Activation of Building Air in a Tokamak Engineering Test Facility

**B. R. Leonard, Jr.
R. T. Perry**

September 1980

**Prepared for
EG&G Idaho, Inc. and
the Department of Energy
under Contract DE-AP07-791-D0020**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

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UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ _____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

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ABSTRACT

The production of radionuclides by neutron reactions in the building air of a conceptual Tokamak Engineering Test Facility has been calculated. The short-lived radionuclides ^{13}N , ^{16}N and ^{41}Ar are all found to greatly exceed their maximum permissible concentration values. Longer-lived radionuclides ^3H , ^{14}C and ^{39}Ar are also found to be produced in significant concentrations. The present results are compared with values calculated for three other fusion devices; TFTR, INS, and FMIT. These comparisons show that the ETF can be a prolific producer of activated air.

EXECUTIVE SUMMARY

The production of radionuclides in the air of a fusion reactor building was estimated for a conceptual Tokamak Engineering Test Facility. The conceptual ETF design used in this study was based on the ORNL-The Next Step (TNS) design study on the assumption that an ETF would be similar to this concept. Although in the ORNL-TNS design concept the reactor building was evacuated, the calculations here were based on a standard atmosphere of air. The results are presented in a manner that the placement of vacuum boundaries at various positions can be evaluated.

The neutron fluxes in the building-air were calculated for a one-dimensional cylindrical blanket model using the ANISN computer code. The neutron transport and the important activation reactions were calculated using ENDF/B-IV nuclear data except for ^{40}Ar which is not an ENDF/B material. The $^{40}\text{Ar}(n,2n)^{39}\text{Ar}$ cross section was taken from an existing theoretical calculation and an $^{40}\text{Ar}(n,\gamma)^{41}\text{Ar}$ cross section was evaluated for this study.

The radionuclides which are of most concern for accidental release were found to be ^{13}N , ^{16}N , and ^{41}Ar . The ^{41}Ar activity was found to dominate the considerations of hold-up time for controlled release. The production rates of the longer-lived radionuclides ^3H , ^{14}C , and ^{39}Ar were also established for consideration in establishing operational venting and hold-up procedures.

The results of this study can be compared with similar calculations made for other fusion devices; the Tokamak Fusion Test Reactor, TFTR, the LASL Intense Neutron Source, INS, and the HEDL Fusion Materials Irradiation Test Facility, FMIT. The amounts of radioactive air to be handled in an unevacuated ETF facility can exceed those of these facilities by factors ranging from 25 to 1000 for the important radionuclides.

ACKNOWLEDGEMENTS

The authors express their appreciation to Brian D. Boyer who greatly helped in assembling and analyzing the data results from the ANISN calculations while a NORCUS summer student appointee with PNL.

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I. INTRODUCTION

It has previously been recognized that the neutrons which penetrate the shields of a DT Tokamak fusion reactor will produce radionuclides in air in sufficiently high concentration to require special attention for their safe disposal. In general, the activated air requires engineered ventilation systems which safeguard against occupational radiation exposure and uncontrolled release to the atmosphere.

Estimates have been made of the air activation levels and resultant handling problems for the Tokamak Fusion Test Reactor (TFTR).⁽¹⁾ The TFTR is designed to produce large instantaneous sources of DT neutrons but of short duration (0.5 s) and a long time between pulses (300 s). Thus, in the TFTR studies important radionuclides, notably ^{41}Ar , do not reach saturated activity concentrations and potentially troublesome long-lived radionuclides present no problem. A Tokamak Engineering Test Facility (ETF) on the other hand is to produce large sources of DT neutrons on a nearly continuous basis. Thus, all short-lived radionuclides which are produced promise to reach saturated activity concentration levels and long-lived radionuclides may reach activity concentration levels which will require attention for their control. Indeed, from the air activation viewpoint, an ETF may present more problems than a power-producing Tokamak reactor since the primary purpose of the torus shielding is to protect the superconducting magnets⁽²⁾ and otherwise will be minimized, consistent with radiation dose and activation levels, to provide maximum flexibility for the engineering tests. For this reason and because an ETF is presently planned as the next step beyond TFTR, an ETF was selected as the subject for the present study of air activation problems.

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II. REFERENCE DESIGN

The conceptual design of an ETF was started in 1979 in the U.S. under the leadership of Oak Ridge National Laboratory (ORNL). However, ORNL in 1978 completed a study of The Next Step (TNS) which they have also identified as an ETF.⁽³⁾ Since it seems probable that the ETF design will fairly closely resemble the plasma characteristics and device shielding of the ORNL-TNS concept, this design has been selected for the present study of air activation problems. The ORNL-TNS design included the concept of an evacuated building with the bulk of the building at a pressure of 10^{-4} torr plus a 4 m thick shell between the vacuum enclosure and the building wall at 20 torr pressure. Air activation problems were not considered as one of the major advantages of the evacuated building concept.^(2,4) Aside from potential air activation problems the value of an evacuated building or part of a building has not been firmly established and there is not at this time a consensus on the optimum location of the vacuum boundary. Therefore, the present study has assumed a normal atmosphere of air beyond the torus shielding. Activation results are presented, however, such that the effect of vacuum boundaries at a number of locations can be evaluated.

REACTOR DESIGN

A schematic representation of a cross-section of the ORNL/TNS reactor and building structure is shown in Figure 1. The diameter of the metal vacuum chamber is 48 m and the inside wall of the concrete enclosure is 56 m diameter. The reactor parameters are summarized in Table I.

STRUCTURE AND COOLANTS

A schematic cross-sectional view of the plasma and shield is shown on Figure 2. The first structural region is a stainless steel, water-cooled, tubular first wall approximately 5 cm thick. This is followed by a 50 cm shield of stainless steel balls cooled with borated water and a 5 cm thick stainless steel outer wall.

FIGURE 1. TNS-ORNL - Reference Design⁽²⁾

TABLE I. Reactor Parameters

Major radius, R	5.0 m
Plasma minor radius, a	1.2 m
Plasma elongation	1.6
Plasma volume	230 m ³
Neutron wall loading	2.4 MW/m ²
Total fusion power	1140 MW
Burn time	500 s
Duty cycle	89%

FIGURE 2. ORNL-TNS Plasma, Shield and Coolant Schematic

III. AIR ACTIVATION CALCULATIONS

CALCULATIONAL METHOD

The plasma, blanket and building air were modeled as an equivalent infinite cylinder. The neutron fluxes were calculated with the one-dimensional discrete ordinates transport code ANISN⁽⁵⁾ in the P_3S_8 approximation. The dimensions and constituents used in the ANISN calculation are shown on Figure 3. The shield area of stainless steel and borated water was homogenized in the ANISN calculation. The air region was divided into nine zones with a total of 50 intervals. Eight of the zones were within 4 m of the surface of the shield so that the effect of vacuum boundaries at various positions in that region could be evaluated. The building air was modeled out to a radius of 26 m which would include part of the proposed rough vacuum zone of the ORNL-TNS concept.

The nuclear data used in the ANISN calculation was a 30 energy group set derived from ENDF/B-IV. The group structure of this set was modeled to use a broadened DT neutron source as is obtained from a plasma driven by energetic neutral beams.⁽⁶⁾ In these calculations the source neutrons were distributed equally in the groups above and below 14.10 MeV.

ACTIVATION NUCLEAR DATA

The radionuclides and their neutron-induced production reactions which were calculated in this study are shown on Table II. The dominant long lived activities were found to be tritium, ^{14}C , and ^{39}A ; the short-lived ones were ^{13}N , ^{16}N , and ^{41}A . The nuclear reactions which dominate the production of these radioisotopes are underlined on Table II. The activation cross sections for the major nuclide constituents of air, ^{14}N and ^{16}O , were obtained from the ENDF/B-IV descriptions as was the $^2\text{H}(n,\gamma)^3\text{H}$ cross section. The $^{13}\text{C}(n,\gamma)^{14}\text{C}$ cross section was taken to be the $^{12}\text{C}(n,\gamma)$ cross section from ENDF/B-IV scaled by the ratio of their thermal capture cross sections. The reaction cross sections of the minor isotopes ^{15}N and ^{17}O were taken from the new descriptions on ENDF/B-V.

FIGURE 3. Dimensions and Constituents of ETF used in ANISN

TABLE II. Radionuclide Production Reactions

${}^2\text{H}(n,\gamma){}^3\text{H}$	${}^{14}\text{N}(n,p){}^{14}\text{C}$	${}^{38}\text{Ar}(n,\gamma){}^{39}\text{Ar}$
${}^{14}\text{N}(n,{}^3\text{H}){}^{12}\text{C}$	${}^{13}\text{C}(n,\gamma){}^{14}\text{C}$	${}^{40}\text{Ar}(n,2n){}^{39}\text{Ar}$
${}^{15}\text{N}(n,{}^3\text{H}){}^{13}\text{C}$	${}^{17}\text{O}(n,\alpha){}^{14}\text{C}$	
	${}^{15}\text{N}(n,d){}^{14}\text{C}$	
${}^{15}\text{N}(n,\gamma){}^{16}\text{N}$		
${}^{16}\text{O}(n,p){}^{16}\text{N}$	${}^{14}\text{N}(n,2n){}^{13}\text{N}$	${}^{40}\text{Ar}(n,\gamma){}^{41}\text{Ar}$
${}^{17}\text{O}(n,d){}^{16}\text{N}$		
${}^{36}\text{Ar}(n,\gamma){}^{37}\text{Ar}$	${}^{15}\text{N}(n,\alpha){}^{12}\text{B}$	${}^{15}\text{N}(n,p){}^{15}\text{C}$
		${}^{17}\text{O}(n,p){}^{17}\text{N}$

The nucleus ${}^{40}\text{Ar}$ does not have an ENDF/B evaluation. Since no evaluation of the ${}^{40}\text{Ar}$ capture cross section could be located a simple evaluation was prepared for this study. Since the first resonances in ${}^{40}\text{Ar}$ are observed above 1.2 keV the capture cross section was assumed to be $1/v$ below that energy normalized to the 2200 m/s value of 650 mb.⁽⁷⁾ Above 1.2 keV the capture cross section was joined smoothly to the measured broad resolution values of Bostrom, et al⁽⁸⁾ from 0.136 to 1.0 MeV. Above 1 MeV the capture cross section was held constant at 1 mb. The capture cross sections of the minor isotopes ${}^{36}\text{Ar}$ and ${}^{38}\text{Ar}$ were assumed to have the same shape as ${}^{40}\text{Ar}$ normalized to their respective thermal capture cross section values.⁽⁷⁾ The ${}^{40}\text{Ar}(n,2n){}^{39}\text{Ar}$ cross section was derived from the nuclear systematics calculations of Pearlstein.⁽⁹⁾

IV. AIR ACTIVATION RESULTS

The six radionuclides which were judged to be the most important considerations for operational safety, accident conditions and release to the environment were incicated on Table II. ^{16}N , ^{13}N and ^{41}Ar are short-lived radionuclides which dominate the potential hazard over time scales of minutes, hours, and days, respectively. ^{16}N and ^{13}N with half-lives of 7.1 s and 9.97 m, respectively, would reach saturated activity values with most proposed building ventilation schemes and 1.83 hr ^{41}Ar might come close to saturated concentration. Their calculated saturated activities for the total building air are shown on Table III compared with their maximum permissible concentration values as given in the Federal Code of Regulations⁽¹⁰⁾ and the ERDA manual on radiation protection standards.⁽¹¹⁾

TABLE III. Formation and Decay of Important Radionuclides

<u>Short-Lived Radionuclides</u>						
<u>Nuclide</u>	<u>T_{1/2}</u>	<u>Saturated Activity ($\mu\text{Ci/ml}$)</u>	<u>MPC ($\mu\text{Ci/ml}$)</u>		<u>Time to Decay to MPC</u>	
			<u>Restricted</u>	<u>Unrestricted</u>	<u>Restricted</u>	<u>Unrestricted</u>
^{13}N	9.97m	5.3(-3)	1.(-6)	3.(-8)	2.0 hr	2.9 hr
^{16}N	7.1 s	8.7(-3)	1.(-6)	3.(-8)	1.5m	2.1m
^{41}Ar	1.83 hr	6.0(-4)	2.(-6)	4.(-8)	15 hr	25 hr

<u>Long-Lived Radionuclides</u>						
<u>Nuclide</u>	<u>T_{1/2}</u>	<u>Formation Rate ($\mu\text{Ci/ml-s}$)</u>	<u>MPC ($\mu\text{Ci/ml}$)</u>		<u>Time to Reach MPC</u>	
			<u>Restricted</u>	<u>Unrestricted</u>	<u>Restricted</u>	<u>Unrestricted</u>
^3H	12.33y	8.2(-11)	5.(-6)	2.(-7)	17 hr	41 m
^{14}C	5730 y	2.3(-12)	4.(-6)	1.(-7)	20 d	12 hr
^{39}Ar	269 y	2.5(-13)	3.(-9)	1.(-10)	3.4 h	7 m

Also shown are the times required to decay to MPC values for occupational and public exposure. It is notable that the ^{13}N and ^{16}N saturated activity values are some four orders of magnitude larger than that allowed for occupational exposure indicating that sudden accidental releases of building air could be extremely serious. For routine operation, however, the ^{41}Ar activity dominates the required holdup time to release.

The calculated formation rates of the major long-lived radionuclides compared with their MPC values are also shown on Table III. The minimum residence time to reach MPC concentrations is seen to be that of ^{39}Ar .

The radionuclide production rates of the six dominant nuclides are shown on Table IV for different radial zones starting at the outer shield boundary. Note that the volumetric production rates for the inner zones are about one order of magnitude larger than in Zone 16. However, the smaller air volume out to 6 m is such that the average building air production rates given in Table IV are strongly weighted by Zone 16. Also shown are production rates calculated for 25 to 26 m, where the ORNL-TNS concept would have a partial vacuum of 20 torr.

TABLE IV. Radionuclide Production Rate ($\mu\text{Ci}/\text{cm}^3\text{-s}$)

Zone	R(cm)	^{13}N	^{14}C	^{16}N	^{39}Ar	^{41}Ar	^3H
8	210-214	4.6(-5)	1.7(-11)	6.4(-3)	1.8(-12)	3.9(-7)	6.2(-10)
9	214-220	4.4(-5)	1.6(-11)	6.3(-3)	1.8(-12)	3.7(-7)	6.0(-10)
10	220-245	4.1(-5)	1.4(-11)	5.8(-3)	1.7(-12)	3.4(-7)	5.5(-10)
11	245-250	3.8(-5)	1.3(-11)	5.4(-3)	1.5(-12)	3.2(-7)	5.1(-10)
12	250-300	3.0(-5)	1.2(-11)	4.7(-3)	1.4(-12)	2.8(-7)	4.5(-10)
13	300-400	2.6(-5)	0.9(-11)	3.7(-3)	1.0(-12)	2.3(-7)	3.4(-10)
14	400-500	2.0(-5)	0.7(-11)	2.8(-3)	0.8(-12)	1.8(-7)	2.6(-10)
15	500-600	1.6(-5)	0.6(-11)	2.3(-3)	0.7(-12)	1.6(-7)	2.1(-10)
16	600-2600	5.1(-6)	2.1(-12)	7.6(-4)	2.1(-13)	5.6(-8)	7.2(-11)
	2500-2600	3.2(-6)	1.3(-12)	4.5(-4)	1.3(-13)	2.7(-8)	4.3(-11)
AVERAGE AIR	210-2600	6.1(-6)	2.3(-12)	8.5(-4)	2.5(-13)	6.3(-8)	8.2(-11)

The calculated volume averaged neutron flux energy distributions are shown on Table V for different spatial regions of air. The first region shown is for the first cm of air outside the shield. The second constitutes the bulk of the building air and the third is for the last meter of air. These neutron flux spectra could be used to estimate activities induced in other materials or for differing assumptions of air activation nuclear data.

COMPARISON WITH OTHER FUSION DEVICES

Air activation rates have been estimated previously for the TFTR,⁽¹⁾ the proposed LASL Intense Neutron Source, INS,⁽¹³⁾ and the Fusion Materials Irradiation Test Facility, FMIT.⁽¹⁴⁾ In this section, the air activations calculated in this study are compared with the projections for these facilities.

TFTR

Preliminary air activation calculations for a conceptual TFTR were reported in a Westinghouse Fusion Power Systems (WFPS) report in 1975.⁽¹⁾ The characteristics of the conceptual TFTR assumed in the WFPS calculations happened to be such that the total instantaneous production rates of radioisotopes in the TFTR building air were nearly the same as in the present ETF study. The maximum proposed duty cycle of 1/600 for the TFTR, however, results in much less severe problems.

For the production of ^{41}Ar from neutron capture on ^{40}Ar the present calculations give almost an order of magnitude larger instantaneous rate than obtained in the WFPS calculations. The WFPS production rate, however, was estimated using only the production from the thermal neutron group. In the present calculations the thermal group accounts for only about 20% of the total captures which are dominated by the epithermal neutron captures.

TABLE V . Volume Average Neutron Flux
in Different Spatial Regions of Air
(n/cm²-s)

GROUP	E _L (ev)	R (distance from plasma center)		
		2.10-2.11 m	6.0-26.0 m	25.0-26.0 m
1-4	1.35(+7)	4.02(+9)	4.61(+8)	2.75(+8)
5	1.221(+7)	1.24(+9)	1.47(+8)	8.96(+7)
6	1.105(+7)	9.95(+8)	1.17(+8)	6.98(+7)
7	1.00(+7)	1.15(+9)	1.30(+8)	7.70(+7)
8	6.07(+6)	4.54(+9)	5.24(+8)	3.14(+8)
9	3.67(+6)	3.48(+9)	3.95(+8)	2.34(+8)
10	2.23(+6)	6.17(+9)	6.71(+8)	3.91(+8)
11	1.35(+6)	1.09(+10)	1.15(+9)	6.60(+8)
12	8.21(+5)	1.68(+10)	1.76(+9)	9.95(+8)
13	4.98(+5)	1.84(+10)	1.96(+9)	1.10(+9)
14	3.02(+5)	1.40(+10)	1.52(+9)	8.11(+8)
15	1.83(+5)	7.81(+9)	9.66(+8)	5.16(+8)
16	6.74(+4)	1.12(+10)	1.31(+9)	6.81(+8)
17	2.48(+4)	4.66(+9)	6.19(+8)	3.11(+8)
18	9.12(+3)	3.78(+9)	4.77(+8)	2.31(+8)
19	3.36(+3)	2.28(+9)	3.09(+8)	1.48(+8)
20	1.23(+3)	3.06(+9)	3.69(+8)	1.71(+8)
21	4.54(+2)	2.40(+9)	3.13(+8)	1.44(+8)
22	1.67(+2)	2.46(+9)	3.12(+8)	1.41(+8)
23	6.14(+1)	2.18(+9)	2.85(+8)	1.28(+8)
24	2.26(+1)	1.52(+9)	2.13(+8)	9.61(+7)
25	8.32	1.62(+9)	2.08(+8)	9.26(+7)
26	3.06	1.37(+9)	1.80(+8)	8.03(+7)
27	1.855	5.66(+8)	7.73(+7)	3.45(+7)
28	1.166	4.16(+8)	5.87(+7)	2.62(+7)
29	0.625	3.86(+8)	5.65(+7)	2.53(+7)
30	Thermal	1.45(+8)	3.35(+7)	1.47(+7)
Total:		1.28(+11)	1.46(+10)	7.86(+9)

INS

The INS was a proposed facility with a continuously operated unshielded small volume source of 10^{15} DT neutrons per sec. The air activation in the test cell was calculated for a sphere of air of 4.27 m radius surrounded by concrete. Although the neutron source is a pure 14 MeV source, the test cell flux has an appreciable fraction of lower energy and thermal neutrons from return from the concrete. The results of the INS air activation calculations were reported in the INS Final Environmental Statement⁽¹²⁾ and are compared with the ETF values on TABLE VI.

TABLE VI. Comparison of Air Activation of ETF with INS Prediction

<u>Nuclide</u>	<u>Production Rate (Ci/s)</u>		<u>ETF/INS</u>
	<u>ETF</u>	<u>INS*</u>	
^{13}N	0.37	2.4(-3)	154
^{14}C	1.4(-7)	8.0(-10)	175
^{16}N	51.	0.39	131
^{39}Ar	1.5(-8)	1.1(-10)	136
^{41}Ar	3.8(-3)	4.4(-5)	86

*Values from Table 2.1.6.1.3-1 of reference 12.

The INS production rates of the radionuclides produced primarily by near 14 MeV neutrons are all in about the same ratio, with respect to each other, as the ETF values. Also, the ETF/INS ratios are close to the ratio of air volume for each device, 185. However, this agreement within a factor of two is considered to be fortuitous. The INS value was calculated assuming only a thermal return neutron flux from the concrete. A more exact calculation might give a significant different result.

The operational procedure proposed for controlled release of the radioactive gas was to vent the 325 m³ test cell at the rate of 2.8 m³/min into a 168 m³ holding pipe which vented to the atmosphere from a 30 m stack. This procedure was dictated by their calculated ^{41}Ar production rate.

FMIT

The FMIT is an accelerator driven neutron source presently being designed by the Hanford Engineering Development Laboratory. A deuteron beam from a linear accelerator impinges over a small area on a flowing lithium target to produce 3×10^{16} n/s. The neutron energy spectrum from this thick lithium target has appreciable intensity from the lowest energies to around 20 MeV and with lessening magnitude to 40-50 MeV depending on the deuteron beam energy. Most of the source neutrons are emitted into an irradiation cubicle about 1.5 x 1.5 x 1.8 m dimensions with thick concrete walls. The results of the calculated air activities for the FMIT test cell were reported in the FMIT Final Environmental Impact Statement.⁽¹³⁾

Because of the significant differences in the neutron spectrum in the FMIT test cell and that in ETF building air, the calculated individual radioisotope production rates are not directly comparable. The total production rates for the ETF building air are in all cases, however, at least a factor of twenty-five greater than those calculated for the FMIT test cell air.

V. CONCLUSIONS

The production of radionuclides in the building air of a conceptual Tokamak Engineering Test Facility has been investigated. It has been determined that the production of ^{16}N would reach concentrations which exceed the maximum permissible value for occupational exposure in about 1×10^{-3} seconds. The saturated concentrations of $7.1 \text{ s } ^{16}\text{N}$, $10 \text{ m } ^{13}\text{N}$ and $1.8 \text{ h } ^{41}\text{A}$ are all several hundred to several thousand times MPC values representing potential problems for accidental release. The $1.8 \text{ hr } ^{41}\text{Ar}$ activity dominates the required hold-up time for routine operational release.

The concentrations of the long-lived radionuclides ^3H and ^{39}Ar can reach occupational MPC values in a matter of hours and they, plus ^{14}C , will require consideration for controlled or accidental release.

The air activation results for the ETF have been compared with existing estimates for three other fusion devices. These comparisons are generally consistent for the Westinghouse study of the TFTR, the LASL INS, and the HEDL FMIT. The total radioactive gas which must be handled for controlled release for the ETF is 25 to 1000 times that of any other presently proposed fusion device.

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