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A FUSION ENERGY CALORIMETER
FOR THE TOKAMAK FUSION TEST REACTOR

D. L. Jassby and G. R. Imel*

Princeton University Plasma Physics Laboratory
Princeton, NJ 08540

Summary

One and two-dimensional neutronic analyses treating the transport and scattering of neutrons and the production and transport of gamma rays in the TFTR demonstrate that the fusion energy production in a D-T pulse in the TFTR can be determined with an uncertainty of ±15% or less, simply by integrating the measured profile of temperature increase along the central radial axis of a large hydrocarbon moderator that fills the bay between adjacent toroidal-field coils, just outside the vacuum vessel. Limitations in thermopile temperature measurements dictate a minimum fusion-neutron fluence at the vacuum vessel of the order of 10^{11} n/cm² per pulse (a source strength of 10^{18} n/pulse in TFTR), in order that this simple calorimeter can provide useful accuracy.

Introduction

In a pulsed fusion reactor such as the TFTR (Tokamak Fusion Test Reactor[1]), the fusion energy production per pulse can be monitored by means of an adiabatic total neutron-absorption calorimeter located just outside the vacuum vessel wall, as indicated in Figures 1 and [illegible] In each fusion pulse, the neutron moderating region of the calorimeter will experience a temperature rise proportional to the absorbed fusion-derived energy. The calorimeter under consideration for the TFTR is large enough to serve as a simple blanket module, and in fact represents a primitive first step toward a power-producing blanket.

The present paper discusses some basic physical considerations for the design of a calorimeter for a pulsed fusion device. Detailed neutronics analyses of the power deposition profiles in a calorimeter with a pure hydrocarbon moderator, located in

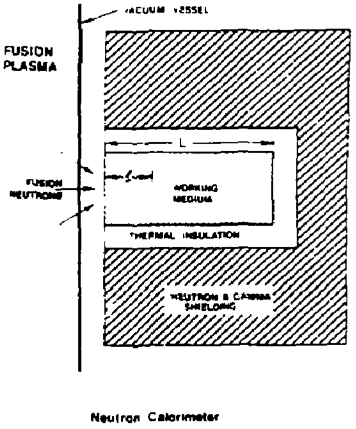

Fig. 1. Schematic drawing of a neutron calorimeter. [81P0307]

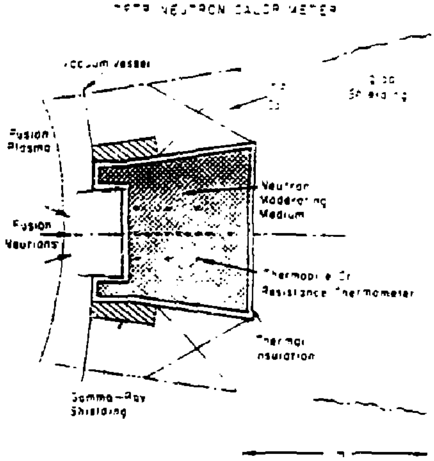

Fig. 2. Plan view showing location of the neutron calorimeter with respect to the TFTR plasma. [81P0309]

the TFTR geometry, are described in Ref. 3. It is worthwhile to implement a calorimeter of the type discussed herein when the D-T fusion neutron fluence becomes as large as 10^{12} n/cm² per pulse. This level of neutron production may be reached in the TFTR in the mid-1980s, but only in a small number of pulses. However, fluences of the order of 10^{13} to 10^{14} n/cm² per pulse can be expected in the TFTR in the late-1980s, and in a rather large number of pulses.

Characteristics of an Ideal Adiabatic Calorimeter

The neutron moderating medium where the temperature increase is measured is referred to as the "working medium." An ideal neutron calorimeter (which cannot be built) would have the following characteristics:

(1) It views only "virgin" fusion neutrons.

(2) The incident fusion neutrons are completely thermalized in the calorimeter working medium.

(3) There is negligible degradation or enhancement of neutron energy in the material interposed between the plasma and the working medium.

(4) The working medium has perfect thermal isolation.

(5) The working medium has both low density and low specific heat, thereby providing high sensitivity.

(6) The calorimeter is insensitive to ambient gamma-ray fields.

(7) The neutrons do not excite exothermic reactions in the working medium.

(8) All gamma rays produced by inelastic collisions in the working medium are captured in the medium.

If the above conditions are satisfied, then the average temperature change, ΔT, in the working medium induced by a fusion pulse of length τ is

$$\langle \Delta T \rangle = \frac{E_n \int_0^{\tau} F_n(t)\,dt}{\rho S L} \qquad (1)$$

where ρ is the density, S is the specific heat, and L is the length of the working medium (see Fig. 1) which absorbs essentially all the neutron energy, F_n is the fusion neutron flux at the calorimeter entrance, and E_n is the fusion neutron energy. Note that <ΔT> is independent of the area of the entrance window.

Choice of Neutron Moderator

The preferred moderator has (i) low density, (ii) low specific heat, (iii) high cross section for elastic neutron moderation, and (iv) low heat conduction. These requirements imply that moderators with low-Z atom constituents are favored.

Table 1 shows the relevant properties of candidate neutron moderating media. Liquid hydrogen has the highest sensitivity, but it would require an elaborate cryogenic facility, and would always present the danger of explosion. From the points of view of sensitivity, safety, ease of handling and cost, certain oils that are pure hydrocarbons appear to be the most suitable liquid moderating media. Polyethylene (CH_2) is a favorable solid candidate. These materials have a sensitivity as large as 2.5 to 3 times that of water. Here sensitivity is defined as $1/(\rho S \lambda_E)$, where the energy absorption length λ_E is the distance over which 90% of the incident neutron energy is given up. (However, the neutron flux at a distance λ_E from the front face will be considerably larger than 10% of the incident flux and will result in significant energy deposition by gamma rays at distances beyond λ_E.)

A solid working medium would be free of the potential problem of convection, which could affect the measurements of ΔT. On the other hand, a liquid medium has the advantages that the temperature

Table 1

PROPERTIES OF CANDIDATE NEUTRON MODERATING MEDIA

Moderating Medium	Temperature (°C)	Density ρ (g/cm³)	Specific Heat, S cal/g/°K	Hydrogen Atom Density (normalized)	Energy Absorp. Length* λ_E (cm)	Sensitivity $(\rho S \lambda_E)^{-1}$ (normalized)
Light water	20	1.00	1.00	1.00	~25	1.00
Heavy water	20	1.11	1.08	1.00 (D)	~15	0.60
C_2H_5I	20	1.90	0.16	0.59	~35	[illegible]
Lubricating Oil	20	[illegible]	0.40	0.99	~25	[illegible]
Ethyl Alcoh. C_2H_5OH	20	0.79	0.58	0.93	~25	2.2
Polyethylene CH_2	20	0.94	0.55	1.19	~25	[illegible]
Paraffin $C_{30}H_{62}$	20	0.89	0.69	1.14	~20	[illegible]
Liquid Ethane, C_2H_6	-90	0.56	0.60	1.01	~25	3.3
Liquid Methane, CH_4	-163	0.42	0.80	0.95	~25	3.0
Liquid Hydrogen, H_2	-255	0.077	[illegible]	0.69	~33	4.6

*Length for the absorption of at least 90% of the energy of incident 14-MeV neutrons.

sensors are likely to be in better thermal equilibrium with the surrounding medium, and the flexibility of the liquid shape makes it easier to investigate experimentally the optimal geometry for the moderating medium.

In the neutronics calculations reported in Ref. 3 and summarized in the following, the moderator was taken as a pure hydrocarbon with a hydrogen-to-carbon atom ratio of 2:1 and a density of 0.6 g/cm^3. The H/C ratio describes the polyethylene molecule, but the density used is much lower, so that the calculations give larger neutron slowing-down lengths than would be the case for an actual polyethylene moderator.

Analyses of Power Deposition

The principal purpose of the neutronics calculations is to determine to what extent measured temperature increases in the moderator can be related "absolutely" to the fusion neutron fluence incident on the calorimeter front face, and thence to the fusion neutron source.

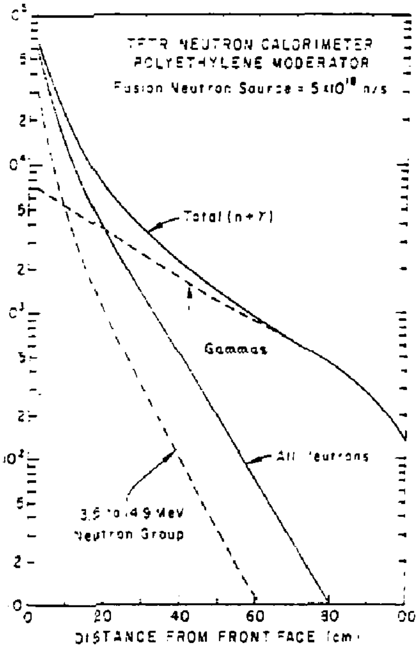

Fig. 3. ANISN calculations of energy deposition profiles in a polyethylene moderator, using the model of Fig. 4. [803649]

One-Dimensional Calculations

The neutron transport code ANISN-PPL was used for 1-D calculations.[3] The geometric model (see Fig.4) was an infinite cylinder with rotational symmetry. The input source spectrum and intensity were calculated by the DOT-3.5 code; the calculation took into account ambient neutrons and gammas generated by scattering from the TFTR components in the vicinity of the calorimeter (see Fig. 2).

Figure 3 shows calculations of the radial power deposition profiles in CH_2 for the source neutrons (13.5-14.9 MeV group), all neutrons, and gammas. Kerma factors were used to calculate reaction rates, which in turn gave the energy deposition rates. Near the front face, about 50% of the energy deposited is due to source neutrons, ≈35% is due to fast neutrons with energies below that of the first group, and 10 to 15% is due to gamma radiation. The gammas are the dominant component of the total energy deposition at locations 30 cm or more from the front face. However, the total energy deposition at this point and beyond is down by an order of magnitude from the value near the front face.

Other ANISN calculations show that gammas produced in the CH_2 account for about 60% of the total gamma energy deposition (including ambient TFTR gammas) along the major radial axis. The

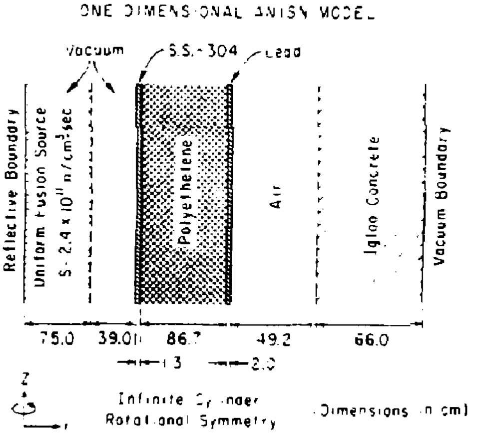

Fig. 4. One-dimensional ANISN model used for the neutron calorimeter. [806305]

amount of energy lost from the calorimeter by the escape of gamma rays produced in endothermic reactions has been estimated[3] to be less than 5% of the energy associated with inelastic collisions, and is probably comparable with the energy gained by exothermic capture reactions.

Boundary Effects

Maximizing the lateral extent of the moderator, rather than adding shielding or reflecting material, appears to be the optimal method for insuring adequate isolation of the central region from boundary effects. The half-width of the moderator in the TFTR calorimeter can be as large as *40 cm in each direction (see Fig. 2). Two-dimensional* calculations made with the DOT-3.5 code[3] demonstrate that this half-width is sufficiently large so that scattered low-energy neutrons entering the sides, either by reflection of moderator neutrons or from the TFTR ambient, have less than 10% effect on the total energy deposition *along the major radial axis.*

Except at the front face, ambient gammas from the TFTR structure can be stopped by approximately 6 cm of lead shielding. However, additional gammas will be produced in the lead by impinging fast neutrons.

The 2-D calculation gives nearly the identical total energy deposition profile along the major radial axis as predicted by the 1-D ANISN calculation. However, the 2-D calculations shows that at distances beyond about 40 cm from the front face, the fast-neutron population below 14 MeV make up a larger contribution, and the gammas a smaller contribution to the total energy deposition, than predicted by the 1-D calculation.

Conclusions Concerning Power Deposition

Other aspects of the power deposition calculations are given in Ref. 3. The principal conclusions from the 1-D and 2-D analyses are the following:

(1) A 1-D neutronics model is adequate for calculating the energy deposition along the central radial axis of the calorimeter up to the decade point; beyond, the 1-D model introduces errors because of the non-representation of neutron streaming to points away from the front face. However, in integrating the total power deposition along the central axis, the overall integrated error is less than 10%.

(2) The toroidal-field coils provide additional attenuation of neutrons entering the sides of the calorimeter, and thus increase the isolation of the central axis. Scattering off the coils, and extra gamma rays produced in the coils are not significant additions to the total power deposition along the central axis.

(3) Externally generated gamma rays deposit significant amounts of energy in the calorimeter, so that it might be desirable to install a lead shield around the sides. With such a shield in place, the central axis is isolated from all gammas except those produced in the vacuum vessel in front of the calorimeter. It is estimated that the maximum error introduced by neglecting gammas produced in the vacuum vessel is 5%; by neglecting loss from the calorimeter of gammas produced by inelastic collisions in the moderator – also 5%; and by neglecting exothermic capture gammas in the moderator – again 5%.

(4) *Assuming no errors in the measurement of temperature changes in the moderator,* the "equivalent-fusion-neutron" fluence incident on the calorimeter front face can be determined with an uncertainty of less than ±10% simply from integration of the measured profile of temperature increase along the central axis. The fusion *neutron source strength can then be inferred* by accounting for attenuation through the vacuum vessel and certain geometrical factors. If each of the latter calculations has an uncertainty of ±7%, for example, then the source neutron production can be estimated "absolutely" with an uncertainty of ±15%, on the basis of the measured profile of temperature increase along the central axis.

Conclusion #(4) may be altered if the surface of the vacuum vessel, all around the torus, is sufficiently reflective so that the current of reflected neutrons into the calorimeter is much larger than accounted for by our neutronics calculations. While in such a case the neutron current may be substantially higher than calculated, the actual power deposited is unlikely to experience a major increase.

Calorimeter Response

In view of the above conclusions, the spatially averaged temperature increase in the moderator, per fusion pulse, can be calculated from Eq. (1) as a function of equivalent-fusion-neutron fluence incident on the calorimeter face. Using power deposition profiles such as those in Fig. 3, one can calculate the expected ΔT in each region of the moderator.

Figure 5 shows the expected temperature increase within the front 10 cm of the moderator, for the various TFTR operating modes listed in Table 2. Using one of the most sensitive hydrocarbons as the working medium, D-T operation in the TFTR with fusion power amplification $Q \approx 1$ for 1.0 s will give $\Delta T = 0.3°C$ near the front face, which would produce an easily measured 0.2% change in resistance of a resistance thermometer. (Mode III operation is assumed.) With pulses of several seconds length, as in Mode V, a wellinsulated calorimeter could undergo a ΔT of several tens of degrees during a multihour run at a duty factor of the order of 0.01.

Deuterium Plasmas

If we stipulate that ΔT = 0.01°C is the minimum temperature change needed for a usefully accurate measurement, then it appears that the calorimeter technique will always be marginal for use with deuterium-only plasmas in the TFTR, unless the fusion pulse length is at least several seconds. However, if heat losses from the working medium can be made very small, then ΔT could be built up from pulse to pulse, and might achieve interesting values in deuterium-only operation even with 1-s pulses, after 50 to 100 of such pulses. At any rate, the calorimeter technique could be used with predominantly deuterium plasmas containing at least a few per cent of tritium.

[In either D-T or D-D operation, ΔT could be multiplied substantially by seeding the working medium with fissionable material. However, the calibration would then depend partly on neutronics calculations, and would be sensitive to the spectrum of the incident neutrons.]

Experimental Considerations

Temperature Sensors

Temperature increases will be measured by thermopiles and platinum-resistance thermometers distributed along the major radial axis and at other positions, as indicated in Fig. 2. An appropriate thermopile would consist of about 20 thermocouples in series, perhaps made of Pt-Rh wires; the thermopile response would be of the order of 100 μV for ΔT = 0.1°C. While thermistors would be much more sensitive, thermistor measurements have been generally found to be irreproducible or even incomprehensible when the thermistors are located in intense radiation fields.[4]

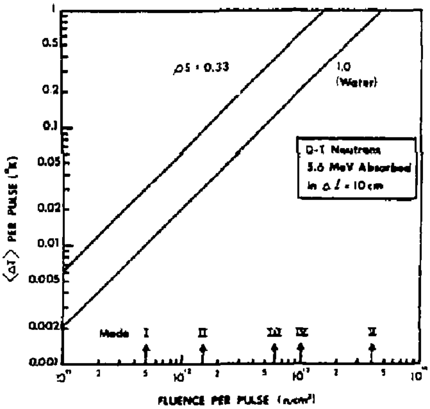

Fig. 5. Expected temperature increase per D-T fusion pulse, averaged through the front 10 cm of the calorimeter, as a function of fusion neutron fluence per pulse. Operating modes are defined in Table 2.

Table 2

OPERATING MODES WITH DEUTERIUM-TRITIUM IN THE TFTR

MODE	EXPECTED DATE*	# SHOTS PER RUN**	PULSE LENGTH	BEAM POWER†	FUSION GAIN	TYPICAL FLUX n/cm² s***	FLUENCE PER RUN n/cm²***
I	1984	3-5	0.5 s	15-20 MW	0.1-0.3	1×10^{12}	2×10^{12}
II	1985	10	0.5 s	20-25 MW	0.3-1	3×10^{12}	1.5×10^{13}
III	1986	20-30	1-1.5 s	20-30 MW	0.5-1	5×10^{12}	1×10^{14}
IV	1988	30-50	1.5 s	25-35 MW	~1	8×10^{12}	4×10^{14}
V	1988	50-100	3-5 s	[illegible] MW	[illegible]	1.5×10^{13}	1×10^{15}

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* Dates given are tentative.

** Interval between shots ~ 5 to 10 min

† Including fractional-energy particles.

*** 14-MeV fusion neutrons

If the resistance measurement is automated, then the time response for the calorimeter system is essentially the time for the thermopile to come into equilibrium with the working medium, or a period of several seconds. Thus it would not be possible to monitor changes in the fusion energy production during a single pulse in TFTR, even for Mode V operation. In any event, transient noise caused by gamma radiation might prevent useful temperature measurements until immediately after the power pulse.

Thermal Insulation

Neutronics results such as those illustrated in Fig. 3 indicate that the depth of the working medium should be at least 60 cm to absorb more than 95% of the incident neutrons and also the gammas that are both incident and produced in the moderator. The moderator region should be enclosed in a thin material that has a low affinity for neutrons of moderate to high energy and that also has a low thermal conductivity.

The moderator must be surrounded by thermal insulation (see Fig. 2), to prevent temperature changes in the liquid due to variations in ambient temperature, and to minimize heat loss from the moderator so that the full value of ΔT on the central axis will be measured. The thermal insulation can be a solid such as Johns-Manville MIN-K. Another approach is to enclose the absorbing medium in a controlled-temperature bath of oil or other fluid that would maintain the container wall at a constant temperature. (In this case, the container wall should have high conductivity.) This technique would be especially applicable to the case of a working medium with a boiling point below room temperature (see Table 1).

Calibration

There are two aspects of the calorimeter calibration:

(1) The response of the device to a given absorbed energy. For this calibration, heating elements would be placed at a number of positions in the working medium, to simulate the expected nuclear energy deposition profile. The response of the measurement system would be determined for a known amount of energy dissipated in these heating elements.

(2) The relation of the incident neutron and gamma energy to the total fusion neutron production. As a check on the conclusions of the neutronics analyses discussed in earlier sections, the device could be calibrated against a known neutron source by integrating the neutron intensity and spectrum, and gamma-ray intensity at the calorimeter front face, when a deuterium beam bombards a tritiated target inside the torus (as is planned for calibration of the TFTR neutron detectors). An integration period of at least several hours would be required for this calibration.

Conclusions

Advantages of the Neutron Calorimeter

(1) The detection equipment is simple and robust. No pneumatic transport tubes are necessary to get pulse-by-pulse measurements.

(2) The measurement equipment is simple. Long decay times allow easy collection and storage of data.

(3) The detector response is limited and cannot be saturated.

(4) The system is insensitive to back-scattered low-energy neutrons which may enter the calorimeter.

(5) The method is capable of providing a direct measurement of fusion power production, rather than by inference from flux and spectral measurements.

(6) The method will become increasingly appropriate as experimental fusion reactors produce larger neutron yields per pulse.

Disadvantages of the Neutron Calorimeter

(1) The lower limit to useful detection is about 10^{11} fusion neutrons per cm^2.

(2) Considerable space is required to accommodate the bulk moderator needed to prevent fast neutrons and gammas from entering the central region of the calorimeter from the sides.

(3) Time resolution is poor — of the order of 1 to several seconds.

Application to Long-Pulse Test Reactors

The demonstration of the ability to correlate the power deposition in an isolated "blanket module" to the total fusion power production, as well as the testing of the ability of neutronics codes to predict the measured power deposition profiles, will provide valuable information for the design of experimental power modules for next-generation tokamak test reactors. In toroidal geometry, reflected neutrons may have a significant effect on the power deposition in an isolated module. The ability of neutronics codes to describe the correct neutron field can be tested only in the TFTR, in the 1980s.

In the ETF/INTOR type of test reactor, the D-D neutron flux is expected to be of the order of 4×10^{11} n/cm^2/s. Then a 100-s pulse would produce a temperature increase of about 1°C in a calorimeter of the type discussed here, and slow variations in power output during the pulse could be followed. Hence a neutron calorimeter could find valuable application in the shakedown phases preceding D-T operation, as well as for monitoring the neutron power generated during the more intense D-T operations.

Acknowledgment

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4. J. Schivell, private communication; S. Kronenberg, private communication.

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*On leave from EG&G Idaho, Inc., Idaho Falls, ID 83415.