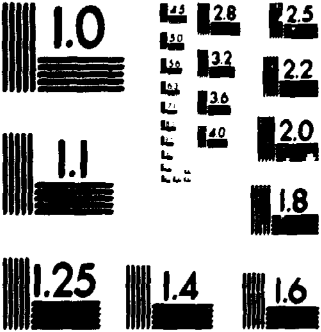

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FEASIBILITY STUDY OF INCORE FISSION CHAMBER APPLICATION FOR NEUTRON FLUX MEASUREMENTS ON THE NET BLANKET

COMITATO NAZIONALE PER LA RICERCA E PER LO SVILUPPO DELL'ENERGIA NUCLEARE E DELLE ENERGIE ALTERNATIVE

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ASSOCIAZIONE EURATOM-ENEA SULLA FUSIONE

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RT/FUS/87/11

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Summary A feasibility study has been carried out on the use of in-core fission chambers as neutron diagnostic tools to perform neutron flux measurements on the blanket component of NET. The high neutron and gamma fluxes and the severe thermal-mechanical and magnetic conditions of the blanket structure have been taken into account in this analysis. Preliminary design criteria and specifications of an in-core detector are presented for NET application. A research and development programme is outlined which aims to obtain more information on the tecnological constraints arising from the severe conditions of the NET blanket.

Riassunto Uno studio di fattibilità è stato condotto sul possibile utilizzo di camere a fissione in-core per misure di flusso neutronico nella struttura blanket (Mantello) della macchina termonucleare NET. In questa analisi sono state considerate le difficili condizioni termomeccaniche e magnetiche in cui opera il blanket. Vengono presentati in questo rapporto criteri preliminari di progettazione e specifiche di una camera a fissione da utilizzare sul NET. Viene inoltre proposto un programma di ricerca e sviluppo concernente i limiti.tecnologici, dovuti alle difficili condizioni del blanket.

1. INTRODUCTION

The NET-Technology Fusion Programme [1] will play a very important role in giving determining information on critical issues related to the feasibility of fusion reactors (DEMO).

For the many technological objectives of NET, the knowledge of neutron fluxes, fluences and energy spectra in the various components (especially in the blanket) is a relevant parameter for the improvement of fusion reactor design concepts.

The aim of this study is to assess the diagnostical possibilities of local fission probes/chambers in measuring the neutron fluxes into the blanket component of the NET device. The fission chambers (FC) are generally cylindrical ionization chambers with a fissile coating on the walls to enhance the ionization current.

The neutron diagnostic systems of today's large tokamaks (JET, TFTR, FTU, etc.) use fission chamber systems to monitor the neutron emission, primarily because of their gamma discrimination and high sensitivity. In nuclear power plants the fission chambers are used as standard instrumentation for monitoring reactor power and neutron flux profiles.

With regard to this feasibility study, the in-core fission chambers have been considered as the only possible diagnostic tool able to operate in the extremely severe thermal-mechanical conditions and high magnetic and neutron-gamma radiation fields of the NET-blanket environment.

In Sec. 2 the main features of the fission chambers and their operation are revised. In Sec. 3 the NET-blanket environment features and their influence on the fission detectors are analyzed, and the feasibility of in-core FC application on the NET device is discussed. Section 4 deals with the design criteria and the required specifications of a feasibile in-core fission chamber for neutron flux measurements in the NET blanket. In Sec. 5, the needs of a technological R&D programme on the in-core fission detectors are pointed out. The main conclusions emerging from this feasibility study are presented in Sec. 6.

2. GENERAL CONSIDERATIONS ON FISSION CHAMBERS

The main features and the state of the art of fission chambers are outlined in the following.

2.1 Principle of operation of the fission chamber (FC) [2,3,4,5]

The detection of neutrons always proceeds through a conversion reaction (generally neutron-induced) which transfers the information of interest to the secondary charged particles (protons, fission fragments, etc.). Most neutron detectors are based on the effects produced when a secondary charged particle passes through a gas. The primary modes of interaction involve ionization and excitation of gas molecules along the particle track.

The ionization chambers are gas-filled detectors which collect all the charges created by direct ionization within the gas through the application of an electric field. The main components of a detector are electrodes, insulator, active gas, and cables. Ionization chambers with fissile material coatings on the electrodes are called fission chambers (FC) (Fig.1).

2.1.1 The ionization process in gases As charged particles move through the gas, the ionization process takes place creating ions and free electrons, also known as ion pairs. The practical quantity of interest is the total number of ion pairs created along the radiation track.

During the ionization process some phenomena can occur which affect the ion-pair formation: diffusion, charge exchange, attachment, recombination.

Diffusion - The gas molecules are in thermal motion (m.f.p. $10^{-4} \div 10^{-5}$cm). The ion-pairs take part in this random motion and diffuse away from regions of high density, undergoing many types of collisions.

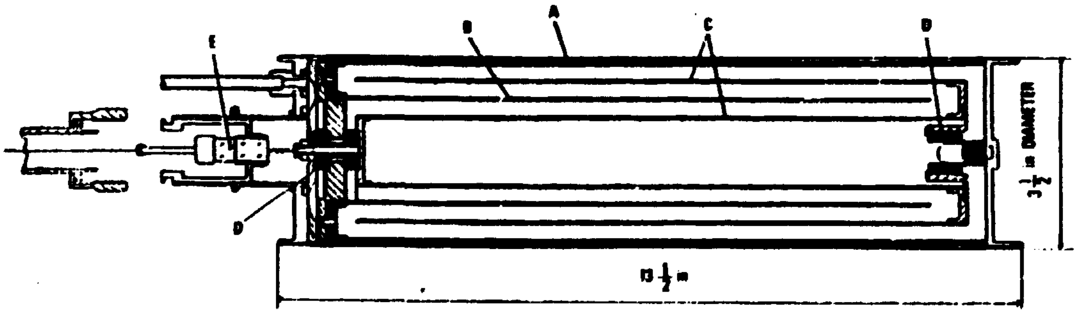


Fig.1

Mechanical layout of a high sensitivity fission chamber

Charge exchange - A positive ion encounters a neutral molecule. An electron is transferred from the molecule to the ion exchanging the charge.

Electronic attachment - In electronegative gases (O, etc.) the free electrons may be captured by the neutral gas to form negative ions (H, N, Ar, hydrocarbon gases have low attachment coefficients and are generally used as filling gases).

Recombination - Collisions between free electrons and positive ions may result in recombination where the electron is captured by the positive ion and the charge neutrality state is established again. This effect is significant in regions with high concentration (Columnar Recombination).

2.1.2 Charge migration-drift velocity-collection time

When an electric field is applied between the electrodes of the FC, the ion pairs move along the field lines. The net motions of the particles consist of superposition of a random thermal velocity together with a net drift velocity in a given direction.

The drift velocity depends on the filling gas (usually a mixture of argon and methane) and on the applied electric field. Consequently the collection time of the charges is related to the drift velocity (generally 10^{-3}s for ions and 10^{-6}s for electrons). This drift of the charged particles constitutes an induced current, called ionization current.

2.1.3 Ionization current-ion saturation Figure 2 illustrates the basic elements of an idealized ionization chamber. A volume of gas is enclosed within a region where an electric field is created by the application of an external voltage. The current-voltage characteristics of such a chamber are sketched in Fig.3. No net current flows when no voltage is applied. As the voltage increases, the electric field separates the ion pairs more rapidly and recombination diminishes. At a sufficiently high applied voltage, recombination is totally suppressed and all original charges, created through the ionization process, contribute to the ion current. Increasing the voltage further, the current cannot increase because all the charges are collected.

This is the region of ion saturation in which the ionization chambers operate conventionally. The current measured in the external circuit is a true indication of the rate of formation of all the charges due to ionization within the active volume of the chamber.

2.1.4 Effects influencing the ion saturation regime Many effects can influence the saturation region. The most important are diffusion, recombination and high radiation level.

Net diffusion

Due to the presence of the electrodes, a gradient in concentration exists for species free to migrate. Therefore a net diffusion process takes place in the direction of decreasing concentration.

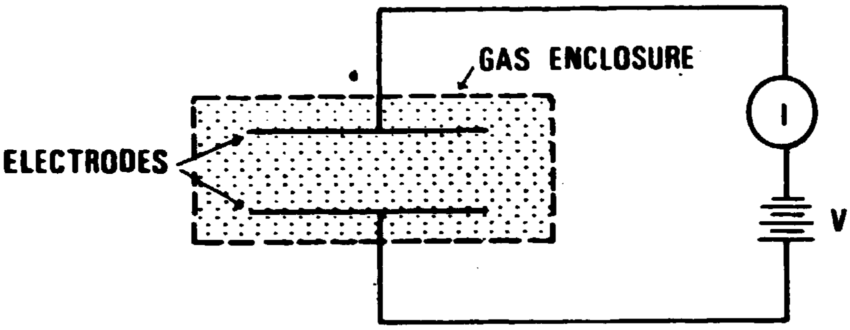


Fig. 2

Basic components of an ideal fission chamber

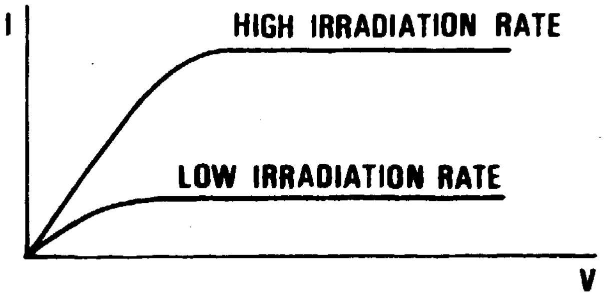


Fig. 3

The corresponding current-voltage characteristics

Recombination

The columnar recombination along the track of heavy charged particles (especially fission fragments) is particularly significant and requires high voltages to achieve the ion saturation plateau.

High radiation effect

The magnitude of the ion current, i.e., the intensity of radiation, influences the recombination. At high radiation levels the density of ion pairs is high and consequently the recombination rate will be more significant than at a low level of intensity (Fig. 3).

These effects become negligible by applying higher electric fields within the active volume of the chamber.

2.1.5 Operational modes of the fission chamber The detector can be operated in the pulse or current modes (Fig. 4 a,b). The former is based on the well-known pulse shape discrimination technique, selecting only the neutron pulses. Conventional detectors achieve rates up to 10^5 cps; particular chamber designs and pulse processing electronics can raise this limit up to 10^7 cps [6]. The latter mode measures the ionization current directly when very high flux levels have to be detected (more than 10^{11} n/cm^{2}s) and the gamma contribution (which is not discriminated) to the direct current can be taken into account by gamma compensation techniques (Campbell, etc.) (Fig. 4 b) [7].

The lifetime of fission chambers, or the maximum fluence detectable without a loss of the neutron sensitivity, can be largely improved (factor 3) by using combined fertile/fissile coatings to reduce the gradual burn-up of the neutron sensitive material (Fig. 5) [8].

2.2 Nuclear reactions and neutron sensitivity

As stated in subsection 2.1, the fission detector is an ionization chamber with its inner surface coated with fissile deposit.

The neutron-induced fission reactions have the outstanding characteristic of a high Q value (200 MeV), with 160 MeV appearing as the kinetic energy of the fission fragments which have a high ionization power. The

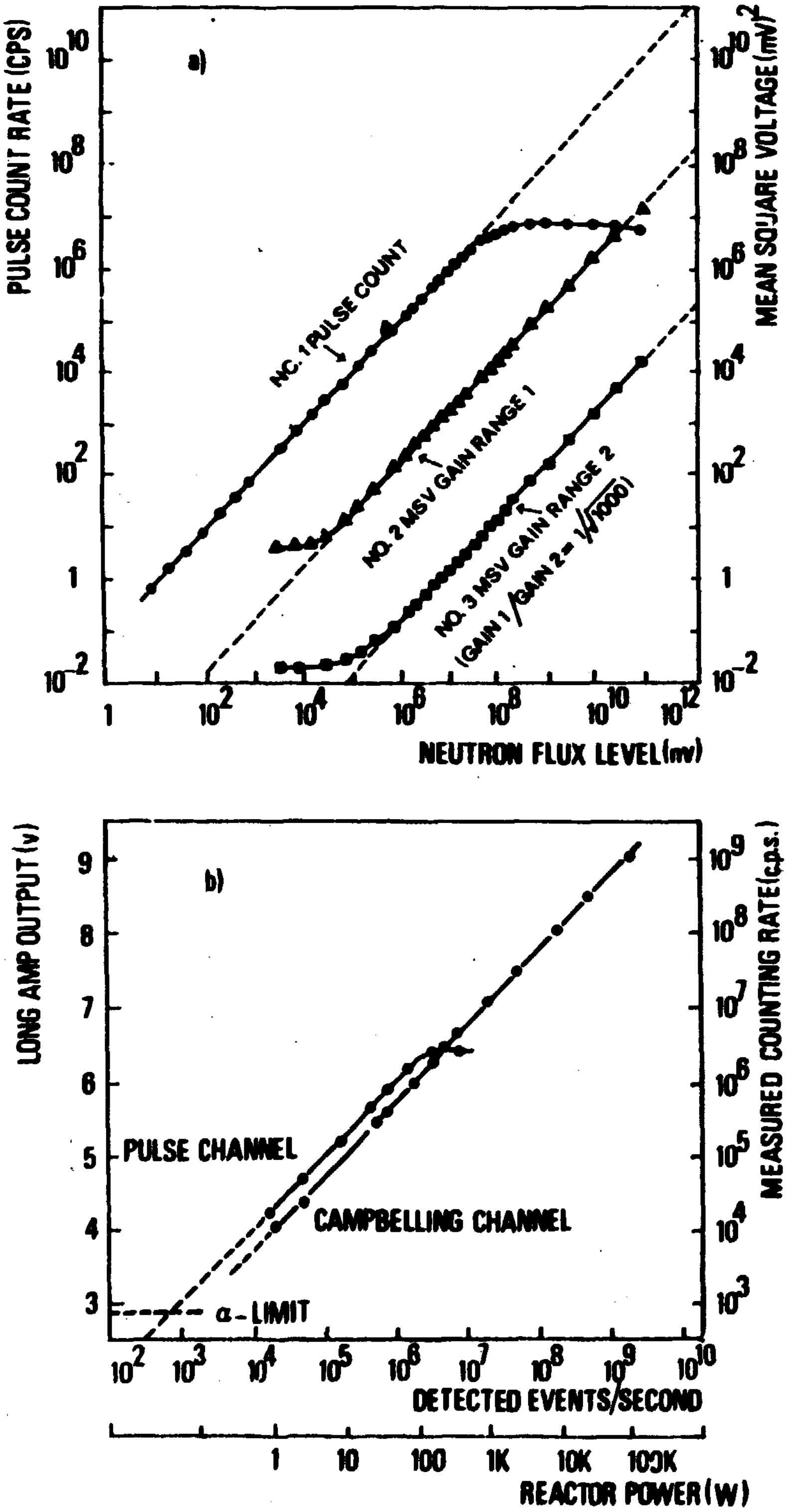


Fig. 4

Response of FC to a wide range of neutron fluxes (a) and reactor power (b). The detectors are operated in pulse and current modes.

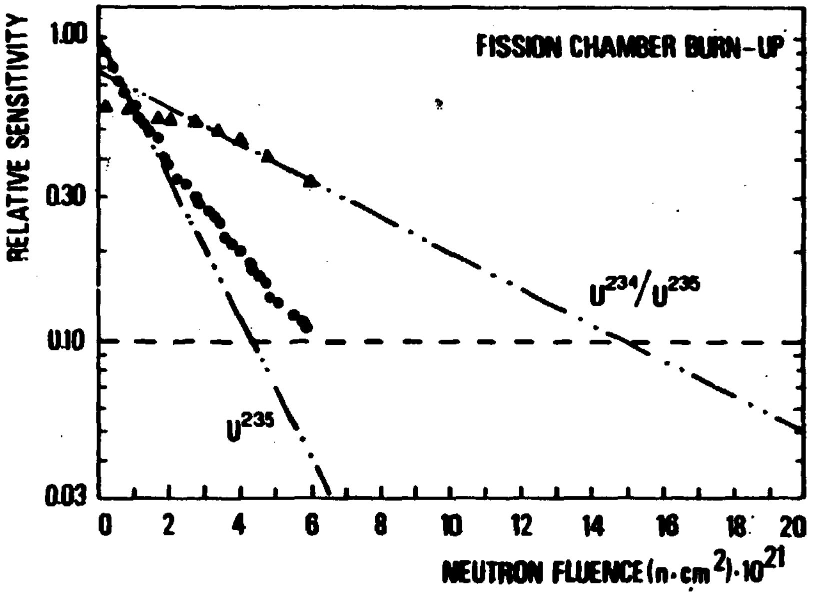


Fig. 5

Burn-up behaviour of standard and fertile/fissile fission chambers with neutron fluence

neutron-induced fission reactions can therefore be expected to be of a larger magnitude in most detectors than any other competing reaction or other event, due to background or counter contamination. Under these circumstances, extremely low background rates can be achieved and neutron counting can be practically carried out at very low counting rates.

Figure 6 shows the fission cross sections of various fissile nuclides, including some for the detection of fast neutrons.

The detection efficiency or neutron sensitivity of the FC depends on fissile deposit thickness, geometrical characteristics of the detector and the fissile nuclide.

Two effects generally perturbate the detection of neutron fluxes - self-shielding and flux depression - caused respectively by the mechanical parts and the total

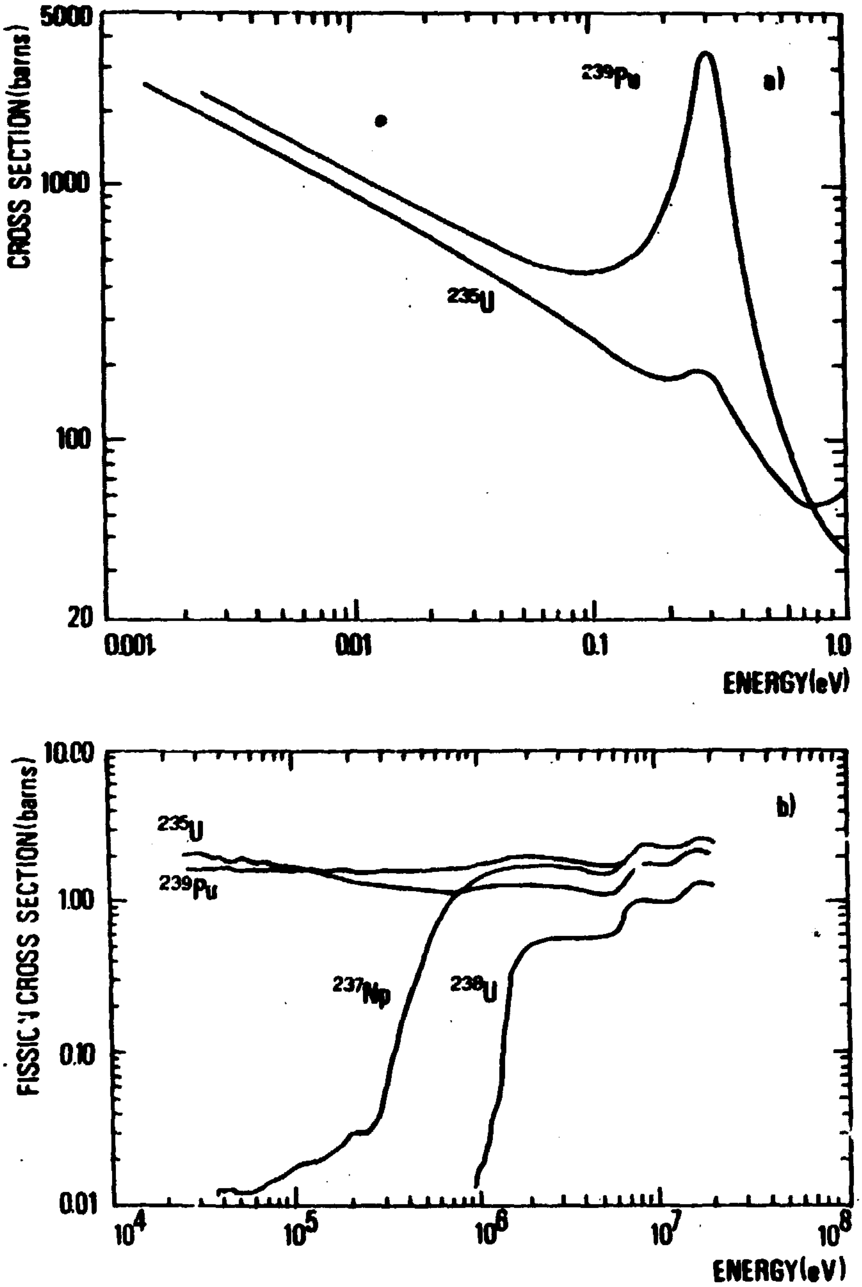


Fig. 6

Fission cross sections of various fissile nuclides

volume of the fission chamber. These effects can be estimated with accuracy by means of numerical neutron transport codes such as the MCNP [9] and the experimental data can therefore be corrected.

2.3 Applications of fission chambers

In nuclear reactors the safety and reactor control systems are generally based on detectors that respond primarily to neutrons. The neutron sensors are usually of the gas-filled type because of their inherent gamma ray discrimination properties, wide dynamic range, long term stability, and resistance to radiation damage. The fission chambers are the detectors most widely used for monitoring the reactor power and getting maps of the flux profiles [10]. The extreme conditions associated with reactor operation often lead to particular designs of the neutron detectors to withstand the severe constraints (high temperatures, high pressures, etc.).

It is conventional to subdivide the reactor detection instrumentation in two categories: <u>out-core</u> and <u>in-core</u>.

Out-core detectors are located some distance from the core (also outside the pressure vessel) and give information on the neutron flux integrated over the entire core. They are usually placed in a nonsevere environment with the following typical conditions: thermal neutron flux up to 10^{11} n/cm^{2}s; gamma irradiation rates up to 10^6 R/hr; operating temperatures and pressures respectively of 100°C and 0.1 MPa. The characteristics of such instruments must take into account the expected neutron level signals with noise levels, the speed of response, and gamma discriminations. Multiple detector systems are usually provided, each properly designed to cover a specific subset of the power range (Fig.7). Figure 8 shows a typical commercial FC out-core detector, manufactured by Westinghouse (WL 23830).

In-core sensors are usually located in the reactor core and are used to provide detailed knowledge of the neutron flux shape in the core. These sensors can either be movable or fixed in a selected location. Compactness and miniaturization are the primary features of the in-core detectors (external diameter < 2 cm, length = 3 ÷ 10 cm). Typical operating conditions are thermal neutron flux up to 10^{14} n/cm^2 s, gamma flux up to 10^9 R/hr, operating temperatures up to 550° C, and pressures up to 15 MPa. The characteristics of an in-core detector are listed in Fig. 9. The <u>in-core fisssion chambers</u> have established a satisfactory performance notwithstanding the severe in-core reactor environment (high fluxes and temperatures) [10,11].

The NET-blanket environment is of severe thermal - mechanical and magnetic constraints with high neutron

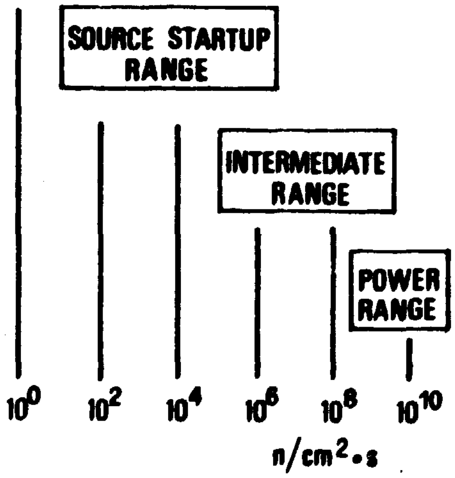
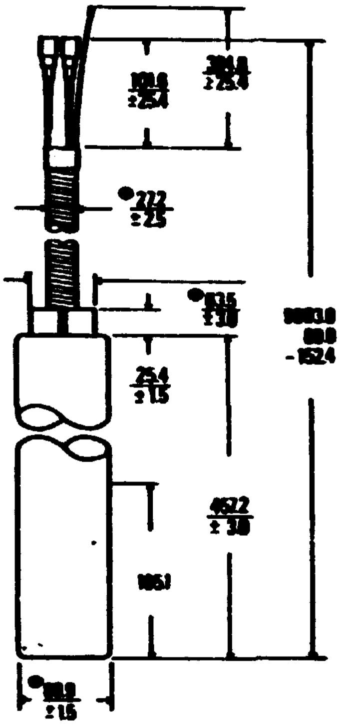


Fig. 7

Typical multiple detector systems for controlling reactor power

MECHANICAL

Diameter:	
Shield can	(89.9 mm)
Cable:	
Signal	(4.32 mm)
Neutron	(3.81 mm)
Electrostatic Shield	(27.2 mm)
Length:	
Shield Can	(45.7 cm)
Cable	Approx. (869 cm)
Overall	(909+0.15 cm)
Sensitive Length	(20.2 cm)
Sensitive Area	1138 cm^2
Electrode Spacing	0.20 cm
Electrode Coating	1.0 mg/cm^2
Gas Fill Pressure	133 cm-Hg
Connectors	Coaxial



WL - 23830

MATERIALS

Neutron Sensitive Material	Uranium enriched in U^{235}
Gas Fill Mixture:	
Ar	92%
N	7%
He	1%
Case and Electrode Materials	Aluminium
Cable Sheath Material	Stainless Steel
Insulation Materials:	
Detector	99.5% Al_2O_3
Cable	Sillica
Internal	99.5% Al_2O_3
External	Glass Cloth Tape (3M Type 27)
Shield Can Material	Aluminium
Conduit Material	Aluminium

IMPEDANCE

Detector plus Cable Resistance			
Signal Electrode to Case	10^{12}	Min	Ohms
HV Electrode to Case	10^{12}	Min	Ohms
Signal Electrode to HV Electrode	10^{12}	Min	Ohms
Detector Case to Shield Can	10^{10}	Min	Ohms
Detector plus Cable Capacitance			
Signal Electrode to Case	845	Max	pf
HV Electrode to Case	1070	Max	pf

MAXIMUM RATINGS

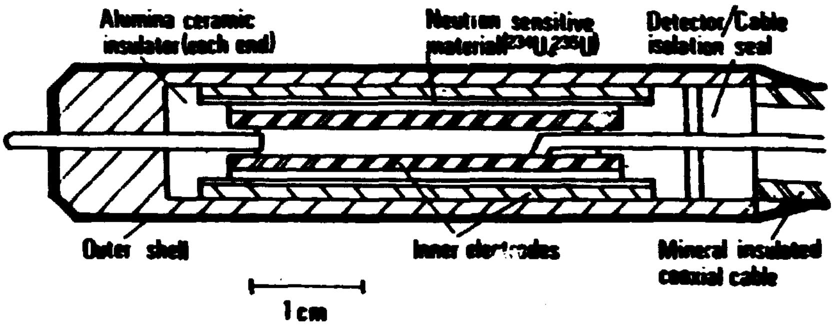
Voltage between Electrodes		±1000	Max	Volts dc
Temperature	(178°C)	350°	Max	F
External Pressure	(3.5 kg/cm^2)	50	Max	psig
Thermal Neutron Flux		$2x10^{10}$	Max	nv

OPERATING RATINGS

Operating Voltage	-500		Volts
Thermal Neutron Flux Range			
Lower Limit	1		nv
Upper Limit	$2x10^{10}$		nv
Thermal Neutron Sensitivity	0.7		cps/nv
Gamma Flux Range	0.10^6		R/HR
D.C. Mode Gamma Sensitivity	$<5x10^{-11}$		A/R/HR
D.C. Mode Neutron Sensitivity	$1.2x10^{-13}$	Min	a/nv
A.C. Mode Neutron Sensitivity	$1x10^{-10}$	Min	$<V^2>$/nv
A.C. Mode Neutron to Gamma Sensitivity Ratio	4.5	Min	R/HR/nv

Fig. 8

Data sheet of a commercial out-core fission chamber



FISSION CHAMBERS: RS-C6-1100-21X regenerative LPRM

Four miniature fission chambers are used in each LPRM Assembly. Each chamber is approximately 6.4 cm long, and is attached to a hermetically-sealed, mineral-insulated signal cable which extends beyond the reactor vessel boundary. The fission chambers and cable are designed for exposure to the reactor coolant; the sheaths of the signal cables are brazed into the seal plug, which is a part of the reactor pressure boundary. All materials are in conformance with the required codes for in-core safety related equipment. Following are specifications for each detector.

MATERIALS

Outer shell .... 304L stainless steel
Inner electrodes .... Titanium
Insulation .... High-purity Al_2O_3
Neutron sensitive material
($^{234}U \rightarrow ^{235}U$ during operation) .... ^{234}U and ^{235}U

NUCLEAR DESIGN

Neutron sensitivity .... 0.88×10^{-17} amp/n/cm²s⁻¹ in test reactor (note 1)
0.5×10^{-17} amp/n/cm²s⁻¹ in BWR spectrum
Thermal neutron flux range .... 1.4×10^{12} to 1.4×10^{14} n/cm²s⁻¹
Deviation of neutron signal from linearity at nominal voltage .... ± 1% (note 2)
Gamma sensitivity .... 2×10^{-14} amp/R/hr
Burn-up life .... 8.4 yrs @ 6.7×10^{13} n/cm²s⁻¹ in a BWR spectrum (note 3)

ELECTRICAL DESIGN

Design operating voltage .... 100 Vdc
Maximum operating voltage .... 200 Vdc
Insulation resistance (IR) (includes cable) > 10^{11} ohms, 25°C
> 10^{9} ohms, 300°C
Initial calibration current .... ~500µA

THERMAL DESIGN

Maximum design temperature (continuous) .... 288°C

NOTES:

1. Flux level in test reactor is determined by activation foils. Measured sensitivity of miniature fission chambers is greater in the test reactor because the effective thermal neutron cross-section is greater.
2. Gamma-induced currents in the signal cable are substantially lower than those for the detector, and do not affect the linearity of the detector.
3. Burn-up life corresponds to a reduction in neutron sensitivity to the point where neutron-to-gamma signal ratio is calculated to be 5:1. Extension of lifetime is possible through user experience, including gamma flux and electronics calibration.

Mineral-insulated cable: RS-C6-1100-21X regenerative LPRM

Mineral-insulated coaxial cables are used to carry signal currents from the miniature fission chambers through the reactor pressure boundary to the instrumentation connecting cables. At the connector end, the coaxial signal cable termination is protected by a moisture-resistant coating on the insulator. The connector mates with existing LPRM connecting cables for full interchangeability between LPRM assemblies of varying manufacture. Problems with this seemingly routine connection generally account for more LPRM detectors being in bypass than any other single cause, including seal failure. Reuter-Stokes provides detailed connection and waterproofing instructions with each LPRM Assembly to reduce connection time and provide secure, watertight connections.

MATERIALS

Outer sheath .... 304L stainless steel
Inner conductor .... 304L stainless steel
Insulation, cable .... High-purity Al_2O_3
connector .... Rexolite

IMPEDANCE

Resistance @ 25°C (includes fission chamber) .... > 10^{12} ohms (w/o connector)
Resistance @ 300°C (includes fission chamber) .... > 10^{9} ohms (w/o connector)
Cable Capacitance .... ~300 pf/meter

Mineral-insulated cables used in the RS-C6-1100-21X regenerative LPRM meet or exceed all maximum ratings for the Assembly as a whole, including lifetime, maximum temperature, maximum pressure, and maximum radiation levels. The gamma-induced current in the cables is negligible, and will not affect linearity.

© [illegible] Reuter-Stokes

Fig. 9

Characteristics of an in-core fission chamber and mineral-insulated cables and gamma fluxes. These extreme conditions lead to considering the in-core fission chambers as the only possible diagnostic tool for neutron flux measurements on NET.

3. NET ENVIRONMENT

3.1 NET blanket characteristics

For this feasibility study the neutron emission of the NET burn-up phase [1] has been considered, particularly the high neutron and gamma fluxes on the first wall outboard (FWO) and on the blanket outboard (BO). The neutronic characteristics and working conditions of the NET blanket at the FWO and BO positions [12] are

1 - Neutron flux $10^{14} \div 10^{13}$ n/cm^{2}s (20% with En>10 MeV
70% with En>0.1 MeV)

2 - Gamma flux $10^{8} \div 10^{6}$ R/hr (70% with Eg>0.4 MeV)
or $10^{14} \div 10^{13}$ ph/cm^{2}s

3 - Absorbed energy dose rate $10^{4} \div 10^{2}$ Gy/s

4 - Magnetic fields up to 5 Tesla

5 - Working temperature of the blanket breeding modules
200 ÷ 600°C

6 - H_2O blanket cooling pressure 8 Mpa

In the following, the NET environment features and their influence will be analyzed for each component of the in-core detector:

- Electrodes (cathode outer cage, anode)
- Insulator
- Cables (mineral insulated)
- Filling gas

The commercial in-core fission chambers are generally designed for operation in thermalized neutron fluxes. Their application to the NET blanket might be limited because of the high energy neutron component (fusion peak) and magnetic field.

3.2 NET influences

In this subsection the NET constraints on the FC components are analyzed as follows:

A - Neutron and gamma-induced heating

B - Neutron and gamma damage

C - Gamma exposure

D - Magnetic field

E - High working temperatures and pressures

A - Neutron and gamma-induced heating

Taking into account the neutron-gamma fluxes and spectra [12], the radiation-induced heating has been evaluated for the different components of the in-core detector at two locations of the NET DN-outboard blanket (respectively behind the first wall - FWO - and just after the blanket - BO):

	Deposit of energy (W/cm^3)		DT/dt	(°C/s)
	FWO	BO	FWO	BO
Electrodes SS316	16	1	4	0.25
Insulator Alumina (A1203)	7	0.3	2	0.05
Mineral Insulated Cable (MgO)	7	0.3	2	0.07
Filling gas Argon (0.1 MPa)	$7*10^{-4}$	10^{-4}	0.8	0.1

The energy deposit achieves high values. The NET discharges will last at least 200 s up to 1000 s and consequently the rise in temperature will be quite high. From this evaluation it results that the in-core detector must be necessarily cooled at any location in the blanket.

B - Neutron and gamma damage

In the NET blanket the radiation will reach high values:

Fluence	10^{26} n/m^2
Dose rate	$10^2 \div 10^4$ Gy/s
Working temperature	250 ÷ 600° C.

A significant degradation of the mechanical and electrical properties of the various materials is expected. Particular care must be taken in the choice of the materials for the in-core FCs because of the radiation damage.

Electrodes/cage The commercial FC are generally of SS316 or SS304. The SS316 L austenitic steel and 1.4914 martenstic steel have been selected as potential materials for the structural components of the NET blanket [13]. These materials can be also selected for the incore FCs. A lower content of Ni, Mn, Cr, Co would be desirable in order to minimize the neutron-induced activation which perturbates the detection of the neutron flux.

Insulator The ceramic A1203 alumina is the most widely used electric insulator. Its mechanical/structure and electrical properties have been tested in high dose rates at high fluences for different temperatures [14, 15, 16] (Figs 10, 11). In recent experiments [17] values of $3*10^{-5}$ $(ohm*m)^{-1}$ have been measured at 400°C and at a dose rate of 5000 Gy/s for the alumina. The electrical conductivity increases strongly with the ionizing dose rate. The influence of the radiation damage on the dielectric breakdown strength has not yet been sufficiently investigated.

Based on available data relating to the main requirements of low electrical conductivity and radiation damage [13, 18], the selected materials for the insulator of the in-core FC should be

AL2O3 or MgAl2O4

<u>Cables</u> Due to the high temperatures, the MgO mineral-insulated cables must be considered for the in-core detector.

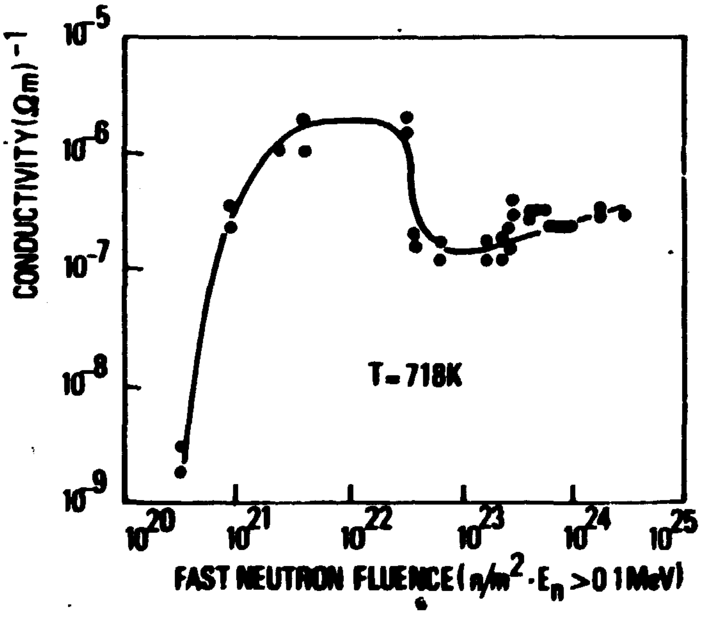


Fig. 10

Electrical conductivity of alumina as a function of neutron fluence

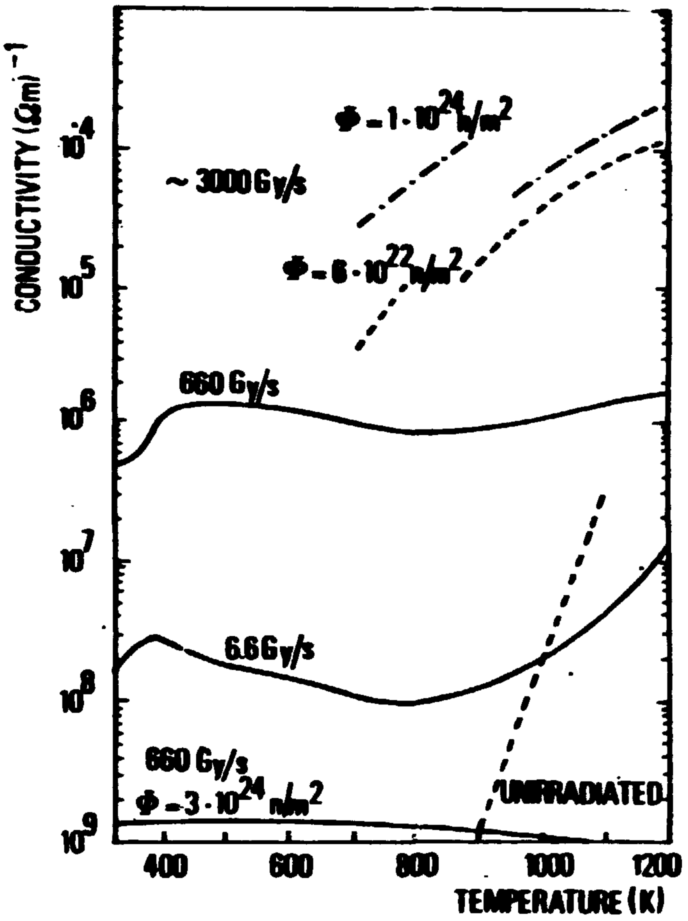


Fig. 11

Electrical conductivity of alumina as a function of temperature at different dose rates [14]

The electrical degradation effect also takes place in the mineral-insulated cables and the processes (γ, n, e; γ, e), due to the high radiation field, can induce a spurious current in the cables [19].

Experiments have been carried out on the electrical conductivity and the radiation-induced current for different temperatures at various dose rates. No good proportionality between conductivity and dose rate has been found and the experimental data are still insufficient [19, 20, 21] (Fig. 12).

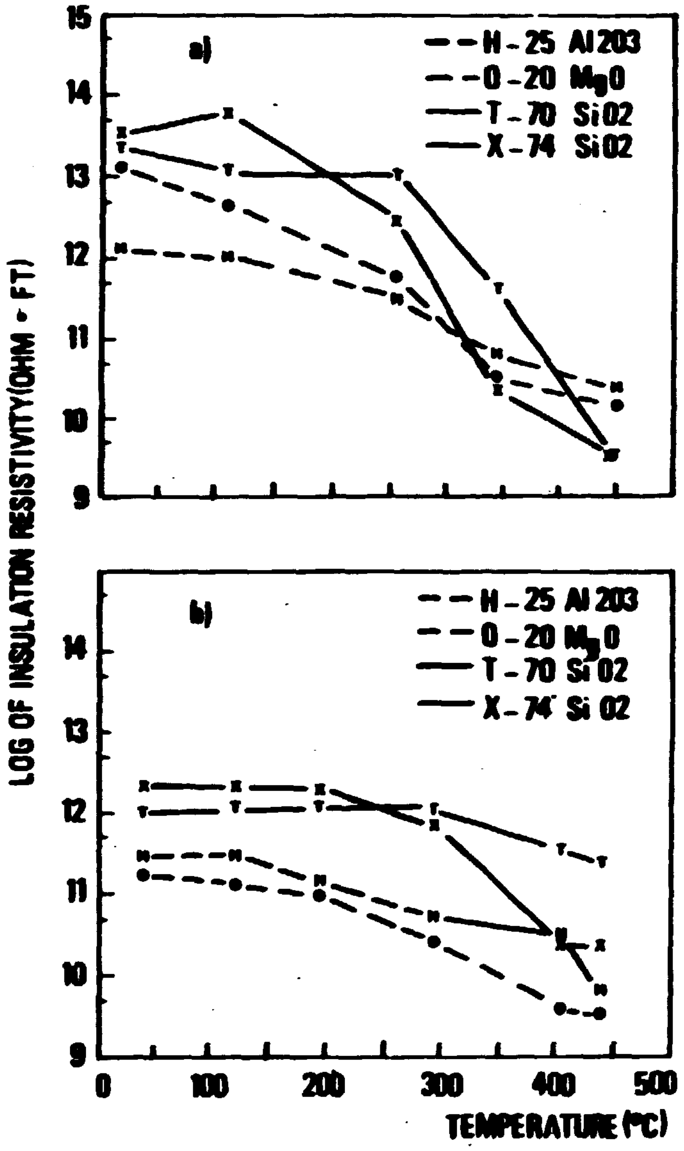


Fig. 12

Insulation resistance vs temperature (a), and in a gamma radiation field of 10^6 R/hr (b)

Further studies are necessary on the electrical conductivity and the dielectric breakdown strength of the FC insulating materials and on the radiation-induced current in function of the temperature at high dose rates (up to 10^4 Gy/s) and at high gamma-neutron fluences (Fast Breeder Reactors).

Gas fill No important neutron-gamma damage occurs on the gases generally used in the fission chambers. The only effect is the photocurrent, induced in the gas by the gamma radiation, which can strongly contribute to the ionization-saturation current.

C - Gamma exposure

The gamma radiation can produce significant ionization in the FC gas if the gas photosensitivity is high, affecting the detection of the neutron flux. Therefore, the saturation current is the sum of the gamma contributions plus the contributions of the neutron-induced fissions. The general rule to minimize this deleterious effect is to keep the active volume, as regards the electrodes, small (i.e., small cathode surface and interelectrode spacing).

The gamma exposure at the locations behind the first wall and the outboard blanket has been evaluated:

$$\phi_{FWO} \cdot 2*10^{8}\ R/hr \qquad \phi_{BO}\ \ 2.5*10^{6}\ R/hr$$

The available in-core detectors can operate up to 10^{9} R/hr and their sensitivities to n and gamma fields are as follows:

Thermal neutron sensitivity	$1*10^{-17}$ A/(n/cm^{2}s)
E_n>0.1 MeV neutron sensitivity	$1*10^{-19}$ A/(n/cm^{2}s)
Gamma sensitivity	$2*10^{-14}$ A/(R/hr)

The expected total ionization currents of two in-core detectors (one with U235 deposit, the other with U238 content) have been evaluated for the location behind the first wall with the above specifications, taking into account the neutron and gamma contributions [12]:

Total neutron flux		$4.0 * 10^{14}$ n/cm^{2}s
n - flux with En$\geq$1.0 MeV (40% total flux)		1.6 *
n - flux with En$\geq$0.1 MeV (70% total flux)		2.8 *
n - flux with E $\leq$0.1 MeV (30% total flux)		1.2 *
Gamma flux		$2.0 * 10^{8}$ R/hr
In-core FC with U235	neutron current	$6.8 * 10^{-5}$ A
	gamma current	$0.4 * 10^{-5}$ A
	total current	$7.2 * 10^{-5}$ A
In-core FC with U238	neutron current	$1.6 * 10^{-5}$ A
(detection only of neutrons with En 1 Mev)	gamma current	$0.4 * 10^{-5}$ A
	total current	$2.0 * 10^{-5}$ A

The gamma/neutron signal ratios vary from 0.1 to 0.25, for the U235 FC and U238 FC respectively. In order to have a "gamma background contribution" of 5% on the total ionization current, the neutron sensitivity must be higher, requiring a greater thickness or deposit of uranium content.

A common method to avoid the gamma radiation effect is to employ a gamma compensation technique. Two identical FCs are irradiated by the same neutron-gamma fluxes. Only the first detector is lined with fissile material. The current of the first detector is the sum of the neutron and gamma contributions; whereas the second FC detects only the gamma current. By measuring the difference between the two currents, a signal current is derived which is proportional only to the neutron flux.

D - Magnetic field

The in-core detectors will operate in the presence of magnetic fields up to 5 Tesla; the FC detection processes will be affected by the E × B drift of the free electrons not reaching the anode with the consequent decrease of the ionization current and lack of proportionality between the neutron flux and the ionization current.

The two main parameters playing an important role in this effect are

- the drift angle α (E,B), proportional to B and to m.f. path

$\alpha = \mathrm{arctg}(\omega\tau)$

τ = m.f. time collisions electrons

ω = Larmor frequency electrons

- the average drift velocity w (E,B), inversely proportional to B

$w = k*(E/B)*\omega\tau/(1+\omega^2\tau^2)^{0.5}$ $k = 0.75$

In order to minimize the magnetic influence, generally high electric field and high filling densities (i.e., small m.f.p.) are applied. No experimental and theoretical studies exist of the magnetic effect on fission chambers, whereas with regard to MultiWire Proportional Chambers (MWPC), the magnetic influence has been investigated both experimentally and theoretically [22]. The drift and diffusion behaviours of free electrons in gases with and without magnetic fields are the same in fission chambers as in MWPC.

A detailed investigation [23] has been undertaken with an existing appropriate code [22] in predicting the drift angle α and velocity w values due to strong magnetic fields (4 ÷ 6 T), with applied electric fields (up to 7 kV/cm) at different environment temperatures (200÷600°C) and filling pressures (1 ÷ 10 atm) of suitable gases (Fig. 13).

The results of this numerical evaluation suggest the application of argon at 3-1 atm with electric fields of 3-5 kV/cm respectively, or carbon dioxide at 1 kV/cm within 1 ÷ 3 atm and that the high environment temperatures do not affect the detection processes of the detector.

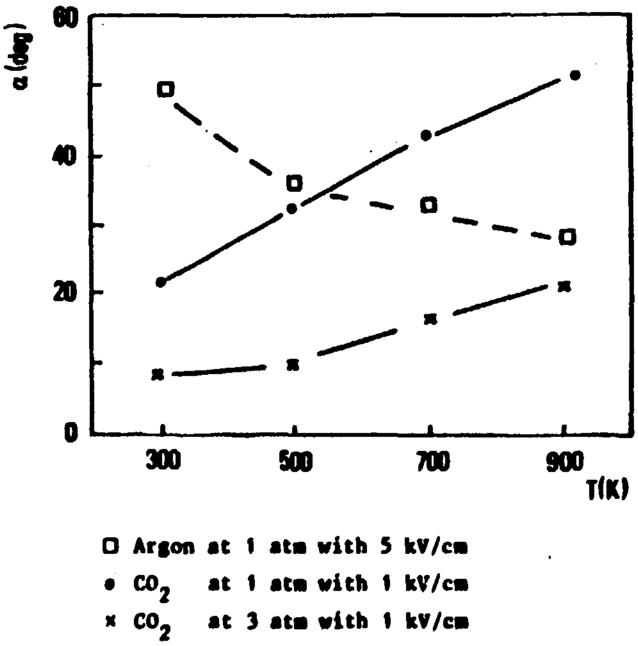


Fig. 13

Drift angle α as a function of temperature at B = 5 Tesla for Ar and CO_2 gases

E - High working temperatures and pressures

The available in-core detectors with suitable neutron sensitivity for NET application can withstand temperatures up to 350 ÷ 400 degrees only. In-core fission chambers exist operating at 550°C but without the required neutron sensitivity for NET.

The pressure constraint (8 MPa in the NET-blanket cooling system) can be easily avoided by putting the chamber in a stainless steel thimble, especially designed to withstand the high pressures.

At high temperature ranges, all FC components can work correctly but their electrical properties are degraded also because of the high values of absorbed energy dose rates.

4. DESIGN CRITERIA

This section gives the main guidelines to determine the design criteria for a feasible in-core fission chamber (FC) to be applied to the NET blanket. As in the previous section, the neutron emission of the NET burn-up phase, i.e., the neutron and gamma fluxes on the first wall outboard have been considered.

The indicative criteria result from the analyses carried out in the previous section on the severe thermal-mechanical and magnetic constraints and on the high nuclear power densities.

In subsection 4:1 the most stringent constraints are briefly recalled and first criteria/parameters are determined. Subsection 4.2 presents the data sheet with the required specifications for an in-core fission chamber to be applied to the NET blanket at the first wall outboard (FWO) position.

4.1 NET - Constraints

A - Neutron sensitivities

This parameter plays an important role in determining the conceptual design criteria of a feasible chamber for NET.

In current mode operation an in-core detector can work up to 1 mA and considering the expected fluxes [12] behind the FWO the required sensitivity (with U235 deposit) is

$$S_{n,therm} = 1 \div 2 \quad 10^{-16} \ \mathrm{A/[n/cm^2 s]}$$

An evaluation of the expected current, due to the neutron flux, shows that the largest contribution (60% of the total current) comes from 21% of the total flux within the neutron energy range between 0.025 eV and 15 keV (see Table 1), due to the high fission cross section values at such energies.

TABLE 1

Neutron sensitivity	$Sn \simeq 10^{-16}$ A/[n/cm^{2}s] at thermal energy
Total neutron flux at FW	$\Phi n \simeq 4 * 10^{14}$ n/cm^{2}s
Total current expected	$It \simeq 3 * 10^{-4}$ A

En	0.025eV-20eV	20eV-15keV	15keV-1MeV	1MeV-14MeV
Φn(%)	3	18	39	40
$I_t(10^{-}$ A)	0.6	1.2	0.6	0.6

Fast neutron detection (i.e., U238 deposit) is therefore necessary to monitor correctly the neutron emission into the NET blanket.

As 40% of the total flux has energy higher than 1 MeV, the required fast neutron sensitivity should be

$$S_{n,fast} > 2 * 10^{-18} \ A/[n/cm^2 s]$$

The presently available fast sensitivity is around $5 * 10^{-19}$ A/[n/cm^{2}s]: in order to achieve the required value, higher uranium content (maximum technical limit is 2 mg/cm^2) and longer sensitive lengths should be used.

With regard to the limit of the maximum fluence, i.e., lifetime of the fission chambers, current values are of 10^{20} n/cm^2 for high temperature in-core detectors.

Taking into account the expected neutron fluxes with their energy dependence, the above mentioned neutron sensitivities, and a maximum detectable fluence value of 10^{20} n/cm^2, the detector with U235 deposit should be operative for 100 days of NET continuous irradiation; while the fast FC (U238) should operate for 1000 days.

B - Gamma sensitivity

It is quite important to reduce the gamma radiation sensitivity in order to obtain a true measurement of the neutron flux.

The active volume where the ionization processes take place should be as small as possible (1 R/hr $\triangleq$ $\triangleq$ $5 * 10^{-14}$ A/cm^3 at NTP).

In the NET blanket the gamma radiation will achieve

$2 * 10^{8}$ R/hr; therefore, to keep the gamma contribution at a low level (a few percent of the total current) the gamma sensitivity should be

$$S_{g} \simeq 1 \div 2 * 10^{-14} A/(R/hr)$$

Due to these sensitivity constraints, the geometrical dimensions of the in-core detectors have to be appropriate to achieve the required parameters. The main indications regarding the sensitivities are

- smallest active volume
- largest uranium coating density

C - Nuclear heating and damage

The evaluations on the radiation-induced heating point out the need of cooling for the in-core detectors. The energy deposited varies from 7 W/cm^{3} for insulating material (alumina) to 16 W/cm^{3} for structural components (SS316), with an increase of temperature of 2°C/sec and 4°C/sec respectively; moreover, the fission chamber will operate in a hot environment (up to 600°C).

The most important macroscopic effect is the decrease (one order per 100 degrees) of the resistivity of the FC electrical components. At 600°C the resistance values of the chamber plus the cables are generally about $10^{6} \div 10^{7}$ ohm with typical applied voltages of 200 ÷ 400 volts.

For the NET application the resistance should not be less than 10^{8} ohm at 600 degrees.

D - Magnetic influence

The toroidal magnetic field can affect the operation of the FC producing a loss in current (or in counting-rate) between 10 and 20% of the expected total current or count-rates.

To avoid this effect, suitable designs of the electrodes and filling gases such as CO_2 (at 1 ÷ 3 atm and 1kV/cm) and argon (at 3 - 1 atm and 3 - 5 k V/cm respectively) should be considered [23].

Low voltages and filling pressures are to be preferred because of the operational voltage and gamma sensitivity limits of the fission chambers.

4.2 Data sheet of the in-core detector for NET

The following subsection gives the required specifications of a fission chamber, operating in the current mode, to be located behind the first wall outboard/inboard for the detection of the neutron fluxes during the burn-up phase of the NET device.

DATA SHEET

MECHANICAL

Maximum diameter	4 ÷ 10 mm	
Sensitivity length	30 ÷ 100 mm	depends on the fissile coating density
Mineral insulated cable length	10 ÷ 20 m	

MATERIALS

Fission chamber

Chamber	SS316 L(low activation components)
Electrodes	SS316 L/titanium
Insulation	High purity alumina (A1203) or MgA1204

Cable mineral insulated

Inner/outer sheath	SS316 L
Insulation	MgO

NUCLEAR CHARACTERISTICS

Fissile material	U235
	U238 (fast detection) or Np 237
Coating density	0.01 ÷ 1 mg/cm^2 for U235
	2 mg/cm^2 or maximum achievable for U238

ELECTRICAL CHARACTERISTICS

Electrode spacing	0.5 mm		
Filling gas	argon	/	CO_2
Pressure	1-3 atm	/	1÷3 atm
Electric field	5-3 kV/cm	/	1 kV/cm
Voltage	200÷400	/	100÷200
Resistance at 20°C (FC + cables)	$> 10^{12}$ ohm		
Resistance at 600°C	$> 10^{8}$ ohm		
Capacitance	low values		

MAXIMUM RATINGS

Neutron flux	$5 \div 10 * 10^{14}$	n/cm^2s
Gamma flux	10^9	R/hr
Temperature	600	°C

TYPICAL OPERATION

Operating voltage	$25 \div 250$	V
Neutron flux	$5*10^{12} \div 10*10^{14}$	n/cm^2s
Thermal neutron sensitivity	$1 \div 2*10^{-16}$	$A/[n/cm^2s]$
Fast neutron sensitivity	$1 \div 2*10^{-18}$	$A/[n/cm^2s]$
Gamma sensitivity	$1 \div 2*10^{-14}$	A/[R/hr]

5. RESEARCH AND DEVELOPMENT PROGRAMME

The analyses carried out to date on the state of the art of in-core fission chambers and on their possible application for neutron flux detection in the NET blanket point out the need of greater effort, in the frame of an R&D programme, on the technological aspects of this investigation to achieve the requirements necessary to withstand the severe constrains in NET.

Considerable work could be performed to upgrade existing FC chambers and to develop prototypes [24] and a fast chamber with a fast electronics system for pulse, fluctuation and current operation in order to achieve a wider flux detection range (ten decades).

Particular attention must be paid to electronic acquisition systems in order to follow correctly the fast rise time of the neutron emission which requires properly designed multiple detector systems to cover a specific subset of the neutron emission range.

Efforts must be made to increase the fast neutron sensitivity (U238 deposit up to 1 ÷ 2 mg/cm^2, suitable sensitive lengths and diameters) and to decrease the gamma sensitivity (i.e., small active volume) for the in-core detectors to obtain a satisfactory ratio of neutron/gamma signals. Gamma compensation techniques should also be envisaged.

As already stated in Sec.3, only appropriate tests and analyses of the nuclear damage at high temperature on the materials and on prototypes of in-core fission chambers can give the desired information.

In the following, an attempt is made to outline the requirements of such an R&D programme:

1) More experimental data on the electrical properties (conductivity and breakdown strength, etc;) of the insulating materials (A1203, MgA1204) with regard to the temperature dependence (200 ÷ 600°C) at high absorbed energy dose rates (up to 10^4 Gy/s) and high neutron fluences (with $E_n > 0.1$ MeV).

2) More experimental data on the properties of mineral-insulated cables (MgO) and on the passive radiation-induced current in the cables for the same set of operating conditions as in point 1.

3) Experimental research on the fast neutron sensitivity and on the gamma sensitivity in order to achieve the required specifications for NET.

4) Design and construction of FC prototypes for fast and thermal detection, assuming the preliminary criteria already mentioned (Sec.4).

5) Development of the general layout of the detection systems with the correlated electronic circuitry and acquisition system.

6) Calibration of the in-core detectors at different neutron energies (14 MeV - 2.5 MeV neutron sources, etc.) and measurement of the gamma sensitivity (possibly at $E_g > 0.4$ MeV) and the radiation-induced current.

7) Performance tests of FC prototypes in a similar NET environment (high temperature, high neutron and gamma fluxes, high energy dose rate) to be performed on fast breeder reactors.

8) Tests of the magnetic influence on the FC operation.

9) Tests of the influence of tokamak transient operation on the FC performances.

10) Feasibility study of a fast fission chamber with fast electronics systems for pulse, fluctuation and current modes over a wide flux detection range (ten decades).

11) In order to have neutron energy-spectral information, a study (and possible developments) is suggested on fission chambers with different absorbing materials for different neutron energy thresholds.

6. CONCLUSIONS

The most important indications resulting from this study on in-core fission chambers as possible neutron diagnostic tools for NET are

- It is feasible to perform measurements of time-resolved local neutron fluxes with in-core fission chambers on NET.
- More experimental data are required on the electrical properties of the FC components with respect to the working conditions of NET.
- A preliminary design concept of an in-core detector for the NET blanket is presented.

However further work is necessary to improve this neutron diagnostic tool with regard to the NET requirements. A Research and Development Programme for the application of the above mentioned neutron detectors to NET is proposed to obtain

A - More detailed experimental data about the electrical properties of insulating materials at high fluence and temperatures.

B - Improvement of the fast neutron sensitivity of fission chambers.

C - Design of an in-core fission chamebr prototype with correlated electronic and acquisition systems.

D - Experimental tests of the FC prototypes.

E - Experimental data of the magnetic influence on the fission chamber operation.

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