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SPECIFICATIONS OF THE TCV POLOIDAL FIELD COILS C,D,F

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1) INTRODUCTION

The TCV tokamak (fig.1) is designed to produce plasmas with currents up to 1.2 MA with variable cross sections in order to study the possibility of optimizing the plasma performances by shaping the magnetic flux surfaces. This objective requires that the poloidal field in TCV is controlled by many coils as shown in the fig. 2. The coils A, B1, B2, C1, C2, D1 and D2 form the induction and ohmic heating coil system. The coils E1 to E8 and F1 to F8 are the shaping coils that control the plasma cross section. The coil set A, B1, B2, E1-E8 are part of a single unit, the central column, already described in int.156.89. The variable configuration of the plasma implies that the TCV coils must be able to withstand very varied load conditions with considerable electromagnetic forces reaching 100 to 200 tons on some of the coils.

In this report, the specifications and maximum load conditions of the C, D and F coils are defined.

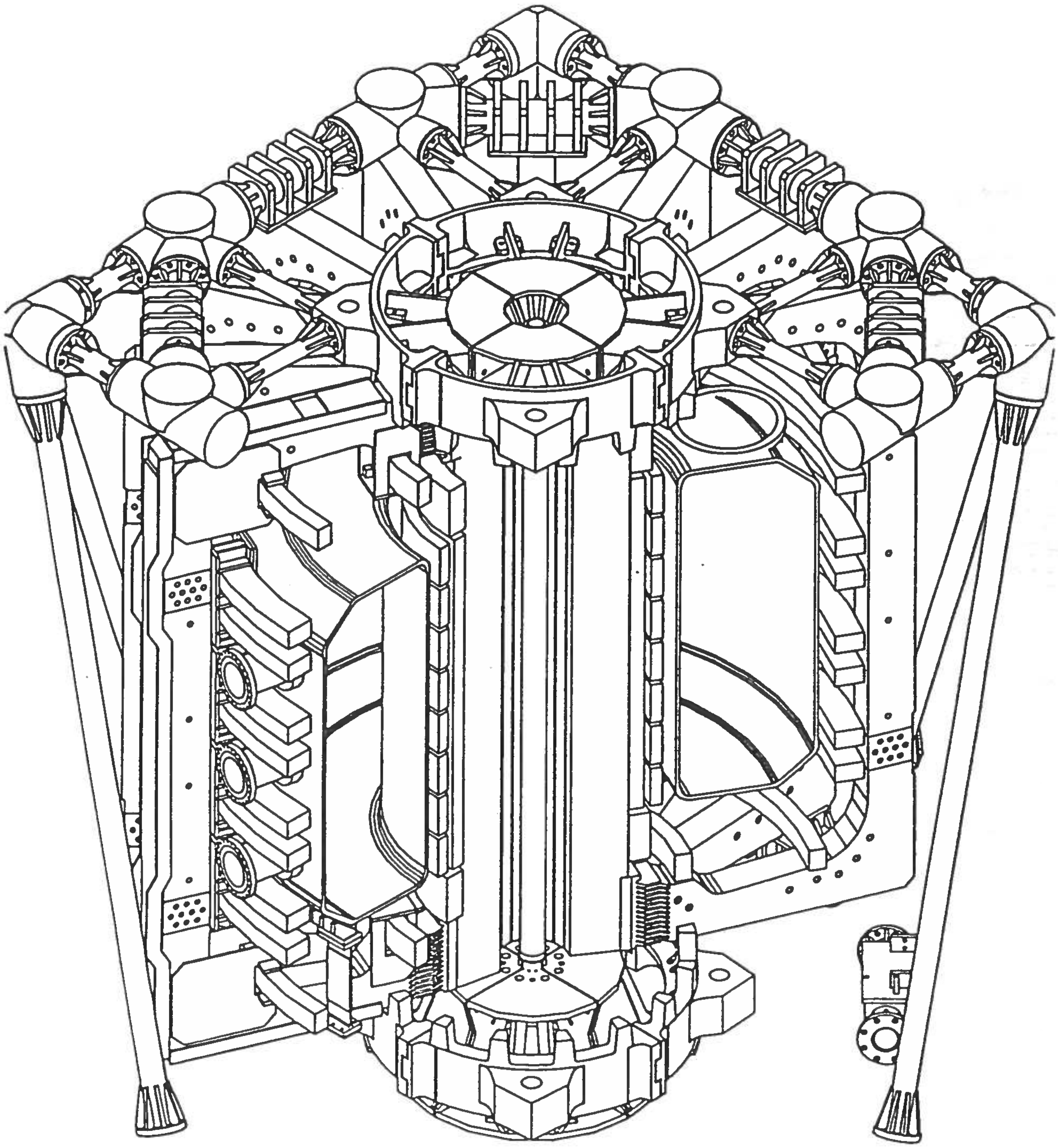


Fig. 1 General view of the TCV tokamak

Fig. 2 Disposition of the poloidal field coils

2) GENERAL SPECIFICATIONS OF THE C, D AND F POLOIDAL FIELD COILS

Definition of the terms in table 1

Coil dimensions

R	:	radius to the center of the coil
Z	:	vertical position of the center
H	:	height of the coil (overall dimension)
W	:	width (overall dimension)
N_s	:	effective number of turns
N_l	:	number of layers

Conductor and insulation dimensions

These values are given as an example. The final dimensions of the conductors and insulation thickness will have to be defined by the manufacturer. Only the external coil dimensions are fixed.

h_c	:	height of the conductor
w_c	:	width
S_h, d	:	xsection and diameter of the cooling hole. It is determined from the conditions defined in the thermal characteristics.
S_{cu}	:	copper xsection ($= h_c x w_c - S_h$)
L_{cu}	:	conductor length (approximation, not including leads)
M_{cu}	:	mass of copper
i_c	:	insulation thickness around the conductor
i_l	:	insulation thickness in between layers
i_e	:	insulation thickness around the coil
C_r	:	filling coefficient $= S_{cu}/(H \times W)$
M_i	:	mass of insulation (approximation)
V_w	:	volume of cooling water in the coil

Electrical characteristics

R_Ω	:	electrical resistance for $\rho = 1.9\ 10^{-8}\ \Omega \cdot m$
L	:	inductance

I_{max} : maximum current
U_{DCmax} : maximum DC voltage
U_{AC1} : peak to peak ripple voltage at U_{DCmax}
U_{AC2} : peak to peak ripple voltage at 0 U_{DC}
f : frequency of ac voltage
U_{Tmax} : transient maximum voltage. This voltage is given by the power supplies protection circuits
U_{G1} : maximum DC voltage to ground
U_{G2} : maximum transient voltage to ground

Load conditions of the coils : The C and D coils are powered in series with the B coils as shown in the fig. 3. The current in the B C D coils flows always in the same direction than that of the A coil. All the F coils (as well as the E coils) are powered independently and therefore can have any distribution of currents.

Thermal characteristics.

T_{min} : minimum temperature of the coil = minimum temperature of the cooling water to avoid condensation.
T_{max} : maximum temperature of the coil (given by the insulating material)
ΔT_{max} : maximum temperature difference in the coil (given by the cooling system).
$P_{\Omega max}$: ohmic power at I_{max}
$P_{\Omega av}$: average ohmic power over a cycle $= P_{\Omega max} \cdot t_{pmax}/t_{cmin}$
t_{pmax} : maximum pulse duration at I_{max}
ΔE_{max} : maximum thermal energy deposited in the coil at I_{max} = $(P_{\Omega max} \cdot t_{pmax})$
t_{cmin} : minimum cooling time between pulses at I_{max}
ΔT_{ad} : adiabatic temperature rise at $P_{\Omega max}$
ΔR : increase in radius for $\Delta T = 40^{o}C$
ΔE_n : estimate of the thermal energy deposited in the coil during a plasma shot.
ΔT_n : estimate of the temperature rise during a plasma shot.
t_{pn} : normal activation time of the coil during a plasma shot

E_n, ΔT_n et t_{pn} are given only as an indication. They must not be used to design the coils.

n_c	:	number of cooling channels (in parallel)
l_c	:	length of the cooling channel
ϕw	:	flow of cooling water.
v_w	:	water speed.
R_e	:	Reynolds number ($= v_w \cdot d/\nu$) between 20 to 50 ^{o} C
Δp	:	water pressure drop in the coil (not including the leads).

The cooling parameters of the coils are determined by the following conditions. The cooling water circulates with a $\Delta Tmax$ = Tout-Tin constant of 15^{o}C regulated by the heath exchanger (if the input temperature of the water is larger than Tmin) ; a Δp of 10 bar and a flow such that the cooling power multiplied by the minimum cooling time t_{cmin} of a cycle is equal to the energy ΔE_{max} deposited in the coil. These conditions determine the minimum cross section of the cooling hole and limit the temperature difference in the coil at ΔT_{max} .

The formulas for computing the diameter of the cooling hole are developed in the appendix.

Table 1 CHARACTERISTICS OF THE POLOIDAL FIELD COILS C D F

		C1-C2	D1-D2	F1 to F8
R	[m]	0.62	1.175	1.308
Z	[m]	-1.11	-1.17	-0.77/-0.61/-0.31/-0.15
		+1.11	+1.17	+0.77/+0.61/+0.31/+0.15
H	[m]	0.126	0.096	0.081
W	[m]	0.072	0.072	0.126
N_s	-	12	8	36
N_l	-	3	4	9
h_c	[mm]	28	42.8	16.75
w_c	[mm]	20	14.5	11.33
S_h,(d)	[mm^2 , mm]	29.6 (Ø 6.14)	36.17 (Ø 6.79)	45.88 (Ø 7.64)
S_{cu}	[mm^2]	530	587.3	143.9
L_{cu}	[m]	47	59	296
M_{cu}	[kg]	221	310	380
i_c	[mm]	1	1	1
i_l	[mm]	0	0	0
i_e	[mm]	3	3	3
C_r	-	0.701	0.68	0.508
M_i	[kg]	18	28	53
V_w	[ltr]	1.4	2.14	13.6
R_Ω	[mΩ]	1.7	1.91	39.6
L	[mH]	0.31	0.34	7.42
I_{max}	[kA]	±26	±26	±7.5
U_{DCmax}	[V]	± 1400 *	± 1400 *	± 1240
U_{AC1}	[V]	35 *	35 *	32
U_{AC2}	[V]	260 *	260 *	230
f	[Hz]	1150-1440	1150-1440	1150-1440
U_{Tmax}	[V]	± 3000 *	±3000 *	±2700
U_{G1}	[V]	1400*	1400*	1240
U_{G2}	[V]	3000*	3000*	2700
T_{min}	[°C]	room temp.	room temp	room temp
T_{max}	[°C]	70	70	70

ΔT_{max}	[°C]	15	15	15
$P_{\Omega max}$	[MW]	1.13	1.3	2.2
$P_{\Omega av}$	[KW]	5.65	6.5	11
tp_{max}	[S]	1.5	1.5	1.5
ΔE_{max}	[MJ]	1.7	1.94	3.3
tc_{min}	[S]	300	300	300
ΔT_{ad}	[°C/S]	13.3	10.8	15
ΔR	[mm]	0.44	0.83	0.93
ΔE_n	[MJ]	0.72	0.81	0.5
ΔT_n	[°C]	8.5	6.8	3.4
t_{pn}	[S]	2	2	2
nc x lc	[m]	1 x 47	1 x 59	2 x 148
ϕ_w	[l/s]	0.09	0.103	2 x 0.0875
v_w	[m/s]	3.04	2.84	1.91
Re	-	37000-74000	39000-78000	29000-58000
Δp	[bar]	10	10	10

* The voltages indicated apply to the 6 coils B1- B2 , C1- C2 , D1-D2 connected in series to the power supply as shown in the fig. 3.

Electrical connection of the B , C , D coils

The six coils are connected in series. (The water cooling is however connected in parallel on all the coils).

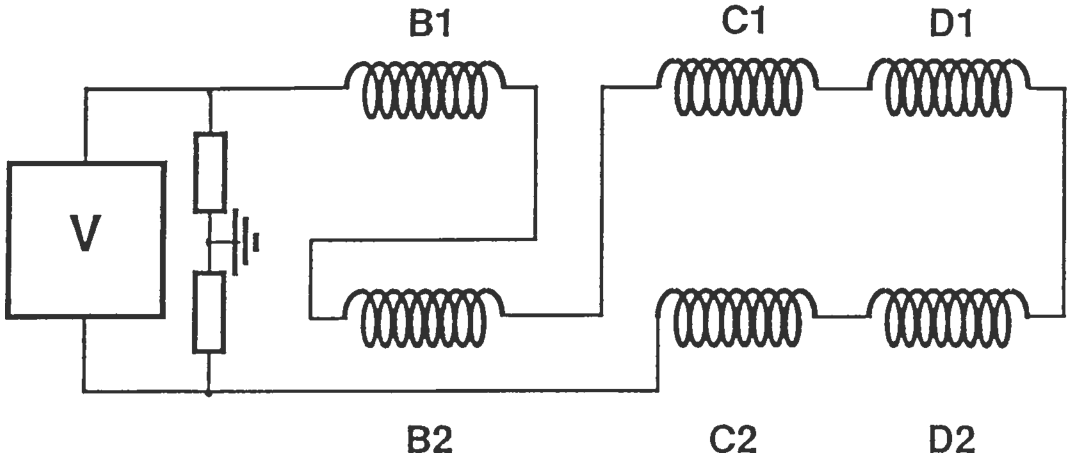


Fig. 3 Electrical connections of the coils B C and D . A soft ground is provided by two large resistors connected to earth.

Maximum DC voltage	±1400 V
peak to peak ripple voltage (at $U_{DC\ max}$)	35 V
peak to peak ripple voltage (at $U_{DC} = 0$ V)	260 V
AC frequency	1150 -1440 Hz
Maximum transient voltage	± 3000 V
Maximum current	± 26000 A
Maximum pulse duration at I_{max}	1.5 S
Maximum voltage to earth DC	700 (1400) V
" transient	1500 (3000) V

These voltages to earth suppose that the middle point is connected to the earth. If the earth is connected to a pole of the power supply, these voltages must be doubled (number in brackets). As an earth fault is always possible, the doubled voltages must be used for the design as given in the table 1. The same remark apply to the F coils.

Table 2. PHYSICAL PARAMETERS OF THE COIL MATERIALS

Copper 99.9 % Cu 0.1 % Ag

Electrical	20^{o} C	r_{es}	$1.7\ 10^{-8}$	Ωm
resistivity	50^{o} C	r_{es}	$1.9\ 10^{-8}$	Ωm
Specific mass		ρ_{cu}	$8.93\ 10^{3}$	kg/m^{3}
Specific heat capacity		C_{cu}	$3.85\ 10^{2}$	$J/kg^{o}K$
Thermal conductivity		γ_{cu}	$3.7\ 10^{2}$	$W/m^{o}K$
Thermal expansion coefficient		α_{cu}	$1.77\ 10^{-5}$	$^{o}K^{-1}$
Elastic modulus		Y_{cu}	$1.2\ 10^{11}$	Pa
Shear modulus		G_{cu}	$4.6\ 10^{10}$	Pa
Yield strength 0.2%		σ_{cu}	$2.4\ 10^{8}$	Pa
Fatigue strength ($3x10^{5}$ cycles)		σ_{cu}	$1.2\ 10^{8}$	Pa

Insulation epoxy-fibre glass (for Orlitherm or Vetresit)

Specific mass	ρ_{e}	$1.8 - 2\ 10^{3}$	kg/m^{3}
Elastic modulus ‖/⊥	Y_{e}	26-30 / 13	GPa
Shear modulus ‖/⊥	G_{e}	13 / 4.2-4.5	GPa
Tensile strength ‖/⊥	σ_{e}	$> 3.5/1.0\ 10^{8}$	Pa
Thermal expansion coefficient ‖/⊥	α_{e}	$1.5/4.4\ 10^{-5}$	$^{o}K^{-1}$
Thermal conductivity	γ_{e}	$4 - 4.5\ 10^{-1}$	$W/m^{o}K$
Maximum permitted temperature		150	^{o}C

Copper - insulation interface

Maximum tensile stress	$5 - 6\ 10^{7}$	Pa
Maximum shear stress	$4 - 5\ 10^{7}$	Pa

Cooling water

Specific mass	ρ_{w}	10^{3}	kg/m^{3}
Specific heath	C_{w}	$4.185\ 10^{3}$	$J/kg^{o}K$
Kinematic viscosity at 20 ^{o}	ν	$\sim 1\ 10^{-6}$	m^{2}/S
Kinematic viscosity at 50 ^{o}	ν	$\sim 0.5\ 10^{-6}$	m^{2}/S
Friction coefficient ($Re>10^{4}$)	λ(Re)	$\sim 7.1\ 10^{-3}$	-

for the cooling hole in copper conductors.
This is a value obtained from similar coils built for the TCA tokamak.

3) AXIAL AND RADIAL FORCES ON THE C D F COILS

The axial forces F_Z and the hoop forces $F_T = F_R/2\pi$ resulting from the radial forces, are given in the table 4 and 5 for the different loading cases given in the table 3. The cases not mentioned on the list are not relevant to the coils C D F.

The forces are the total net forces acting on the coils. The distribution of forces in the coil is given in graphical form (fig.4, 5) for the loading case 1 and the coil geometry of fig 6).

The loading cases correspond always to the maximum current flowing in the coils. All the coils of the fig. 2 are included in the computation of the forces.

The maximum forces are underlined. The cases 11 to 14 correspond to current configurations that maximize the vertical force on the F coils. The forces on the other coils are not indicated, they are smaller than the maximum underlined forces.

Table 3 : Loading cases

	A	BCD	E1	E2	E3	E4	E5	E6	E7	E8	F1	F2	F3	F4	F5	F6	F7	F8	Remarks
1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	F_Z , F_T max. on C D
2	+	+	-	-	-	-	+	+	+	+	-	-	-	-	+	+	+	+	
2 b	+	0	-	-	-	-	+	+	+	+	-	-	-	-	+	+	+	+	
3	+	+	+	+	+	+	+	+	+	+	-	-	-	-	+	+	+	+	
3 b	+	0	+	+	+	+	+	+	+	+	-	-	-	-	+	+	+	+	
5	+	+	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	
6	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	F_T max. sur F1, F2.
6 b	+	0	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	F_T max. sur F3, F4.
11	+	0	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	F_Z max. on F1
12	+	0	-	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+	F_Z max. on F2
13	+	0	-	-	+	+	+	+	+	+	-	-	+	+	+	+	+	+	F_Z max. on F3
14	+	0	-	-	-	+	+	+	+	+	-	-	-	+	+	+	+	+	F_Z max. on F4
15	+	+	-	-	-	-	+	+	+	+	+	+	+	+	-	-	-	-	
16	0	0	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	

Table 4 : Vertical forces in [MN]

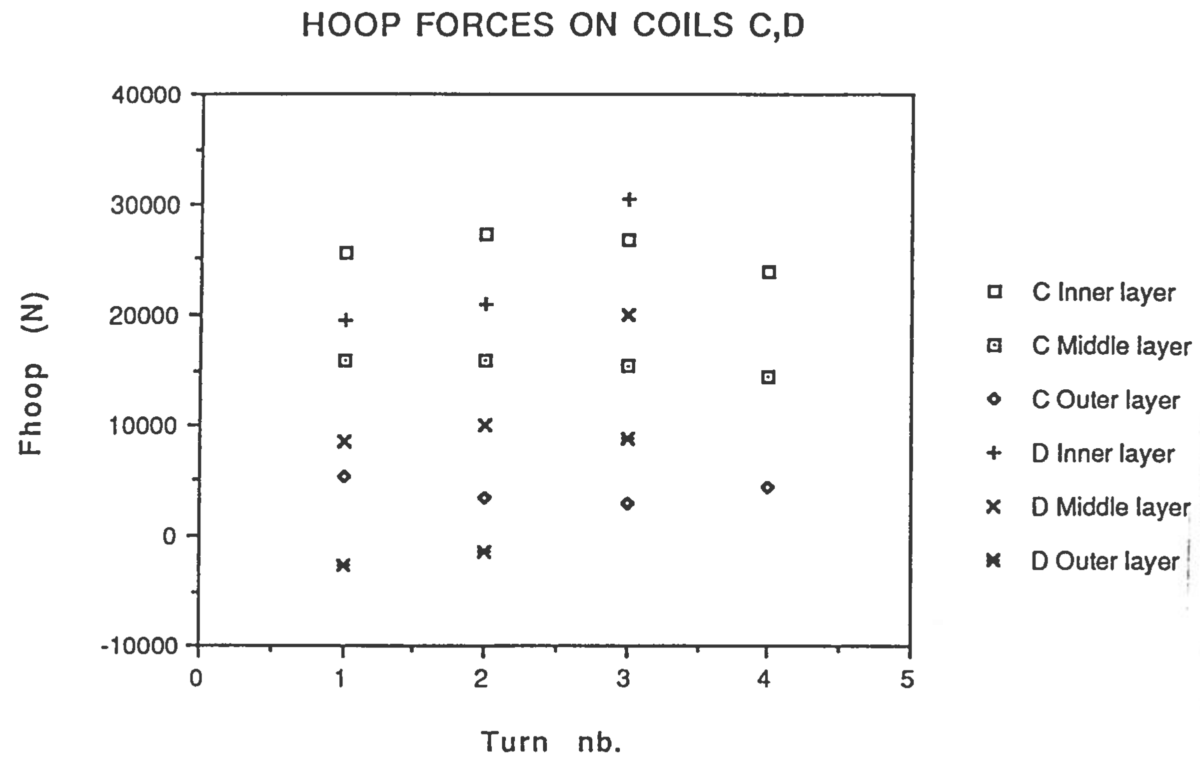
F_z	1	2	2b	3	3b	5	6	6b	11	12	13	14	15	16
C1	1.01	0.383	0	0.749	0	0.601	0.64	0					0.539	0
C2	-1.01	-0.858	0	-0.905	0	-0.601	-0.64	0					-0.702	0
D1	0.914	-0.281	0	-0.146	0	0.72	-0.374	0					0.55	0
D2	-0.914	-0.628	0	-0.686	0	-0.72	0.374	0					0.204	0
F1	1.25	0.879	0.65	0.765	0.536	1.04	1.23	1.0	1.48				0.671	1.235
F2	0.244	-0.341	-0.524	-0.414	-0.597	0.0554	0.186	0.028		1.73			-0.428	0.237
F3	0.636	-0.499	-0.587	-0.467	-0.555	0.529	0.57	0.482			1.9		-0.368	0.689
F4	-0.23	-1.87	-1.91	-1.79	-1.83	-0.283	-0.266	-0.308				1.92	-1.67	-0.137
F5	0.23	1.89	1.85	1.75	1.71	0.283	0.266	0.308					1.65	0.359
F6	-0.636	0.54	0.452	0.40	0.313	-0.529	-0.57	-0.482					0.327	-0.517
F7	-0.244	0.472	0.289	0.355	0.172	-0.055	-0.186	-0.028					0.297	-0.193
F8	-1.25	-0.685	-0.914	-0.785	-1.01	-1.04	-1.23	-1.0					-0.865	-1.249

Remark : The maximum forces on the coils F5 to F8 are the same than the maximum forces on the coils F1 to F4 but for symmetrical current loadings.

The vertical forces on a coil can be inverted by reversing the current on that coil. This is however not true for the C and D coils because of their electrical interconnection (fig. 3).

Table 5 : Tensile hoop forces in [MN]

F_z	1	2	2 b	3	3 b	5	6	6 b	15	16
C 1	0.18	0.008	0	0.041	0	0.136	0.005	0	0.102	0
C 2	0.18	0.123	0	0.135	0	0.136	0.005	0	0.029	0
D 1	0.114	-0.05	0	-0.053	0	0.113	-0.094	0	0.078	0
D 2	0.114	0.07	0	0.074	0	0.113	-0.094	0	-0.059	0
F 1	0.068	0.068	0.047	0.086	0.065	0.083	0.143	0.122	0.030	0.117
F 2	0.09	0.052	0.051	0.075	0.074	0.11	0.14	0.139	0.048	0.127
F 3	0.101	0.039	0.049	0.064	0.074	0.13	0.15	0.16	0.041	0.135
F 4	0.102	0.03	0.043	0.052	0.064	0.14	0.153	0.165	0.024	0.133
F 5	0.102	0.013	0.0009	0.002	-0.010	0.14	0.153	0.165	0.041	0.122
F 6	0.101	0.021	0.011	0.015	0.005	0.13	0.15	0.16	0.059	0.115
F 7	0.09	0.023	0.025	0.025	0.026	0.11	0.14	0.139	0.077	0.103
F 8	0.068	0.008	0.029	0.011	0.033	0.083	0.143	0.122	0.090	0.095



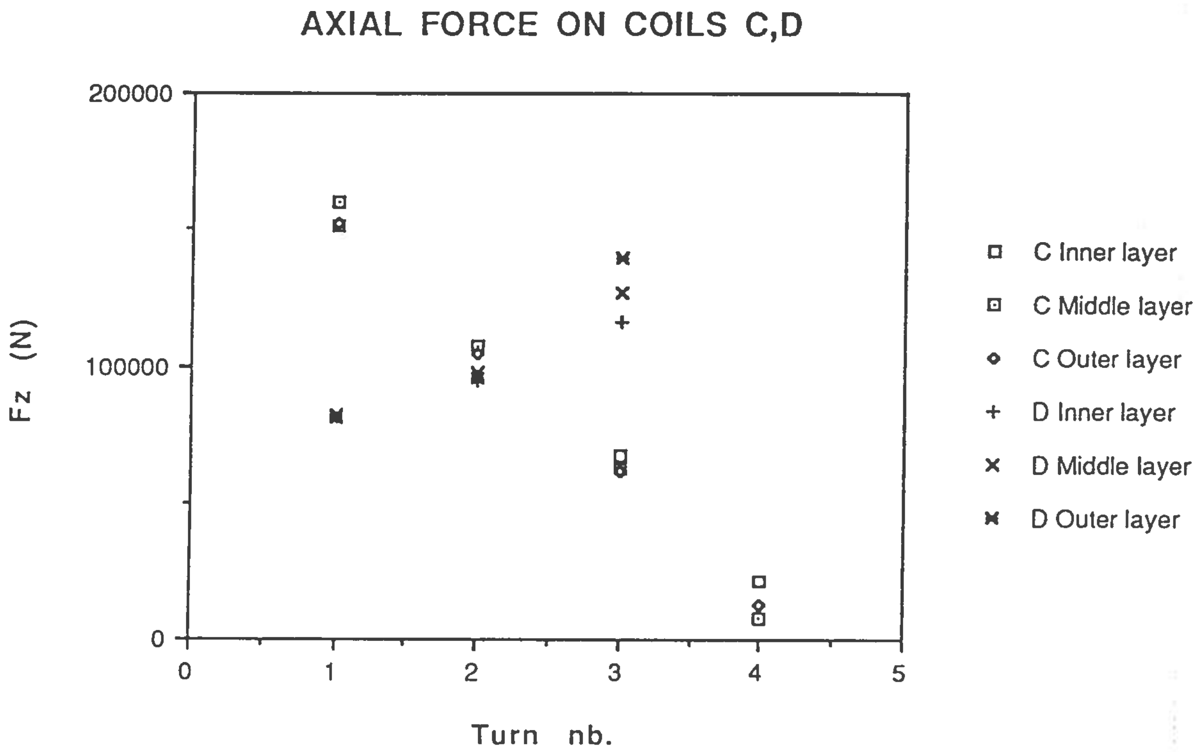
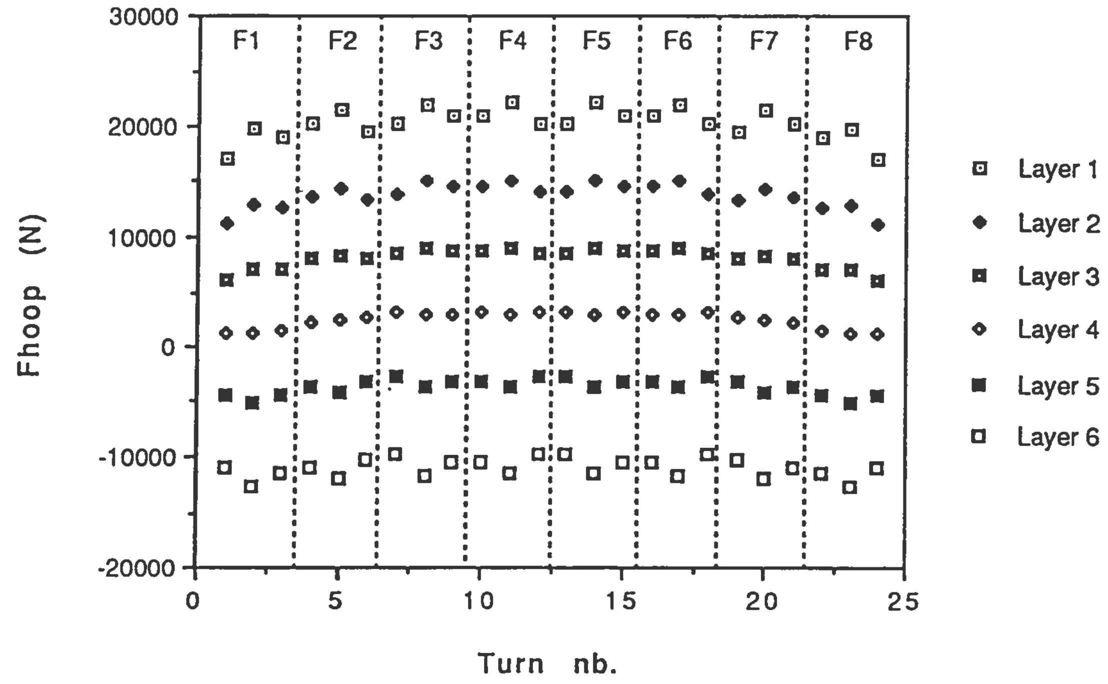


Fig. 4 Forces on the C and D coils for the loading case nb. 1. The xsection of the coils are divided as shown in the fig.6

HOOP FORCES ON COILS F1-F8



AXIAL FORCES ON COILS F1-F8

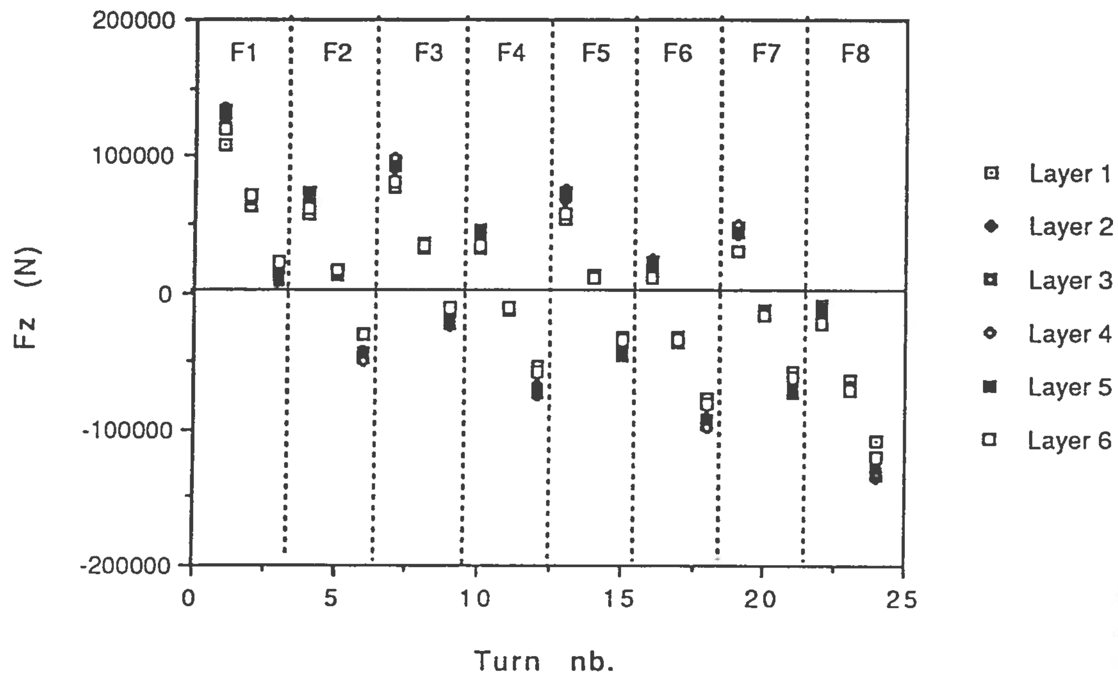


Fig. 5 Forces on the F1 to F8 coils for the loading case nb. 1. The xsection of the coils is divided as shown in the fig 6

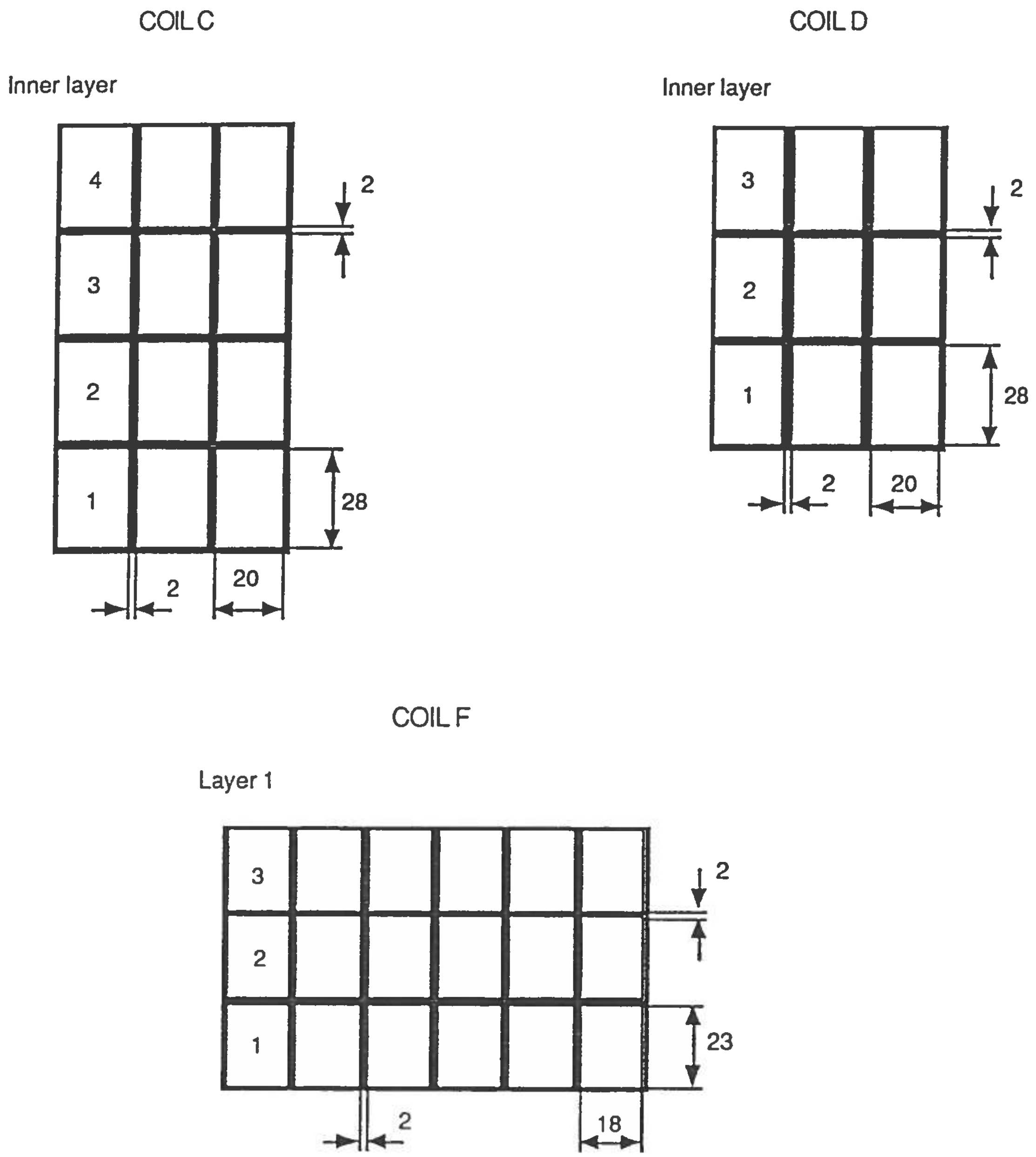


Fig. 6 Configuration used for computing the forces on the coils.

The coil xsection is divided differently than in the real coil for computational reasons. This does not change the calculated net force because the current density has the same value. The distribution of the force within the coil has however to be scaled with the xsection of the conductors. The turns have the same numbering for each layer.

4) EVALUATION OF THE STRESSES.

In the table 6, the following stresses corresponding to the maximum hoop forces (table 5) are given :

$\overline{\sigma_{cu}} = F_T / S_{cu}$: average tensile hoop stress in copper

$\overline{\sigma_e} = \overline{\sigma_{cu}} \cdot Y_e / Y_c$: average tensile hoop stress in epoxy insulation

$\tau = \sqrt{\left(\frac{G_e}{Y_{cu}} \cdot \frac{S_{cu}}{p \cdot t}\right)} \cdot \sigma_{max}$: maximum shear stress in the insulation parallel to the fiber glass tape in the region of the electrical connection (at the electrical connection, the winding is "open" and the hoop force is resisted only by shears in the insulation). This shear is evaluated following the model described in int. 160/89. G and Y are the shear and elastic modulus of, respectively, the insulation and the copper; S_{cu} the xsection of the conductor, p the copper-insulation cemented perimeter, t the thickness of the insulation. and σ_{max} the maximum hoop stress in the coil.

For the F coils, 3-D finite elements calculations have been conducted to determine the stresses resulting from the bending of the coils in between the 16 supports when a strong vertical load is applied. A complete simulation with 36 turns and a cooling hole in the copper conductor would require too many finite elements. Therefore, 3 simpler coil geometries have been defined in order to compare the effects of the model simplifications.

F a) The cross section is divided into 18 conductors separated by a fiber glass reinforced epoxy insulation as shown in the fig. 7. The symmetry of the problem allows to reduce the model to a $1/32^{th}$ of the coil perimeter (including a half support). The circular shape of the coil is taken into account, but there are no cooling holes to reduce the number of elements. The load corresponds to the case 2 for the coil F5. Each conductor is subject to its own vertical and radial forces.

F b) The cross section is as in F a) but with a cooling hole in the conductor. The circular shape of the coil element is neglected which, by symmetry, reduces strongly the number of finite elements. The load corresponds to the same net vertical force than above but it is evenly distributed on all the conductors.

F c) The model is similar to F b) but with 36 turns.

The stresses given in the table 6 are :

σ_{cu} : the maximum Von Misses stress in the copper.

$\tau_{||} = (\tau_{xz}^2+\tau_{yz}^2)^{1/2}$: the maximum shear stress in the insulation in the plane parallel to the fiber glass layers.

τ_{xy} : the maximum shear stress in the insulation perpendicular to the fiber glass layers.

$\sigma_{||}$: the maximum tensile stress in the insulation parallel to the fiber glass layers

$\sigma_{\perp}$: the maximum tensile stress in the insulation perpendicular to the fiber glass layers

The values listed in the table 6 give a consistent picture of the stresses. 3-D finite elements calculations have not been done for the C and D coils. However the maximum load on these coils is about half that of the F coils. Therefore, it is not expected to have stresses larger than those calculated for the F coils.

With the exception of τ, all the stresses are within reasonable values for the manufacturing technology foreseen for these coils. The maximum shear τ at the electrical connections may require a specific design of the electrical feeds to reduce the shear value at around 10 MPa.

Table 6 Stresses in the coils in MPa

	C	D	F a)	F b)	F c)
$\bar{\sigma}_{cu}$	28.3	24.3	31.8	31.8	31.8
$\bar{\sigma}_{e}$	6.13	5.26	6.89	6.89	6.89
τ	21.9	18.1	16.8	16.8	16.8
σ_{cu}	-	-	26.2	33	37.4
$\tau_{\parallel}$	-	-	6.34	5.78	6.25
τ_{xy}	-	-	0.85	0.36	0.36
$\sigma_{\parallel}$	-	-	6.09	7.01	7.8
$\sigma_{\perp}$	-	-	0.48	0.49	0.45

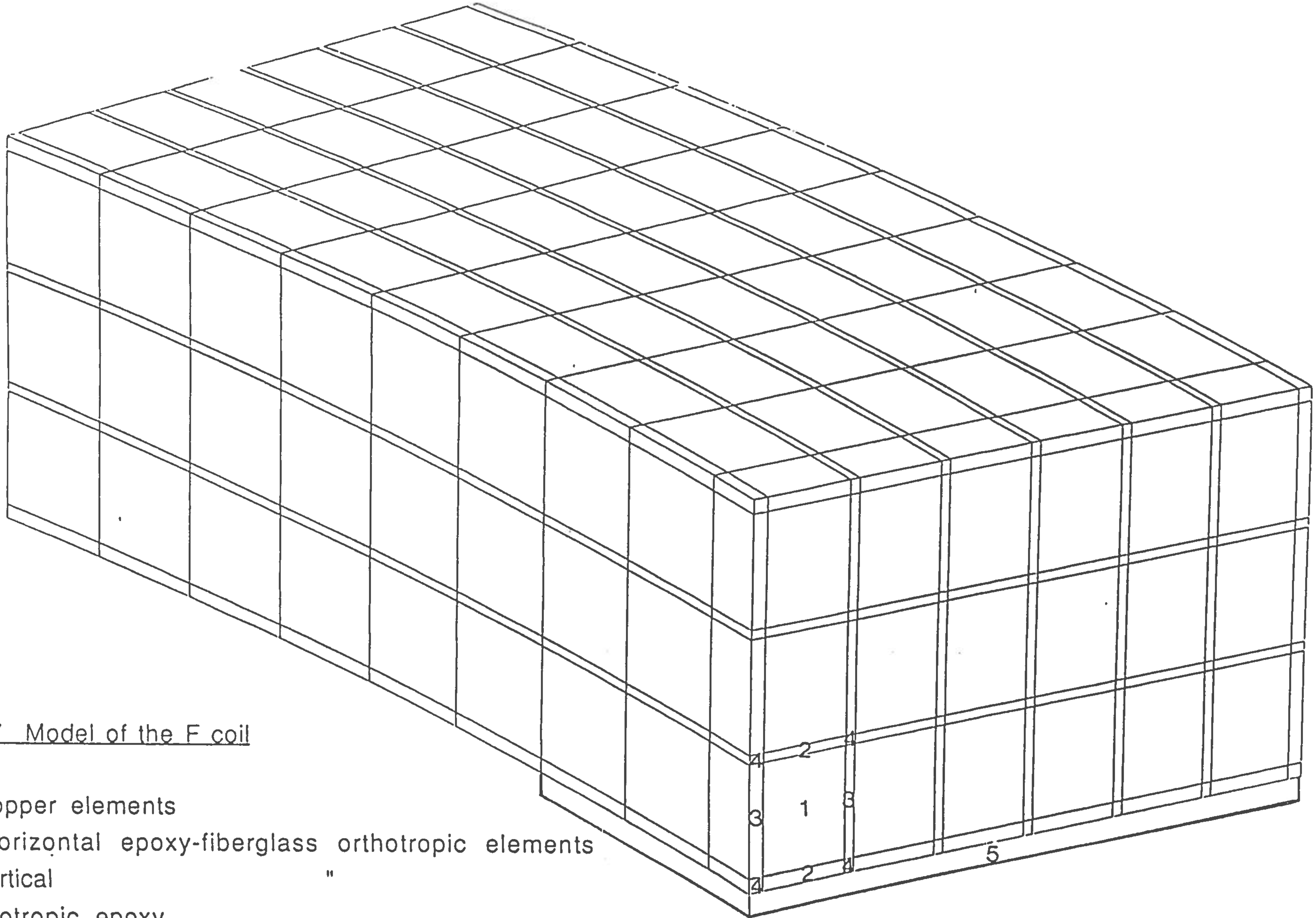


Fig. 7 Model of the F coil

1) Copper elements
2) Horizontal epoxy-fiberglass orthotropic elements
3) Vertical "
4) Isotropic epoxy
5) Elastic support

ANNEX TO INT. 163/89

Determination of the cooling parameters of the coils.

If not specified, all the parameters are as defined in int.163/89.

Reference : Heat, Mass, and Momentum Transfer
Warren, Rohsenow, Choi Prentice-Hall edition

Pressure drop

$$\Delta p = 4 \cdot \lambda(Re) \cdot \rho_w \cdot \frac{v_w^2}{2} \cdot \frac{l_c}{d} \qquad 1)$$

$$v_w = \phi_w / (n \cdot S_h) \qquad 2)$$

$d = 4 \cdot S_h / P_h$ is the hydraulic diameter, P_h being the hole perimeter

$l_c = L_{cu} / n$ n being the number of cooling channels

$\lambda(Re)$ is the friction factor obtained from the attached graphic

$$Re = v_w \cdot d / \nu \qquad 3)$$

ν is the kinematic viscosity of water

For an helical coil of radius R the friction factor λ is modified as follow

$$\lambda(Re) = \lambda_{helical} = \lambda_{straight} \cdot \left(Re \cdot \left(\frac{d}{2R}\right)^2\right)^{0.05} \qquad 4)$$

Energy balance

$$\phi_w \cdot C_w \cdot \rho_w \cdot \Delta T_{max} \cdot tc_{min} = \Delta E_{max}$$

$$\Delta E_{max} = R_\Omega \cdot I_{max}^2 \cdot tp_{max} \qquad 5)$$

$$R_\Omega = r_{es} \cdot L_{cu} / S_{cu} \quad ; \quad S_{cu} = h_c \cdot w_c - S_h$$

$$\alpha = tp_{max} / tc_{min}$$

Cooling conditions.

The cooling system is set such that ΔT_{max} , the difference in water temperature between the coil input and output, is constant and the water flow is such as to remove all the energy ΔE_{max} from the coil during the cooling cycle of time length tc_{min} .

Cooling hole formula

Combining the relations 1) 2) and 5) gives :

$$d^5 = \frac{32}{\pi^2} \cdot \frac{\lambda(Re) \cdot r_{es}^2 \cdot l_c^3 \cdot I_{max}^4 \cdot (tp_{max} / tc_{min})^2}{C_w^2 \cdot \rho_w \cdot \Delta T_{max}^2 \cdot \Delta p \cdot S_{cu}^2} \qquad 6)$$

This formula has to be iterated with :

$$S_{cu}^{(0)} = h_c \cdot w_c \quad \rightarrow \quad d^{(0)}$$
$$S_{cu}^{(n)} = h_c \cdot w_c - \frac{\pi \cdot d^{2\ (n-1)}}{4} \quad \rightarrow \quad d^{(n)}$$

To use this formula it is necessary to know the value of $\lambda(Re)$ .If it is not the case, the formula has also to be iterated for λ . Another possibility is to use one of the fit shown in the graph such as :

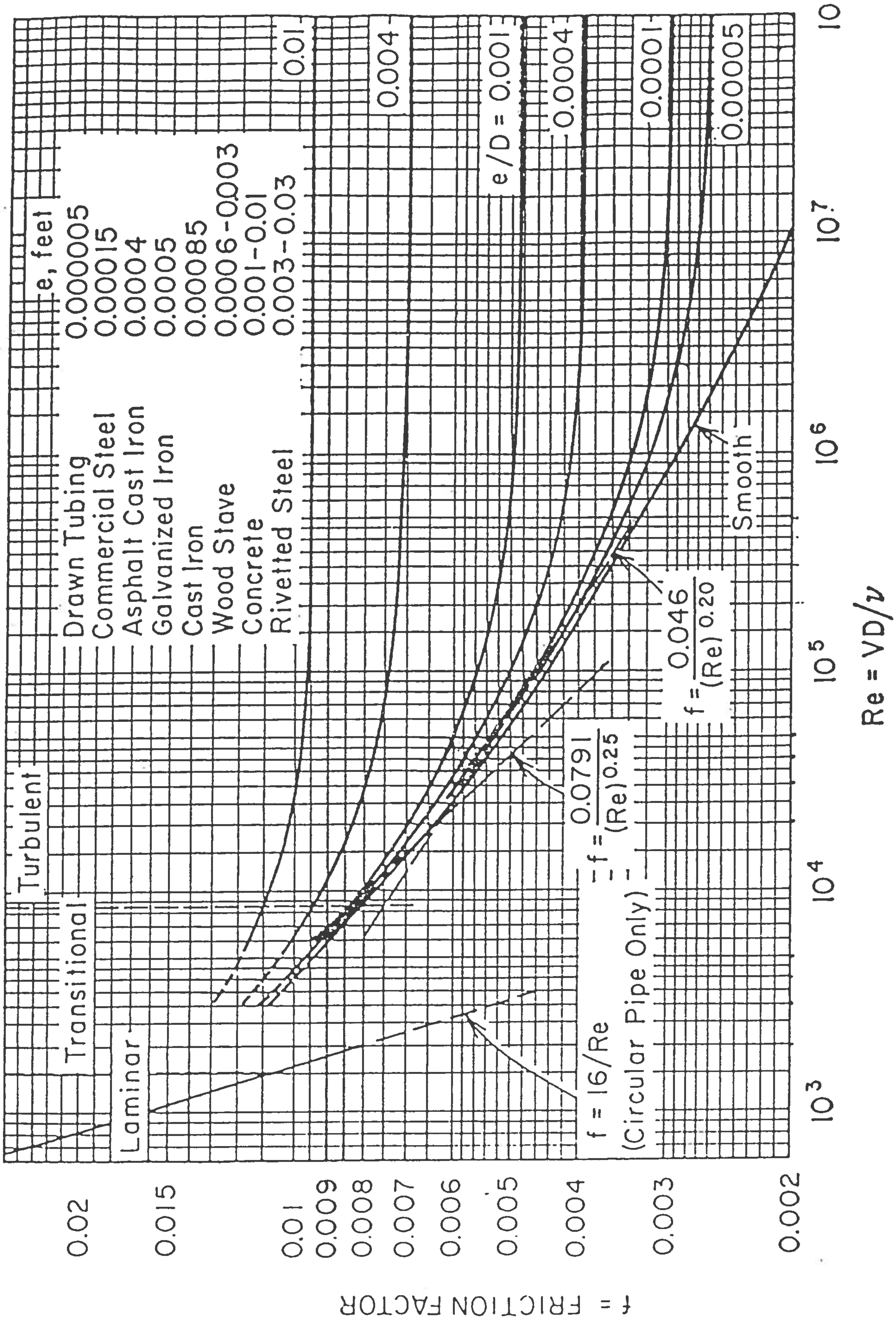
$$\lambda(Re) = 0.046 / (Re)^{0.2} \qquad 7)$$

(which should be valid in the domain $20000 < Re < 100000$ for the kind of pipe used) together with the relations 3) and 4). This gives another formula for d :

$$d^{4.75} = 0.14384 \cdot \frac{\nu^{0.15} \cdot l_c^{2.85}}{\rho_w^{0.85} \cdot (2\,R)^{0.1} \cdot \Delta p} \cdot \left(\frac{r_{es} \cdot I_{max}^2 \cdot \alpha}{C_w \cdot \Delta T_{max} \cdot S_{cu}}\right)^{1.85} \qquad 8)$$

which must also be iterated as 6).

The TCV coil cooling parameters are computed using the formula 6) with a fixed friction factor : $\lambda(Re) = 7.1E-3$. This value has been obtained from similar coils designed for the TCA tokamak. A comparison with the results obtained with 8) shows that 6) gives a slightly larger diameter and is therefore a safe design formula. The values of ν and r_{es} are taken for $T = 50\ ^{o}C$.



Friction factor for flow in circular pipes.