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NUCLEAR ASPECTS OF TOKAMAK FUSION TEST REACTOR (TFTR) DIAGNOSTICS AND INSTRUMENTATION

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Summary

There are five principal aspects of the nuclear radiation from the high temperature plasmas of TFTR on its plasma diagnostic equipment. i) Important information about the plasma properties to be obtained from measurement of the neutrons, or other fusion reaction products. ii) Experimental studies to give design data for future tokamak devices and their instrumentation. iii) Transient noise or damage effects on the array of detectors for the collection of physics data about the plasma. iv) The effect of tritium on detectors that necessarily are in vacuum, directly connected to the tokamak vacuum vessel. v) Damage of diagnostic components mounted close to the vacuum vessel. Each of these topics will be addressed after a brief description of the TFTR tokamak and its radiation environment.

Introduction

The Tokamak Fusion Test Reactor (TFTR) will start to operate at the end of 1982. There will be a period of developing capability for the device to reach two simply-stated goals: i) demonstrate good containment properties for very high input power levels with neutral beams (and, possibly, RF heating), and ii) produce sufficient D-T fusion nuclear reactions that the ratio of the output power to the input power is greater than unity ($Q > 1$). In the latter case, high energy α - particles are created, but only contribute a few percent to the plasma heating. The full capability will be reached in about 1987, when all the necessary equipment and shielding has been installed and fully tested; but there will be significant operation with deuterium throughout and even a brief period of D-T operation during the development period. Since the shielding of the tokamak will not be complete during this period, it has been necessary to plan for serious background radiation effects throughout the program as well as to ensure that the neutron measuring equipment has the capability to operate over a wide dynamic range of fluxes.

Five major nuclear aspects of TFTR operation and their effects on diagnostic instrumentation will be addressed.

i) The use of the neutrons and other product particles to learn directly about the plasma properties. Recent measurements on the PLT and PDX tokamaks at Princeton show that transport and instability properties as well as heating information can be obtained at much lower neutron flux levels than that predicted for final TFTR operation.

ii) Experiments of relevance to future stages of the magnetic fusion program. a) Experiments for measuring the contained α - particles from D-T reactions. For reactors these particles cause a contained "helium-ash" and, while the number of α - particles contained in TFTR is small, their confinement properties are of great importance for future devices. b) Lithium breeding experiments making use of the neutrons whose spectrum and broad-source make them relevant to a practical toroidal fusion reactor. A relatively small module will be used to obtain reactor-relevant integral neutronics data and breeding rates in an experiment to confirm neutronic code estimates.

iii) The effectiveness of a wide variety of detectors in a high background of scattered neutrons and gammas. Measuremens of X rays, charged particles, visible and ultraviolet light, and far infrared radiation are some of the cases where the detectors have to work concurrently with the neutron emission.

iv) The effects of tritium deposition, and the resultant 19 keV β emitted, on detectors in vacuum. A number of diagnostic measurements such as those in the far ultraviolet and soft X-ray spectral regions require that there be no material barrier between the instrument and the plasma and so there is an increase of background signal level.

v) Damage and transient effects on diagnostic components within the main shield boundary. Components close to the tokamak such as windows and cables require special selection, and shielding has to be arranged for all electronic racks. The radiation levels are such that shielding is a much more cost-effective approach than full radiation hardening of components except in the case of an occasional preamplifier.

The sophistication of the instrumentation of TFTR will probably be the highest achieved for tokamaks. The operation of TFTR, like its predecessor devices, is very tightly bound to the understanding of the plasma. This understanding is made possible by the wealth of plasma diagnostics and is critical for the gradual improvement of plasma properties and for the prevention of such phenomena as sudden plasma loss (disruptions) and high levels of impurity atom influx from the walls due to local heating effects. Once these phenomena are understood and can be controlled, future devices with neutron fluences many orders of magnitude larger than that predicted for TFTR should not need such an array of equipment. To some extent, TFTR will be used as a test bed for converting the techniques of measurement of some vital parameters from radiation-sensitive methods to ones that can readily be radiation-hardened.

After a short description of the TFTR tokamak and its mode of operation, this paper will address these five topics. The paper will not describe the diagnostic techniques in detail; general descriptions of tokamak diagnostics are given in Ref. 1, and more detailed descriptions of the TFTR diagnostic instrument requirements are given in Ref. 2.

The Tokamak Fusion Test Reactor

The importance of the TFTR[3] in the magnetic fusion program lies in the very high heating powers applied to the plasma and in its capability for operating with tritium as a fuel and achieving breakeven of power output from the fusion reactions in the plasma equalling the power input. The major differences from previous tokamak design are caused by these two features.

Figure 1 shows an artist's impression of the tokamak whose most important parameters are shown in Table 1. As in all tables of tokamak performance the data is oversimplified. The plasma in a tokamak is created by a current driven in the plasma by external conductors which, in the case of TFTR, are outside the large coils providing the toroidal field for confining the plasma. In addition, a vertical field is necessary to provide equilibrium for the plasma which tends to expand in major radius because of its own pressure and the hoop force of the circular current. The coils for driving current and providing equilibrium are called poloidal field windings in the figure. The plasma itself is formed inside a toroidal vacuum vessel which has a large number of penetrations for vacuum pumping, for neutral beam injection, for diagnostic observation, and for services such as gas injection. Very good vacuum quality is required to sustain low impurity levels in the plasma which is formed at pressures of $O(10^{-4})$ torr. Each neutral beam injector provides $\gtrsim$ 6 MW of power in 120 keV neutral deuterium atoms. The whole of the tokamak (and the neutral beam injectors) will ultimately be enclosed by an "igloo" made from > 2 feet thick borated limestone concrete.

Table 1: Final Operating Parameters for TFTR

Major Radius of Plasma	2.5 m
Minor Radius of Plasma	0.45 - 0.9 m
Compression Ratio	1.48 Max
Base Pressure in Vacuum Vessel	$< 1 \times 10^{-8}$ Torr
Maximum Toroidal Field Strength	5.2 T
Maximum Plasma Current	3.0 MA
Neutral Beam Power	20 - 45 MW
Pulse Length of Neutral Beam	0.5 - 1.5 sec
Maximum Central Plasma Density	1.5×10^{14} cm^{-3}
Maximum Central Electron Temperature	$\lesssim 15$ keV
Maximum Central Ion Temperature	$\lesssim 25$ keV
Q	$\gtrsim 1$
Power to Vacuum Vessel Wall	$\lesssim 50$ W cm^{-2}
Maximum Neutron Yields/Pulse	
D-T Plasmas (14 MeV Neutrons)	2×10^{19}
D-D Plasmas (2.5 MeV Neutrons)	1.3×10^{17}

The complete shielding for the facility is shown in Figure 2. The shielding thicknesses were chosen to be very safe with a design objective for the dose level at the site boundary fence (~ 125 m from the tokamak) of 10 mR Yr^{-1}.[4] It is estimated that about half of this dose is from radiation, including skyshine, and the other half from gaseous release of activated air. However, the concept of an igloo close to the tokamak permits many components to surround the tokamak in the Test Cell without becoming too activated for hands-on maintenance within a few hours of a full power experimental run. This igloo, made from borated limestone concrete, is shown in Fig. 2 as 26 in. thick, but it can be increased to 34 in. for final operation. The high activation levels of the tokamak components are significantly shielded from maintenance workers in the Test Cell.

A large number of calculations of the radiation fluxes, spectra, and doses throughout the facility have been made.[5] Figure 3 shows the prompt neutron and gamma spectrum at a representative point inside the Test Cell but outside the igloo. (The curves are calculated for a source of 14 MeV neutrons of 3.5×10^{18} neutrons/pulse for a 26 in. thick igloo.) These flux levels are very high for diagnostic instrumentation to function comfortably particularly as a complete absence of penetrations in the igloo wall has been assumed. Thus, most equipment in this area requires additional shielding, very careful arrangement of any penetration associated with that equipment, and a philosophy of strict control of shielding for all necessary penetrations. But because of these radiation levels and the difficulty of control, most of the diagnostic instrumentation is in a diagnostic basement immediately under the tokamak, with a six-foot-thick steel and borated limestone concrete structure providing shielding. The relative radiation levels are shown in Table 2 where the flux levels in the basement include 50 small 2.5 in. diameter penetrations immediately under the tokamak. Obviously a lot of ingenuity will be required to hold the penetrations down to such a level where numerous water pipes, copper conductors and diagnostic vacuum pipes pass through the concrete, but this will not be addressed here. The radiation levels will be about an order of magnitude lower in the outer basement, where most of the electronic CAMAC instrumentation will be housed, than in the diagnostic basement.

As a point of reference, a neutron flux of about 2×10^{7} n cm^{-2} sec^{-1} from the PLT tokamak has already caused impossibly high noise background levels for an X-ray multiwire proportional counter and an InSb detector for the far infrared.[2] Shielding of the instruments has now removed the problem.

The activation levels of the vacuum vessel and neighboring components of the tokamak have been evaluated from the flux codes.[5] The experimental program will be carefully orchestrated to keep these levels low, by use of hydrogen gas and only modest operation with deuterium, until the design of much of the mechanical hardware has been proved; ultimately all maintenance within the igloo will be done by remote means and this has already been factored into instrumentation design. Activation of the PLT and PDX tokamaks has already been measured[6] and is presently being compared to code calculations.

Table 2: Summary Data of Background Radiation Levels† at Various Instrumentation Locations

	Close to Vac. Vessel	Test Cell	Diag.Equip. Basement
Neutrons Flux ($n\ cm^{-2}\ sec^{-1}$)	6×10^{13}	2×10^{11}	2×10^{7}
Total Dose Rate [Rad(Si) sec^{-1}]	3×10^{4}	1×10^{2}	5×10^{-2}
Lifetime Dose [Rad(Si)]	1×10^{8}	4×10^{5}	2×10^{2}
Soft X-Ray Flux (Watt cm^{-2})	~1		
Activation Levels for Maintenance (mR hr^{-1})	>> 10		

†These levels do not include streaming through penetrations onto a specific detector or additional shielding to protect such a detector.

Measurement of Fusion Reaction Products

It is important to make use of the neutrons and other fusion products in gaining an understanding of the plasma behavior. For TFTR it is essential that a very precise (within ~ 10%) determination of total neutron flux be made to establish the breakeven Q = 1 result, but much more information about heating rates, ion distribution, and instability levels in the plasma (or even about neutrons generated by high energy runaway electrons hitting material limiters) can be found. In the PLT and PDX tokamaks, Strachan and his co-workers have used the $d(d,n)^3He$, $d(d,p)t$, $d(t,n)\alpha$ and $d(^3He, p)\alpha$ reactions in their studies.[7] In the case of $d(t, n)\alpha$ reaction, the tritons were those already created by the $d(d, p)t$; their interest was in determining how well the tritons were contained in the plasma.[8] Some PLT data are shown in Fig. 4 where the two lower-right pictures show the average plasma density ($\bar{n}e$), the plasma current (I_ϕ) and the voltage around the torus (V_ϕ) for a plasma pulse length of ~ 900 msec.[9] Neutral beams heat the plasma between 0.35 to 0.55 sec with the resultant six-orders of magnitude increase in neutron emission shown on the left. The top-right photograph compares the full time sweep of a moderated NE 422 scintillator measuring neutrons with that of a surface barrier detector detecting, soft X rays exhibiting a "saw-tooth" pattern of waveform. The timescale of these sawteeth with their approximately 15 msec period is expanded in the top-left picture where another unmoderated, neutron detector, an NE 213 liquid scintillator, is also shown. Two important results are visible in these data. 1) The dynamic range of the flux of interest is huge -- in PLT many cross-calibrated BF_3 proportional counters at different distances from the tokamak and with different fractions of ^{10}B are used with an ^{238}U fission fragment proportional counter to cover the range. 2) Sawteeth oscillations which have considerable significance for tokamak operation are visible on neutron signals and not just on X-ray detectors[10] which are particularly susceptible to transient noise and damage effects from neutrons. Detailed discussions of these results can be found in Ref. 9.

In TFTR, four principal neutron measurement systems are planned.[11] An activation foil technique where foils are pneumatically injected to close the vacuum vessel for the duration of a pulse (or many pulses) gives time-integrated fluences. By judicious foil selection, it can be made relatively insensitive to the high intensity of scattered neutrons and gammas. The time dependent flux will be measured by long ^{235}U or ^{238}U fission fragment proportional counters which have complementary dynamic ranges to cover source strengths $<10^{10}$ sec^{-1} of 2.5 MeV neutrons to $>10^{19}$ sec^{-1} of 14 MeV neutrons with time resolution of about 10 msec. By use of counting and Campbelling circuitry provided by Gammametrics the ^{235}U detectors operate over the flux-range of 10^4 - 10^{10} n cm^{-2} sec^{-1} and the ^{238}U detectors operate over the range 10^7 - 10^{13} n cm^{-2} sec^{-1}.

A multichannel collimator using scintillators will give spatial resolution of the neutron source and will be used in studies of the plasma instabilities. In addition a large spectrometer system will be used to view the plasma radially to obtain ion temperature information, or tangentially to determine effects of the slowing down of the fast ions created by the heating techniques. Because very high energy resolution ($\lesssim$ 5%) is required for both these measurements, the spectrometer requires very tight collimation and excellent shielding of the detectors against the background scattered neutrons and gamma fluxes. The same collimator is used for both 2.5 MeV and 14 MeV neutron studies and is shown in concept in Fig. 5. For D-T operation, hydrogen foil radiators can be put in the throat of the instrumentation package to make a proton-recoil telescope with silicon surface barrier detectors; for D-D operation, the radiators are removed and an NE 213 liquid scintillator or ^{3}He sandwich detectors will be used.[12]

Measurement of the 15 MeV protons from the d^{3}He reaction has been used extensively in the PLT tokamak. The fact that two charged products are produced is attractive for TFTR where the neutral beams can only operate most efficiently with 120 keV deuterium beams and studies of plasma behavior without the neutron background will be possible. It is also probable that ion cyclotron resonance heating will operate with ^{3}He. In PLT, minority heating of ^{3}He has been done, and sawtooth oscillations have been observed on the unconfined protons.[13,14] Another measurement to examine the transport of low mass and charge (low-Z) impurities was done by puffing ^{3}He at the outside of the plasma during neutral beam injection. Figure 6 shows the time evolution of the central ^{3}He density by interpolation from proton observations with a silicon surface barrier detector and the comparable neutron observations from D-D reactions for two neutral beam conditions and plasma densities.[15] The visible light is all generated at the edge of the plasma. No low-Z impurities can radiate spectroscopically all the way into the plasma center so that this nuclear technique is very important in the study of light impurities.

The gamma producing reactions $d(t,\gamma)^5He$ and $d(^3He,\gamma)^5Li$ are also of some interest as a future development because of the advantages of γ - diagnostics for measurement of fusion reaction rates for advanced fuel cycles. The reaction cross sections are broad with the gamma to neutron branching ratio $\sim 10^{-4}$. The gamma energies are $\sim$ 17 MeV, significantly above the 14 MeV neutron energy. The use of a scintillator such as Ne 226 with its high gamma sensitivity and low neutron-to-gamma response is currently being studied.[16]

Studies for Future Fusion Devices

It is important that TFTR be used to determine some aspects of fusion reactor physics. Two experiments have been planned so far, one to study the containment of the α - particles and the other to study the neutron interactions in a prototype tritium breeding blanket.

The product α - particles in TFTR do not contribute sufficiently to the heating of the background gas so that their presence can be inferred from ion temperature measurements. However, they are sufficiently numerous that their containment and rate of slowing down in the plasma can be determined -- results important for evaluating the buildup of "helium-ash" in future devices. Post et al.[17] have proposed an experiment of firing a high energy (6 MeV) neutral lithium beam into the plasma, the energy being chosen to optimize the cross section for charge-exchange between the neutral lithium and doubly charged helium. The configuration is shown in Fig. 7. Two techniques can be used for mesuring the presence of the helium; the first spectroscopically makes use of the ultraviolet photons emitted from singly charged He^{+}, and the second measures the fast-neutral He^{o} atoms generated in the charge-exchange process. These techniques are specifically good for looking at the slowing fast α - particles. The spectrometers and charge exchange analyzers are similar to those already in place on TFTR. Doping beams have also been proposed for studying the helium ash,[18] and a scheme for studying the lost α - particles from the plasma using thin Zinc Sulphide scintillators (and associated fiber optics) at the vacuum vessel wall is in conceptual design.[19,2] The latter experiment requires a scintillator that is relatively insensitive to neutrons and gammas and requires an array of detectors to develop the particle history because of the complexity of the orbits of the lost particles.[20] The scintillator has also to be shielded from plasma light and direct X-radiation from the plasma; this can be done if advantage is taken of the curved path of the particles in the tokamak magnetic field and using a carefully-shaped lead aperture for the scintillator.

The 14 MeV neutrons emitted by the plasma will also be used in a small lithium blanket module located between the vacuum vessel and the igloo shield to demonstrate the breeding of tritium.[21] The concept of the module is shown in Fig. 8. It is designed to be as representative of a fusion reactor breeding blanket as possible with the intention of obtaining validation of the numerical code studies of breeding rates for fusion reactors with real neutron spectra in real geometries. The figure shows a central core of stainless steel tubes containing lithium oxide for the breeding studies, the remaining tubes being there for providing uniform neutron fluences at the center and making available space for measurement equipment. In the figure only one neutron activation measurement location is shown (rabbit tube), but this number will almost certainly be increased. After an experimental run of about 10 pulses, the specific activity will be $\sim$ 10 nCi g^{-1} in one of the rods. It can be removed for separation of the tritium and analysis, and the quantity of tritium bred can be measured within 10% accuracy.

Effectiveness of Detectors in High Neutron and Gamma Background Fluxes

Operation of TFTR with deuterium neutral beams causes very high background neutron fluxes even before tritium is used as the target gas so that it is essential that the large variety of plasma diagnostic detectors be able to operate in such an environment. In some cases new development was necessary, particularly for detectors close to the neutron source and which could not be surrounded by layers of shielding. Figure 9 is a photograph of a platinum resistance bolometer[22] which replaces the more commonly used thermistor. They are used in arrays of carefully matched pairs in bridge networks to give a precise time dependent measurement of the total radiation falling on the wall of the vacuum vessel. This bolometer has been used on the PLT tokamak. Another development was required for the X-ray imaging system because the surface barrier detectors cannot tolerate the fluences. A gridded ionization chamber has been developed and has been tested on PLT.[23] Its size, because of lower sensitivity per unit area and the need for a relatively thick window foil, causes a small reduction in spatial resolution. The poor signal to noise level for full power D-T operation makes these detectors inoperable but they do not suffer permanent damage.

Many other diagnostic detectors have been tested in a radiation environment to demonstrate that they can function in a properly shielded instrument. Figure 10 is shown as an example of the tests with a Kaman Sciences 710 Neutron Generator yielding about 10^{11} n sec^{-1} of 14 MeV neutrons. Figure 10a shows the arrangement of Si(Li) detectors used in the X-ray pulse-height analyzer under test.[24] They have to view on a direct line to the plasma. The curves of Fig. 10b show the response of this detector to the neutrons. For the high electron temperatures predicted for this plasma operation, the range of interest for X-ray measurement is from about 5 keV to 50 keV.

The curves show the measured count-rate about 7 times higher than predicted at 6 keV and about 2 times higher at 55 keV. With proper shielding, these detectors can be used on TFTR. The initial experiments showed a much worse neutron enhancement. This was largely caused by neutrons scattering off the liquid nitrogen dewar for cooling the detectors. It was arranged in the normal fashion immediately behind the detectors. A reconfigured detector arrangement mounted off a cooled finger has been used and greatly reduced the scattering.

One of the most sensitive detectors, and one that must be located in the high flux Test Cell region, is the channel electron multiplier array used for charged particles in the charge-exchange analyzer. For 14 MeV neutrons, the detection efficiency is 6.4 x 10^{-3} counts/neutron in the CEMA to be used.[25] For good measurement at charged particle count rates of 10^3 - 10^6 counts sec^{-1}, neutron shielding to reduce the neutron flux by between 10 and 100 times will be required. Similar detectors are used in spectroscopic instruments,[26] mostly housed in the lower flux region of the basement. Microchannel plate multipliers, spatially resolved by Reticon or MAMA code systems, channeltron electron multipliers, magnetic electron multipliers, and photomultipliers have been tested. Radiation damage is not a problem; the neutron sensitivity is so low as to cause no problem directly, but high γ sensitivity can be a problem. Lead shielding surrounding the detector is therefore essential with some neutron shielding outside it to cut down generation of gammas by neutron reactions.

Recent measurements of the neutron sensitivity of ultrasensitive helium cooled bolometers, used in far infrared measurements for determining the electron temperature, show also strong neutron sensitivity.[22] The conclusion of the experiment is that, even in the basement, at least 20 cm of lead and $\lesssim$ 60 cm of concrete shielding are needed to cut the background noise sufficiently for use of the InSb bolometer. A new Germanium bolometer cooled to 0.3°K cannot be used.

Effects of Tritium Deposition on Detectors

A large variety of detectors are mounted inside vacuum chambers directly connected to the tokamak vacuum vessel and hence become liable to contamination by tritium. The conductances of the passage to the tokamak are low, and less than 5 curies is pumped through the complete diagnostic array in any one plasma pulse. Even so, the complete diagnostic vacuum system including the vacuum turbomolecular pumps and vacuum seals has been designed for tritium usage. But this section of the paper will only address detector problems. Table 3 lists some of the detectors that will be used in vacuum. The count rates given are those expected for actual measurement. The last column shows the pressure of tritium for which the electrons from the β-decay at the detector give a low enough count rate for a satisfactory signal-to-noise ratio. For comparison, the pressure of the tritium filling of the vacuum vessel is of order 10^{-2} - 10^{-1} Pa so that these local instrument pressures are not difficult to achieve. Figure 11 shows experimental data of the sensitivity of a channel electron multiplier to tritium.[28] The upper curve shows the prompt sensitivity while the lower curve shows the cumulative buildup on the detector. These levels give no significant operational problem on TFTR apart from requiring some care in maintenance.

Table 3 SOME EXAMPLES OF IN-VACUUM DIAGNOSTICS USED IN TFTR

DIAGNOSTIC	PLASMA PARAMETER MEASURED	PARTICLE DETECTOR	MAXIMUM ANTICIPATED COUNTING RATE (COUNTS s^{-1})	MAXIMUM DETECTOR TRITIUM BACKGROUND PRESSURE (PA)
Charge-Exchange Neutral Detector	Ion Temperature	Channel Electron Multiplier Array (CEMA)	$\sim 10^3 \rightarrow 10^6$	$\sim 10^{-4} \rightarrow 10^{-6}$
Residual Gas Analyzer	Plasma Gas Composition	Electron Multiplier	10^6 (Pulse Counting Mode)	10^{-6}
α - Particle	α - Particle	ZnS Scintillator	$\sim 10^7$	10^{-2}
X-ray Detector	Electron, Ion Temp. Impurity Concentrations Stability Properties	Si(Li)	$\sim 10^5$	$\sim 10^{-4}$
UV Detector		Channel Electron Multiplier		

Neutron and Gamma Ray Damage of Components Close to the Tokamak

The principal diagnostic components close to the tokamak that are liable to damage are the components of magnetic diagnostics and window materials. These components are specified to tolerate twenty temperature cycles up to 250°C for bakeout treatment of the vacuum vessel as well as to withstand 1 x 10^8 rad(Si) of radiation. Windows close to the tokamak have also to withstand $\sim$ 1 W cm^{-2} of soft X rays from the plasma for all pulses during hydrogen and deuterium operation as well as during the much rarer tritium operation.

The magnetic diagnostics have been engineered to make use of radiation qualified materials.[29] They are all outside the vacuum vessel so that no specific vacuum requirement is placed on insulating materials. Hence standard insulation materials qualified for use in fission reactors can be used. Radiation hard motors and encoders are used for movable components, and gate valves are operated pneumatically. In these cases, the radiation environment leads to the use of costlier components but not to a need for new developments for TFTR.

The window problem is a different situation. Table 4 lists the window materials and the vacuum seal technique to be used to withstand the bakeout temperature cycles.[30] The sealing techniques have all undergone bakeout and pressure cycling test for the required window sizes, and while there are definite unresolved manufacturing reproducibility problems in some cases, the techniques appear to be basically sound. Life-testing of the windows in a radiation environment has only been possible for 2-1/2 in. diameter windows in the LAMPF proton accelerator at Los Alamos. A five hour exposure is equivalent to a full life on TFTR. After the exposure, the activity of the windows and their steel support CONFLAT flanges has to decay for about one month before shipping to the vacuum checking laboratory and, at this time, only a crystal quartz sample has been tested. The seal was good. However, for larger windows, there is some concern that the negative dilatation of the windows in the neutron environment will lead to excessive stresses at the seals and cause fracture unless the window material is very carefully prepared to minimize residual stresses.[31]

The soft X-ray effect has been measured by Primak,[31] and Fig. 12 shows a curve of the negative dilatation calculated for a fused silica window as a function of depth for soft X rays for the life of TFTR. One would expect crazing such as occurs on old pottery glazes under such conditions, and experiments with electron beams were done to mock-up the high intensity X rays. It was found that no crazing occurred and that plastic flow stress relaxation took place to surprising depth. While this is an encouraging result, there are clearly many unknowns about the window behavior under X rays, and they will be placed as far as possible from the plasma consistent with the viewing requirements. Thin cover windows which could be changed fairly easily and cheaply to protect the main vacuum windows are also being considered.

None of these window materials exhibits the discoloration normally associated with standard glasses in the neutron radiation test. Lithium fluoride windows were found to absorb heavily in the ultraviolet after irradiation (the window is bright red) and were replaced by magnesium fluoride for use in this spectral region. The infrared transmission of crystal quartz was degraded by a few percent at wavelengths $\lesssim$ 200 μm, with smaller loss at higher wavelengths.

Table 4. TFTR DIAGNOSTIC WINDOWS AND SEAL MATERIALS

WAVELENGTH REGION	WINDOW MATERIAL	SEAL MATERIAL	DEVELOPED BY	LARGEST CLEAR APERTURE
Visible, Near UV	Fused Quartz	Solder	Ceramaseal	8"
Far Infra-red	Crystal Quartz	Ceramic Frit	PPL Vacuum Group	4-1/2"
Ultra-violet	Sapphire	Brazed Metal Bond	Ceramaseal	4"
Ultra-violet	MgFl	Silver Chloride	Harshaw	2-1/2"
Infra-red	ZnSe	Ceramic Frit	PPL Vacuum Group	4"

Some initial data has also been obtained for fused silica fiber optics and on luminescence effects in windows. The effects do not appear to be serious. But, as for all these radiation studies, the neutron fluence levels at the vacuum vessel of TFTR are at least three orders of magnitude less than predicted for the next generation of tokamaks such as INTOR,[32] and the use of simple unshielded windows will have to be carefully rethought for the future devices.

Conclusions and Acknowledgments

This brief review of all the nuclear aspects of TFTR has necessarily been sketchy. There is still a lot of development work to be done to make proper use of the fusion product particles in measurement. There are some serious concerns for diagnostic operation because of difficulties in making the shielding as ideal as has been assumed in the calculations. However, the measurements of neutron effects on detectors and other components make it clear that a very sophisticated set of plasma measurements can be made during all phases of the TFTR operation. It should be stressed, however, that many radiation damage and background noise problems are only just avoided and that future tokamaks, and even the JET[33] tokamak now under construction in Europe, provide significantly greater challenges to making instrumentation work.

A large number of people contributed to the work described here, particularly physicists who have been working on TFTR Diagnostics and the TFTR Physics Program as well as experimentalists associated with the PLT and PDX tokamaks. I hope I have adequately represented the present state of their work.

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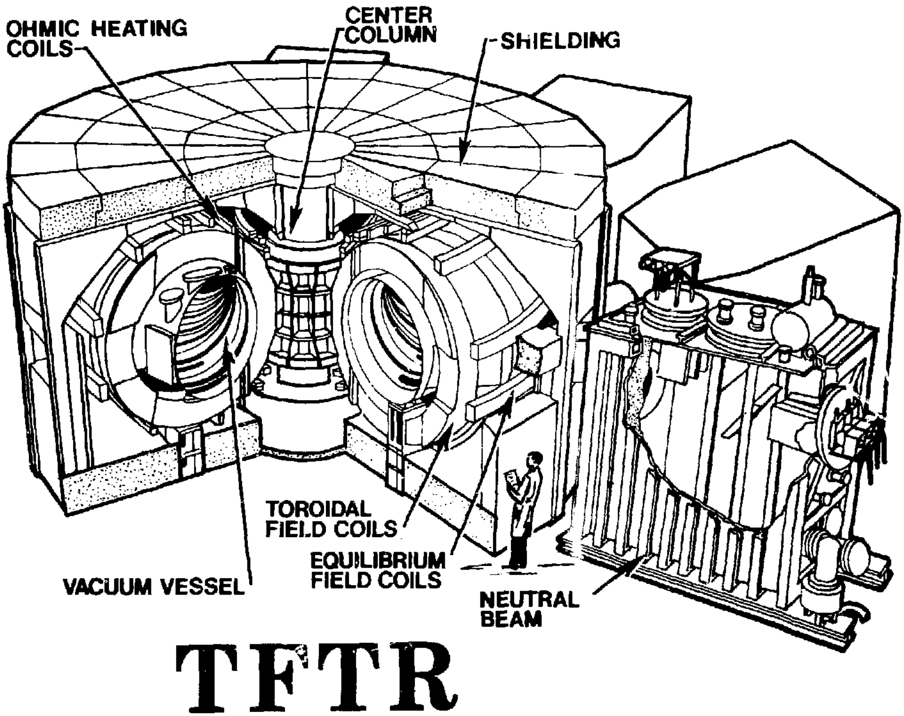

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Fig. 1 An artist's conception of the TFTR tokamak with the principal components identified.

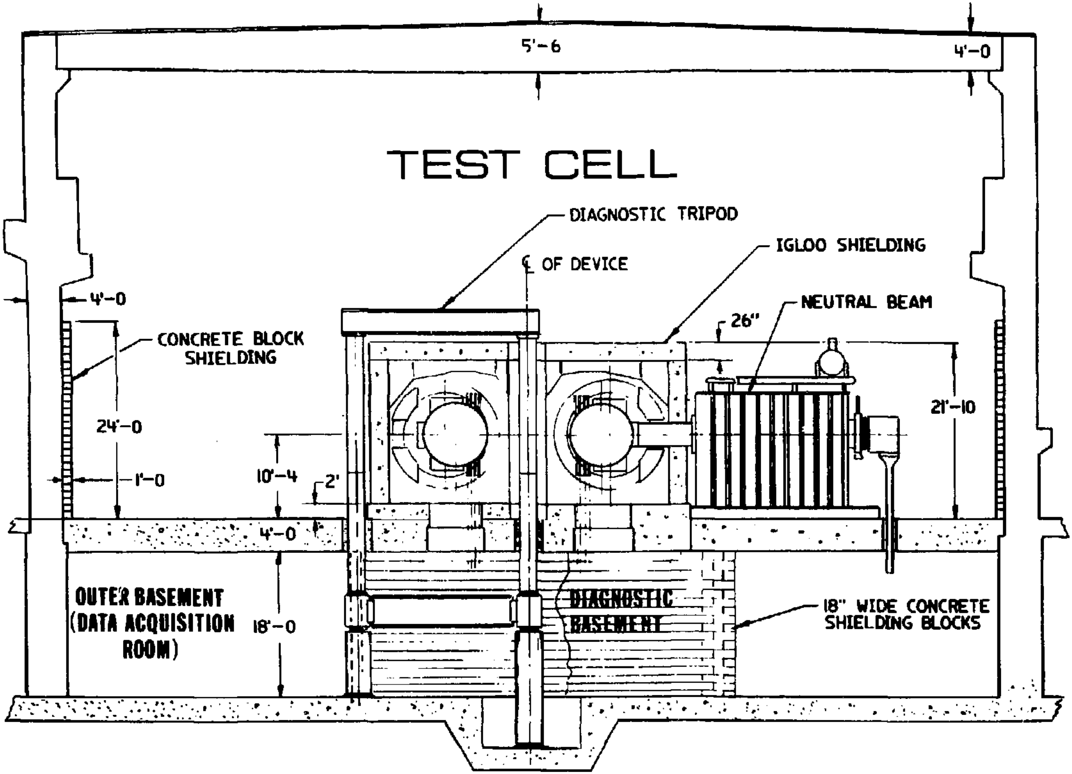


Fig. 2 The TFTR experimental area showing the shielding and main diagnostic instrumentation areas.

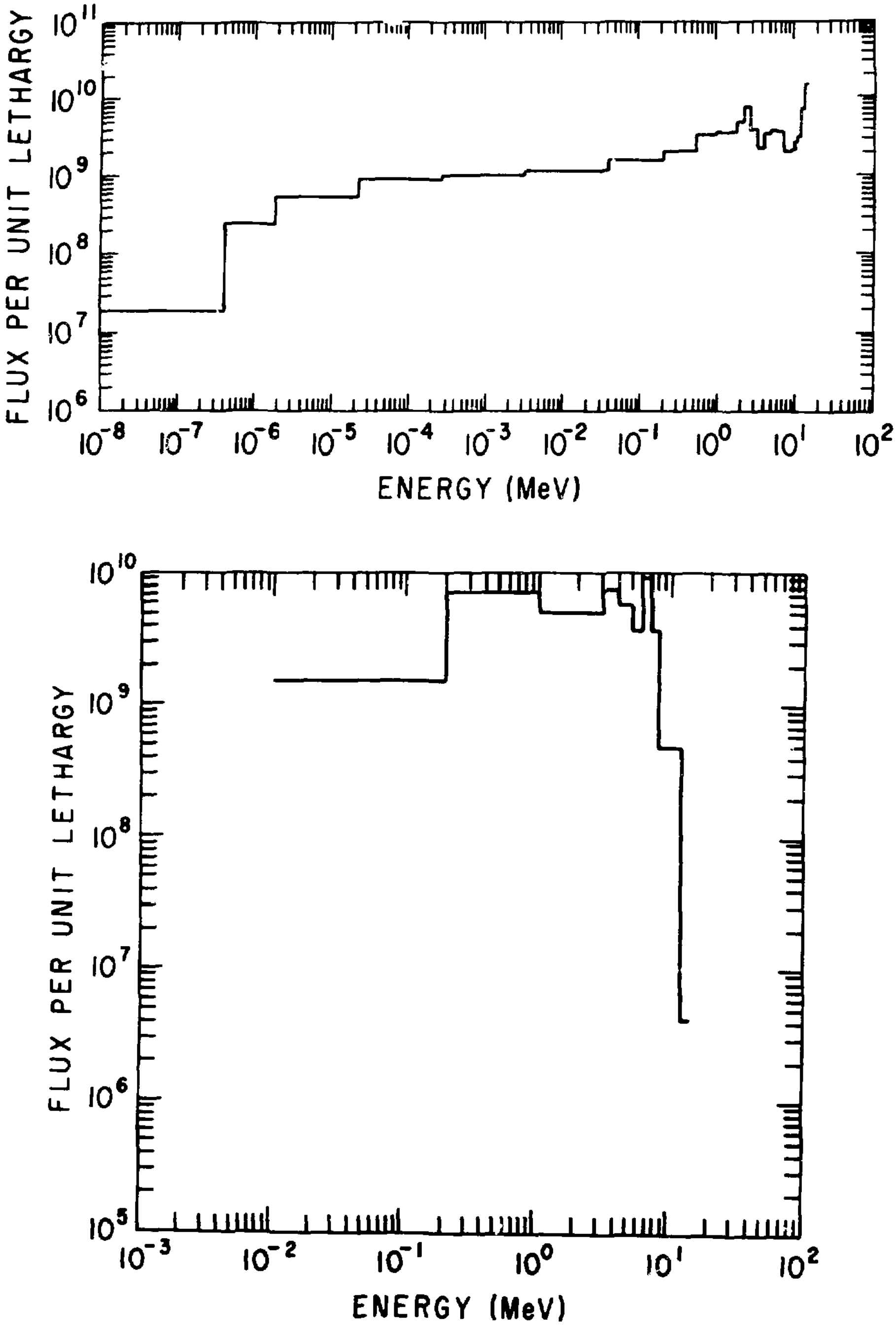


Fig. 3 The prompt neutron and gamma spectra midway between the tokamak and the outer shield wall in the Test Cell.

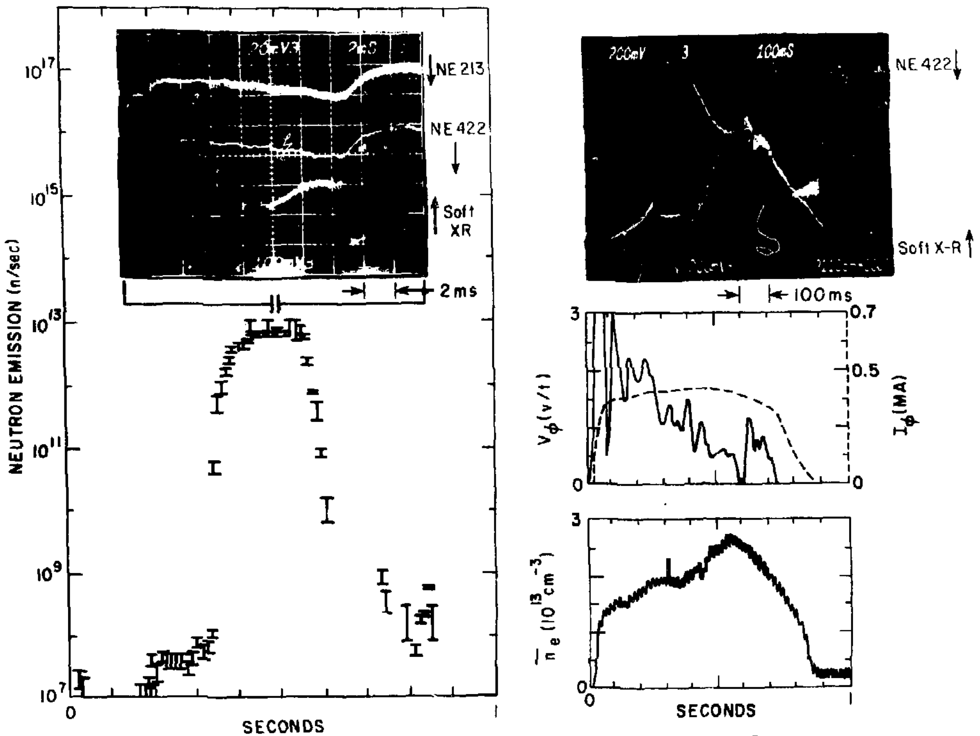


Fig. 4 Representative neutron data from the PLT tokamak.[9] The curves are described in the text.

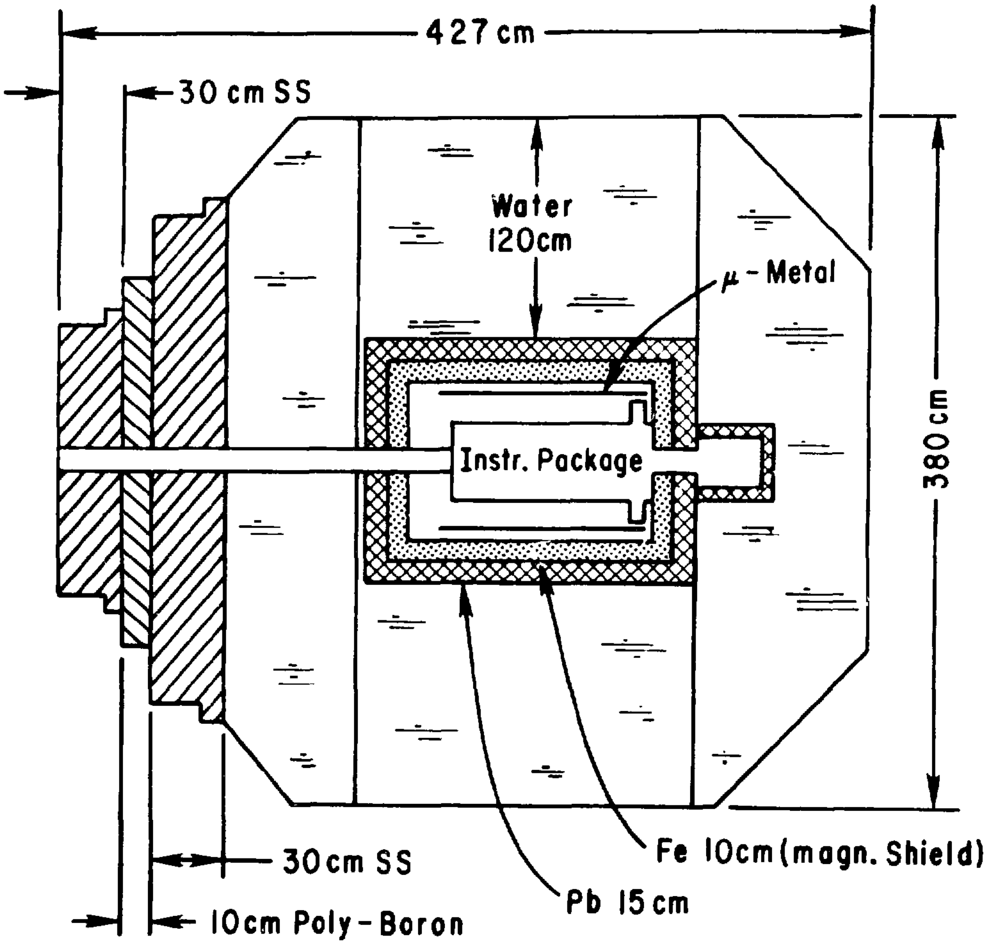


Fig. 5 Conceptual Design of the TFTR neutron spectrcmeter.

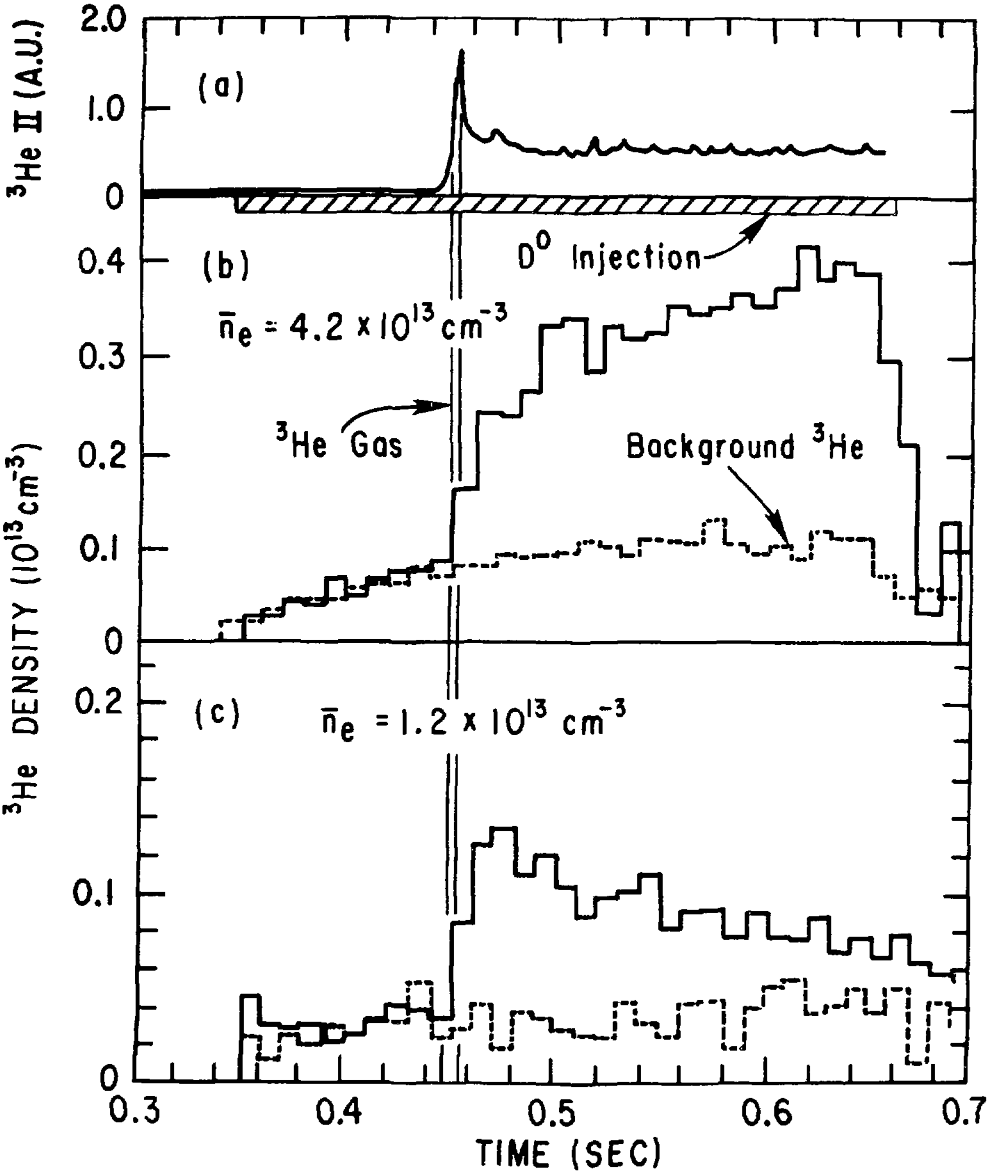


Fig. 6 Interpolated values of the ^{3}He density at the center of the PLT plasmas for two neutral beam heating conditions.[15] The top curve shows the visible light generated by the gas puff at the edge of the plasma.

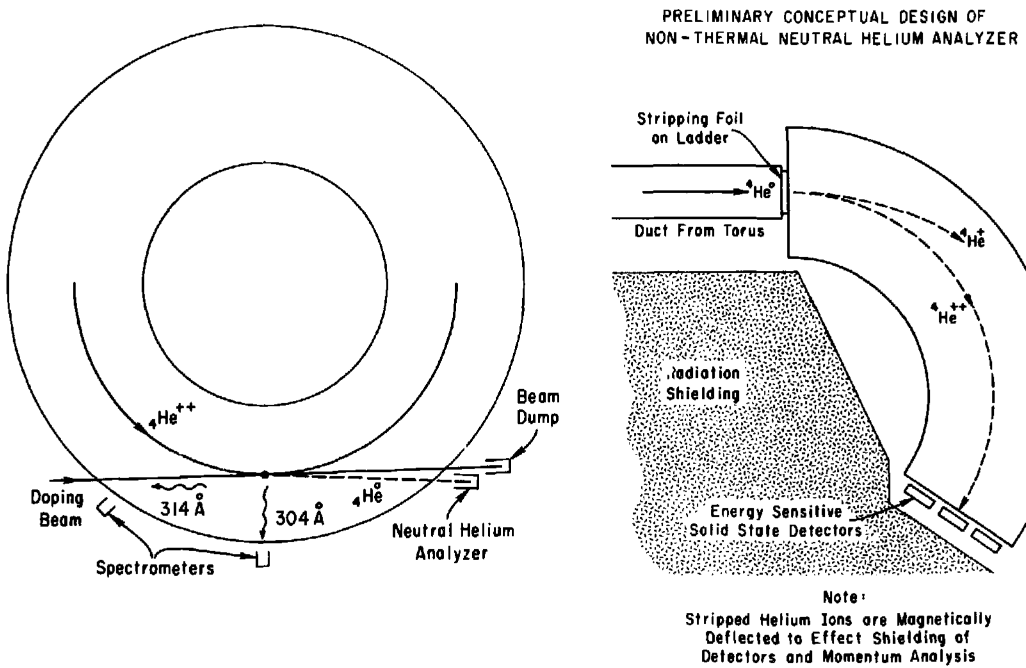


Fig. 7 The concept of injecting a 6 MeV Lithium neutral beam to give data about contained α - particles from the charge exchanged helium atoms. Spectroscopy or neutral helium detectors (right hand picture) can be used for detection.

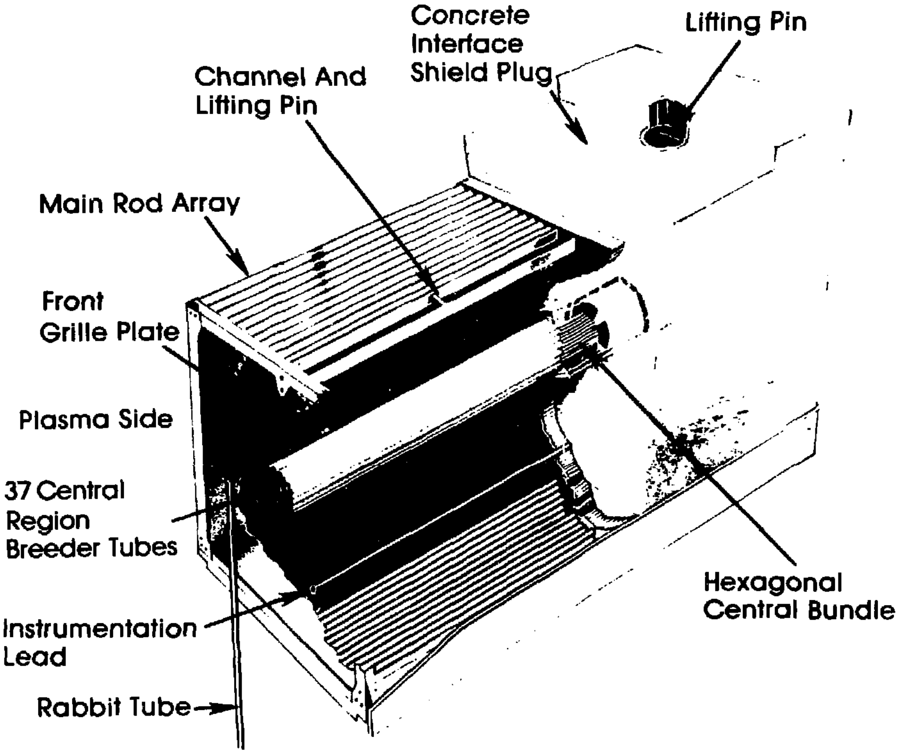


Fig. 8 An artist's impression of the Lithium Blanket Module being designed for tritium breeding experiments on TFTR.

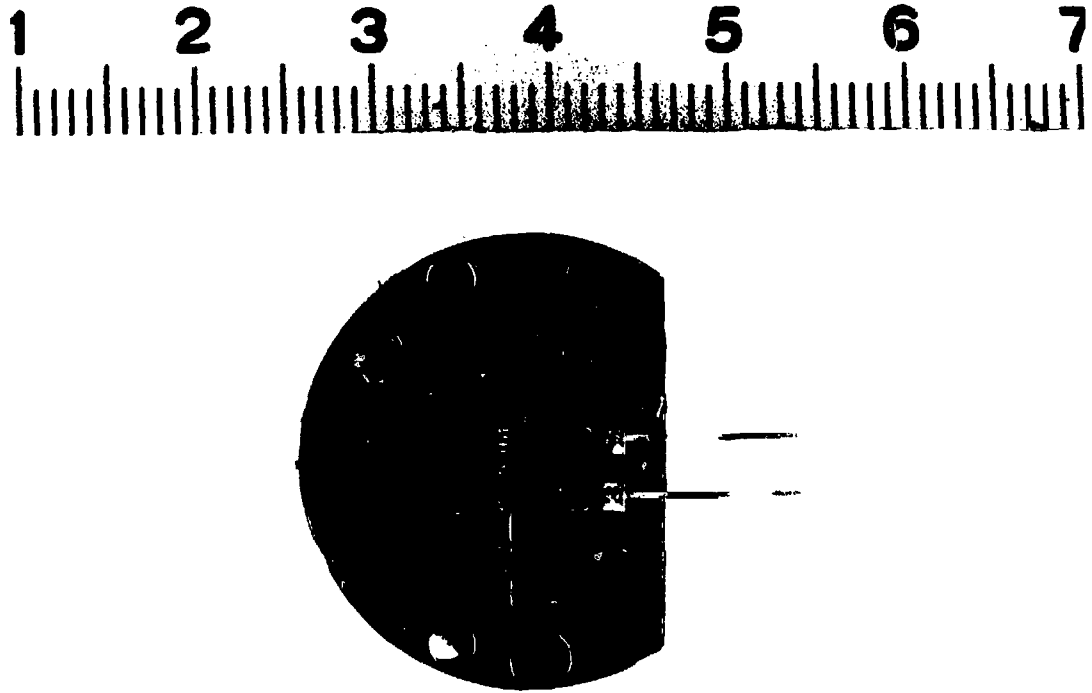
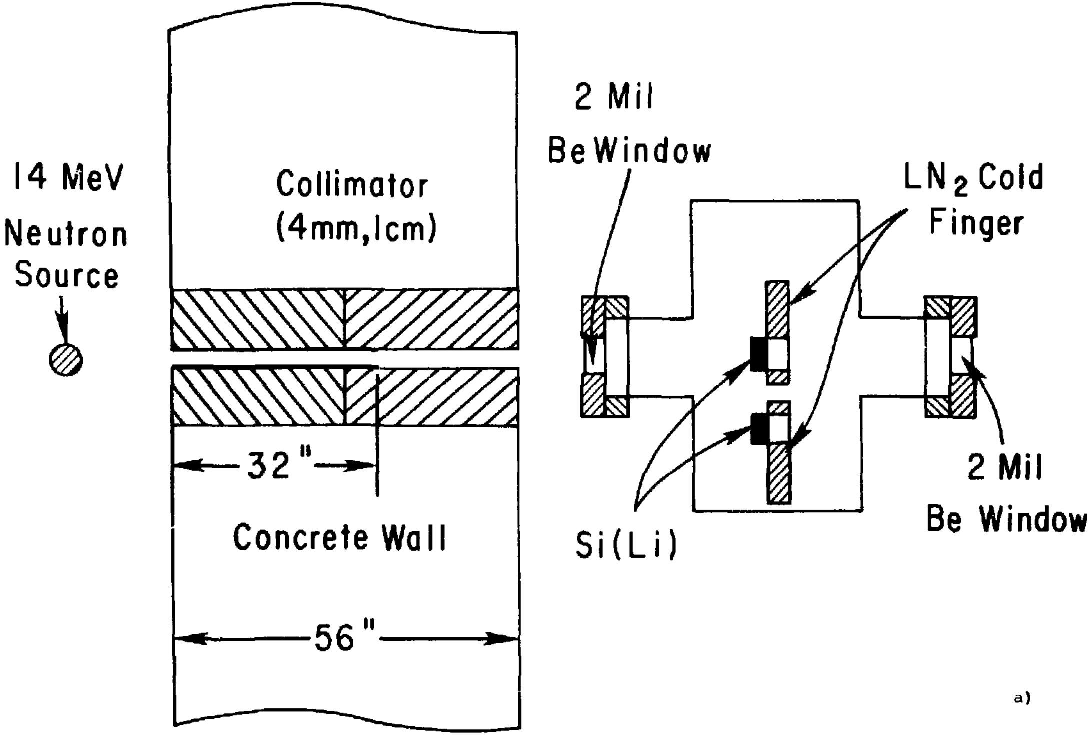


Fig. 9 A photograph of a platinum resistance bolometer for measuring the total energy radiated from TFTR. (The scale is in cm.)



a)

Fig. 10a) Geometric arrangement of Si(Li) detectors under test with a 14 MeV neutron source.

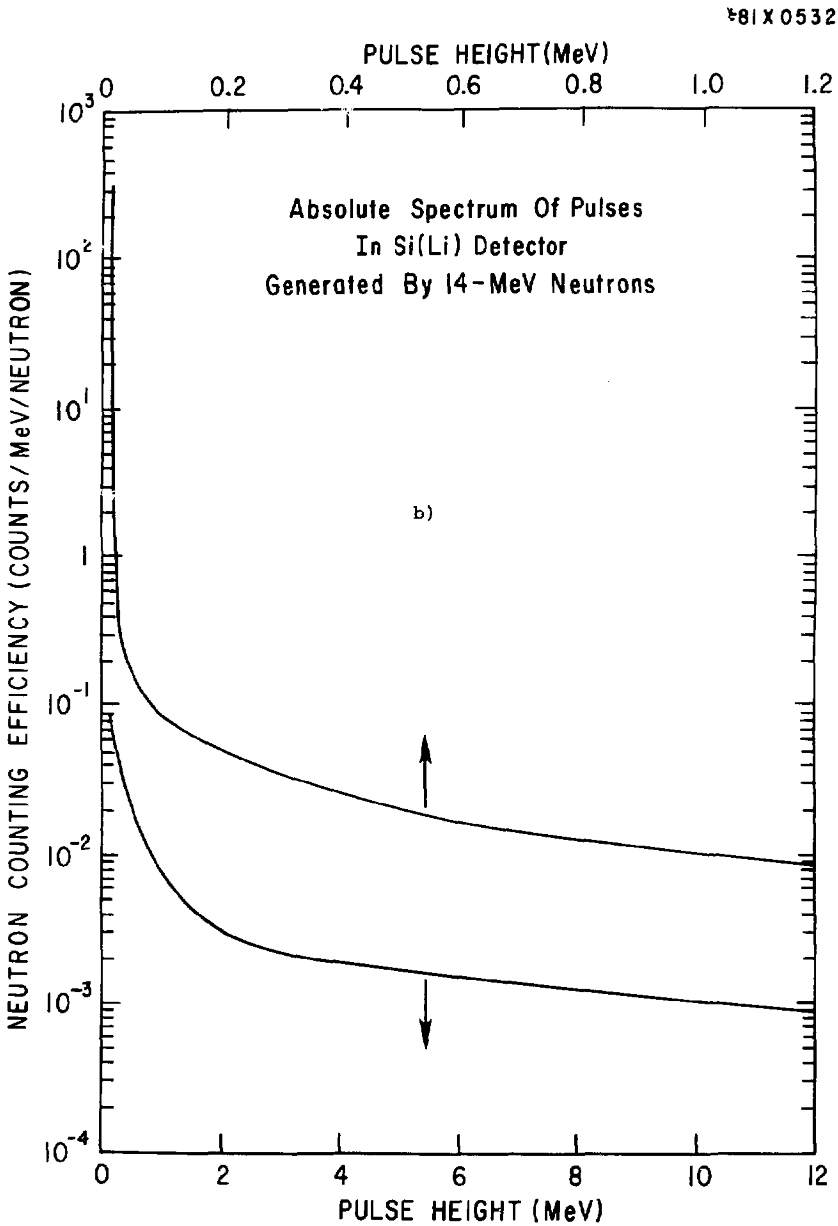
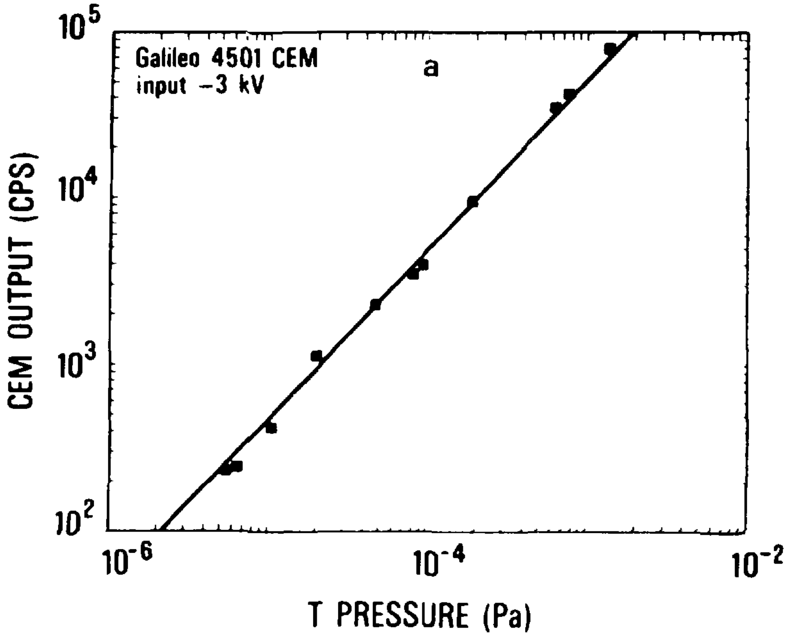


Fig. 10b) Curves of the pulse-height observed as a function of energy.



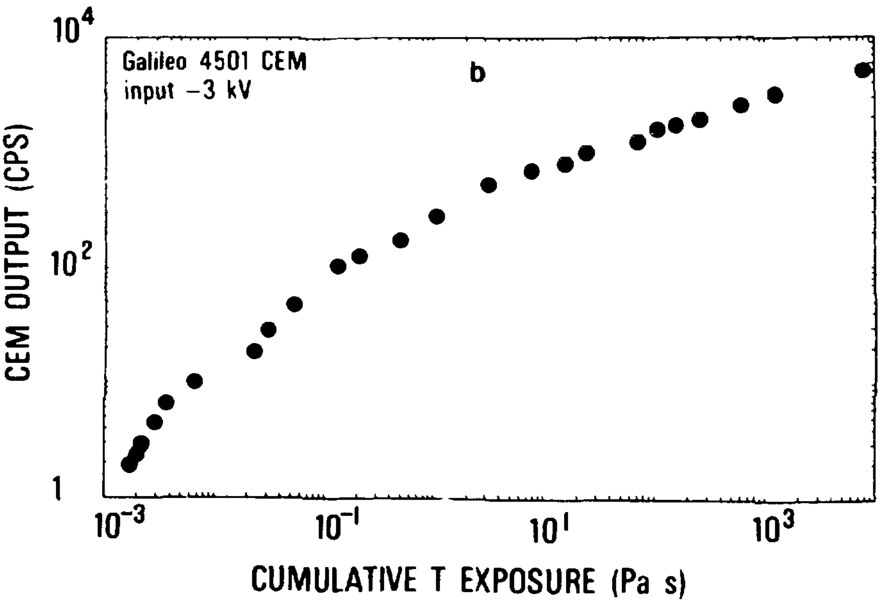


Fig. 11 The sensitivity of a channel electron multiplier to tritium. The upper curve shows the transient effect and the lower shows the effect of time exposure.

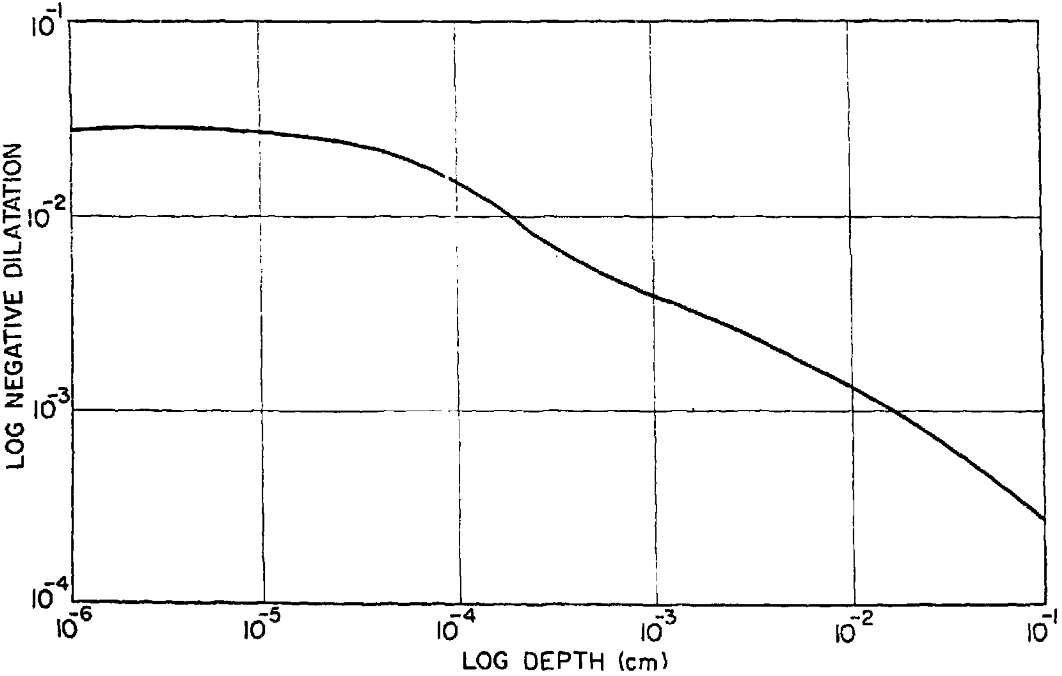


Fig. 12 Dilatation of vitreous silica due to electron bombardment equivalent to a full dose of soft X-rays at the vacuum vessel in the life-time of TFTR.