

A TRITIUM DETECTOR FOR THE TOKAMAK FUSION TEST REACTOR[#]

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ABSTRACT

We have developed a device for on-line dynamic detection of tritium transferred during regeneration of neutral beam injector cryopanel at the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory (PPPL). The detector has been calibrated with various tritium-containing gas mixtures, dynamically tested in flowing gas streams and installed in TFTR's neutral beam forevacuum line. The device measures tritium partial pressure in the regeneration line by beta scintillation detection and total gas pressure by capacitance manometry. The tritium partial pressure detection range is 10^{-5} to 2 Torr- T_2 , covered with three multiplier voltage gain settings. Careful operation, to avoid exposure to high tritium partial pressures, can lower the detection limit to 2×10^{-6} Torr of tritium. The relative error on tritium pressure measurement in a flowing mixture (1% T_2 in D_2) was less than 3%.

I. INTRODUCTION

Routine operation at TFTR requires the transfer of tritium from the delivery system to the neutral beam injectors. Then tritium is injected into the torus as a neutral beam with typical gas efficiency of 3% - 5%; approximately 5% of the amount of tritium consumed is implanted in various beam line components, and roughly 90% is directly pumped by the beam line cryopanel. These cryopanel also provide pumping of the torus, thus removing a fraction of the amount of tritium injected during each pulse. Hence the tritium content of the cryo-panels can be as high as 98% of the amount of tritium injected during experiment pulses. The cryopanel are periodically regenerated and the gas released, with a typical tritium to deuterium composition ratio of less than 2%, is pumped out to a Gas Holding Tank (GHT), where it is blanketed with nitrogen so that the total pressure is in the range 250 to 650 Torr. The GHT and the current tritium detection system are located far from the torus. The amount of

tritium returned to the GHT after regeneration of the neutral beam cryopanel is computed by difference of successive analyses of holding tank inventory [1]. An additional method to measure this tritium regenerated amount has been developed based on integration over time of the product of total gas flow rate and tritium concentration measured in real time and on-line during any regeneration. The newly installed apparatus is located in TFTR's neutral beam vacuum foreline, about midway between the torus and the GHT. The gas flow rate is calculated from pressure drop, measured by capacitance manometry, across a known conductance in the regeneration foreline, where total gas pressure remains below 10 torr. The tritium concentration gas stream is computed from the ratio of tritium partial pressure,

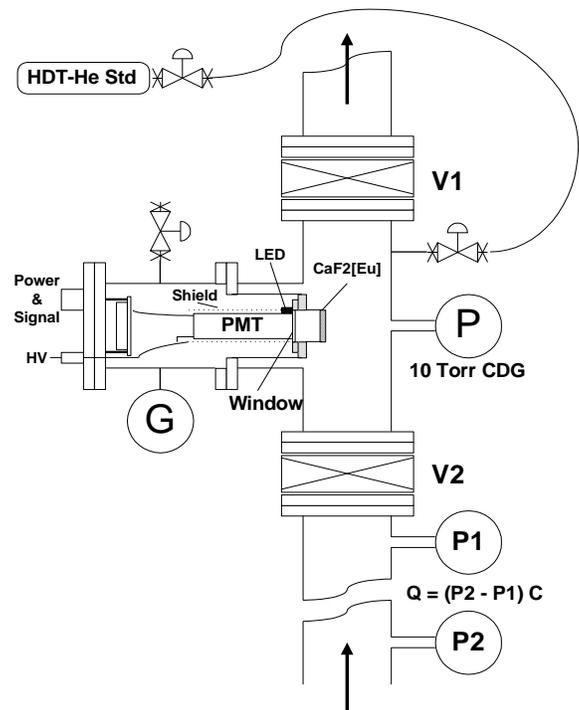


Fig. 1. Schematic view of the BSD as mounted on a TFTR-equivalent tee. Keys: PMT = photomultiplier tube, G = Bourdon pressure gauge, HV = high voltage, P = total pressure from 10 Torr capacitance diaphragm gauge (CDG), P1 and P2 = CDG's to measure flow rate using calculated conductance, C, and V1 and V2 = isolation valves to allow calibration with HDT-He standard mixture.

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measured by a beta scintillation detector (BSD), to the total pressure measured by a capacitance diaphragm gauge (CDG) located across from the BSD sensor shown schematically in Fig. 1. This paper describes the static and dynamic calibration of the beta scintillation detector.

II. APPARATUS AND THEORY OF OPERATION

The foreline beta scintillation detector consists of a 1.0"φ x 0.125" CaF₂(Eu) scintillation crystal mounted in a crystal holder supported on a flange that extends to the edge of the main flowing gas stream as shown in Fig. 1. The light from the crystal is transmitted from the active tritium region through a 2-3/4" UHV viewport window. A Hamamatsu 2060 photomultiplier is attached by Epotek 301 clear epoxy to the outside of the vacuum window to measure the light emitted by the crystal when tritium beta particles deposit energy in the crystal. The photomultiplier is electrostatically shielded at high voltage potential to minimize settling time after a range change. The SS housing with UHV electrical feedthroughs physically protects the electronics of the head and provides a secondary nuclear boundary to assure that if the vacuum window fails, the off gasses of the foreline would be contained. The housing is pressurized with Ar at about 200 Torr and this pressure is monitored by a stainless steel bourdon tube vacuum gauge, G. Changes in reading of G would indicate either window failure or a leak in the secondary chamber.

The photomultiplier dynode string is powered by a high voltage power supply module to provide three pre-selected voltage levels: 194V, 384V and 750V which produce a Low, Medium and High Gain/Sensitivity for light levels. The photocurrent is measured using an Analog Devices 310J electrometer module with a 10⁹ Ohm input resistor. The gain of the photomultiplier can be selected with a three-position front panel switch. While monitoring the 0-10 VDC output of the BSD, the gain selected is indicated by a light on the control panel or by measuring the "HV Sample" voltage level on the rear connectors which is 1.00% of the actual high voltage applied to the photomultiplier tube. Range changes to increase sensitivity from Low to Med to High have settling times of 1 to 2 min. Range changes to decrease sensitivity have settling times of 4 to 8 min. Two calibration light signals (Cal-Lo and Cal-Hi) from a light emitting diode (LED) mounted just outside the viewport (see Fig. 1) provide a system check on the BSD.

The foreline BSD is used to measure a photocurrent that is linearly proportional to the partial pressure of tritium. The photocurrent reading, V_{BSD}, is used with a sensitivity S(V/Torr-T₂) to calculate a tritium partial pressure PP[T₂](Torr):

$$PP[T_2](\text{torr}) = \frac{[V_{\text{BSD}}(P) - V_{\text{BSD}}(0)]}{S} \quad (1)$$

Then, the tritium mole percentage, T₂(Mol-%), is:

$$T_2(\text{Mol-\%}) = \frac{100 * [V_{\text{BSD}}(P) - V_{\text{BSD}}(0)]}{[P - P_0] * S} \quad (2)$$

where V_{BSD}(0) and P₀ are the most recently measured zero readings obtained when the foreline is evacuated. The difference [P - P₀] gives the total sample pressure from CDG readings. A linear response of the BSD requires low pressure, below 10 Torr, so that absorption of the beta energy by collisions with the gas is minimal, i.e. a few percent. The absorption coefficient of N₂ and Ar are about 10 times that of hydrogen; this means that a 10 mol-% impurity of one of these species will double the energy absorption of the gas and cause an error in measurement that is the magnitude of the gas absorption fraction. There is also a very small amount of beta-induced luminosity with non-T₂ gases: For example, one torr of N₂ produces a 1x10⁻⁴ torr-T₂ equivalent signal for 1x10⁻³ torr-T₂ gas present in chamber as the source of beta flux. During the actual tritium/deuterium regeneration from the cryopanel, variations in the tritium composition of the gas flowing by the BSD and CDG is to be expected given the layered nature of deposition. At any given time, the partial flow rate of tritium, q[T₂], is given by

$$q[T_2] (\text{Torr-L} / \text{s}) = Q_{\text{Total}} * PP[T_2] / [P - P_0], \quad (3)$$

where PP[T₂] is calculated from BSD response, total gas pressure, P - P₀, is calculated from CDG readings and the total flow rate, Q_{Total}, is measured by pressure drop across a known conductance. The amount of tritium passing the BSD to the GHT is given by the numerical integration of the partial flow rate of tritium, q[T₂, t], over the total regeneration time:

$$N(g - T_2) = \frac{6.032 (\text{g/mol})}{760 (\text{T/Atm}) 22.414 (\text{L/mol})} \int q[T_2, t] dt \quad (4)$$

III. CALIBRATION AND PERFORMANCE TESTING

An extensive calibration of this BSD was done at EG&G Mound over a four month period prior to installation in TFTR. Calibration consisted of determining the value for sensitivity S(V/Torr- T₂) for known partial pressures of tritium produced from analyzed mixtures by pressure control in a test chamber. In Fig. 2, the BSD unit is mounted in a 6" UHV tee equivalent to the eventual mounting port at PPPL. This assures equivalent beta flux geometry which affects the absolute sensitivity of the BSD. Static pressures and dynamic flows through this test chamber were controlled and measured using an existing mass spectrometer inlet and gas sampling system described elsewhere [2]. Capacitance diaphragm gauges with 1 Torr and 10 Torr ranges were used to measure total gas pressure. These CDGs were operated without heaters on to minimize thermal transpiration effects over the pressure range. Accuracy of pressures are estimated to be 0.5 % of reading plus 0.1% of full scale. This estimate is validated by a fixed 0.6% bias in data between the 1 and 10 Torr CDGs over the pressure range 0.1 to 1 Torr. For pressures of 1 Torr

or less, the 1 Torr CDG was chosen for readability and its known stable performance on the MS inlet system. Additions of gas mixtures were made by viscous flow into lower 3 L volume for static calibration or through the valve to the left of

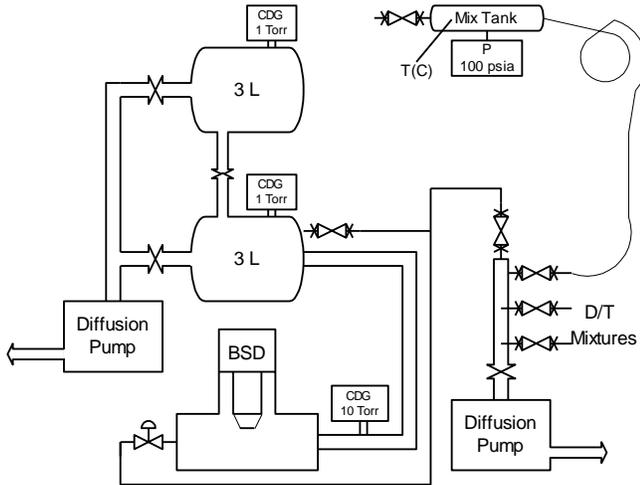


Fig. 2. Static calibration and flow measurement performance testing configuration.

BSD test chamber (Fig. 2) for flow testing of gas additions. Reductions in pressure were accomplished in steps by equilibrated expansions from lower 3 L chamber to the upper to minimize fractionation of the sample. Successive expansions into the evacuated top chamber allowed the use of single samples of a known mixture to produce predictable partial pressures of tritium covering three pressure decades. By choosing samples of analyzed mixtures with 1.10 ± 0.02 mol-% to 93.6 ± 0.2 mol-% T_2 and then reducing pressures by successive expansions, tritium partial pressures ranging from 2 Torr- T_2 down to 2×10^{-6} Torr- T_2 were produced to test the response of the BSD. Static calibration is accomplished by measuring BSD voltage and total pressure, $P - P_0$, of a known tritium mixture and calculating the sensitivity, S , for each step of partial pressure:

$$S(V/\text{Torr-T}_2) = \frac{100 * [V_{\text{BSD}}(P) - V_{\text{BSD}}(0)]}{[P - P_0] * T_2(\text{Mol-\%})} \quad (5)$$

For flow measurement performance testing, a 1 %- T_2 in D_2 mixture was prepared, analyzed and pumped into the 124 cm^3 mix tank, shown in Fig. 2, to 65 psia pressure. This mixture at the high pressure and small volume simulates the variable and decreasing flow rate expected during a 30 to 60 minute cryopanel regeneration, typical of TFTR operation. The flow rate from the volume is limited by a 0.4 mm i.d. capillary line 120 foot long which interconnects the mixing volume (in a separate lab) with the gas sampling system. Using this method, flow rates ranging from 0.6 to 0.1 T-L/s were generated with corresponding pressures in BSD chamber ranging from 2.5 Torr down to 0.3 Torr measured on the 10 Torr CDG. The amount of gas in the 124 cm^3 tank was obtained as a function of time, t , from the total pressure, $P(t)$,

the known volume and the gas temperature. The flow rate was calculated from the change in amount of gas over a ten second time interval. With that small volume, initial changes in pressure were 1 psia in 10 s with 0.01 psia readability.

IV. CALIBRATION RESULTS

Sensitivity of the BSD was first measured by introduction of analyzed mixtures with a nominal 1% T_2 in D_2 composition. The sensitivity with these initial analyzed gas mixture was about 10 percent higher than all final (more stable) sensitivities determined after exposure to a 93% T_2 in D_2 analyzed mixture. Exposure of the crystal and other surfaces to this high level tritium sample for a dose of about 60 Torr-min probably polymerized the normal film of hydrocarbons on the crystal and tritiated all exposed surfaces thereby increasing the background/zero signal, $V_{\text{BSD}}(0)$. The hydrocarbon film makes a non-scintillating “dead layer” that reduces the energy deposited per beta into the crystal which reduces the BSD sensitivity. Reduction of absolute sensitivity and increase in zero BSD output voltage with increased exposure to tritium is shown in Fig 3. The decrease in BSD zero at 140 Torr-min of tritium exposure is the result of a 30 min low pressure

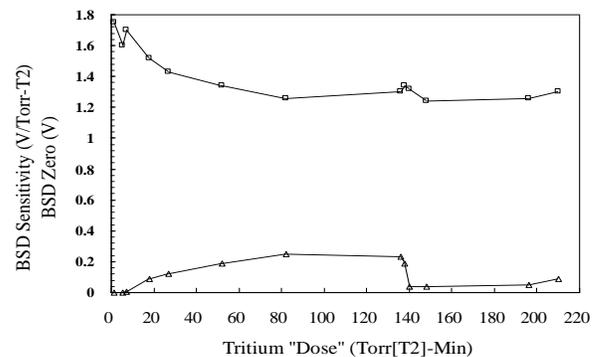


Fig. 3. Loss of absolute BSD sensitivity (□) and increase in $V_{\text{BSD}}(0)$ (Δ) with increased exposure to tritium dose.

purge of (moist) room air to decontaminate the BSD crystal and chamber. Air purge is known to be effective in reducing surface contamination that contributes to background signal [3]. The sensitivity is not substantially changed suggesting that the polymerized film has reached a stable thickness. The composite sensitivity data after high tritium exposure and all later data for Low, Medium, and High gain ranges are shown in Fig. 4. Average values for sensitivities and uncertainties are given in Table I. As a calibration check without introducing tritium, precise Low and High LED light levels are generated for each range using six preset LED current levels. Average responses to LED CAL presets and standard deviations over 2 months are given in Table II. Periodic checks on the stability of the sensitivity can be made with the LED CAL light levels and measurement of sensitivity using a standard or analyzed mixture introduced to the BSD chamber by closing the gate valves in Fig. 1.

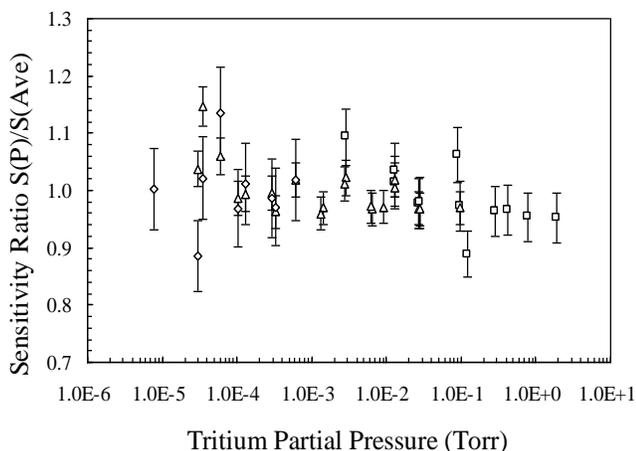


Fig. 4. Inline BSD Ratio of $S(P)/S(Ave)$ versus tritium partial pressure for Low (\square) [$S(Low)/1.304$], Medium (Δ) [$S(Med)/125$] and High (\diamond) [$S(High)/14150$] Gain settings.

Table I.
BSD Mound Calibration Results

Gain Range	Average $S(V/Torr-T)$
Low Gain (194 V)	1.304 ± 0.059
Medium Gain (350V)	125.0 ± 3.2
High Gain (750 V)	14150 ± 880

Table II.
BSD Response (V) to Internal LED Light Levels

Gain Range	LED CAL-Low	LED CAL-High
Low Gain	0.1156 ± 0.0012	1.2261 ± 0.0111
Medium Gain	0.5212 ± 0.0074	8.5568 ± 0.1055
High Gain	1.23 ± 0.05	7.65 ± 0.19

V. FLOW TEST RESULTS

The intended use of this inline BSD is to measure the concentration of tritium (mol-%) in a flowing stream. Tests of this capability were made by flowing known gases through a capillary line through the BSD chamber pumped by a diffusion pump (Fig. 2). Flow through the capillary is proportional to source pressure producing a factor of 30 change in flow rate in 30 minutes as the pressure decreased to 12 psia in the small source volume. Figure 5 shows the BSD and 10-Torr CDG response versus gas flow, Q , through the BSD chamber and the tritium concentration calculated from Eq. 2 as gas flows through the chamber. The measured concentration is constant at 0.953 ± 0.006 mol-% over the smooth changes in flow rate compared with a static measured value of 0.96 ± 0.01 mol-%. Abrupt changes at the start and finish of the flow test show deviations in concentration consistent with the 30 s time constant of BSD response and

the location of the CDG downstream from the BSD (see Fig. 2) compared with the planned location of the CDG in Fig. 1 directly opposite to the BSD. Changes in flow rate at PPPL are expected to be less abrupt.

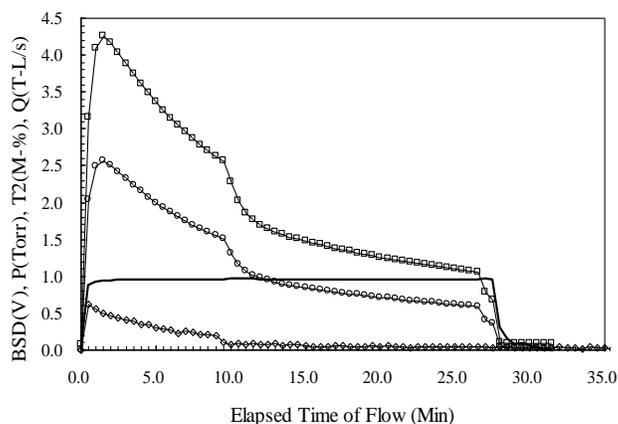


Fig. 5. Measurement of tritium concentration of 0.96 mol-% T_2 in D_2 gas flowing through BSD chamber. Key: (\square) is BSD signal, (o) is total pressure, P , at BSD chamber, (—) is the calculated T_2 (mol-%), and (\diamond) is the flow rate calculated from 124 cm^3 source volume pressure depletion.

VI. SUMMARY

A multi-range BSD for measurement of tritium partial pressure in flowing low pressure gas streams has been developed and calibrated. The accuracy of tritium pressure is about 3% relative on each range of operation due to minor non-linearity (Fig. 4). Range changes to increase sensitivity from Low to Med to High have settling times of 1 to 2 min. Range changes to decrease sensitivity have settling times of 4 to 8 min. Small BSD signals from beta induced glow of N_2 impurities could add small biases to tritium measurements when N_2 is used as a flush gas to the GHT.

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