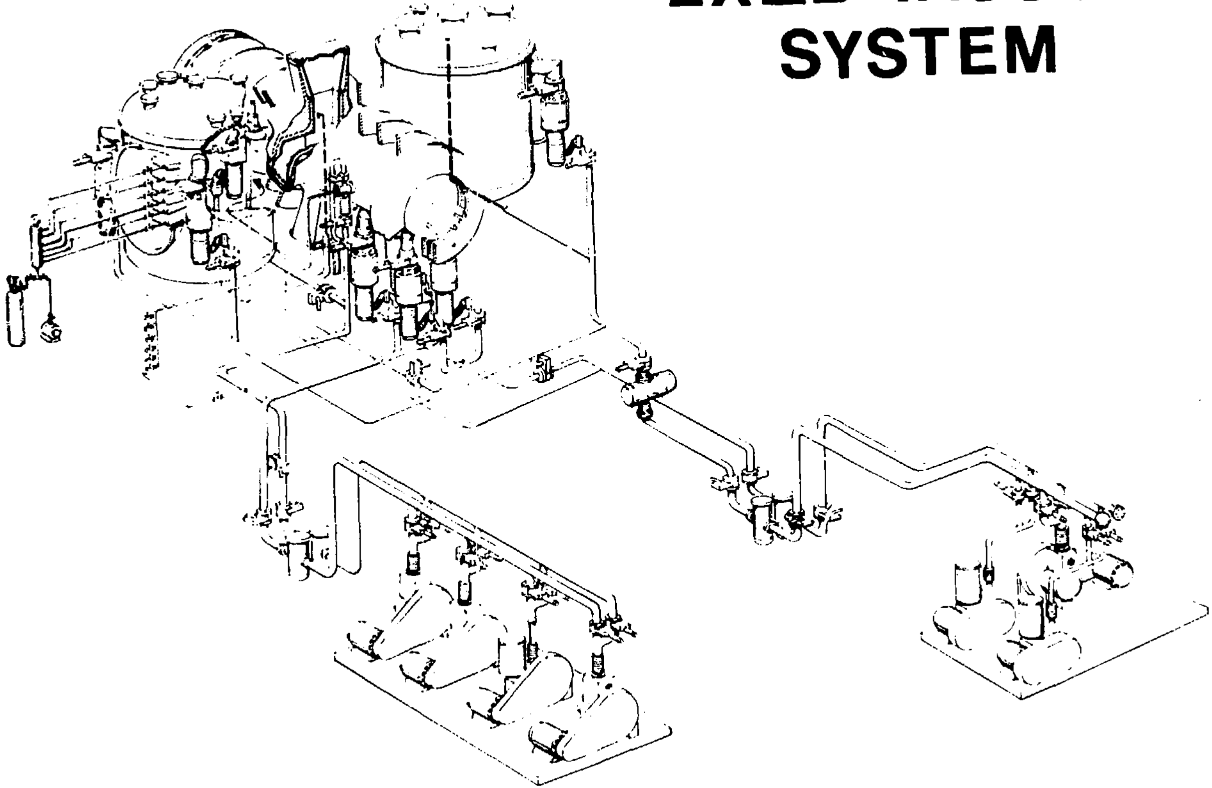


Fig. 8

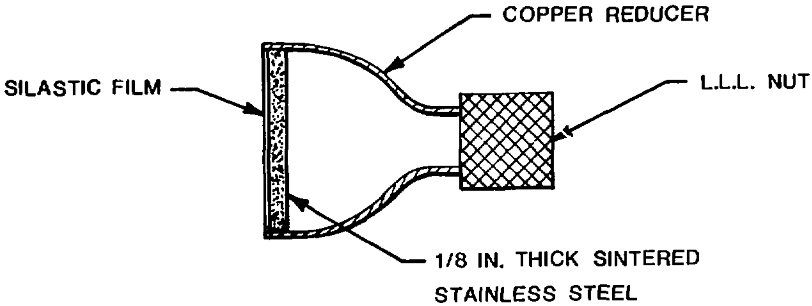

COPPER REDUCER
SILASTIC FILM
L.L.L. NUT
1/8 IN. THICK SINTERED
STAINLESS STEEL

FIG. 9

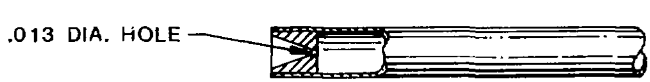


FIG. 10

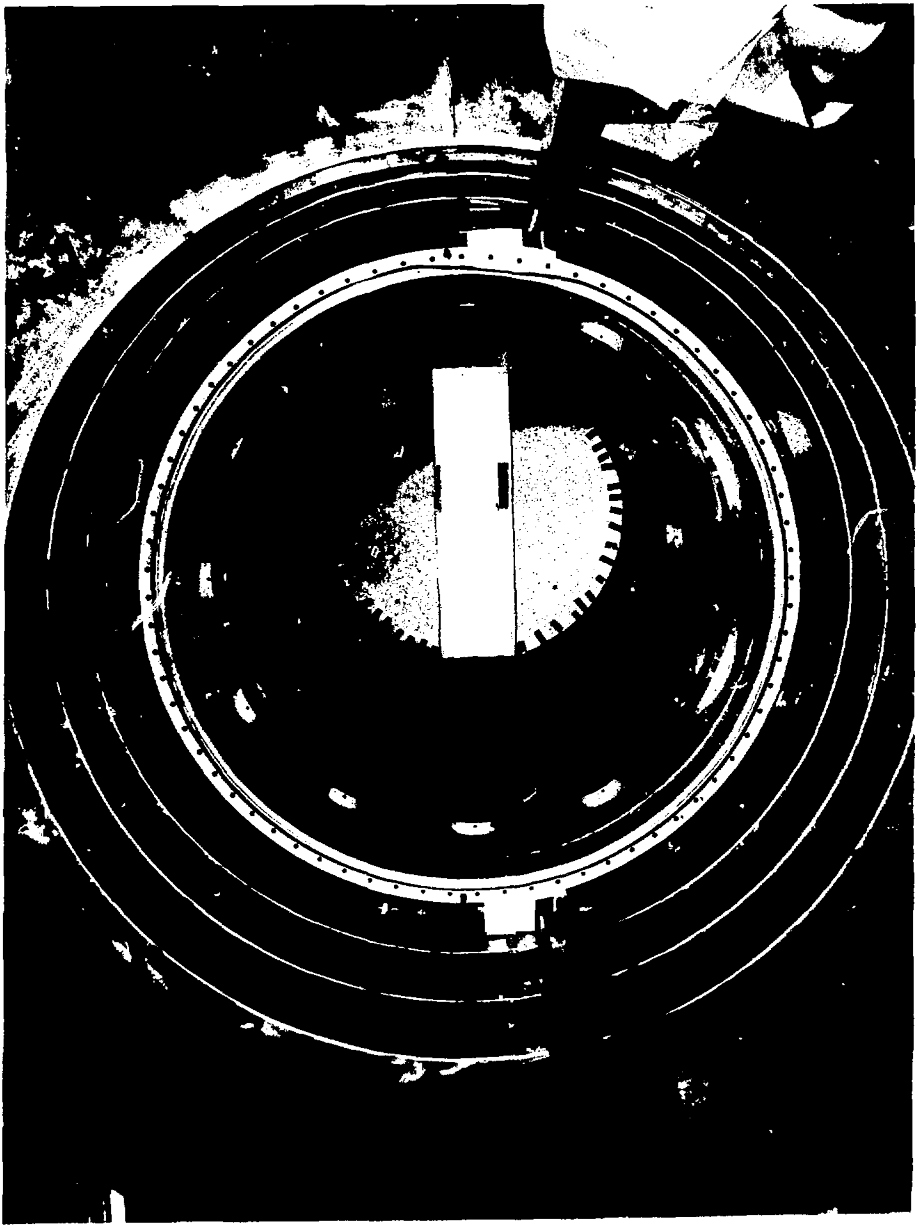
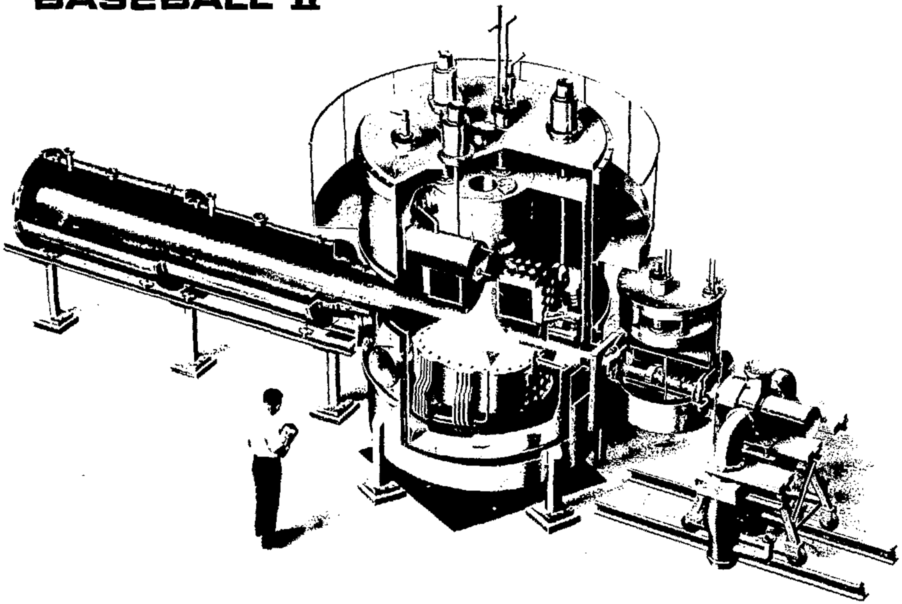


Fig. 11

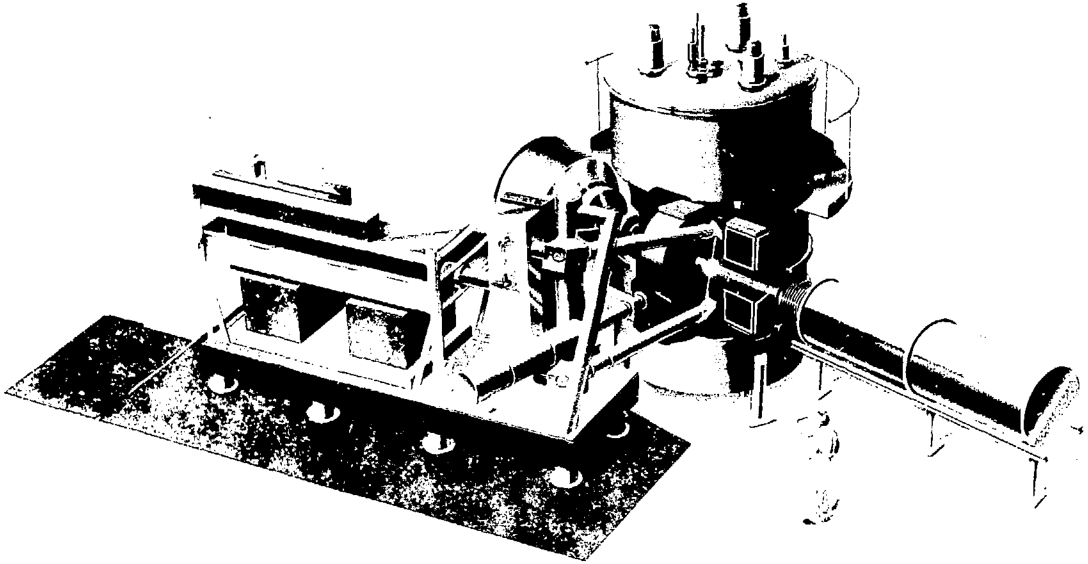
BASEBALL II



SUPERCONDUCTING NEUTRAL INJECTION EXPERIMENT

Fig. 12

BASEBALL IIT



TARGET PLASMA BUILDUP EXPERIMENT

Fig. 13

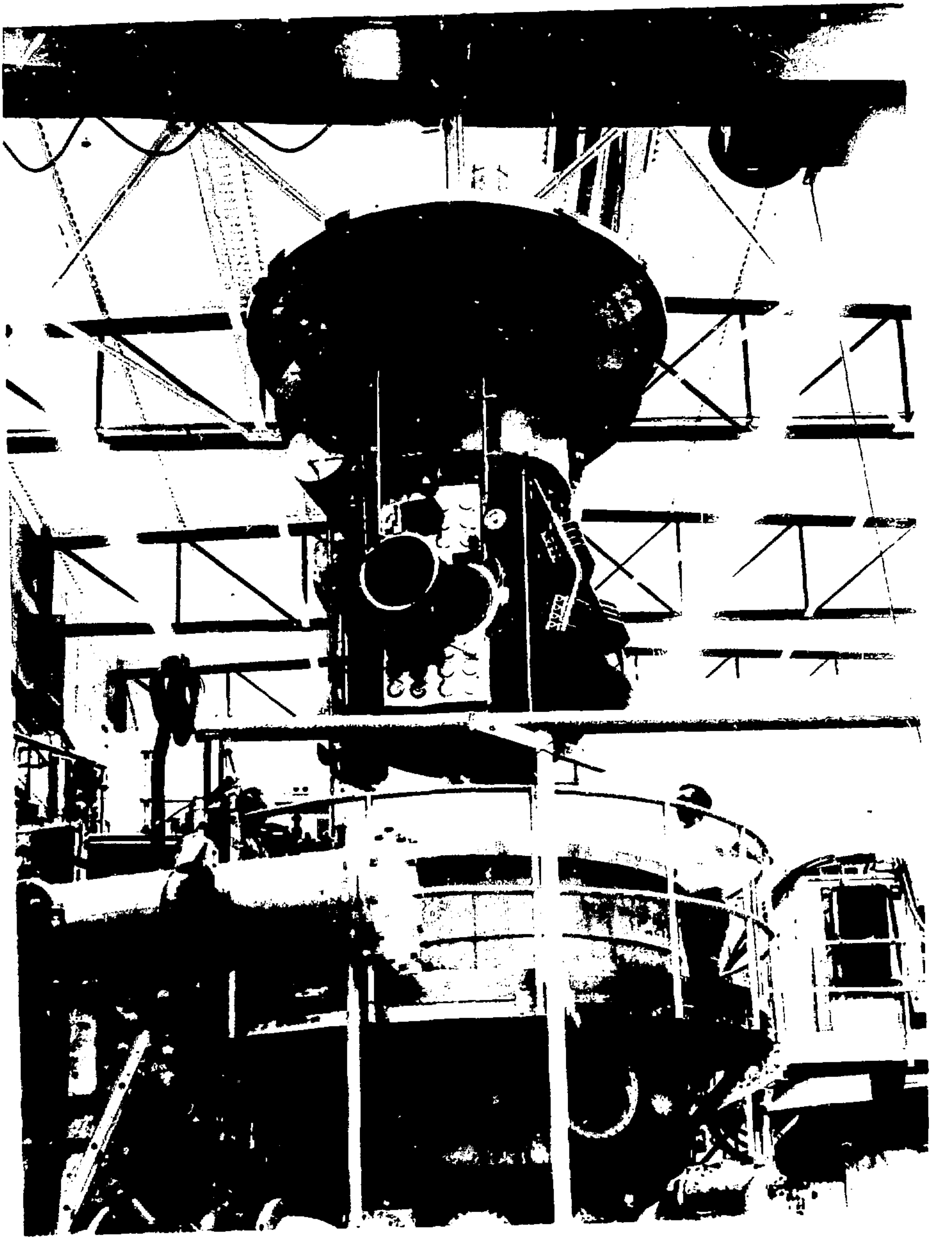


Fig. 14

Fig. 15