[illegible] 2
Colchin
6/30/75

Draft

Conf. 750718--1

THE ISX TOKAMAK AS A RADIATION TEST FACILITY FOR SURFACE STUDIES

R. J. Colchin and T. C. Jernigan
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37830, U.S.A.

and

M. J. Schaffer

General Atomic Company
San Diego, California 92138, U.S.A.

ABSTRACT

ISX (Impurities Study Experiment) is a moderate-sized tokamak facility dedicated to the study of the origin and transport of impurities. This machine is expected to approximate the plasma conditions in the outer layer of a large ohmically heated device, except for neutron effects. The deposition of impurities and limiter material from the walls will be studied by using AES, SIMS, and soft x-ray appearance potential spectroscopy. Chemical reactions with atomic hydrogen, as well as desorption by electrons, ions, and uv radiation, will be studied to determine the evolution of wall material into the plasma. UV spectroscopic and x-ray methods will be used to determine impurity-plasma transport. ISX is designed so that liners may be interchanged easily and quickly. This allows for testing different wall and limiter materials, such as honeycomb walls, with a turnaround of a few weeks. Initial tests will determine the effectiveness of baking and discharge cleaning in attaining clean surfaces. The parameters of the machine are: $r = 25$ cm, $R = 90$ cm, $B_T = 18$ kG, and $I_p = 150$ kA for $q = 4$. Expected plasma parameters are $T_e = 500\text{-}1000$ eV, $T_i = 300\text{-}500$ eV, and $n_e = 2\text{-}7 \times 10^{13}$ cm^{-3}.

MASTER

INTRODUCTION

Impurities in tokamaks arise from desorption, sputtering, and evaporation of wall and limiter materials. Once in the plasma they cause energy loss by the following mechanisms: (1) energy loss to impurity atom ionization, (2) energy to heat electrons resulting from this ionization, (3) energy loss to bremsstrahlung radiation of electrons on impurity atoms, (4) energy loss to recombination radiation, and (5) energy loss to impurity-induced instabilities. This latter effect is easily evidenced in present-day tokamak plasmas. On the basis of energy balance one can show that tokamak reactor plasmas will not ignite if a few percent of high Z impurities are present.

Although the general mechanisms by which impurities are produced are well known, as are their effects on tokamak plasmas, the details of impurity-plasma evolution is not clear. Minimization and control of tokamak impurities depend on knowing these details; for example, they depend on knowing the exact impurity production mechanisms which are most important and how impurities are transported and possibly accumulated in the plasma. It is this set of questions that ISX is designed to address.

The projected size of ISX is $R = 90$ cm and $a = 25$ cm, with a toroidal field of 18 kG. Figure 1 is a conceptual view of ISX. Details of machine dimensions, currents, and vacuum systems are listed in Appendix A.

ISX AS A RADIATION SOURCE

The tokamak impurity problem can be conceptually divided into two parts: impurity production at the plasma-wall boundary and impurity evolution in the plasma region. To first order, a complete separation is not possible since impurity production depends on the presence of a plasma. However, it will be shown below that once a tokamak is big enough to establish a corona region [2], both neutral particle and heat fluxes to the wall are relatively independent of machine size.

The flux of various kinds of radiation to the wall is important since it induces desorption, sputtering, and evaporation of wall particles. Impurity production can occur under wall or limiter bombardment by electrons, ions, or photons. Charged particles reach the wall by convection, and photons are generated as recombination (line), synchrotron, and bremsstrahlung radiation. If ISX is to simulate the impurity production of larger devices, it must have similar radiation characteristics.

Table I [1] shows that the radiation fluxes are similar to those expected in a typical large tokamak under a variety of theoretical assumptions. This is because the corona region forms an effective barrier between the central hot plasma core and the plasma-wall boundary. However, it cannot shield against the neutrons nor against synchrotron radiation which will be produced in fusion power reactors, so that they are not modeled by ISX.

The neutral particle flux at the wall is also relatively independent of both machine size and central ion temperature. Table II [ ] illustrates this point, showing that both the charge exchange flux at the wall and wall sputtering per unit area are independent, within a factor of four, of machine radius and ion temperature. Again, this constancy results from the shielding effect of the corona region.

Figure 2 further illustrates this point, showing that for constant T_i and n_e the charge exchange flux and number of sputtered particles per eV of incident charge exchange energy is constant. Of course the number of neutrals at the plasma center is a strong function of machine size since neutrals are attenuated in the core as well as in the corona region. However, the neutrals in the core do not directly affect impurity transport. Figure 3 shows the expected neutral spectrum in ISX. Since the sputtering coefficient of material has its most pronounced energy dependence in the range below 1 keV, there will be enough fast neutrals in ISX to allow for the exploration of the sputtering regime of interest.

ISX DIAGNOSTICS AND DESIGN

As with impurity sources and transport, impurity diagnostics can be approximately divided into similar classes. The diagnostics capable of looking at impurity sources are those typically used in surface physics: Auger spectroscopy (AES), secondary ion mass spectroscopy (SIMS), low energy electron diffraction (LEED), and electron-induced desorption (EID). The principal diagnostics applied to impurity transport are ultraviolet vacuum spectroscopy and soft x-ray detectors. Of course, a full complement of "conventional" diagnostics must also be on hand to characterize plasma parameters, i.e., Thomson scattering apparatus, microwave interferometer, pickup loops, Rogowski coils, etc.

ISX is not designed to explore new regions of plasma parameter space, but rather for the complete diagnosis of a particular problem. For this reason a design was chosen which makes use of the knowledge accumulated over the last several years on present-day tokamaks. Of prime concern is good diagnostic access, a clean vacuum system, and simple disassembly so that liners can be quickly removed or interchanged.

The ohmic heating and vertical field coils will be placed as shown in Fig. 1 so as to allow clear diagnostic access to the top and bottom of ISX, as well as almost clear entry horizontally from the outside. Typical entries are shown in Fig. 4. All connections with the liner will have bakeable metal seals with electrical breaks to isolate diagnostics from voltages in the liner. Eighteen field coils provide ____ cm wide access at the outside liner face.

A major goal of ISX is to develop the vacuum techniques necessary to insure clean surfaces. Thus the inner liner will be of high vacuum construction, bakeable to 400°C (except the appendages which will bake to 300°C). Another feature will be the ability to clean inner surfaces by direct discharge cleaning [3]. Surface impurities and cleanup will be monitored AES and SIMS. Details of the vacuum system are discussed in Appendix B.

Quick assembly and disassembly are features which allow major machine changes to be affected without undue loss of time. For example, the first important experiment to be performed in ISX will be a test of Ohkawa's theory [4] of impurity flow reversal. This experiment will require a special liner such that gas can be introduced in the upper part and pumped away below. Upon completion of this experiment, less specialized liners will be introduced. Several wall materials such as carbon curtains will be tried, as will be honeycomb-wall liners and a variety of limiters. All this makes easy liner changeability a must.

Assembly and disassembly are facilitated by making the plasma and vacuum tank systems independent of the structural and magnetic field systems. For disassembly the upper part of the OH transformer simply lifts off, and the upper sections of the picture-frame toroidal field coils can be removed. The upper half of the outer vertical field and ohmic heating coil assembly can then be taken off as a unit. This enables the vacuum tank and its contents to be lifted clear, even with radial penetrations attached.

IMPURITY TRANSPORT AND OTHER EXPERIMENTS

The second important part of impurity studies is the transport of impurities which reach the plasma in spite of the above-mentioned controls. It is important to know how they evolve into the plasma both in radius and time. Transport rates can be either classically determined by collision phenomena or they may be determined by the fluctuating fields of plasma turbulence. Impurities lead to increased diffusion classically in increasing collision rates. They can also induce MHD instabilities due to cooling the outside of the plasma column with subsequent current channel shrinkage and decrease in the value of q.

Correlations of plasma transport and MHD activity will be performed in ISX. Selection of applicable transport models requires a detailed comparison with the results of time-dependent transport codes which take into account impurity excitation, ionization, and recombination for several possible diffusion models. These calculations in turn depend on a knowledge of the concentrations and types of impurities as determined by ultraviolet spectroscopy and by soft x-ray diagnostics.

Further into the future, there are a number of important topics which can be studied in ISX. The studies of disruptive instabilities and their effect on operating regimes (i.e., density restrictions) is of great interest. ISX is an ideal test bed for rf heating studies, both at lower frequencies using Alfven waves and higher frequencies near the lower hybrid resonance. A fringe benefit of having rf power available is the possibility of using cyclotron heating at resonance positions near the wall to enhanced discharge cleaning.

CONCLUSION

The problem of controlling impurities in thermonuclear plasmas is critical to the successful development of fusion power. Numerous approaches to impurity control have been suggested. Among these are low-Z walls, special limiters, impurity flow reversal, low sputtering wall geometries (honeycomb walls), etc. Unfortunately, the success or failure of each suggestion depends on a detailed coupling between the plasma and its boundary. There are many channels by which impurities can be carried from walls and limiters into the plasma and only tests with tokamak plasmas can determine which are of controlling importance. As a tokamak of moderate size, ISX will realistically model many of the chemical, thermal, and neutral-flux-related effects expected from larger tokamaks. The development of methods to obtain clean walls and good vacuum will also be of importance. In addition, impurity transport experiments will determine the importance of neoclassical and turbulent transport in a variety of plasma regimes.

Of course, questions of radiation damage, synchrotron radiation, and prolonged thermal loads will have to be investigated on other devices. These questions will be answered by the neutron sources and the Experimental Power Reactors of the future.

REFERENCES

[*] Operated by Union Carbide Corporation for the Energy Research and Development Administration.

1. J. T. HOGAN and J. F. CLARKE, Oak Ridge National Laboratory, Private Communication.

2. The corona region is that region at the boundary of the plasma in which the bulk of the charge-exchange and recombination events occur.

3. A. G. MATHEWSON, *Vacuum*, 24, 505 (1974).

TABLE 1

COMPARISON OF WALL LOADING IN SMALL AND LARGE CONFINEMENT DEVICES

	F/BX (a = 180 cm)			ISX (25 cm)
	TRAPPED ION MODE	PSEUDO CLASSICAL	NEO CLASSICAL	TYPICAL EXPERIMENTAL
PLASMA LOSSES (MW)	12.1	6.3	7.2	.22
PLASMA WALL LOADING (W/cm^2)	2.9	1.5	1.7	2.54
CONDUCTION & CONVECTION (%)	82	22	5	43
SYNCHROTRON (%)	14	32	30	0
BREMSSTRAHLUNG AND LINE RADIATION (%)	4	46	65	57
NEUTRON WALL LOADING (W/cm^2)	3.8	14	16.5	0

TABLE 2

EFFECTS OF PLASMA ENERGY AND SIZE ON SPUTTERING

MINOR RADIUS	CENTRAL PLASMA DENSITY	CENTRAL T_I (KEV)	Γ_{CX}	$F_S (\times 10^3)$
23	$5 \cdot 10^{13}$	.5	$6.5 \cdot 10^{15}$	2.12
23	$5 \cdot 10^{13}$	3.	$1.99 \cdot 10^{16}$	4.16
45	$5 \cdot 10^{13}$	3.	10^{16}	2.6
175	$5 \cdot 10^{13}$	6.	10^{16}	2.0

FIGURE CAPTIONS

Fig. 1. ISX — Profile View.

Fig. 2. Variation with Plasma Minor Radius. The number of gold atoms sputtered/eV of charge exchange energy is shown, along with the ratio of central/edge neutral densities and the total charge exchange flux.

Fig. 3. ISX Charge-Exchange Spectra.

Fig. 4. Typical Penetrations.

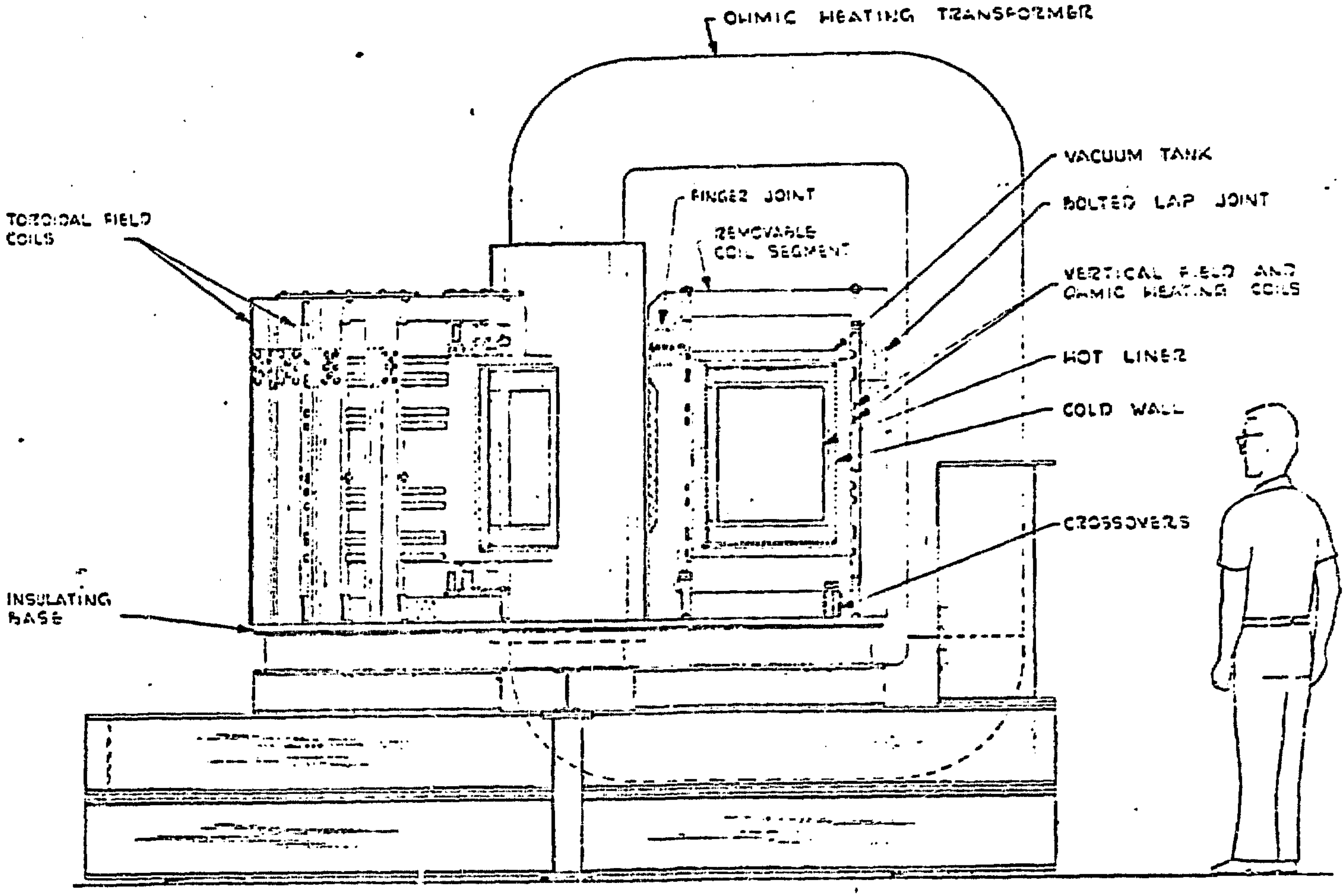
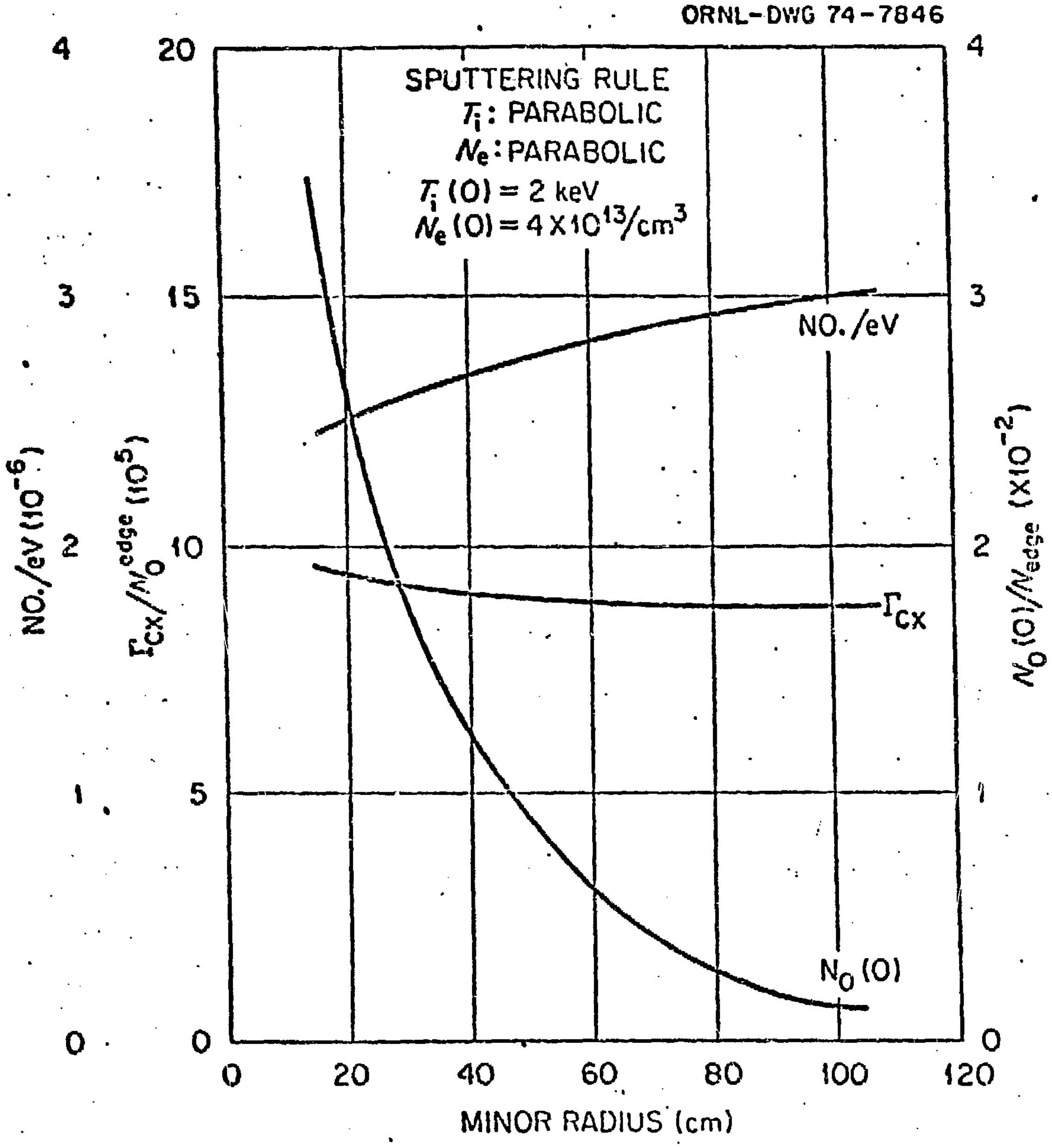
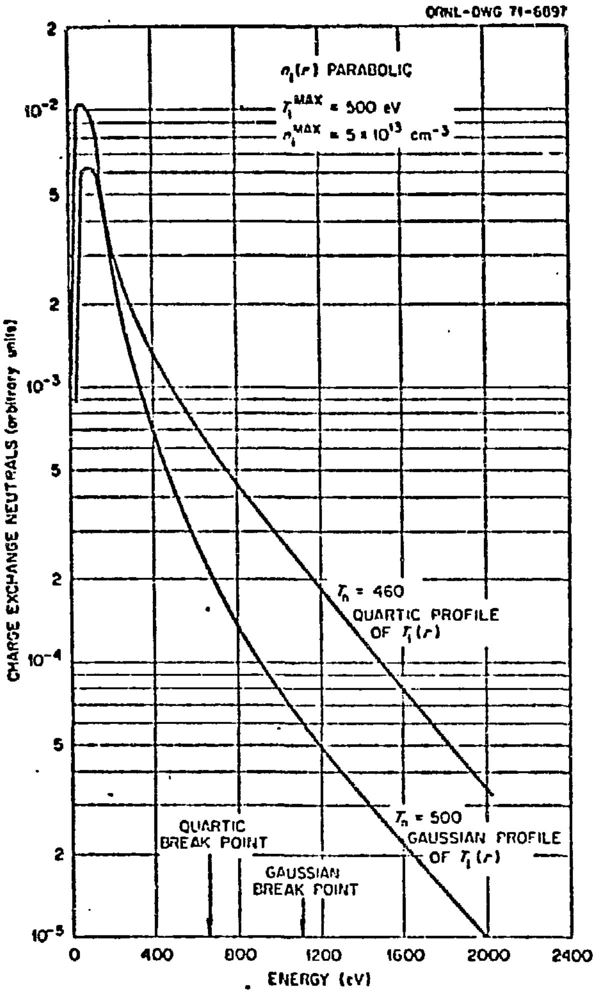


Fig. 1. ISX — Profile View



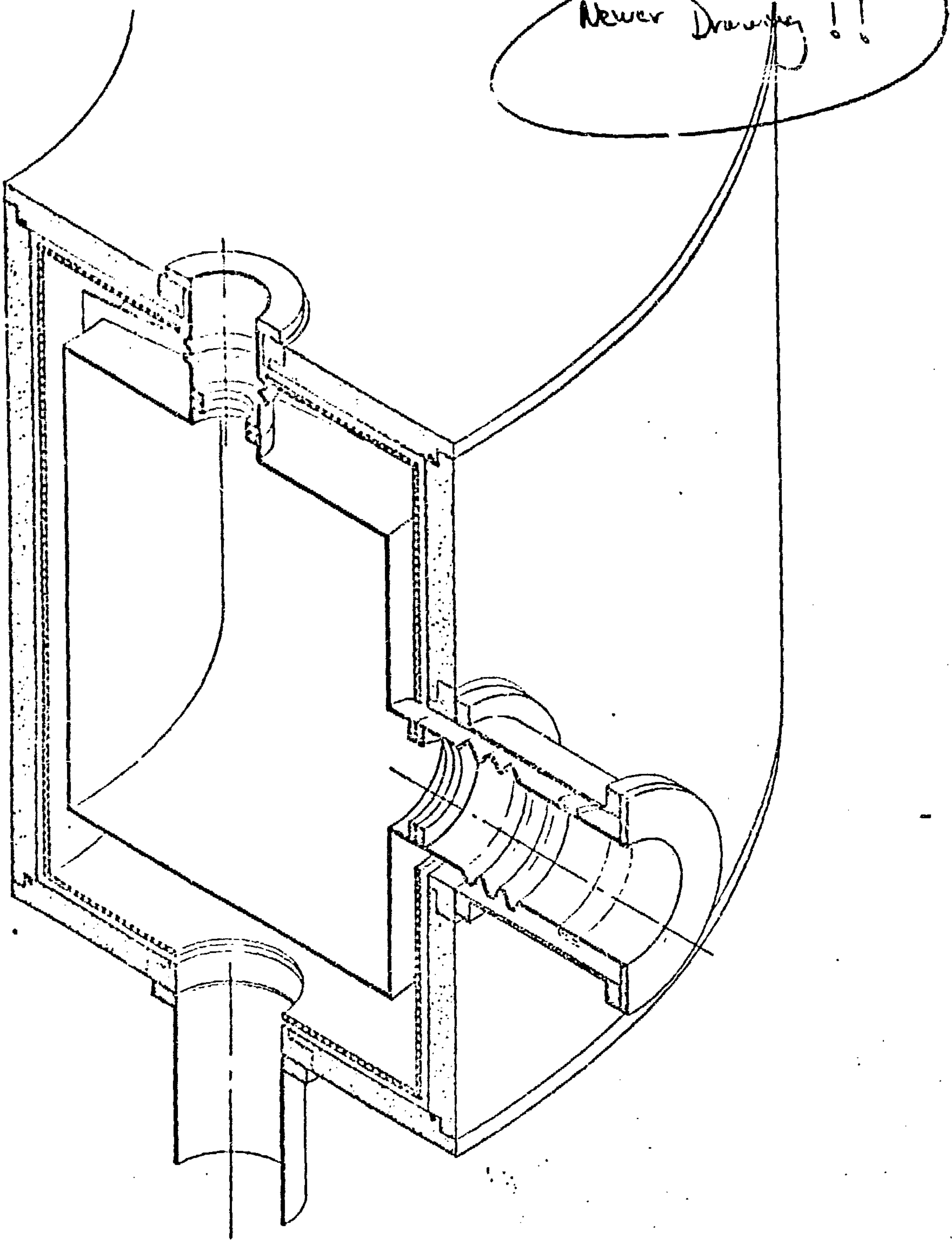
2

Fig. ~~3~~. Variation with plasma minor radius. The number of gold atoms sputtered/eV of charge exchange energy is shown, along with the ratio of central/edge neutral densities and the total charge exchange flux.



3 ISX

Fig. ~~2~~. ~~ORMAK~~ charge-exchange spectra.



Newer Drawing !!

Fig. A~~-2-1~~ 4. Typical Penetrations

APPENDIX A

~~Table 2.1~~. Projected ISX Dimensions and Parameters

~~New Table?~~

Plasma	
Cross section	Circular
Major radius (nominal)	90 ~~23~~ cm
Minor radius (nominal)	25 ~~15~~ cm
Centerline field	18 ~~20~~ kG
Plasma current (max)	150 ~~100~~ kA
Safety factor at limiter (100 kA)	4 ~~3.0~~
Toroidal Field System	
Magnetic field at plasma axis	18 ~~20~~ kG
Repetition rate	1 per minute
Flat top length	250 ~~400~~ ms
Current (max)	120 ~~100~~ kA
Number of turns	72
Number of turns per coil	4 ~~8~~
Ampere turns	8.6 ~~7.2~~ x 10^6
Maximum driving voltage	1000 V
~~Inductance~~	~~2. 1.6 mH~~
~~Resistance~~	~~2.6 mΩ~~
Flattop power	30 MW
Energy per pulse	24 MJ
~~Coil shape~~	~~Rectangular~~
~~Conductor material~~	~~Copper~~
Maximum temperature rise per pulse	12°C
Coolant	Water
~~Vertical aperture~~	~~105 cm~~
~~Radial aperture~~	~~70 cm~~
~~Conductor cross section~~	~~2.5 cm x 10 cm~~
Current density	4000 A/cm^2
~~Conductor weight~~	~~6 x 10^3 kg~~

Table 3.1. (Continued)

Transformer Core and Yoke	
~~Material~~	~~AISI 1010 carbon steel~~
~~Lamination thickness~~	~~20 gage~~
~~Core radius~~	~~29 cm.~~
Flux change	0.9 volt-sec
~~Weight of core and yoke~~	~~2.3×10^4 kg~~
Ohmic Heating System	
~~Coil material~~	~~Copper~~
Current	25 ~~17~~ kA
Turns ratio	6:1
Driving voltage	400 V initial; 50 V flattop
~~Conductor area~~	~~10 cm^2~~
Temperature rise per pulse	0.5°C
Cooling	Air, natural convection
Vertical Field System	
~~Coil material~~	~~Copper~~
Maximum current	20 kA
Total turns	8
Driving voltage	20 V
Cooling	Air, natural convection
Vacuum Pumping	
Primary	
Type	500 ℓ/sec turbomolecular pumps
Number	2
Design base pressure	3×10^{-9} torr
Secondary	
Type	6-in. oil diffusion pump

~~Table [illegible] (continued)~~

Vacuum Pumping (con't)	
Number	2
Design base pressure	2×10^{-6} torr
<u>Primary Vacuum Vessel</u>	
Type construction	All welded
Material	Austenitic stainless steel
Cross section	40 cm x 50 cm
Wall thickness	0.5 mm
Baking temperature	400°C
~~Limiter~~	
~~Inside wall~~	~~Fixed bar~~
~~Outside wall~~	~~Fixed bar~~
~~Upper~~	~~Fixed bar~~
~~Lower[a]~~	~~Movable toroidal ring~~
<u>Secondary Vacuum Vessel</u>	
Type construction	Fiberglass/epoxy
Cross section	58 cm x 78 cm
Wall thickness	3.2 cm
Thermal protection	Water-cooled stainless steel panels attached to inner surfaces

---

~~[a] Included as part of impurity flow reversal experiment.~~

APPENDIX B

Any plasma experiment intended for the study of impurities in the discharge must have excellent vacuum conditions in the discharge chamber. The goal for ISX is a base pressure in the range 10^{-8}–10^{-9} torr. In order to maintain a high degree of flexibility to experiment with plasma walls of differing materials or consturction (e.g., honeycomb walls), it is desirable to minimize the engineering requirements and costs of the vacuum vessels. A dual coaxial vacuum system consisting of a thin metal liner inside a fiberglass/epoxy pressure-resisting vessel is thought to be the solution. However, a single, thin vessel with reinforcing sections is also being considered. A thin-walled liner eliminates the need for an insulating break and allows easy and inexpensive replacement.

The liner is an all-welded, thin wall vessel. The resulting elimination of mechanical joints, except for appurtenances, renders the liner as leak-tight as possible. All parts use high-temperature metal seals. The inital liner planned for ISX is of 0.5-mm-thick austenitic stainless steel with external stiffeners.

The secondary vacuum vessel is made from nonconducting epoxy/fiberglass to avoid an electrical break and to allow rapid penetration of the vertical field produced by external coils. It is assembled from two concentric cylinders forming the inner and outer walls plus two annular pieces forming the top and bottom walls. Elastomer O-ring seals are used at all secondary vacuum joints. The experience at GAC with the Doublet II-A G-10 epoxy/fiberglass secondary vacuum enclosure has been incorporated in the conceptual design. However, associated studies are being conducted to determine the optimum composite matrix considering cost, mechanical strength and vacuum properties.

A water-cooled cold wall, assembled from commercial heat transfer panels, is attached to the inside surface of the secondary vacuum vessel to protect it during liner baking. These panels are of stainless steel and broken into several sections to minimize induced electrical currents. Demineralized water is used for cooling.