Measurements of the PLT and PDX Device Activation

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Measurements of the activation levels around the PLT and PDX tokamaks have been made using a Ge(Li) gamma spectrometer and a Geiger counter. The activation results from radiation induced in the plasma by 14 MeV neutrons from the d(t,n)α fusion reaction, 14.7 MeV protons from the d(^{3}He,p)α fusion reaction, 10 → 20 MeV hard x-rays from runaway electron induced bremsstrahlung, and 2.5 MeV neutrons from the d(d,n)^{3}He fusion reaction. The magnitude of the activation is compared to that predicted for PDX on the basis of one-dimensional activation codes.

1. INTRODUCTION

Neutron activation is an important consideration in the design of a fusion reactor due to its influence on the operation, maintenance, and eventual disposal of the reactor. Although present research devices and, in particular, tokamaks have not been hampered by activation, this situation will change in the next generation of large tokamaks. In fact, neutron activation is one of the major concerns in planning the experimental program for the Tokamak Fusion Test Reactor (TFTR) [1] whose principal goal is to achieve scientific energy breakeven with deuterium-tritium operation. It is hoped to complete most of the important TFTR experiments before remote maintenance becomes imperative. The experimental flexibility of the device will be reduced after the long-lived vessel contact activity exceeds about 10 mR/hr. In this paper, we report measurements of machine radioactivity following experiments on the PLT and PDX tokamaks. These devices have considerably less radioactivity than is expected for TFTR since the neutron emission level is many orders of magnitude smaller and also since 2.5 MeV neutrons from the $d(d,n)^3He$ fusion reaction dominate while TFTR will be dominated by 14 MeV neutrons from the $d(t,n)\alpha$ fusion reaction. However, the measurements reported here do provide a check point for neutron activation codes and are the first measurements of neutron activation around a tokamak.

2. RADIATION CHARACTERISTICS

Activation occurs on the PLT (Princeton Large Torus) and the PDX (Poloidal Divertor Experiment) tokamaks due to radiation in the form of 14 MeV neutrons, 14.7 MeV protons, 10 → 20 MeV hard x-rays, and 2.5 MeV neutrons

(Table 1). The large yields of 14 MeV neutrons (~ 10^{11}/shot) occur from $d(t,n)\alpha$ fusion reactions where the tritons have been produced by the d(d,p)t fusion reaction. These 1 MeV tritons are confined inside the tokamak plasma and slow down through the maximum of the dt cross section [2]. The large yields of 14.7 MeV protons (~ 2 x 10^{12}/shot) arise from ICRF (Ion Cyclotron Range of Frequency) heated PLT plasmas [3] where a ^{3}He minority species is heated directly by the ion cyclotron waves to energies ~ 80 → 100 keV, thus inducing $d(^3He,p)\alpha$ fusion reactions. The 10 → 20 MeV hard X-rays occur on PLT or PDX due to thick target bremsstrahlung resulting from runaway electron bombardment of the limiter which defines the plasma boundary [4-6]. Levels of ~ 400 R/shot have been observed when, under adverse conditions, considerable plasma current is carried by runaway electrons. The large yields of 2.5 MeV neutrons (~ 2 x 10^{13}/shot) have occurred during 40 → 50 keV deuterium neutral beam injection (3 MW on PLT, 8 MW on PDX) and results from beam-target $d(d,n)^3He$ fusion reactions [7].

3. PLT ACTIVATION DUE TO 14 MeV NEUTRONS

Since the production of 14 MeV neutrons in PLT depends primarily on the confinement of the fusion produced 1 MeV tritons, the levels of dt neutron production are only ~ 0.01 → 1% of the levels of dd neutron production. This means that on PLT/PDX the activation due to the 14 MeV neutrons is relatively unimportant although some $^{27}Al(n,\alpha)\,^{24}Na$(15h) activation can be unambiguously identified with the 14 MeV neutrons. On TFTR, these 1 MeV tritons will be better confined and will spend a longer time slowing down so that a larger burnup fraction or dt/dd ratio of ~ 0.5 → 5% can be expected. Still, as for PLT, this component will produce a relatively small activation compared to the dd neutrons.

The important 14 MeV neutron activation on TFTR will occur with deuterium beam injection into tritium plasmas. The ensuing TFTR activity levels cannot be estimated from the above PLT 14 MeV neutron emission. Instead, by calibrating dd activation codes to PLT dd activation levels, one can probably also usefully calculate the dt activation level.

4. PLT ACTIVATION DUE TO 14.7 MeV PROTONS

The 14.7 MeV protons are lost from the PLT plasma along particle orbits affected by the gradient and curvature drifts so that they tend to strike the lower outside part of the vacuum vessel (Fig. 1). $^{56}Fe(p,n)$ $^{56}Co(79d)$ activity has been observed in the vaccum vessel and limiter while $^{48}Ti(p,n)^{48}V(16d)$ activity has been observed in the titanium evaporated onto the PLT vessel for gettering. The energetic proton activation is small compared to the 2.5 MeV neutron activation since Coulomb drag quickly reduces the proton energy below activation thresholds.

Confinement of the 14.7 MeV protons in TFTR is only marginal so that many protons will leave the plasma as on PLT. Some 14.7 MeV proton production will occur from burnup of the 0.8 MeV ^3He ion produced by the $d(d,n)^3He$ fusion reaction. Again, this production rate should be small compared to the 2.5 MeV neutron production. Major ICRF experiments are also planned for TFTR which will result in high 14.7 MeV proton emission. At present, these experiments are planned to follow Q=1 dt experiments so that the added activation will be minor.

5. PLT/PDX ACTIVATION DUE TO HARD X-RAY BREMSSTRAHLUNG

Energetic runaway electrons (10 → 20 MeV) have an outward drift orbit displacement (~ 5 → 13 cm) from the magnetic surfaces which are centered in the vacuum vessel. Thus, energetic runaway electrons leave the plasma on the horizontal midplane and cause most of their activation on the outside limiter (Fig. 1,2) [4-6]. The limiter activation is due to photoreactions (Table III) which have a lower energy threshold for higher mass limiters. The energy distribution of runaway electrons in PLT drops about 10^2 between 10 MeV and 20 MeV [6] so that considerable activation is possible in tungsten limiters where the photo-thresholds are low and little is observed in carbon limiters where the photo-thresholds are high. Carbon has the additional advantage of leaving short-live radio-isotopes.

In TFTR, larger runaway electron currents are possible, and the runaways will probably get to higher energies since their confinement times are likely to be ≈ 4x longer. A reasonable consequence is that ≈ 10^2 more activation could occur on the TFTR TiC limiters due to runaway electrons than is observed on PLT/PDX.

Photoactivation also occurs in the forward cone of hard x-rays leaving the limiter. On PLT $^{65}Cu(\gamma,n)^{64}Cu$ was observed in the toroidal field coils in the forward radiation cone. $^{90}Zr(\gamma,n)\ ^{89}Zr$(78h) and $^{96}Zr(\gamma,n)\ ^{95}Zr$(64d) were observed on zirconium foils placed in the forward radiation cone. This may impact the maintenance of zirconium-aluminum getters which are expected to be used on TFTR. Attempts to reduce the photonuclear limiter activation problem on TFTR could logically center around controlling the runaway electron population and turning off plasmas with high runaway electron levels.

6. PLT/PDX ACTIVATION DUE TO 2.5 MeV NEUTRONS

The 2.5 MeV neutron emission is uniform toroidally and slightly asymmetric poloidally due to the outward Shafranov shift of the plasma [8] Fig. 1. Measurements of the activity were made at the vacuum vessel on the horizontal midplane using a Ge(Li) detector (Table II). The efficiency of the Ge(Li) detector was determined as a function of source position as well as energy. The conversion of observed counts to activity (mR/hr) was obtained by presuming isotropic irradiation of the Ge(Li) detector. The uncertainty in this conversion might be 50%. In addition, the vacuum exhaust lines, water cooling pipes, and the concrete shield walls were monitored with the Ge(Li) detector. Measurements were taken either during or immediately following PLT neutral beam runs, but no γ activity was observed. Activation surveys were performed with a calibrated Geiger counter and indicated maximum total activity levels at the vacuum vessel of $\sim 1 \div 2$ mR/hr following the most intense PLT runs and 0.8 mR/hr following the most intense PDX runs. The activity level fell off appreciably when the Geiger counter was moved radially away from the vessel (Fig. 3). These activity levels decayed appreciably overnight (Fig. 4). The total activity levels per emitted neutron measured by either the Geiger counter or the Ge(Li) detector can be compared to the levels predicted for PDX [9] at the vacuum vessel following 2.5 MeV neutron irradiation (Table IV). Activation codes are one dimensional models of the tokamak geometry and include neutron and gamma transport through the devices. The major uncertainties in these calculations are in modeling the composition of the device and in modeling the tokamak geometry. The PDX predictions for the activity level per emitted neutron are reasonably consistent with the measured levels. We consider the quantitative activity levels to be one useful result of this paper since the short term irradiation history can be accurately specified as can the major machine components which cause the short term activity. The accuracy of the neutron irradiation is about 30% [8].

The dominant longer-lived isotopes include ^{58}Co (71d), ^{56}Co (79d), ^{60}Co(5.3y), ^{54}Mn(312d), ^{82}Br(35h), and ^{51}Cr(28d) (Table IV.) The PDX calculations predict a decay to considerably lower activity levels after one week than was observed experimentally (Table V). This can probably be explained by the uncertainties in quantifying the long-lived activity since the actual PLT/PDX irradiation history is difficult to document for long times. However, the code has not included materials (Br, W, Sb, Na) which have led to observable activation. These materials are used in such things as paints, diagnostics, and brazing alloys which can be easily overlooked when modeling device composition. We consider this identification of the longer lived isotopes to be another useful result of this paper since this points out possible problem materials.

ACKNOWLEDGMENT

The authors thank D. Meade for helpful discussions. The technical assistance of G. Estepp and the PLT and PDX experimental teams is gratefully acknowledged. The work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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TABLE I. PLT/PDX ACTIVATION RADIATION

DEVICE	EXPERIMENT	REACTIONS	PEAK LEVELS (PER SHOT)	ACTIVATING RADIATION
PDX	8 MW NBI $D^0 \rightarrow H^+$	$d(d,n)^3He$	2×10^{13}	2.5 MeV neutrons
PLT	3 MW NBI $D^0 \rightarrow H^+$	a) $d(d,n)^3He$ b) $d(t,n)\alpha$	a) 2×10^{13} b) $\approx 10^{11}$	a) 2.5 MeV neutrons b) 14 MeV neutrons
PLT	1 MW ICRF ^3He minority D majority	$d(^3He,p)\alpha$	5×10^{11}	14.7 MeV protons
PLT/PDX	ohmic	Runaway electron induced bremsstrahlung	$\approx 10^3$ R	$10 \rightarrow 20$ MeV X-rays

TABLE II. PLT/PDX NEUTRON INDUCED RADIONUCLIDES

RADIO NUCLIDE	HALF LIFE	PLT ACTIVITY (nCi)	PDX ACTIVITY (nCi)	ACTIVATION	SOURCE
^{64}Cu	13 h	4.2×10^2	---	$^{63}Cu(n,\gamma)$	coils
^{56}Mn	2.6 h	36	---	$^{55}Mn(n,\gamma)$	vessel
^{51}Cr	28 d	0.47	0.052	$^{50}Cr(n,\gamma)$	vessel
^{187}W	24 h	0.43	---	$^{186}W(n,\gamma)$	laser dump
^{58}Co	71 d	0.34	0.028	$^{59}Ni(n,p)$ / $^{59}Co(\gamma,n)$	vessel
^{65}Ni	2.5 h	0.32	---	$^{64}Ni(n,\gamma)$	vessel
^{82}Br	35 h	0.25	0.001	$^{81}Br(n,\gamma)$	paint
^{54}Mn	312 d	0.085	0.002	$^{54}Fe(n,p)$	vessel
^{122}Sb	3 d	0.062	0.001	$^{121}Sb(n,\gamma)$	brazing alloy
^{24}Na	15 h	0.049	---	$^{23}Na(n,\gamma)$	epoxy
^{56}Co	79 d	0.039		$^{56}Fe(p,n)$	vessel
^{60}Co	5.3 y	0.037	0.004	$^{59}Co(n,\gamma)$	vessel
^{59}Fe	46 d	---	0.002	$^{58}Fe(n,\gamma)$	vessel

PLT: May 22, 1980 -- Measurements made 2 hours after the run with 3.5×10^{14} neutrons emitted that day. 60 nCi of annihilation radiation, 3 nCi of unidentified activity

PDX: November 5, 1980 -- Measurements made about 1 week after the last run. The previous run week had $\approx 10^{14}$ neutrons.

TABLE III. PLT/PDX RUNAWAY ELECTRON INDUCED RADIONUCLIDES

DEVICE	LIMITER	ACTIVITY LEVEL (mR/hr)*	RADIO NUCLIDE	HALF LIFE	ACTIVATION	THRESHOLD (MeV)
PLT	W	40	^{181}W	130 d	$^{182}W(\gamma,n)$	8.1
			^{185}[illegible]	[illegible] d	$^{186}W(\gamma,n)$	7.2
			^{182}[illegible]	115 d	$^{183}W(\gamma,p)$	7.2
PDX	Ti	6	^{46}Sc	84 d	$^{47}Ti(\gamma,p)$	10.5
			^{47}Sc	3.4 d	$^{48}Ti(\gamma,p)$	11.4
			^{48}Sc	44 h	$^{49}Ti(\gamma,p)$	11.3
PLT	steel	4	^{57}Co	270 d	$^{58}Ni(\gamma,p)$	8.5
			^{60}Co	5.3 y	$^{61}Ni(\gamma,p)$	10.2
			^{54}Mn	300 d	$^{55}Mn(\gamma,n)$	10.5
			^{51}Cr	28 d	$^{52}Cr(\gamma,n)$	12.0
			^{57}Ni	36 h	$^{58}Ni(\gamma,pn)$	12.2
			^{56}Co	77 d	$^{58}Ni(\gamma,pn)$	19.6
			^{56}Ni	6 d	$^{58}Ni(\gamma,2n)$	22.5
PLT	C	--	--	--	--	--

*Measurements made 2-3 weeks after the last run.

TABLE IV: ACTIVITY LEVEL AT THE VACUUM VESSEL IN $\left(\frac{\text{mR/hr}}{\text{EMITTED 2.5 MeV NEUTRON}}\right)$

DEVICE	SOURCE OF MEASUREMENT	ACTIVITY LEVEL AFTER 10 MIN.	ACTIVITY LEVEL AFTER 1 WK.
PLT	Remmeter	6.6×10^{-15}	---
PLT	Ge(Li) detected gamma lines	1.1×10^{-15}	4.9×10^{-18}
PDX	Remmeter	2.3×10^{-15}	---
PDX	Fig. 53, 57; Ref. 9	5.5×10^{-15}	4.5×10^{-19}

TABLE V. DOSE RATES EXTRAPOLATED TO ONE WEEK AFTER LAST SHOT

ISOTOPE	HALF LIFE	DOSE RATE (mrem/hr) PLT MEASUREMENT	PDX CODE* REF. 9
^{65}Na	2.530 h	---	---
^{56}Mn	2.579 h	---	---
^{64}Cu	12.70 h	10^{-5}	8.96 (-5)
^{24}Na	15.02 h	7.6×10^{-8}	
^{187}W	23.9 h	1.4×10^{-6}	
^{82}Br	35.34 h	2.5×10^{-5}	
^{122}Sb	2.68 d	4.8×10^{-6}	
^{51}Cr	27.70 d	1.3×10^{-5}	3.52 (-6)
^{58}Co	70.8 d	3.2×10^{-4}	5.72 (-5)
^{56}Co	78.8 d	1.1×10^{-4}	
^{54}Mn	312.0 d	7.2×10^{-5}	
^{60}Co	5.271 y	8.9×10^{-5}	
total		7.7×10^{-4}	1.5×10^{-4}

*The irradiation history is based on the actual PLT irradiation history.

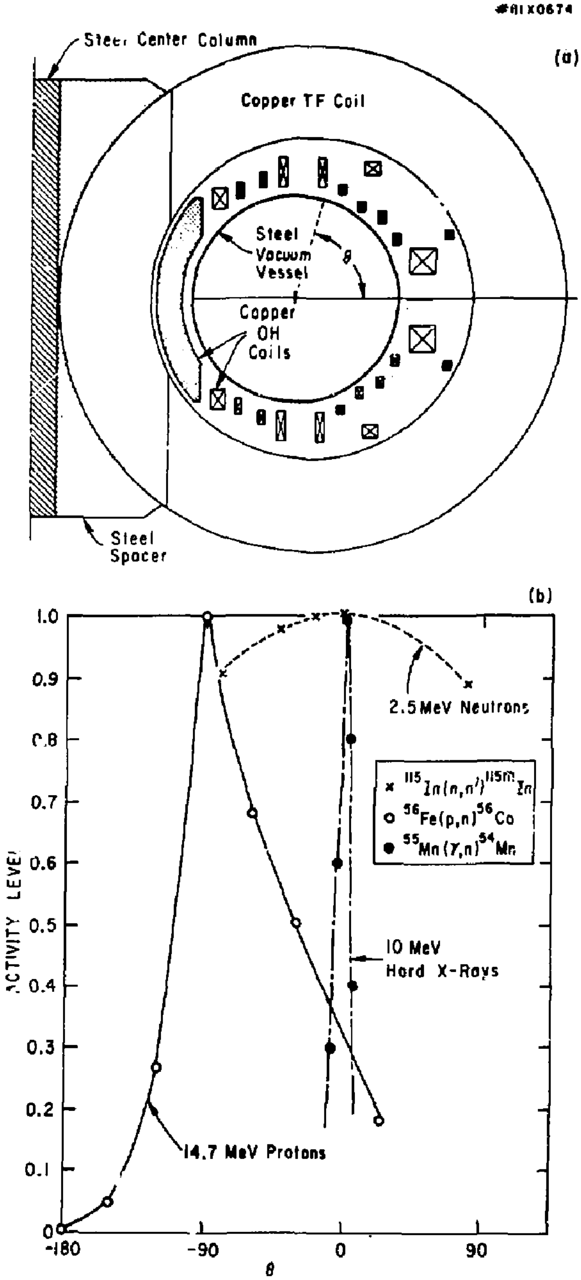

Fig. 1 a) Poloidal cross-section of the PLT tokamak, (b) poloidal distribution of the PLT radioactivity due to 2.5 MeV neutrons (x) [8], 14.7 MeV protons (O) [3], and 10 MeV x-rays (•) [6].

Fig. 2 a) Photograph of the PLT tungsten limiter indicating melted region due to runaway electron impact, b) 24 hour exposure x-ray contact print [Ref. 4].

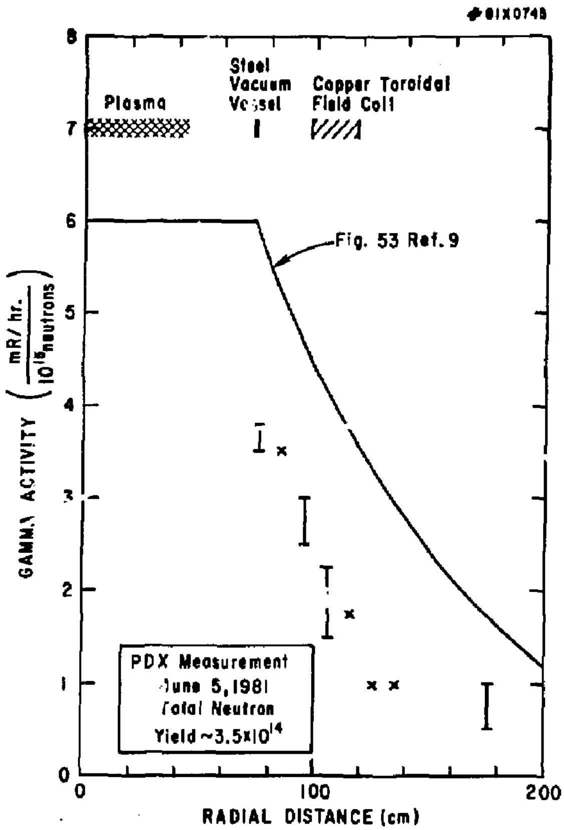

Fig. 3 Spatial distributions of the neutron induced activity along the horizontal midplane of PDX.

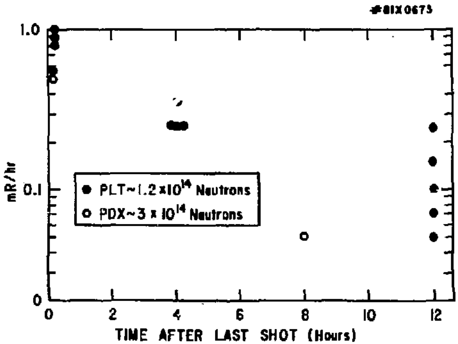

Fig. 4 Activity decay of the PLT vacuum vessel (●) and the PDX vacuum vessel (O) following the last plasma discharge.