KfK 4365
Februar 1988

A Study on Nuclear Heat Load Tolerable for NET/TF Coils Cooled by Internal Flow of Helium II

A. Hofmann
Institut für Technische Physik
Projekt Kernfusion

Kernforschungszentrum Karlsruhe

KERNFORSCHUNGSZENTRUM KARLSRUHE
Institut für Technische Physik
Projekt Kernfusion

KfK 4365

A Study on Nuclear Heat Load Tolerable for NET/TF Coils Cooled by Internal Flow of Helium II

A. Hofmann

Kernforschungszentrum Karlsruhe GmbH, Karlsruhe

Kernforschungszentrum Karlsruhe GmbH
Postfach 3640, 7500 Karlsruhe 1

ISSN 0303-4003

Summary

NbTi cables cooled by internal flow of superfluid helium are considered an option for the design of NET/TF coils with about 11 T peak fields. Starting from an available winding cross section of 0.61 x 0.61 m^2 for a 8 MA turns coil made of a 16 kA conductor it is shown that sufficient hydraulic cross section can be provided within such cables to remove the expected thermal load resulting from nuclear heating with exponential decay from inboard to outboard side of the winding. The concept is a pancake type coil with 1.8 K helium fed-in in the high field region of each pancake. The temperature distribution within such coils is calculated, and the local safety margin is determined from temperature and field. The calculation takes account of nuclear and a.c. heating, and of thermal conductance between the individual layers and the coil casing. It is shown that operation with 1.8 K inlet and about 3 K outlet temperature is possible. The electrical insulation with about 0.5 mm thickness proves to provide sufficient thermal insulation. No additional thermal shield is required between the coil casing and the winding package. Two different types of conductors are being considered: a) POLO type cable with quadratic cross section and a central circular coolant duct, and b) an LCT type cable with two conductors wound in hand. Both concepts with about 500 m length of the coolant channels are shown to meet the requirements resulting from a peak nuclear heat load of 0.3 mW/cm^3 in the inboard turns. The hydraulic diameters are sufficient to operate each coils with self-sustained fountain effect pumps. Even appreciably higher heat loads with up to 3 mW/cm^3 of nuclear heating can be tolerated for the POLO type cable when the hydraulic diameter is enlarged to its maximum of 17 mm.

Studie zu Grenzwerten der nuklearen Wärmelast in NET-TF-Spulen mit interner Helium-II-Kühlung

Zusammenfassung

Es wird als aussichtssreich erachtet, NET/TF-Spulen mit etwa 11 T Maximalfeld aus NbTi-Leitern mit innerer Kühlung durch superfluides Helium aufzubauen. Ausgehend von dem verfügbaren Wicklungsquerschnitt von 0,61 x 0,61 m^2 einer Spule mit 8 MA-Windungen wird gezeigt, daß bei einem 16 kA-Leiter ein hinreichend großer hydraulischer Querschnitt zur Verfügung gestellt werden kann, um die Wärmelast, die vor allem aus der Neutronenabsorption mit exponentiellem Abfall von innen und außen herrührt, abzuführen. Das Konzept ist eine aus Scheiben aufgebaute Spule mit 1,8 K-Heliumeinspeisung im Hochfeldbereich. Die Rechnungen berücksichtigen nukleare Erwärmung, Wechselstromverluste und thermische Kopplungen zwischen den einzelnen Lagen und dem Gehäuse. Es wird gezeigt, daß ein Betrieb mit 1,8 K Eintritts- und etwa 3 K Austrittstemperatur zulässig ist. Die elektrische Isolation aus 0,5 mm Kaptonschichten erweist sich auch als ausreichend zur thermischen Entkopplung. Zwischen Gehäuse und Wicklung wird kein zusätzlicher Wärmeschirm benötigt. Zwei unterschiedliche Leitertypen werden betrachtet:

a) ein Kabel vom Typ des POLO-Leiters mit quadratischem Querschnitt und zentralem kreisförmigen Kühlkanal und
b) ein Leiter vom Typ des LCT-Kabels mit zwei parallel gewickelten Leitern.

Für beide Konzepte wird gezeigt, daß bei 500 m Kühlkanallänge die Anforderungen, die aus einer nuklearen Belastung mit 0,3 mW/cm^3 an der inneren Lage resultieren, erfüllt werden können. Die Strömnungsquerschnitte reichen aus, um solche Spulen mit sogenannten selbsterregten thermomechanischen Pumpen zu betreiben. Auch beträchtlich höhere Wärmelasten, bis zu 3 mW/cm^3 bei einem Kabel vom POLO-Typ mit maximal möglichem Kühlkanaldurchmesser von 17 mm, können bewältigt werden.

Fundamentals

The specifications of NET/TF coils with about 11 T peak magnetic field may be met with NbTi cables internally cooled by forced flow of helium II. It has been shown /1/ that a total heat load of about 500 W per coil can be removed by forced flow of helium II. In that study, however, only the global heat load was considered. The fact that the heat load, especially the nucleate heat, has a high peak at the inboard layers where the magnetic field is also maximum may cause problems, and it needs more detailed investigations.

The concept of the coil is the same as in references 1 and 2, namely 61 cm x 61 cm winding cross section and 25.6 m of mean length per turn. Nuclear heat per cm^3 of conductor is assumed as

$$q_{nucl} = q_{nucl,\, max} \cdot \; exp\ (-x/9.03\ cm) \qquad (1)$$

with the reference situation

$$q_{nucl,\, max} = \begin{cases} 0.3\ W/cm^3 \text{ at half coil perimeter close to the central column} \\ 0 \text{ elsewhere} \end{cases} \qquad (2)$$

Other values will also be considered. Additional heat load such as a.c. load is assumed as 250 W per coil, homogenous in the whole volume.

If the design of the coil is made so that the conductor is operated at $B_0 = 10.7$ T and $T_0 = 1.8$ K with a safety margin s_0 defined by

$$\frac{I_c(B_o, T_o)}{I} = 1 + s_o \qquad (3)$$

where I and I_c are operational and critical current, respectively. Then the conductor is operated with the local safety margin s which results from

$$\frac{1+s}{1+s_o} = \frac{I_c(B,T)}{I_c(B_o,T_o)} \equiv j_{CN} \qquad (4)$$

For stable operation it is necessary that

$$s = (1 + s_o) j_{CN} - 1 > 0. \tag{5}$$

The normalized critical current density

$$j_{CN} = j_c (B, T) / j_c (B_o, T_o) \tag{6}$$

can be scaled by

$$j_{CN} = 1 + \alpha\, (B - B_o) + \beta\, (T^2 - T_o^2). \tag{7}$$

The constants α and β are derived from empirical data (e.g. from Fig. 3 of ref. 1). This yields

(a)

$$\left(\frac{d j_{CN}}{dB}\right)_T = \alpha \approx 0.5\, T^{-1} \tag{8}$$

and

(b)

$$j_c\, (11.5\, T, 1.8\, K) = j_c\, (8\, T, 4.2\, K) \tag{9}$$

This yields

$$\beta = -\alpha \frac{8 - 11.5}{4.2^2 - 1.8^2} = 0.24\, \alpha = -0.12\, K^{-2} \tag{10}$$

and finally

$$j_{CN} = 1 - 0.5\, (B - B_o) - 0.12\, (T^2 - T_o^2) \tag{11}$$

So, the local safety margin s can be calculated if the local values of B and T are known.

For further design work the field distribution is approximated by /2/

$$B\, (r') / T = \begin{cases} 10.7 - 7.9\, r' \text{ for } 0 < r'\, 0.59 \\ 6.5 - 0.8\, r' \text{ for } 0.59 \le r' \le 1 \end{cases} \tag{12}$$

where r' measures the radial position of a layer in the winding with r' = 0 at the inner surface of a TF coil (facing the plasma), and r' = 1 at the outer surface. The temperature distribution results from the thermal balance at a conductor element as discussed below.

Temperature distribution in the coil

The 8 MA turns coil be set-up of M pancakes with N turns each with M·N ≈ 500 windings of a 16 kA conductor. Conductors with different aspect ratios (width to thickness) will be considered:

a) a POLO-type conductor with quadratic cross section and

b) an LCT-type conductor with rectangular cross section.

The coolant inlet is at the innermost layer and the outlet at the outermost layer of each pancake. Thus there will be a temperature gradient in the winding package and hence also conductive heat flows between the neighbouring turns.. Additionally, there is conducting coupling through the wall of the coil case. To take account of these effects, it is assumed that the reference conductor has a 0.5 mm thick fiberglas/epoxy insulation with a thermal conductivity of $k = 0.03\ W\ m^{-1}\ K^{-1}$ at 2 K /3/. For simplification it is assumed that all pancakes are at the same temperature levels, hence there is no transversal heat flow, and the further consideration can be restricted to a single pancake as schematically depicted in Fig. 1. Fig. 1 b is a cross section at the end of the windings. Each element represents one turn. The energy balance of an inner element is given by

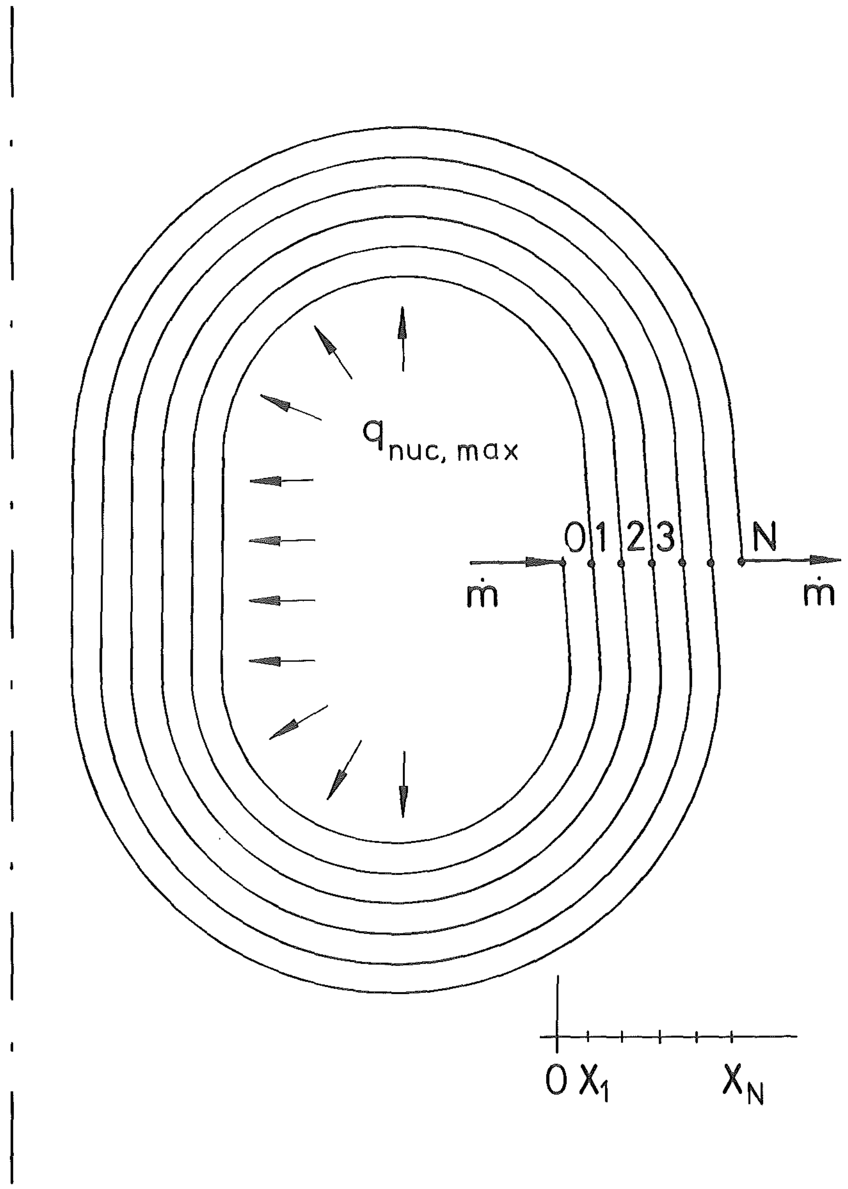
$$Q_n + \dot{m}\,h_{n-1} + A\,\frac{k}{\delta}\left[T_{n+1} - T_n\right]$$

$$= \dot{m}\,h_n \quad + A\,\frac{k}{\delta}\left[T_{n+1} - T_n\right] \qquad (13)$$

where Q is the intrinsic heat load (nuclear + a.c. load) of the respective turn, $\dot{m}$ is the flow rate of the coolant with enthalpy h, A is the interlayer contact area with the thickness 2 δ of the insulator with the thermal conductivity k.

The inner and outermost layers are in contact with the coil casing and there is conducting heat flow from the outer layer with turn number N to the inner layer. For simplification, the transverse heat flow from the casing to the outermost pancakes is neglected. Thus, there is the heat flow

$$Q^* = a_3\,(T_N - T_o) \qquad (14)$$



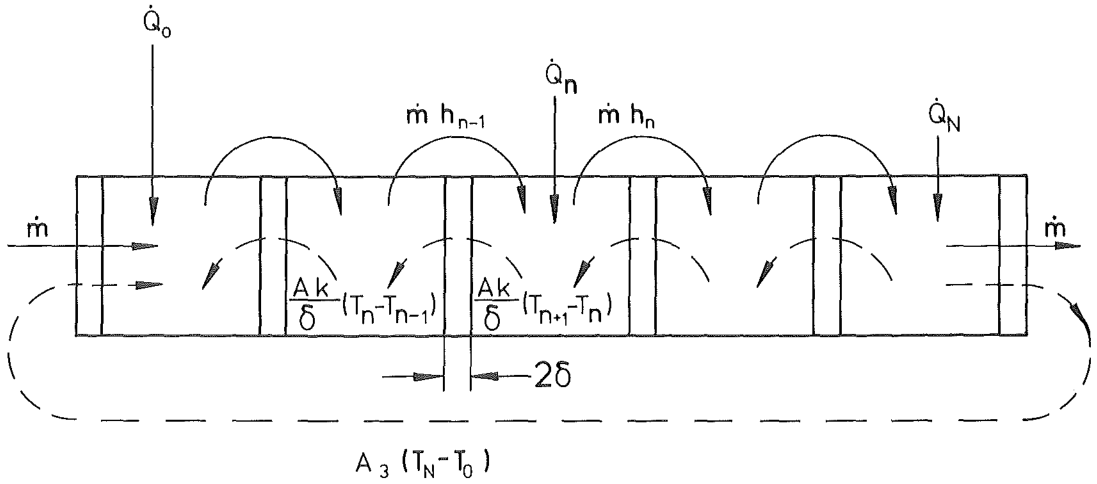


Fig. 1: a) Scheme of the coil with the coolant flow $\dot{m}$

b) Model for calculations (The symbols are explained in the text.)

from the outer to the inner layer. Here a_3 describes the overall conductance of this path. Further simplification is obtained with

$$\Delta h = c_p \, \Delta T \tag{15}$$

and the approximation

$$c_p = \Delta h_{max} / \Delta T_{max} \tag{16}$$

calculated from the enthalpy difference between inlet and outlet (s. appendix A).

With the notation

$$a_1 = \dot{m} \, c_p, \tag{17}$$

and

$$a_2 = A \, k / 2\delta, \tag{18}$$

we get the following system of linear equations to determine the temperatures at the ends of the individual turns:

$$\begin{aligned}
&T_o = 1.8\ \mathrm{K} \\
&Q_1 - a_1 (T_1 - T_o) + a_2 (T_2 - T_1) + a_3 (T_N - T_o) = 0 \\
&\vdots \\
&Q_n - a_1 (T_n - T_{n-1}) + a_2 (T_{n+1} - 2\,T_n + T_{n-1}) = 0 \\
&\vdots \\
&Q_N - a_1 (T_N - T_{N-1}) + a_2 (T_N - T_{N-1}) - a_3 (T_N - T_o) = 0
\end{aligned} \tag{19}$$

This can be rearranged to

$$\begin{bmatrix} 1.8 \\ Q_1 \\ Q_2 \\ : \\ : \\ Q_n \\ : \\ : \\ Q_{N-1} \\ Q_N \end{bmatrix} + \begin{bmatrix} -1 & 0 & 0 & & & 0 & 0 \\ a_1-a_3 & -a_1-a_2 & a2 & & & 0 & a_3 \\ 0 & a_1+a_2 & -a_1-2a_2 & a_2 & & & \\ & & & & & & \\ & & & & & & \\ 0 & 0 & a_1+a_2 & -a_1-2a_2 & a_2 & 0 .. & \\ . & & & & & & \\ & & & & & & \\ 0 \; ... & & & a_1+a_2 & -a_1-2a_2 & a_2 & \\ a_3 & & & & a_1+a_2 & -a_1-a_2-a_3 & \end{bmatrix} \cdot \begin{bmatrix} T_o \\ T_1 \\ T_2 \\ \\ \\ T_n \\ \\ \\ T_{N-1} \\ T_N \end{bmatrix} = 0 \quad (20)$$

The following approximations are made to get an impression for the weight of the different parameters in this system:

Let the total heat load be 500 W per coil, and let the outlet temperature be below 3 K at 1.8 K inlet temprature. This requires a total flow rate of 130 g/s. In an arrangement of 22 pancake with 22 turns each, the flow rate per pancake becomes 5.7 g/s. This yields $a_1 = 17$ W/K. The contact area between the layers of a pancake is A = 0.7 m^2, the insulation have 2 δ = 1 mm thickness with k = 0.03 W m^{-1} K^{-1} conductivity. This yields $a_2 = 21$ W/K. Obviously both terms a_1 and a_2 are of the same order. For approximation of the term a_3 we consider the heat flow through the side walls of a stainless steel case with 5 cm thickness on both sides. Related to one pancake we get

$$a_3 = \frac{A_{ss}\, k_{ss}}{N_{pancakes} \cdot \delta_{ss}} = \frac{25.6 \cdot 0.1 \cdot 0.1}{22 \cdot 0.61} = 0.02\, \frac{W}{K} \qquad (21)$$

where A_{ss} and δ_{ss} are the cross sectional area and the length of the side wall of the casing, and $k_{ss} = 0.1$ W m^{-1} K^{-1} is the thermal conductivity of stainless steel. This term a_3 being 1000 times smaller than a_2, might be negligible.

In the following computer study it will be investigated how the terms a_1, a_2 and a_3 can be modified to obtain operational conditions with sufficient safety margin $s > 0$.

Computing

The computer program written in SPEAKEASY-language is listed in Tab. 1. Its main topics are self explaning. Some comments might be useful.

Line 5 to 10	are inputs for the geometry of coil and conductor
Line 11 to 12	calculate the coordinates of the turns measured from the plasma side
Line 13 to 19	describe the distribution of nuclear and a.c. heat loads in the pancake
Line 20 to 48	define the coefficients of the lin.eq. system. The mean specific heat, CP, is found by iteration from 21 to 48.
Line 27 to 47	fill the vector Q and the Matrix M
Line 45	is the solution of the lin. eq. giving the vector T
Line 49	produces a graph of T(N)
Line 50 to 55	define the field B(N)
Line 56 to 59	calculate the critical current and the safety margin
Line 60	produces a graph SAFETY (N)
Line 61 to 63	calculate the total thermal load per pancake and per coil
Line 64 to 78	produce the output of tables and graphs

Runs are made after the inputs of

: MGS	= flow rate in g/s
: NUCLHTMAX	= peak spec. nuclear heating in mW/cm^3
: THERMCON	= thermal conductivity of the interlayer insulation in W /(mK)
: A 3	= f*A2, where f is the factor of thermal coupling from ther outer to the innermost layer.

All variables listed in Tab. 2 can optionally be used for outputs.

Table 1: Listing of the SPEAKEASY program for parametric studies of NET-type coils cooled by internal flow of helium II

```
PROGRAM
$  PROGRAM: NET1                          $
$ LAST MODIFICATION: 10.11.1987           $
$ CALCULATION WITH VARIABLE CP            $
COILTHICNKNESS=61
COILWIDTH=61
TURNS=22
PANCAKES=22
CABLETHICKNESS=COILWIDTH/TURNS
CABLEWIDTH=COILWIDTH/PANCAKES
N=VARIABLE(0,TURNS,1)
X=CABLETHICKNESS*(N)
COILPERIMETER=25.6*100
SPECNUCHT=0.5*NUCLHTMAX/1000*EXP(-X/9.03)
COILACLOAD=250
COILVOLUME=COILPERIMETER*COILWIDTH*COILTHICKNESS
N(1)=1
SPECACLOA=COILACLOAD/COILVOLUME*N/N
N(1)=0
CP=3
FOR K=1,10,1
A1=MGS*CP
INSULTHICKN=0.001
CONTACTAREA=COILPERIMETER*CABLEWIDTH/10000
A2=CONTACTAREA*THERMCOND/INSULTHICK
Q0=(SPECNUCHT+SPECACLOA)*CABLEWIDTH*CABLETHICKNES*COILPERIMETER
Q(1)=-1.8
FOR J=2,TURNS+1,1
Q(J)=Q0(J-1)
NEXT J
M=MATRIX(TURNS+1,TURNS+1:)
M(1,1)=1
M(2,1)=A1-A3
M(2,TURNS+1)=A3
M(2,2)=-(A1+A2)
M(2,3)=A2
FOR I=3,TURNS
M(I,I-1)=A1+A2
M(I,I)=-(A1+2*A2)
M(I,I+1)=A2
NEXT I
M(TURNS+1,1)=A3
M(TURNS+1,TURNS)=A1+A2
M(TURNS+1,TURNS+1)=-(A1+A2+A3)
T=-INVERSE(M)*MFAM(Q)
ENTHAL=INTERPOL(T,TH(,2),TH(,1))
CP=(ENTHAL(TURNS+1)-ENTHAL(1))/(T(TURNS+1)-T(1))
NEXT K
GT=NICEGRAPH(T:N)
DETAX=X(2)-X(1)
RPRIME=(X-DETAX)/COILTHICKNESS
B=10.7-7.9*RPRIME
```

```
WHERE (B.LT.6) B=6.5-0.8*RPRIME
BO=10.7
B(1)=BO
JCO=1
JCN=1-0.5*(B-BO)+0.12*(TO**2-AFAM(T)**2)
GJCN=NICEGRAPH(JCN:N)
SAFETY=(1+SAFETYO)*JCN-1
GS=NICEGRAPH(SAFETY:N)
Q(1)=0
LOADPC=SUM(Q)
LOAD=LOADPC*PANCAKES
TI="TABLE OF OPERATIONAL PARAMETERS:"
TAB=TABULATE(N,X,B,Q,T,JCN,SAFETY:TITLE,TI)
PRINT " "
PRINT "THERMAL COND. OF INSULATION: ",THERMCOND," W/(M K)"
PRINT "FLOW RATE PER PANCAKE:       ",MGS," G/S"
PRINT "SPEC. MAX. NUCL. HEAT:       ",NUCLHTMAX," MW/CM**3"
PRINT "LOAD PER PANCAKE:            ",LOADPC," W"
PRINT "TOTAL LOAD PER COIL:         ", LOAD, " W"
PRINT "COEFFICIENTS (W/K): ",A1,A2,A3
PRINT " "
TAB
PRINT " "
GS
PRINT " "
PRINT "FIG."
:%end
```

Table 2: List of all variables

```
:_names
ANSWER, A1, A2, A3, B, BCO, BO, CABLEARE, CABLETHI, CABLEWID, COILACLO,
COILAREA, COILLOAD, COILPERI, COILTHIC, COILVOLU, COILWIDT, CONTACTA, CP,
DETAX,
ENTHAL, GIC, GJCN, GS, GT, HSIZE, I, INSULTHI, J, JCN, JCO, K, LOAD, LOADPC,
M,
MGS, N, NET (A PROGRAM), NUCLHTCO, NUCLHTMA, NUCLHTPC, NUCLTHMA, NUCLTHTM,
PANCAKES, Q, QO, RPRIME, SAFETY, SAFETYO, SPECACLO, SPECNUCH, T, TAB, TH,
THERMCON, TI, TURNS, TO, X, XYMIN, XYSTEP
```

Results for a coil with POLO-Type conductor

With such a quadratic cross section area conductor the winding area of 61 x 61 cm^2 can be filled with 22 pancakes of 22 turns each. The interlayer thermal coupling is given by a 1 mm thick insulation layer. Its thermal conductivity (thermcond) is taken as 0.03 $Wm^{-1} K^{-1}$ at 2 K. This is a typical but conservative value for fiberglass/epoxy /3, 4/. This results coefficient $a_2 = 21.3$ W/K (eq. 18). The thermal coupling between the inner and outermost turns is described by a_3 (eq. 21). Parametric studies are done for

$$0 \leqq a_3/a_2 < 0.1.$$

Realistic values are in the range of $a_3/a_2 \approx 0.001$ as shown by the approximation in eq. 21.

The following calculations have been done with the assumption of 50 % current safety margin ($s_o = 0.5$) at the inlet with $B_o = 10.7$ T and $T_o = 1.8$ K. The safety margin within the coil depends upon the local field and temperature. For a given load it depends upon the flow rate. Table 3 shows the results for a flow rate of 3 g/s. The safety margin is seen to become negative from the outlet of the first turn (N = 1) to the outlet of the 4th turn. Here, the conductor is operated above its local critical current. Because of the decrease of the magnetic field (Fig. 3) the outermore turns, although beeing operated with temperatures above 4 K, have positive safety margin (Fig. 2).

Table 4 and Fig. 4 show the operational state for a flow rate increased so far that the minimum of the safety margin is positive but close to zero. So the flow rate of about 4 g/s is the lowest limit to achieve superconductivity in the whole coil. Stable operation however needs even higher flow rate so that the safety margin s becomes sufficiently greater than zero. But what is sufficient? Due to the very favourable heat transfer properties of He II the safety margin may be close to zero at temperatures $T < T_\lambda \approx 2.2$ K and it must be higher in He I. With 8 g/s of flow rate (Tab. 5, Fig. 5) we get a situation with $s > 1$ at the He II/He I transition which is in the 5th layer. This means that outermore winding are operated with the 100 % to 370 % safety margin in current. The minimum with $s = 0.4$ is at the end of the first layer. Here, the temperature is 1.98 K. This is close to the optimum temperature for He II cooling /5/. Thus, it can be expected that this flow rate provides sufficient safety margin at all positions of the coil. Hence, this flow rate of 8 g/s is taken as reference for further considerations.

Table 3: Calulation with input of too small flow rate to achieve positve safety margin in all turns.

```
THERMAL COND. OF INSULATION:  THERMCON =  .03    W/(M K)
FLOW RATE PER PANCAKE:        MGS =  3    G/S
SPEC. MAX. NUCL. HEAT:        NUCLHTMA =  .3    MW/CM**3
LOAD PER PANCAKE:             LOADPC =  22.5    W
TOTAL LOAD PER COIL:          LOAD =  495    W
COEFFICIENTS (W/K):  A1 =  8.37   A2 =  21.3   A3 =  0
```

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	*****	*****	*****	****	*****	******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	3.47	2.77	.471	-.293
2	5.55	10.3	2.69	2.98	.501	-.248
3	8.32	9.98	2.11	3.16	.551	-.173
4	11.1	9.62	1.69	3.3	.618	-.0726
5	13.9	9.26	1.38	3.43	.698	.0474
6	16.6	8.9	1.15	3.53	.789	.183
7	19.4	8.55	.984	3.63	.887	.33
8	22.2	8.19	.861	3.71	.991	.486
9	25	7.83	.77	3.79	1.1	.648
10	27.7	7.47	.703	3.87	1.21	.815
11	30.5	7.11	.653	3.94	1.32	.986
12	33.3	6.75	.617	4	1.44	1.16
13	36	6.39	.591	4.07	1.56	1.33
14	38.8	6.03	.571	4.13	1.67	1.51
15	41.6	5.99	.557	4.19	1.63	1.45
16	44.4	5.95	.546	4.25	1.59	1.39
17	47.1	5.92	.538	4.3	1.56	1.33
18	49.9	5.88	.532	4.36	1.52	1.28
19	52.7	5.85	.528	4.4	1.49	1.24
20	55.5	5.81	.525	4.44	1.47	1.2
21	58.2	5.77	.523	4.47	1.45	1.18
22	61	5.74	.521	4.49	1.45	1.18

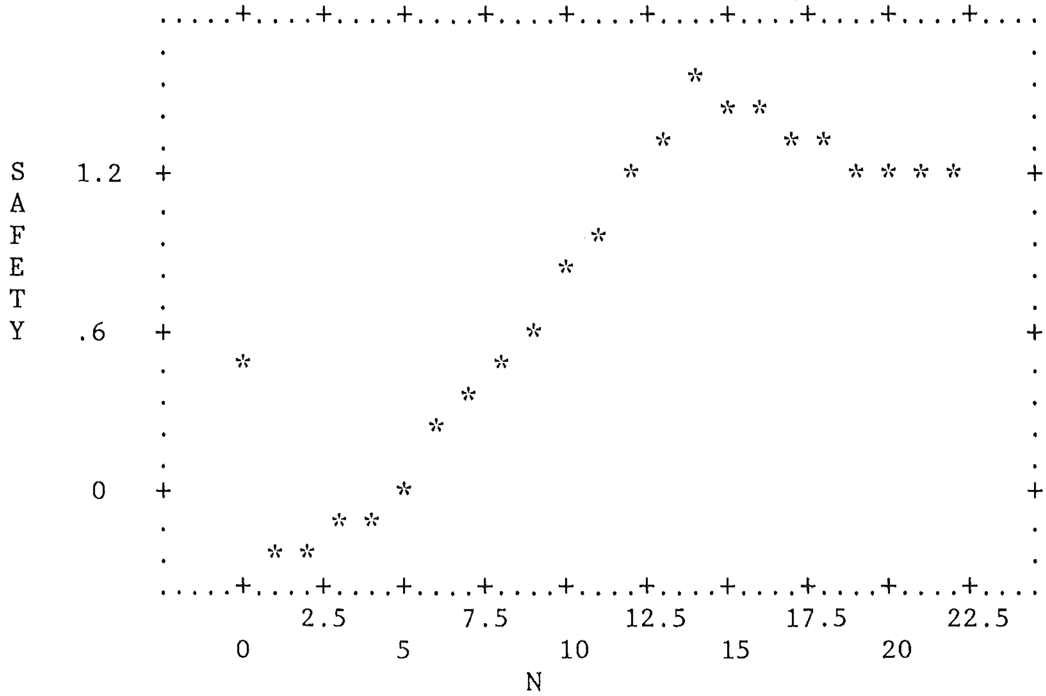


FIG. 2 : Safety margin vs. turn number N for helium flow rate of 3 g/s.

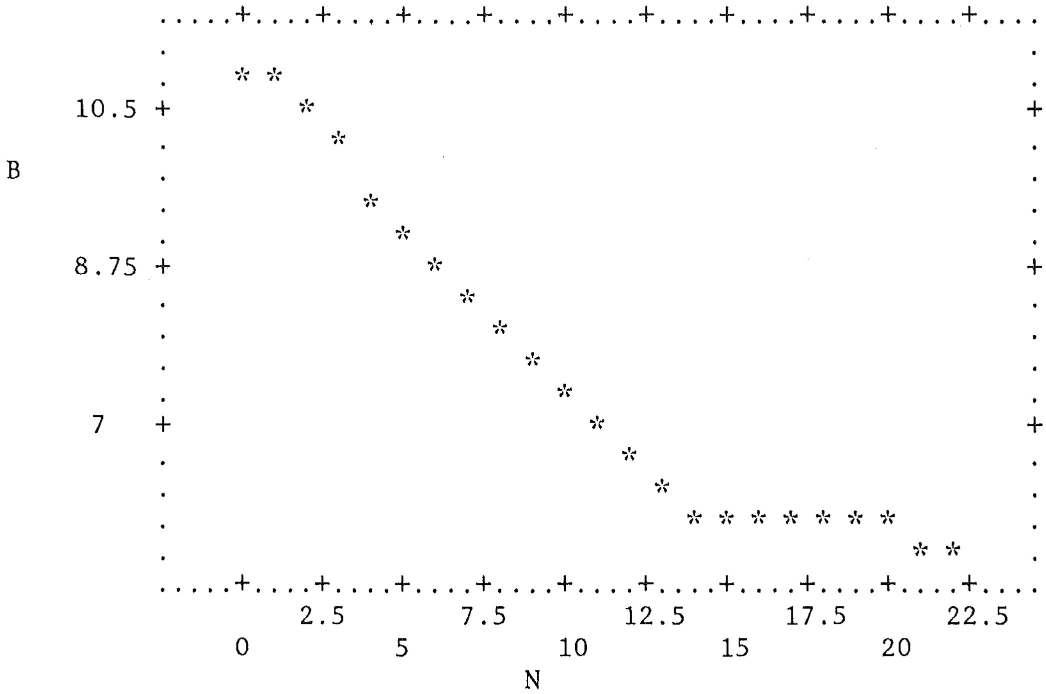


Fig. 3 : Distribution of the magnetic field.

Tab.4 : Calculation with minimum flow rate to achieve positive safety margin in all turns.

THERMAL COND. OF INSULATION: THERMCON = .03 W/(M K)
FLOW RATE PER PANCAKE: MGS = 4 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = .3 MW/CM**3
LOAD PER PANCAKE: LOADPC = 22.5 W
TOTAL LOAD PER COIL: LOAD = 495 W
COEFFICIENTS (W/K): A1 = 11.6 A2 = 21.3 A3 = 0

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	*****	*****	*****	****	*****	******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	3.47	2.41	.69	.0345
2	5.55	10.3	2.69	2.58	.767	.15
3	8.32	9.98	2.11	2.72	.859	.288
4	11.1	9.62	1.69	2.83	.963	.445
5	13.9	9.26	1.38	2.93	1.08	.615
6	16.6	8.9	1.15	3.01	1.2	.798
7	19.4	8.55	.984	3.08	1.33	.988
8	22.2	8.19	.861	3.15	1.46	1.19
9	25	7.83	.77	3.21	1.59	1.39
10	27.7	7.47	.703	3.26	1.73	1.59
11	30.5	7.11	.653	3.31	1.87	1.8
12	33.3	6.75	.617	3.36	2.01	2.01
13	36	6.39	.591	3.41	2.15	2.22
14	38.8	6.03	.571	3.46	2.29	2.43
15	41.6	5.99	.557	3.51	2.27	2.4
16	44.4	5.95	.546	3.55	2.25	2.37
17	47.1	5.92	.538	3.59	2.23	2.35
18	49.9	5.88	.532	3.63	2.21	2.32
19	52.7	5.85	.528	3.67	2.2	2.3
20	55.5	5.81	.525	3.7	2.19	2.28
21	58.2	5.77	.523	3.73	2.18	2.28
22	61	5.74	.521	3.74	2.19	2.28

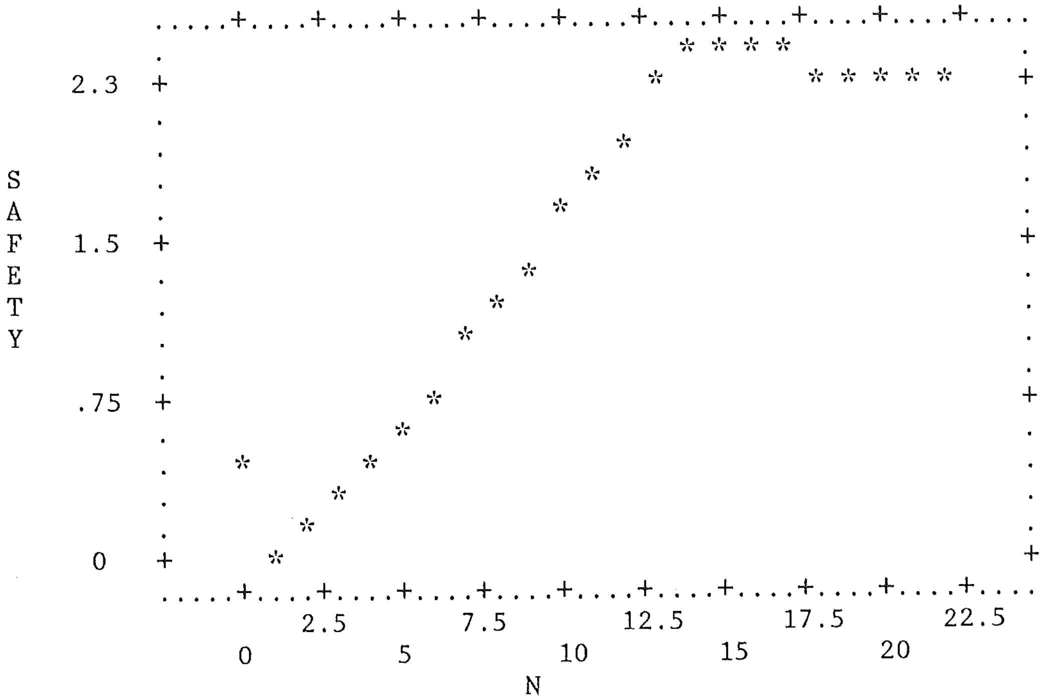


FIG. 4

Tab. 5: Calculation with input data to achieve 100 % safety margin at the HeII/HeI transition.

```
THERMAL COND. OF INSULATION:  THERMCON =  .03    W/(M K)
FLOW RATE PER PANCAKE:        MGS =  8    G/S
SPEC. MAX. NUCL. HEAT:        NUCLHTMA =  .3    MW/CM**3
LOAD PER PANCAKE:             LOADPC =  22.5    W
TOTAL LOAD PER COIL:          LOAD =  495    W
COEFFICIENTS (W/K):  A1 =  28.6   A2 =  21.3   A3 =  0
```

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	*****	*****	*****	****	*****	******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	3.47	1.98	.917	.376
2	5.55	10.3	2.69	2.06	1.06	.586
3	8.32	9.98	2.11	2.13	1.2	.806
4	11.1	9.62	1.69	2.18	1.36	1.04
5	13.9	9.26	1.38	2.22	1.51	1.27
6	16.6	8.9	1.15	2.26	1.67	1.51
7	19.4	8.55	.984	2.29	1.84	1.75
8	22.2	8.19	.861	2.32	2	2
9	25	7.83	.77	2.35	2.16	2.25
10	27.7	7.47	.703	2.37	2.33	2.5
11	30.5	7.11	.653	2.39	2.5	2.75
12	33.3	6.75	.617	2.41	2.67	3
13	36	6.39	.591	2.43	2.83	3.25
14	38.8	6.03	.571	2.45	3	3.5
15	41.6	5.99	.557	2.47	3.01	3.52
16	44.4	5.95	.546	2.49	3.02	3.53
17	47.1	5.92	.538	2.51	3.02	3.54
18	49.9	5.88	.532	2.53	3.03	3.55
19	52.7	5.85	.528	2.55	3.04	3.56
20	55.5	5.81	.525	2.56	3.05	3.57
21	58.2	5.77	.523	2.58	3.06	3.58
22	61	5.74	.521	2.59	3.07	3.6

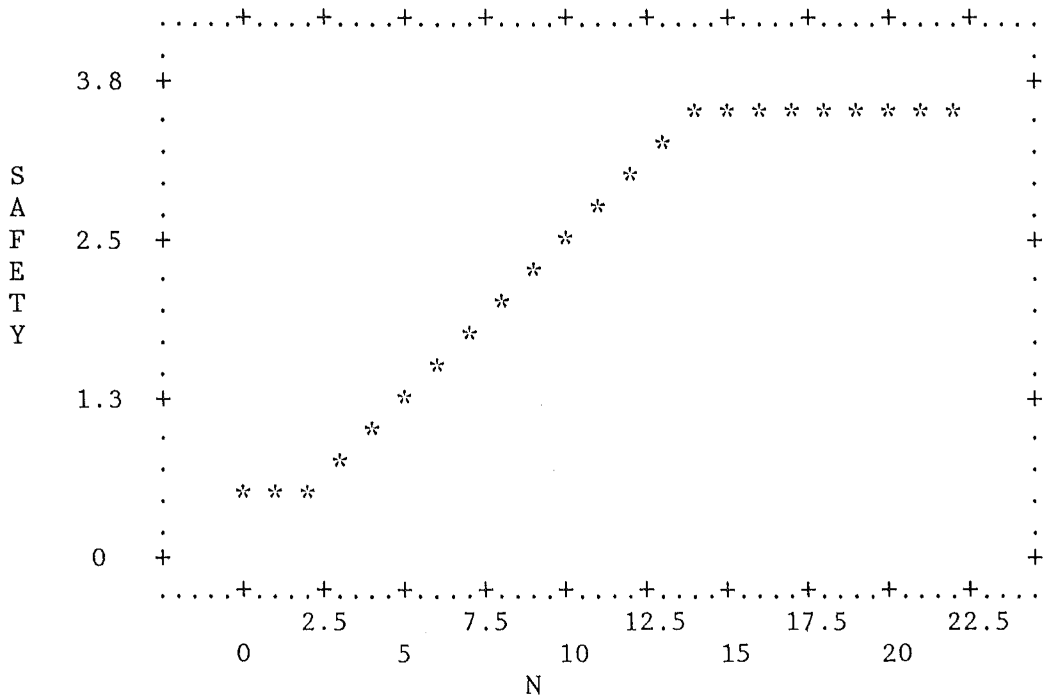


FIG. 5

The effects of interlayer and coil-to-case insulation

So far the studies have been done for interlayer and coil-to-case insulations which are believed to be realistic approximations. But it is interesting to know how sensitively the results depend on those assumptions. Results for the ideal set-up with zero thermal coupling between the layers (therm.cond. = 0) and with zero conductivity of the casing ($a_3 = 0$) are shown in Tab. 6a. Compared with the reference system (Tab. 5), the safety margin minimum is increased from 0.38 to 0.42. This shows that the reference system is not very far from an ideal one (at least for the flow rate as considered here).

Tab. 6b shows the impact of deteriorated interlayer insulation (0.1 W(mK) thermal conductivity of 1 mm thick insulation at about 2 K is an extremely conservative assumption). Even in this case the decrease in safety margin proves to be quite moderate (0.30 in minimum and 0.7 at He II/He I transition).

The impact of the coil-to-case coupling is shown by Tab. 7. In the first case (Tab. 7a) unrealistically strong coupling ($A_3 = 0.1\ A_2$), by a factor of 100 higher than approximated for a realistic system has been assumed. The degradation proves to be still moderate (min (SAFETY) = 0.333). If this factor is reduced to 10 ($A_3 = 0.01\ A_2$), then, as shown by comparison of Tab. 7b and 5, the deviation from a coil with an ideal case ($A_3 = 0$) is negligeable with respect to the operational parameters T and safety.

This result is very important. It shows, that such a coil will not need an additional thermal barrier between the case and the He II cooled conductor. The electrical insulation, necessary anyhow, together with the thermal impedance of the case proves to provide sufficient thermal insulation.

Tab. 6: Effects of interlayer and coil-to-case insulation
a) Perfect insulation, i.e. thermcond=0 and A3=0.

THERMAL COND. OF INSULATION: THERMCON = 0 W/(M K)
FLOW RATE PER PANCAKE: MGS = 8 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = .3 MW/CM**3
LOAD PER PANCAKE: LOADPC = 22.5 W
TOTAL LOAD PER COIL: LOAD = 495 W
COEFFICIENTS (W/K): A1 = 28.6 A2 = 0 A3 = 0

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	******	******	******	*****	******	*******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	3.47	1.92	.946	.419
2	5.55	10.3	2.69	2.02	1.08	.621
3	8.32	9.98	2.11	2.09	1.22	.836
4	11.1	9.62	1.69	2.15	1.37	1.06
5	13.9	9.26	1.38	2.2	1.53	1.29
6	16.6	8.9	1.15	2.24	1.69	1.53
7	19.4	8.55	.984	2.27	1.85	1.77
8	22.2	8.19	.861	2.3	2.01	2.01
9	25	7.83	.77	2.33	2.17	2.26
10	27.7	7.47	.703	2.35	2.34	2.51
11	30.5	7.11	.653	2.38	2.51	2.76
12	33.3	6.75	.617	2.4	2.67	3.01
13	36	6.39	.591	2.42	2.84	3.26
14	38.8	6.03	.571	2.44	3.01	3.51
15	41.6	5.99	.557	2.46	3.02	3.53
16	44.4	5.95	.546	2.48	3.03	3.54
17	47.1	5.92	.538	2.5	3.03	3.55
18	49.9	5.88	.532	2.51	3.04	3.56
19	52.7	5.85	.528	2.53	3.05	3.57
20	55.5	5.81	.525	2.55	3.05	3.58
21	58.2	5.77	.523	2.57	3.06	3.59
22	61	5.74	.521	2.59	3.07	3.6

b) Winding with very bad interlayer insulation (thermcond = 0.1 W/(m K) and with perfect coil-to-case insulation).

THERMAL COND. OF INSULATION: THERMCON = .1 W/(M K)
FLOW RATE PER PANCAKE: MGS = 8 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = .3 MW/CM**3
LOAD PER PANCAKE: LOADPC = 22.5 W
TOTAL LOAD PER COIL: LOAD = 495 W
COEFFICIENTS (W/K): A1 = 28.6 A2 = 71 A3 = 0

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	******	******	******	*****	*****	*******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	3.47	2.08	.87	.304
2	5.55	10.3	2.69	2.14	1.02	.525
3	8.32	9.98	2.11	2.2	1.17	.754
4	11.1	9.62	1.69	2.24	1.33	.989
5	13.9	9.26	1.38	2.28	1.49	1.23
6	16.6	8.9	1.15	2.31	1.65	1.47
7	19.4	8.55	.984	2.33	1.81	1.72
8	22.2	8.19	.861	2.36	1.98	1.97
9	25	7.83	.77	2.38	2.14	2.22
10	27.7	7.47	.703	2.4	2.31	2.47
11	30.5	7.11	.653	2.43	2.48	2.72
12	33.3	6.75	.617	2.45	2.65	2.97
13	36	6.39	.591	2.46	2.81	3.22
14	38.8	6.03	.571	2.48	2.98	3.48
15	41.6	5.99	.557	2.5	2.99	3.49
16	44.4	5.95	.546	2.52	3	3.5
17	47.1	5.92	.538	2.53	3.01	3.51
18	49.9	5.88	.532	2.55	3.02	3.53
19	52.7	5.85	.528	2.56	3.03	3.54
20	55.5	5.81	.525	2.57	3.04	3.56
21	58.2	5.77	.523	2.58	3.05	3.58
22	61	5.74	.521	2.59	3.07	3.6

Tab. 7: Effect of coil-to-case insulation.
a) medium interlayer insulation (thermcond = 0.03 W/(m K) and weak coil-to-case insulation (A3 = 0.1*A2).

THERMAL COND. OF INSULATION: THERMCON = .03 W/(M K)
FLOW RATE PER PANCAKE: MGS = 8 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = .3 MW/CM**3
LOAD PER PANCAKE: LOADPC = 22.5 W
TOTAL LOAD PER COIL: LOAD = 495 W
COEFFICIENTS (W/K): A1 = 28.6 A2 = 21.3 A3 = 2.13

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	*****	*****	*****	****	*****	******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	3.47	2.04	.889	.333
2	5.55	10.3	2.69	2.12	1.03	.542
3	8.32	9.98	2.11	2.19	1.17	.761
4	11.1	9.62	1.69	2.24	1.33	.988
5	13.9	9.26	1.38	2.28	1.48	1.22
6	16.6	8.9	1.15	2.32	1.64	1.46
7	19.4	8.55	.984	2.35	1.8	1.7
8	22.2	8.19	.861	2.38	1.97	1.95
9	25	7.83	.77	2.4	2.13	2.2
10	27.7	7.47	.703	2.43	2.3	2.45
11	30.5	7.11	.653	2.45	2.46	2.7
12	33.3	6.75	.617	2.47	2.63	2.95
13	36	6.39	.591	2.49	2.8	3.2
14	38.8	6.03	.571	2.51	2.97	3.45
15	41.6	5.99	.557	2.53	2.97	3.46
16	44.4	5.95	.546	2.55	2.98	3.47
17	47.1	5.92	.538	2.57	2.99	3.48
18	49.9	5.88	.532	2.58	3	3.49
19	52.7	5.85	.528	2.6	3.01	3.51
20	55.5	5.81	.525	2.61	3.02	3.52
21	58.2	5.77	.523	2.61	3.03	3.55
22	61	5.74	.521	2.59	3.07	3.6

Tab. 7 :
b) medium interlayer and medium coil-to-case insulation (thermcond = 0.03 W/(m K) and A3 = 0.01*A2).

THERMAL COND. OF INSULATION: THERMCON = .03 W/(M K)
FLOW RATE PER PANCAKE: MGS = 8 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = .3 MW/CM**3
LOAD PER PANCAKE: LOADPC = 22.5 W
TOTAL LOAD PER COIL: LOAD = 495 W
COEFFICIENTS (W/K): A1 = 28.6 A2 = 21.3 A3 = .213

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	*****	*****	*****	****	*****	******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	3.47	1.99	.915	.372
2	5.55	10.3	2.69	2.07	1.05	.582
3	8.32	9.98	2.11	2.13	1.2	.802
4	11.1	9.62	1.69	2.19	1.35	1.03
5	13.9	9.26	1.38	2.23	1.51	1.27
6	16.6	8.9	1.15	2.27	1.67	1.5
7	19.4	8.55	.984	2.3	1.83	1.75
8	22.2	8.19	.861	2.33	2	1.99
9	25	7.83	.77	2.35	2.16	2.24
10	27.7	7.47	.703	2.38	2.33	2.49
11	30.5	7.11	.653	2.4	2.49	2.74
12	33.3	6.75	.617	2.42	2.66	2.99
13	36	6.39	.591	2.44	2.83	3.24
14	38.8	6.03	.571	2.46	3	3.5
15	41.6	5.99	.557	2.48	3.01	3.51
16	44.4	5.95	.546	2.5	3.01	3.52
17	47.1	5.92	.538	2.52	3.02	3.53
18	49.9	5.88	.532	2.53	3.03	3.54
19	52.7	5.85	.528	2.55	3.04	3.55
20	55.5	5.81	.525	2.57	3.04	3.57
21	58.2	5.77	.523	2.58	3.05	3.58
22	61	5.74	.521	2.59	3.07	3.6

Lay-out of the conductor

So far, the conductor has been specified by different requirements such as

Operational current,	I = 16 kA
Critical current,	I_c (10.7 T, 1.8 K) = 1.5 I
He flow rate,	$\dot{m}$ = 8 g/s
Length of the coolant channel,	L = 563 m
Thickness of electr. insulation,	δ = 0.5 mm.

Those requirements might be conflicting and it must be checked whether a respective design which might for example be based on the POLO concept is possible.

For the cable we assume present POLO data /10/:

NbTi/CuNi/Cu	= 1:1:2
j_c (8 T, 4.2 K)	= 190 A/mm^2
void factor: A_{He}/A_{Cond}	= 0.34

Scaling this conductor with (12) yields

$$j_c(10.7, 1.8\,K) = 1.38\, j_c(8\,T, 4.2\,K) = 262\ A/mm^2$$

So a cable cross section area (including He void) of

$$A_c = \frac{1.5\, I}{j_c(10.7, 1.8)} \left(1 + \frac{A_{He}}{A_{Con}}\right) = 123\ mm^2$$

is required for 16 kA with 50 % safety margin at 10.7 T and 1.8 K. This can be placed in an annular gap with 11.4 and 9.5 mm mayor and minor radius. The question how the strands must be arranged within the annulus is beyond the scape of the present considerations. So, the cable concept as shown in Fig. 6 provides a coolant channel with D_h = 17.0 mm hydraulic diameter for the He flow. The pressure drop calculated from

$$\Delta p = \xi \frac{\rho v^2 L}{2 D_H} = \xi \frac{\dot{m}^2 L}{2 \rho A_h^2 D_h} \qquad (22)$$

with $\xi = 0.03$ as conservative approximation for a rough stainless steel tube proves to be $\Delta p = 4260$ Pa (0.043 bar). Such small pressure drops and also appreciably higher flow rates can easily be achieved by self-sustained fountain effect pumps /7/.*) Therefore, this option is being considered as reference for the helium pump. The reserves inherent to this cable and the operational concept may be used in different ways:

(a) Operation at highest possible flow rate to increase the safety margin.

(b) Allowance of higher thermal load, especially higher nuclear heat load.

(c) Reduction of the cable cross section area and hence reduction of the coil size.

(d) Increase of safety margin by incorporating more superconducting material.

Cases a, b and c will be discussed in some more details.

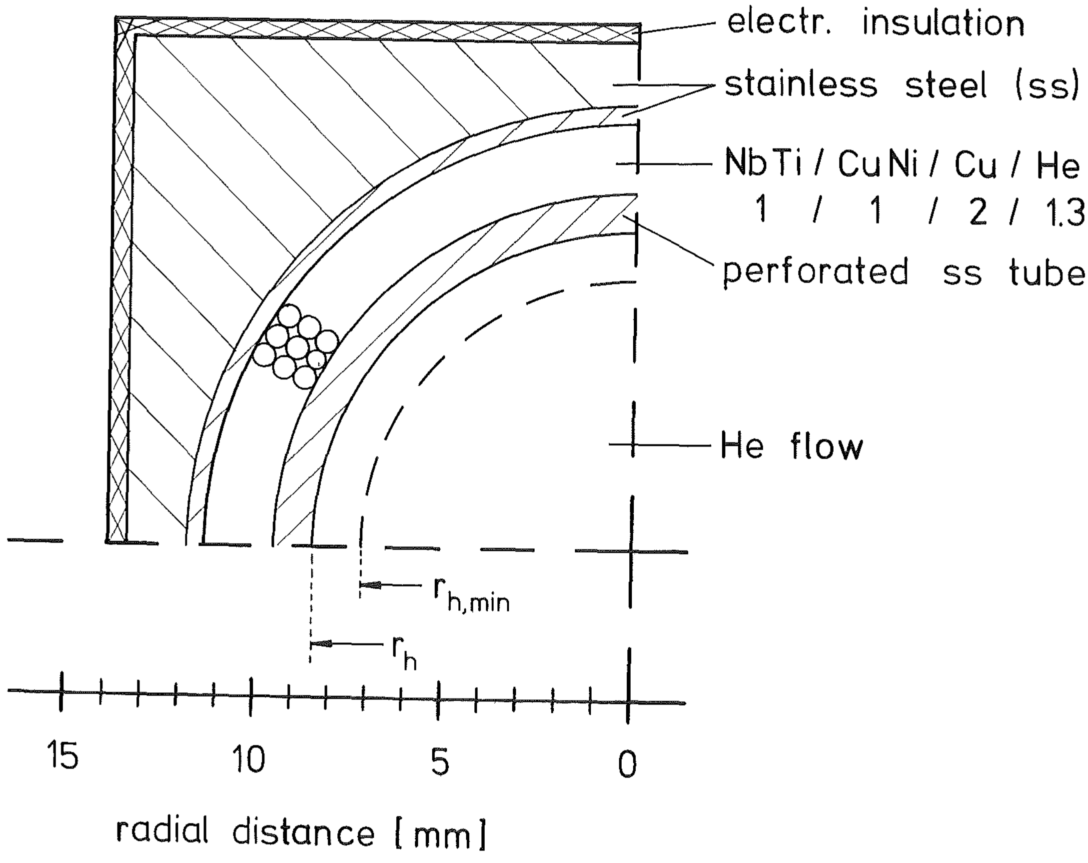


Fig. 6: The concept of a "POLO" type cable fitted to the requirements of a NET-II TF coil.

*) The respective refrigeration system is shown in Fig. A1 (appendix).

Operational characteristic of a coolant system with a self-sustained fountain effect pump (FEP)

For discussing self-sustained FEP loops it is convenient ro rearrange eq. 22 to get the term

$$\beta Q = \sqrt{\frac{\xi L}{2 A_h^2 D}} \cdot Q = \frac{Q}{\dot{m}} \sqrt{\Delta p \, \rho} \tag{23}$$

The right hand side with fountain pressure Δp, helium density ρ, and the term

$$\frac{Q}{\dot{m}} = h_N - h_o \approx c_p \, (T_N - T_o) \tag{24}$$

proves to be a function of inlet and outlet temperatures T_o and T_N, respectively /1, 11/ and it is independent of the geometry of the loop. So it is convenient to discuss the operational parameters such as coil outlet temperature T_N and pressure drop Δp as funtion of the scaled heat load βQ, where

$$\beta = \sqrt{\frac{\xi L}{2 A_h^2 D}} \tag{25}$$

is a geometry factor of a rough surface tube with constant friction factor ξ and with the hydraulic cross section area A_h and the diameter D.

The program listed in Tab. A1 (appendix) has been used to calculate the operational parameters such as outlet temperature T_N (equivalent to T_2 in the program), and fountain pressure Δp as function of the scaled heat load βQ. Those plots are given by Fig. 7 and Fig. 8. The graph of enthalpy difference between outlet and inlet, namely $h_2 - h_1 = f(\beta, Q)$ as given by Fig. A1, may be used to determine the flow rate

$$\dot{m} = \frac{Q}{h_N - h_o} \tag{26}$$

in such a channel with known β and with total heat load Q (h_1, h_o and h_2, h_N are equivalent).

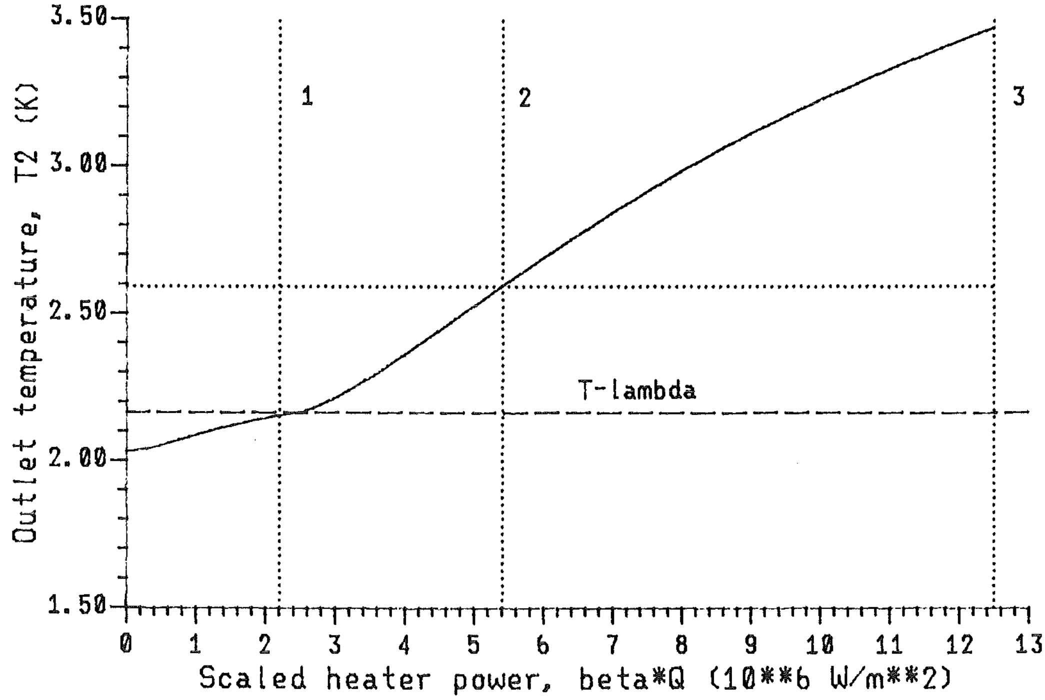


Fig. 7: Cooling characteristic of a self-sustained Fountain Effect Pump Loop. Coil outlet temperature T_2 vs. scaled heat load βQ (see text for definiation of the termin βQ).

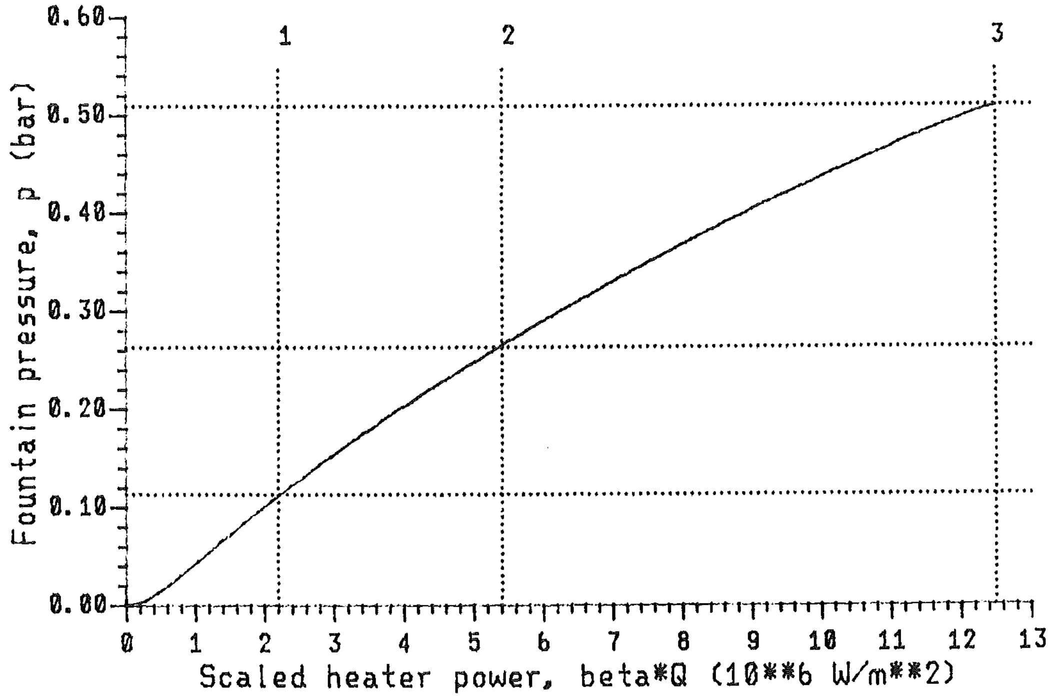


Fig. 8: Pressure heat of a self-sustained FEP as function of the scaled load.

This geometry factor is $\beta_1 = 9.82 \cdot 10^4 \, m^{-2}$ for a system with L = 563 m length and D_1 = 17 mm diameter of the coolant channel. Hence, in self-sustained FEP operational mode the coil with the total load of Q_1 = 22.5 W per pancake (resultant from Tab. 5) is operated at $\beta_1 Q = 2.2 \cdot 10^6 \, W/m^2$ and the outlet temperature T_2 resulting from Fig. 7 is close to T_λ. The resultant safety margin would be very high, but the low overall temperature must be payed with unnecessarily high operation costs of the refrigerator. So it might be better to reduce the flow rate either by limiting the pump capacitance or preferably by reduction of the hydraulic diameter of the cable.

Optimization of the cable

To achieve the same operational state as in the reference case as described by Tab. 5, the hydraulic diameter can be reduced thus that the outlet temperature becomes T_2 = 2.59 K. The respective geometry factor β_2 results from Fig. 7, namely $(\beta Q)_2 = 5.4 \cdot 10^6 \, W/m^2$, i.e. $\beta_2 = 24.0 \cdot 10^4 \, m^{-2}$ for Q = 22.5 W per pancake. The resultant hydraulic diameter is D = 11.9 mm. This reduction from 17.0 to 11.9 mm corresponds to about 15 % reduction of the overall cross section area of the cable and also of the total winding. So the winding area of such a coil can be reduced from 0.372 m^2 to 0.315 m^2. The cross section of the optimized cable becomes $A_{cable, opt}$ = 25.5 x 25.5 mm^2 instead of 27.7 x 27.7 mm^2 as assumed initially.

Reserves in nuclear heat load

The optimized cable with D_{opt} = 11.9 mm inner diameter of the coolant channel is operated at a scaled heater power of $(\beta Q)_2 = 5.4 \cdot 10^6 \, W/m^2$ when the peak nuclear heat load amounts to 0.3 mW/cm^3. The self-sustained FEP circuit, however, allows operation at maxiumum scaled heater power of $(\beta Q)_{max}$ = $12 \cdot 10^6 \, W/m^2$) hence at 2.2 times higher total heat load. In this case, the flow rate will adjust so that the outlet temperature becomes $T_{2, max}$ = 3.4 K (Fig. 7), i.e. to $\dot{m}_{max} = Q_{max}/\Delta h_{max}$ = 10.5 g/s (s. Fig. A2).

The operational parameters of this mode are listed in Tab. 8. The peak nuclear heat load has been raised to 1.32 mW/cm^3. This causes a steep temperature increase from 1.8 K to 2.3 K within the first layer. Here the safety margin achieves a minimum of 0.13 K at 2.3 K. But the safety margin is positive everywhere. So stable operation might be possible even at such high heat load.

Tab. 8: Cable with 11.9 mm i.d coolant channel operated at maximum heat load to be removeable by a self-sustained FEP (nuclhtmax = 1.0 mW/cm**3, outlet temp.=3.4 K).

THERMAL COND. OF INSULATION: THERMCON = .03 W/(M K)
FLOW RATE PER PANCAKE: MGS = 10.5 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = 1 MW/CM**3
LOAD PER PANCAKE: LOADPC = 48.5 W
TOTAL LOAD PER COIL: LOAD = 1068 W
COEFFICIENTS (W/K): A1 = 30.2 A2 = 21.3 A3 = 0

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	*****	*****	******	****	*****	******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	10.4	2.3	.756	.134
2	5.55	10.3	7.76	2.52	.809	.213
3	8.32	9.98	5.84	2.68	.885	.328
4	11.1	9.62	4.43	2.81	.981	.472
5	13.9	9.26	3.4	2.91	1.09	.641
6	16.6	8.9	2.64	2.98	1.22	.83
7	19.4	8.55	2.08	3.04	1.36	1.03
8	22.2	8.19	1.66	3.09	1.5	1.25
9	25	7.83	1.36	3.13	1.65	1.47
10	27.7	7.47	1.14	3.17	1.8	1.7
11	30.5	7.11	.973	3.2	1.96	1.94
12	33.3	6.75	.852	3.22	2.12	2.18
13	36	6.39	.764	3.25	2.28	2.42
14	38.8	6.03	.698	3.27	2.44	2.66
15	41.6	5.99	.65	3.29	2.45	2.67
16	44.4	5.95	.615	3.31	2.45	2.67
17	47.1	5.92	.589	3.33	2.45	2.68
18	49.9	5.88	.57	3.35	2.45	2.68
19	52.7	5.85	.556	3.36	2.46	2.69
20	55.5	5.81	.545	3.38	2.46	2.69
21	58.2	5.77	.538	3.4	2.47	2.7
22	61	5.74	.532	3.41	2.48	2.72

For the cable with the 17 mm inner diameter even much higher heat load can be tolerated. this cable is operated at $\beta Q = 2.2 \cdot 10^6$ W/m^2 when the reference load with 0.3 W/cm^3 nuclear heat is applied. So the total load can be increased by a factor of 5.4 to achieve operation at the fountain effect pump limit with $\beta Q = 12 \cdot 10^6$ W/cm^2 (dotted line 3 of Fig. 7). The respective operational data are listed in Tab. 9. The peak nuclear heat load has been increased to 3.0 mW/cm^3 (10 times higher than for the reference case!). The flow rate increases to 26 g/s. Again, the safety margin proves to be positive in all layers of the coil.

Finally, when operating this cable with 17 mm diameter coolant channel under reference conditions thus that in self-sustained FEP operational mode the safety factor becomes SAFETY $\approx$ 1 at the He II/He I transition then the nuclear heat load can be increased to NUCLHTMA = 0.9 mW/cm^3. the respective results are listed in Tab. 10. The flow rate adjusts to 18 g/s. (The input parameters of flow rate and nuclear heating have been modified so that the resultant parameters βQ and outlet temperature T_N (equivalent to T_2) become consistant with Fig. 7, the FEP-loop characteristic).

Tab. 9 : Conductor with 17 mm i.d. operated at highest heat load tolerable for a self-sustained FEP loop.

THERMAL COND. OF INSULATION: THERMCON = .03 W/(M K)
FLOW RATE PER PANCAKE: MGS = 26 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = 3 MW/CM**3
LOAD PER PANCAKE: LOADPC = 123 W
TOTAL LOAD PER COIL: LOAD = 2704 W
COEFFICIENTS (W/K): A1 = 74.9 A2 = 21.3 A3 = .213

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	******	******	*******	****	*****	*******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	30	2.28	.762	.144
2	5.55	10.3	22.2	2.56	.781	.172
3	8.32	9.98	16.5	2.77	.829	.244
4	11.1	9.62	12.3	2.92	.905	.357
5	13.9	9.26	9.16	3.03	1	.504
6	16.6	8.9	6.88	3.12	1.12	.678
7	19.4	8.55	5.19	3.18	1.25	.873
8	22.2	8.19	3.96	3.23	1.39	1.09
9	25	7.83	3.05	3.27	1.54	1.31
10	27.7	7.47	2.38	3.3	1.7	1.54
11	30.5	7.11	1.89	3.33	1.86	1.78
12	33.3	6.75	1.52	3.35	2.02	2.03
13	36	6.39	1.26	3.36	2.19	2.28
14	38.8	6.03	1.06	3.38	2.36	2.53
15	41.6	5.99	.918	3.39	2.37	2.55
16	44.4	5.95	.812	3.4	2.38	2.56
17	47.1	5.92	.734	3.41	2.39	2.58
18	49.9	5.88	.676	3.42	2.4	2.6
19	52.7	5.85	.634	3.43	2.41	2.61
20	55.5	5.81	.603	3.43	2.42	2.63
21	58.2	5.77	.58	3.44	2.43	2.65
22	61	5.74	.563	3.44	2.45	2.67

Tab. 10: Cable with 17 mm i.d. operated at its optimum load to achieve SAFETY = 1 at HeII/HeI transition (operation in self-sustained FEP mode).

THERMAL COND. OF INSULATION:	THERMCON =	.03	W/(M K)
FLOW RATE PER PANCAKE:	MGS =	18	G/S
SPEC. MAX. NUCL. HEAT:	NUCLHTMA =	.9	MW/CM**3
LOAD PER PANCAKE:	LOADPC =	44.8	W
TOTAL LOAD PER COIL:	LOAD =	986	W

COEFFICIENTS (W/K): A1 = 72 A2 = 21.3 A3 = .213

TABLE OF OPERATIONAL PARAMETERS:

N	X	B	Q	T	JCN	SAFETY
**	*****	*****	*****	****	*****	******
0	0	10.7	0	1.8	1	.5
1	2.77	10.7	9.37	1.96	.928	.393
2	5.55	10.3	7.03	2.05	1.06	.596
3	8.32	9.98	5.31	2.12	1.21	.814
4	11.1	9.62	4.04	2.17	1.36	1.04
5	13.9	9.26	3.11	2.21	1.52	1.28
6	16.6	8.9	2.42	2.24	1.68	1.52
7	19.4	8.55	1.92	2.27	1.85	1.77
8	22.2	8.19	1.55	2.29	2.02	2.03
9	25	7.83	1.28	2.31	2.19	2.28
10	27.7	7.47	1.08	2.32	2.36	2.54
11	30.5	7.11	.927	2.33	2.53	2.8
12	33.3	6.75	.819	2.34	2.7	3.06
13	36	6.39	.739	2.35	2.88	3.32
14	38.8	6.03	.68	2.36	3.05	3.58
15	41.6	5.99	.637	2.37	3.07	3.6
16	44.4	5.95	.605	2.38	3.08	3.62
17	47.1	5.92	.582	2.39	3.1	3.64
18	49.9	5.88	.564	2.4	3.11	3.66
19	52.7	5.85	.552	2.4	3.12	3.68
20	55.5	5.81	.542	2.41	3.14	3.7
21	58.2	5.77	.536	2.42	3.15	3.73
22	61	5.74	.531	2.42	3.17	3.75

Cable with smooth coolant channel

The calculation done so far are for rather conservative assumptions on the flow impedance of the coolant channel. The Fanning friction factor of $\xi = 0.03$ corresponds to a relative roughness of K/D = 0.005 /8/. Experiments with helium flow in 11 mm i.d. Cu tubes /9/ show that smooth tube correlations can be used to describe the respective pressure drop; i.e., appreciably smaller (about 50 % smaller) friction factors can be assumed for realistic systems.

The normalized self-sustained FEP loop coolant characteristic for a smooth channel is shown in Fig. 8 /7/. For T_2 = 2.44 K outlet temperature the scaled heat load is

$$\alpha Q = 1.6 \cdot 10^8 (W/m^{19/9}) \tag{27}$$

with

$$\alpha = \frac{1}{A_n} \frac{L^{5/9}}{D^{2/3}} \tag{28}$$

For the reference load of 22.5 W per pancake this yields $\alpha = 7.11 \cdot 10^6$ $m^{-19/9}$, and the hydraulic diameter results as D_{min} = 11.0 mm instead of 12.9 mm required for a rough tube. Hence, a cable with about the same hydraulic diameter as the KfK POLO cable is shown to be suited for NET TF coils.

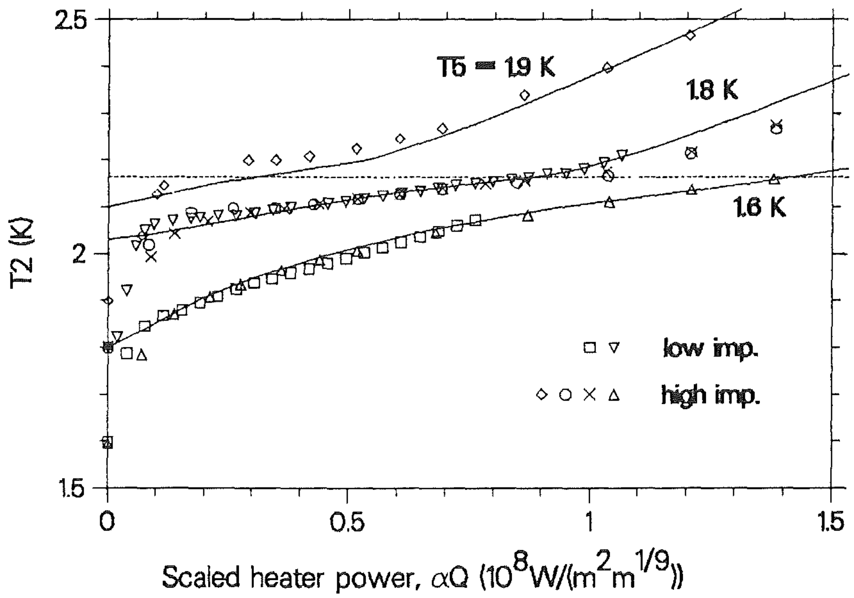


Abb. 8: Cooling characteristic outlet temperature T_2 vs. heat load Q of a self-sustained FEP loop with smooth tube flow impedance (geometry factor $\alpha = \pi L^{5/9}/(4 D^{8/3})$). Parameter T_5 is coil inlet temperature.

Coil with LCT type conductor

With a rectangular cross section conductor wound over its wider side the number of pancakes will be decreased and the number of turns will be increased according to the aspect ratio. The coil concept developed in an earlier paper /1/ has 14 pancakes with 36 turns. The respective 10 kA/11 T conductor (Fig. 9) has the following parameters:

conductor width:	43.6 mm
conductor thickness:	16.9 mm
He flow area, A_{He}:	227 mm2
hydraulic diameter, D_H =	4.25 mm

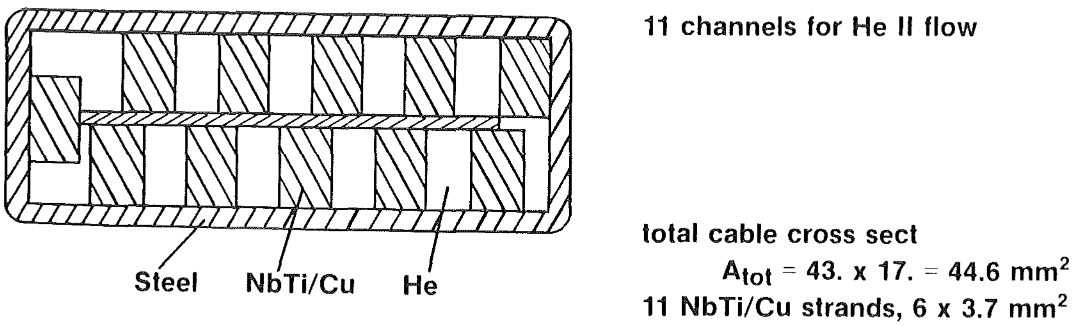


Fig. 9: Cross section of an LCT-type cable /1/.

The winding length of one pancake will be 920 m. This is considered to be too long for the hydraulic path. Therefore we assume pancake design with two conductors in hand with L = 460 m length of each coolant path. The innermost of both conductors experiences the highest nuclear heat load and it is exposed to the higher field. Therefore this channel needs the most careful attention.

For simplifaction of such calculations the interlayer and the coil-to-case thermal conduction have been neglected. To begin with, the flow rate necessary to achieve a safety factor $\geqq$ 1 at the He II/He I transition is determined. This result is shown by Tab. 11. The indices 1 and 2 describe the inner and the outermore of the two parallel channels, respectively. The same flow rate of $\dot{m}$ = 6 g/s has been assumed in both. The modified program is listed in Tab. A2 (appendix).

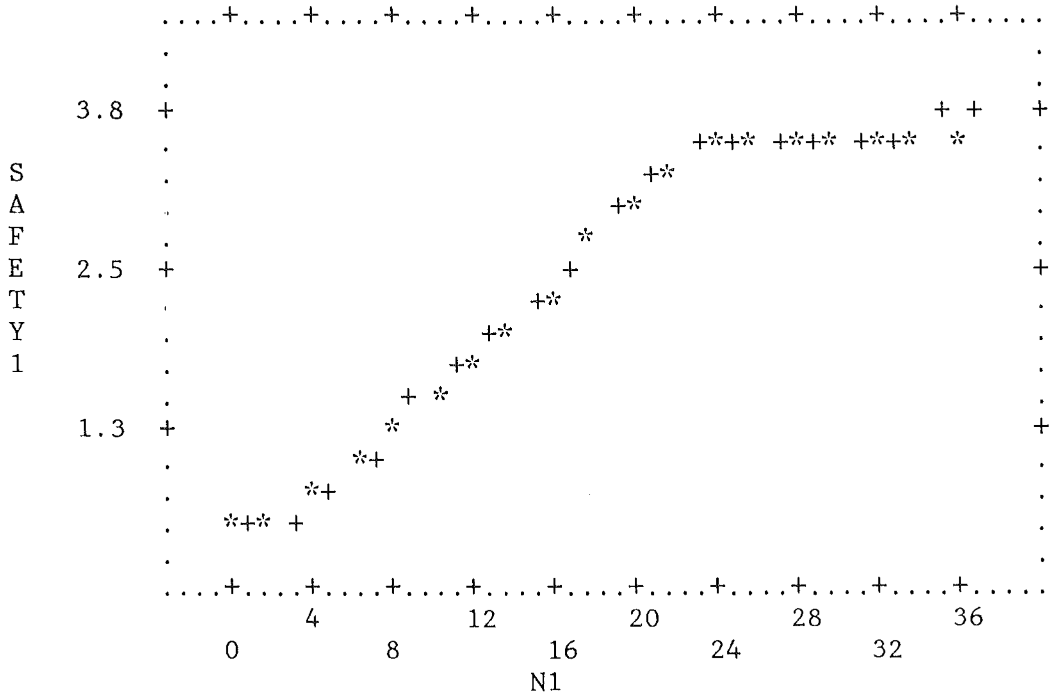
Tab. 11 : Operational parameters of a coil with two conductors wound in hand . The flow rate has been adjusted to achieve a safety margin > 1 at the HeII/HeI transition when the peak nuclear heat load is 0.3 mW/cm**3.

```
FLOW RATE PER CHANNEL:           MGS =  6     G/S
SPEC. MAX. NUCL. HEAT:           NUCLHTMA =  .3     MW/CM**3
LOAD PER INNERMOST CHANNEL:      LOADCH1 =  18     W
LOAD PER OUTERMOST CHANNEL:      LOADCH2 =  16.4     W
LOAD PER PANCAKE:                LOADPC =  34.4     W
TOTAL LOAD PER COIL:             LOAD =  482     W
THERMAL COND. OF INSULATION:     THERMCON =  0     W/(M K)
COEFFICIENTS (W/K):  A1 =  22    A2 =  0    A3 =  0
```

TABLE OF OPERATIONAL PARAMETERS:

N1	N2	X1	X2	B1	B2	Q1	Q2	T1	T2	SAFETY1	SAFETY2
**	**	*****	*****	*****	*****	*****	*****	****	***	*******	*******
0	1	0	1.69	10.7	10.7	0	0	1.8	1.8	.5	.5
2	3	3.39	5.08	10.7	10.5	3.33	2.85	1.96	1.93	.389	.578
4	5	6.78	8.47	10.3	10	2.44	2.11	2.08	2.03	.631	.838
6	7	10.2	11.9	9.82	9.6	1.83	1.61	2.17	2.1	.891	1.11
8	9	13.6	15.3	9.38	9.16	1.42	1.26	2.24	2.16	1.16	1.4
10	11	16.9	18.6	8.94	8.73	1.13	1.02	2.3	2.2	1.45	1.69
12	13	20.3	22	8.51	8.29	.93	.856	2.34	2.24	1.74	1.99
14	15	23.7	25.4	8.07	7.85	.794	.743	2.38	2.28	2.04	2.29
16	17	27.1	28.8	7.63	7.41	.701	.666	2.42	2.31	2.34	2.59
18	19	30.5	32.2	7.19	6.97	.637	.613	2.45	2.33	2.64	2.9
20	21	33.9	35.6	6.75	6.53	.593	.576	2.48	2.36	2.94	3.21
22	23	37.3	39	6.31	6.09	.563	.551	2.51	2.39	3.24	3.52
24	25	40.7	42.4	6.01	5.99	.542	.534	2.53	2.41	3.45	3.57
26	27	44.1	45.8	5.97	5.94	.527	.522	2.56	2.43	3.46	3.58
28	29	47.4	49.1	5.92	5.9	.518	.514	2.58	2.46	3.46	3.6
30	31	50.8	52.5	5.88	5.86	.511	.508	2.61	2.48	3.47	3.61
32	33	54.2	55.9	5.83	5.81	.506	.504	2.63	2.5	3.48	3.62
34	35	57.6	59.3	5.79	5.77	.503	.502	2.66	2.53	3.49	3.64
36	37	61	62.7	5.74	5.72	.501	.5	2.68	2.55	3.5	3.65

SYMBOL * IS SAFETY1   + IS SAFETY2 $ IS OVERPLOT



The load of the innermost channel results as LOADCH1 = 18 W. Its "rough channel geometry factor" resulting from eq. 25 is $\beta = 17.8 \cdot 10^4$ m^{-2} and the scaled heater power becomes $\beta Q = 3.20 \cdot 10^6$ W/m^2. This yields the outlet temperature $T_2 = 2.27$ K. This temperature as it would adjust when operated with a self-sustained fountain effect pump is again less than the outlet temperature of 2.68 K which results for 6 g/s flow rate and standard heat load (Tab. 11).

This means, that this type of cable can also be operated with higher heat load. The margin by which the heat load may be increased can again be derived from Fig. 7: For $T_{max} = 2.54$ K outlet temperature the scaled heat load is $(\beta Q)_{max} = 5.34 \cdot 10^6$ W/m^2. This is equivalent to $Q_{max} = 30.0$ W per pancake on the innermost channel. The respective operational parameters are listed in Tab. 12. The peak nuclear heat load has been increased to NUCLHTMAX = 0.7 mW/cm^3. This yields about 791 W of total load. The flow rate adjusting by FEP operation with 2.68 K outlet temperature becomes 11.0 g/s in the innermost channels. The safety margin has a minimum of about 0.38 and it is greater than 1 in the He II range. The He II/He I transition is in the 6th layer.

This shows that the LCT-type cable can also be operated with heat load appreciably higher than the reference value.

Tab. 12: LCT-type cable operated with maximum heat load and with flow rate adjusting by self-sustained fountain effect pumps (The limit in heat load is given by the criterion SAFETY = 1 at He II/He I - transition).

FLOW RATE PER COOLANT CHANNEL: MGS = 10.3 G/S
SPEC. MAX. NUCL. HEAT: NUCLHTMA = .6 MW/CM**3
LOAD PER INNERMOST CHANNEL: LOADCH1 = 27 W
LOAD PER OUTERMOST CHANNEL: LOADCH2 = 23.9 W
LOAD PER PANCAKE: LOADPC = 51 W
TOTAL LOAD PER COIL: LOAD = 713 W
THERMAL COND. OF INSULATION: THERMCON = 0 W/(M K)
COEFFICIENTS (W/K): A1 = 44.1 A2 = 0 A3 = 0

TABLE OF OPERATIONAL PARAMETERS:

N1	N2	X1	X2	B1	B2	Q1	Q2	T1	T2	SAFETY1	SAFETY2
**	**	*****	*****	*****	*****	*****	*****	****	***	*******	*******
0	1	0	1.69	10.7	10.7	0	0	1.8	1.8	.5	.5
2	3	3.39	5.08	10.7	10.5	6.17	5.2	1.96	1.92	.394	.586
4	5	6.78	8.47	10.3	10	4.39	3.73	2.07	2	.642	.855
6	7	10.2	11.9	9.82	9.6	3.17	2.71	2.15	2.06	.909	1.14
8	9	13.6	15.3	9.38	9.16	2.34	2.02	2.21	2.11	1.19	1.43
10	11	16.9	18.6	8.94	8.73	1.76	1.54	2.25	2.14	1.48	1.74
12	13	20.3	22	8.51	8.29	1.36	1.22	2.29	2.17	1.79	2.04
14	15	23.7	25.4	8.07	7.85	1.09	.991	2.32	2.19	2.09	2.36
16	17	27.1	28.8	7.63	7.41	.906	.836	2.34	2.21	2.4	2.67
18	19	30.5	32.2	7.19	6.97	.778	.729	2.36	2.23	2.71	2.99
20	21	33.9	35.6	6.75	6.53	.69	.656	2.38	2.24	3.03	3.3
22	23	37.3	39	6.31	6.09	.629	.606	2.39	2.26	3.34	3.62
24	25	40.7	42.4	6.01	5.99	.587	.572	2.41	2.27	3.56	3.69
26	27	44.1	45.8	5.97	5.94	.559	.548	2.42	2.28	3.58	3.71
28	29	47.4	49.1	5.92	5.9	.539	.532	2.44	2.3	3.6	3.73
30	31	50.8	52.5	5.88	5.86	.526	.521	2.45	2.31	3.62	3.76
32	33	54.2	55.9	5.83	5.81	.516	.513	2.46	2.32	3.64	3.78
34	35	57.6	59.3	5.79	5.77	.51	.508	2.48	2.33	3.66	3.81
36	37	61	62.7	5.74	5.72	.506	.504	2.49	2.34	3.68	3.83

References

/1/ A. Hofmann and A. Khalil, Considerations on magnet design based on forced flow of He II in internally cooled cables, in "Fusion Technology 1986", Vol. 2, published for CEC by Pergamon Press Oxford, p. 1811.

/2/ R. Flükiger et al., An A15 conductor design and its implication for the NET-II TF coils, KfK-Report 3937 (1985), Karlsruhe

/3/ Yu. P. Dmitrevsky, S.S. Kozub and U. Escher, Thermal conductivity of various glass-reinforced plastics at temperatures below 80 K, Cryogenics 27 (1987) 429.

/4/ TORE SUPRA Report EUR. CEA. FC. 1276.

/5/ R. Srinivasan and A. Hofmann, Investigations on cooling with forced flow of He II, Part 1 and 2, Cryogenics 25 (1985) 641-657.

/6/ S. Förster et al., A 2 MJ, 150 T/s pulsed ring coil. Status of the design and the test arrangement. Proc. of the 9th Int. Conf. on Magnet Technology, Zürich 1985, p. 32-35.

/7/ A. Hofmann, A. Khalil and H.P. Krämer, Operation characteristics of loops with Helium II flow driven by fountain effect pumps, Proc. CEC/ICMC 1987 (to be published in Adv. Cryogenic Eng., Vol. 33).

/8/ VDI Wärmeatlas (1963), VDI-Verlag, Düsseldorf.

/9/ H. Katheder, M. Süßer, Pressure drop of adiabatic and nonadiabatic horizontal two phase helium flow. Proc. of the 11th Cryogenic Eng. Conf., Butterworths, Guildford (UK) 1986, p. 429-433.

/10/ U. Jeske, Priv. Communication.

/11/ A. Hofmann, thermomechanically driven helium II flow, an option fusion magnets with internally cooled conductors?, Proc. 11th Int. Cryog. Eng. Conf., publ. by Butterworth (1986), p. 306.

Appendix

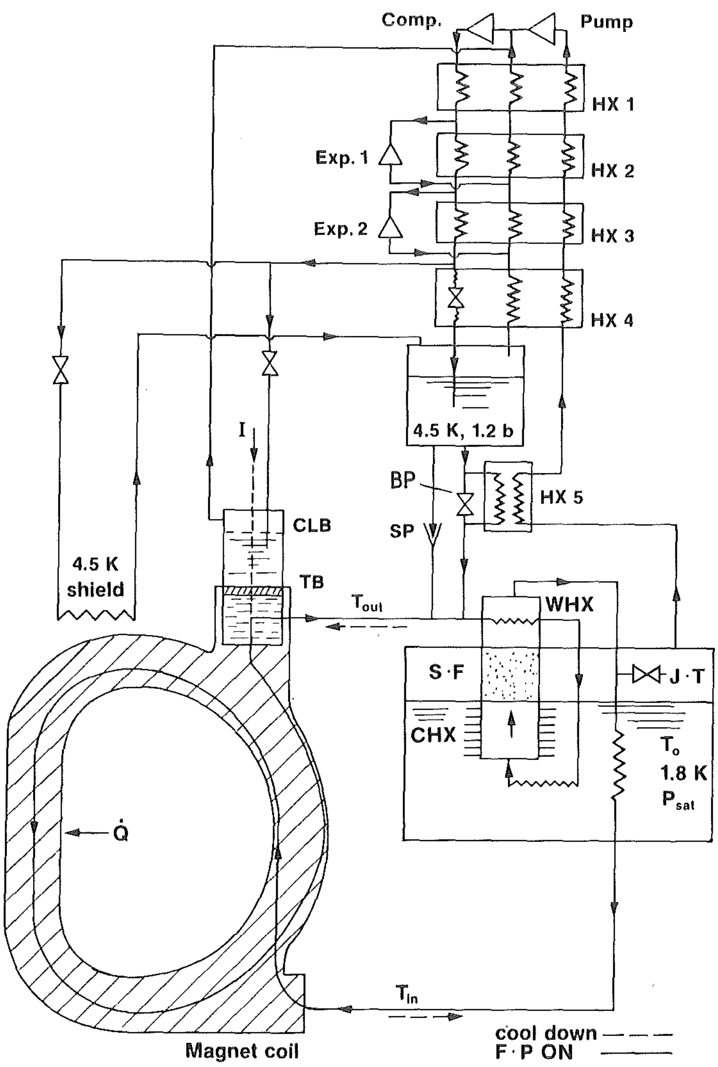


Fig. A1: Scheme of a 1.8 K refrigerator with a Fountain Effect Pump (FEP) to circulate subcooled He II in a magnet coil (HX = Heat Exchanger, CLB = Current Lead Bath, SF = Superfilter, CHX = Cold end Heat Exchanger, WHX = Warm end Heat Exchanger, SP = Safety Plug, TB = Thermal Barrier).

TABLE A1: FORTRAN-PROGRAM TO CALCULATE THE COOLING CHARACTERISTIC
OF A SELF-SUSTAINED FEP LOOP WITH CONSTANT FANNING FRICTION
FACTOR.

```
//ITP960A  JOB  (0960,130,P3C7K),HOFMANN,TIME=(,30),
// MSGCLASS=H,NOTIFY=ITP960
//*MAIN ORG=RM011
//*MAIN LINES=15
//LIST EXEC PLG,PARM.G='/80',LIB=ITP,NAME=INPRE
//G.SYSPRINT DD SYSOUT=C
//G.OUTPUT DD DISP=(NEW,PASS),DSN=&&INPRE,
// UNIT=SYSDA
// EXEC  F7CLG,LIB=ITP
//**EXEC F7CLG,LIB=ITP,PARM.C='DEBUG,ASTER'
//C.SYSPRINT DD  SYSOUT=8
//C.SYSIN DD DISP=SHR,DSN=TSO960.HE2PFF.FORT(LOOPNETP)
//        DD DISP=SHR,DSN=TSO960.HEHT.FORT(ROOT01)
//        DD DISP=SHR,DSN=TSO960.HELARP.FORT(QEPT86)
//        DD DISP=SHR,DSN=TSO960.HELARP.FORT(ROOTAB)
//C.SYSPRINT DD SYSOUT=*
//L.SYSPRINT DD SYSOUT=*
//L.SYSIN DD *
//G.FT05F001 DD DSN=&&INPRE,DISP=(OLD,DELETE)
//G.FT10F001 DD DSN=TSO960.TEMP.DATA,DISP=SHR
//G.FT06F001 DD SYSOUT=C
//G.FT02F001 DD SYSOUT=8
C
C
C     HE2-KUELHKREIS MIT SELBSTANGETRIEBENER FOUNTAIN-PUMPE
C     ==================================================
C     BERECHNUNG VON:
C         T2 = TEMPERATUR AUM AUSTRITT DER LAST
C         T6 = TEMPERATUR AUF DER WARMEN SEITE DER FOUNTAINPUMPE
C         DPF= DRUCKDIFFERENZ DER FOUNTAINPUMPE
C     ALS FUNKTION VON Q/M = THERM. LAST/MASSENSTROM
C
C     ACHTUNG: IN DIESEM PROGRAMM WERDEN DIE HEI/HEII-ROUTINEN VON
C              V. D. ARP/NBS  VERWENDET
C
C     LETZTE MODIFIKATION: 22.10.1987(HOFMANN)
C     ___________________
C
C     RECHNUNG ZUR STUDIE "REMOVAL OF NUCL. HEAT FROM A HE2 COOLED
C     NET COIL"
C
C     ANNAHME: KONSTANTER WIDERSTANDSKOEFFIZIENT IM KUEHLKANAL
C     ========
C                      RECHNUNG MIT ENDLICHER TEMPERATURDIFFERENZ
C                      AND DEN WAERMEAUSTAUSCHERN.
C                      DIE EINGABE DER T-DIFFERENZ ERFOLGT IN
C                      FUNCTION FT6(T) UND IN DCADRE(PFOUNT,T5,T6,...).
C
C     ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

```
      IMPLICIT REAL*4(A-H,O-Z)
      REAL*4 LOGZ
      COMMON/SUB1/ TT,PP,UP,QM,ETAP
      COMMON/SUBT6/ HH2,PP0,PP1,HH3,T0
      COMMON/SUB/AR,BR,AT,BT,KSUB
      COMMON /Q/ IQ, PRESS,QT, DENS, CP, CV, GAMMA, ALFA, GRUN, CKT
     1,SOUND2, CJT, DPDD, DPDT, ENTROP, ENTHAL, UU
     2,SL, HL, TL, DT, LOGZ
      EXTERNAL FT6,PFOUNT,DCADRE,UERSET, QEPT
      T0=1.80
      P0=1.0E5
      ETAP=1.00
      DELTT=0.01
      T1=T0
      UP=1.01325E5
      P1=P0
      PATM1=P1/UP
      PATM0=P0/UP
      CALL QEPT(P0, T0, 1)
      TLAM2=TL
      WRITE(6,300) TLAM2
      WRITE(6,201)
      T2=T1
   10 CONTINUE
      CALL QEPT(P0,T2,0)
      H2=ENTHAL
      CP2=CP
   40 HH2=H2
      PP0=P0
      PP1=P1
      A=1.40
      B=TLAM2
      EPS=.001
      ETA=.01
      CALL ROOT01(A,B,EPS,ETA,FT6,T,IFAIL)
      IF(IFAIL) 50,60,50
   50 WRITE(6,51)
   51 FORMAT(30H T6 LIEGT AUSSERHALB VON T0,TM)
      I=I+1
      IF(I.GT.30)GO TO 999
      GOTO 102
   60 T6=T
      CALL UERSET(0,1)
C     T5=T1+DELTT5
      T5=T1
      DPF=DCADRE(PFOUNT,T5,T6,.001,.001,ERROR,IER)
      P1=P0+DPF
      PP1=P1
      PATM1=P1/UP
      CALL QEPT(P1,T0,0)
      H1=ENTHAL
      D1=DENS
      QM=H2-H1-ABS(DPF/D1)
       TEFF=DPF/QM/D1
      CEFF=1-T0/T2
      IF(DPF) 80,80,90
   80 QSCALE=0.
      GOTO95
```

```
   90 CONTINUE
      QSCALE=QM*SQRT(DPF*D1)
      QR=(H2-HH3)/QM
   95 WRITE(6,100) T0,P0,QR,T2,T6,P1,DPF,QSCALE,TEFF,CEFF
      WRITE(10,104) QSCALE*1E-6,T2
C     WRITE(10,104) QSCALE*1E-6,DPF*1E-5
C     WRITE(10,104) QSCALE*1E-6,(H2-H1)*1E-3
C     WRITE(10,104) T2          ,(H2-H1)*1E-3
C     WRITE(10,104) T2          ,CP2*1E-3
  100 FORMAT(F10.3, F10.0,3F10.3,F12.0,F12.0,E12.3,2F10.3)
  102 T2=T2+DELTT
      IF(T6.GT.TLAM2)GO TO 999
  104 FORMAT(F12.3,F12.3)
  150 GOTO 10
  201 FORMAT(5X,5HT0(K),5X,6HP0(PA),4X,9HQ6/QM ,1X,5HT2(K),5X,5HT6(K)
     1,5X,6HP6(PA),6X,7HDPF(PA),1X,15HQ*(W/(M2*M1/9)), 2X,5HQ6(W))
  300 FORMAT(5X, 8HTLAMBDA=,F6.3,2H K)
      GOTO 10
  999 STOP
      END
      FUNCTION FT6(T)
C     ===============
      IMPLICIT REAL*4(A-H,O-Z)
      REAL*4 LOGZ
      COMMON/SUB1/ TT,PP,UP,QM
      COMMON /SUBT6/ H2,P0,P1,H3,T0
      COMMON /Q/ IQ, PRESS,QT, DENS, CP, CV, GAMMA, ALFA, GRUN, CKT
     1,SOUND2, CJT, DPDD, DPDT, ENTROP, ENTHAL, UU
     2,SL, HL, TL, DT, LOGZ
      EXTERNAL  QEPT
      CALL QEPT(P0,T,0)
      S6=ENTROP
      DELTT3=.0
      CALL QEPT(P0,T+DELTT3,0)
      H3=ENTHAL
      FT6=H2-H3-S6*T
      RETURN
      END
      FUNCTION PFOUNT(T)
C     ===============
      IMPLICIT REAL*4(A-H,O-Z)
      REAL*4 LOGZ
      COMMON/SUB1/ TT,PP,UP,QM,ETAP
      COMMON /SUBT6/ H2,P0,P1
      COMMON /Q/ IQ, PRESS,QT, DENS, CP, CV, GAMMA, ALFA, GRUN, CKT
     1,SOUND2, CJT, DPDD, DPDT, ENTROP, ENTHAL, UU
     2,SL, HL, TL, DT, LOGZ
      EXTERNAL  QEPT
      QT=T
      PATM1=P1/UP
      CALL QEPT(P1,T,0)
      D6=DENS
      S6=ENTROP
      PFOUNT=D6*S6
      PFOUNT=ETAP*PFOUNT
      RETURN
```

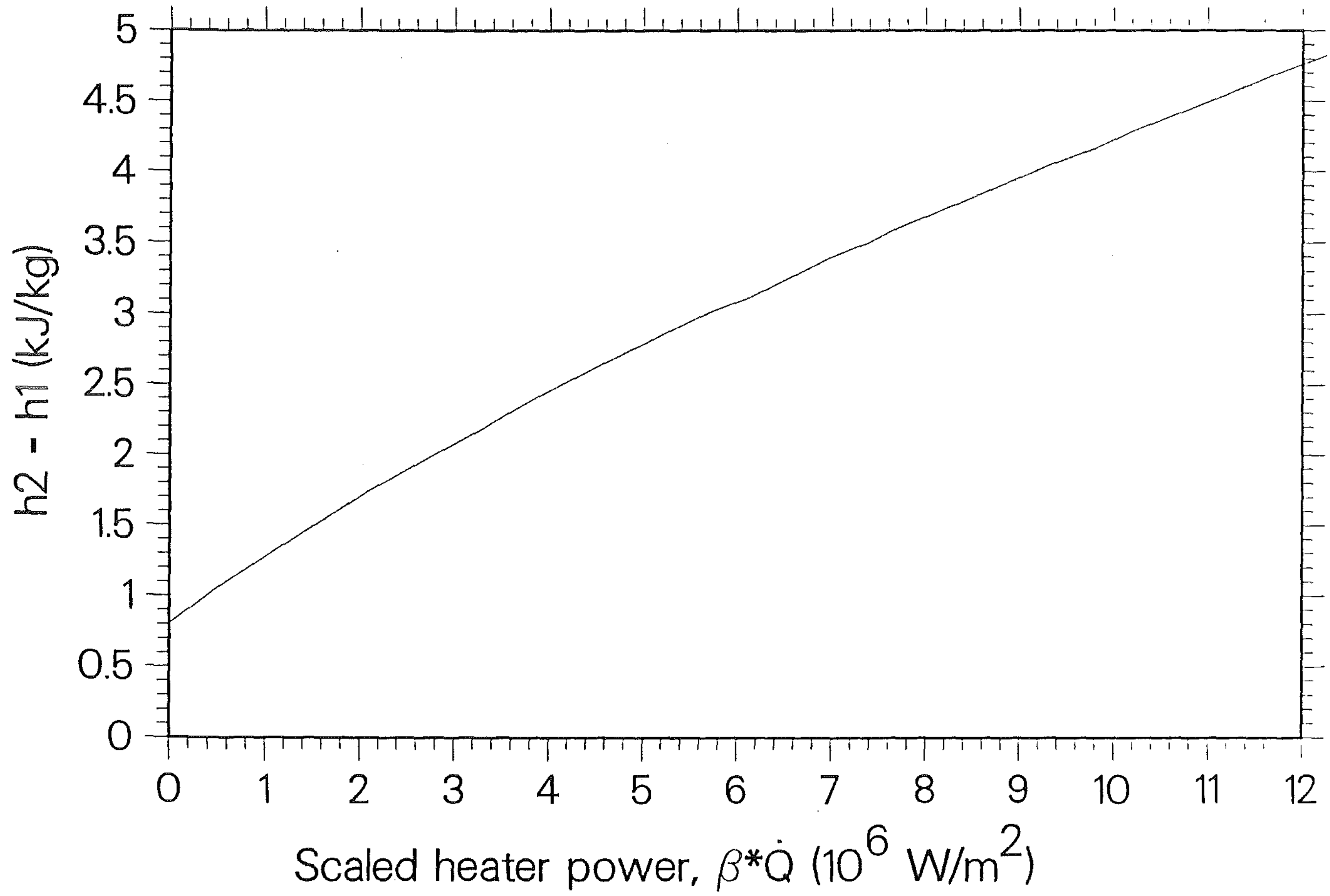


Fig. A 2: Enthalpy difference between outlet an inlet of a coolant channel with heat load Q and geometry factor β (inlet condition T = 1.8 K, p = 1 bar).

Tab A2 : List of the SPEAKEASY programm to study coils with two parallel coolant channels per pancake.

```
EDITING NET
   1.00 PROGRAM
   2.00 $  PROGRAM: NET7                 $
   3.00 $ LAST MODIFICATION: 10.11.1987 $
   4.00 $ CALCULATION WITH VARIABLE CP $
   5.00 COILTHICNKNESS=61
   6.00 COILWIDTH=61
   6.10 LAYERS=36
   6.20 PARDUCTS=2
   6.30 PANCAKES=14
   7.00 TURNS=LAYERS/PARDUCTS
   9.00 CABLETHICKNESS=COILWIDTH/LAYERS
  10.00 CABLEWIDTH=COILWIDTH/PANCAKES
  11.00 N1=VARIABLE(0,LAYERS,PARDUCTS)
  11.10 N2=N1+1
  12.00 X1=CABLETHICKNESS*(N1)
  12.10 X2=CABLETHICHNESS*(N2)
  13.00 COILPERIMETER=25.6*100
  13.10 N=N1; X=X1
  14.00 SPECNUCHT=0.5*NUCLHTMAX/1000*EXP(-X/9.03)
  15.00 COILACLOAD=250
  16.00 COILVOLUME=COILPERIMETER*COILWIDTH*COILTHICKNESS
  17.00 N(1)=1
  18.00 SPECACLOA=COILACLOAD/COILVOLUME*N/N
  19.00 N1(1)=0
  20.00 CP=3
  21.00 FOR K=1,10,1
  22.00 A1=MGS*CP
  23.00 INSULTHICKN=0.001
  24.00 CONTACTAREA=COILPERIMETER*CABLEWIDTH/10000
  25.00 A2=CONTACTAREA*THERMCOND/INSULTHICK
  27.00 Q0=(SPECNUCHT+SPECACLOA)*CABLEWIDTH*CABLETHICKNES*COILPERIMETER
  28.00 Q(1)=-1.8
  28.10 FOR J=2,TURNS+1,1
  28.20 Q(J)=Q0(J-1)
  28.30 NEXT J
  29.00 M=MATRIX(TURNS+1,TURNS+1:)
  30.00 M(1,1)=1
  31.00 M(2,1)=A1-A3
  32.00 M(2,TURNS+1)=A3
  33.00 M(2,2)=-(A1+A2)
  34.00 M(2,3)=A2
  35.00 FOR I=3,TURNS
  36.00 M(I,I-1)=A1+A2
  37.00 M(I,I)=-(A1+2*A2)
  38.00 M(I,I+1)=A2
  39.00 NEXT I
  40.00 M(TURNS+1,1)=A3
  41.00 M(TURNS+1,TURNS)=A1+A2
  42.00 M(TURNS+1,TURNS+1)=-(A1+A2+A3)
  43.00 T=-INVERSE(M)*MFAM(Q)
  44.00 ENTHAL=INTERPOL(T,TH(,2),TH(,1))
  45.00 CP=(ENTHAL(TURNS+1)-ENTHAL(1))/(T(TURNS+1)-T(1))
```

```
 46.00 NEXT K
 48.00 DETAX=X(2)-X(1)
 49.00 RPRIME=(X-DETAX)/COILTHICKNESS
 50.00 B=10.7-7.9*RPRIME
 51.00 WHERE (B.LT.6) B=6.5-0.8*RPRIME
 52.00 B0=10.7
 53.00 B(1)=B0
 54.00 JC0=1
 55.00 JCN=1-0.5*(B-B0)+0.12*(T0**2-AFAM(T)**2)
 57.00 SAFETY=(1+SAFETY0)*JCN-1
 59.00 Q(1)=0
 59.10 Q1=Q
 59.11 LOADCH1=SUM(Q1)
 59.20 T1=T
 59.30 SAFETY1=SAFETY
 60.00 B1=B; T1=T; SAFETY1=SAFETY
 78.00 N=N2; X=X2
 79.00 SPECNUCHT=0.5*NUCLHTMAX/1000*EXP(-X/9.03)
 81.00 COILVOLUME=COILPERIMETER*COILWIDTH*COILTHICKNESS
 82.00 N(1)=1
 83.00 SPECACLOA=COILACLOAD/COILVOLUME*N/N
 84.00 N1(1)=0
 85.00 CP=3
 86.00 FOR K=1,10,1
 87.00 A1=MGS*CP
 88.00 INSULTHICKN=0.001
 89.00 CONTACTAREA=COILPERIMETER*CABLEWIDTH/10000
 90.00 A2=CONTACTAREA*THERMCOND/INSULTHICK
 92.00 Q0=(SPECNUCHT+SPECACLOA)*CABLEWIDTH*CABLETHICKNES*COILPERIMETER
 93.00 Q(1)=-1.8
 93.10 FOR J=2,TURNS+1,1
 93.20 Q(J)=Q0(J-1)
 93.30 NEXT J
 95.00 M(1,1)=1
 96.00 M(2,1)=A1-A3
 97.00 M(2,TURNS+1)=A3
 98.00 M(2,2)=-(A1+A2)
 99.00 M(2,3)=A2
100.00 FOR I=3,TURNS
101.00 M(I,I-1)=A1+A2
102.00 M(I,I)=-(A1+2*A2)
103.00 M(I,I+1)=A2
104.00 NEXT I
105.00 M(TURNS+1,1)=A3
106.00 M(TURNS+1,TURNS)=A1+A2
107.00 M(TURNS+1,TURNS+1)=-(A1+A2+A3)
108.00 T=-INVERSE(M)*MFAM(Q)
109.00 ENTHAL=INTERPOL(T,TH(,2),TH(,1))
110.00 CP=(ENTHAL(TURNS+1)-ENTHAL(1))/(T(TURNS+1)-T(1))
111.00 NEXT K
113.00 DETAX=X(2)-X(1)
114.00 RPRIME=(X-DETAX)/COILTHICKNESS
115.00 B=10.7-7.9*RPRIME
116.00 WHERE (B.LT.6) B=6.5-0.8*RPRIME
117.00 B0=10.7
118.00 B(1)=B0
```

```
 119.00 JC0=1
 120.00 JCN=1-0.5*(B-B0)+0.12*(T0**2-AFAM(T)**2)
 122.00 SAFETY=(1+SAFETY0)*JCN-1
 124.00 Q(1)=0
 125.00 LOADCH2=SUM(Q)
 125.10 Q2=Q
 125.20 B2=B;T2=T;SAFETY2=SAFETY
 126.00 LOADPC=LOADCH1+LOADCH2
 126.10 LOAD=LOADPC*PANCAKES
 126.20 GS=NICEGRAPH(SAFETY1,SAFETY2:N1,N2)
 127.00 TI="TABLE OF OPERATIONAL PARAMETERS:"
 128.00 TAB=TABULATE(N1,N2,X1,X2,B1,B2,Q1,Q2,T1,T2,SAFETY1,SAFETY2:TITLE,TI)
 129.00 PRINT " "
 131.00 PRINT "FLOW RATE PER COOLANT CHANNEL:     ",MGS," G/S"
 132.00 PRINT "SPEC. MAX. NUCL. HEAT:          ",NUCLHTMAX," MW/CM**3"
 132.10 PRINT "LOAD PER INNERMOST CHANNEL:  ",LOADCH1," W"
 132.20 PRINT "LOAD PER OUTERMOST CHANNEL:  ",LOADCH2," W"
 133.00 PRINT "LOAD PER PANCAKE:            ",LOADPC," W"
 134.00 PRINT "TOTAL LOAD PER COIL:         ", LOAD, " W"
 134.10 PRINT "THERMAL COND. OF INSULATION: ",THERMCOND," W/(M K)"
 135.00 PRINT "COEFFICIENTS (W/K): ",A1,A2,A3
 136.00 PRINT " "
 137.00 TAB
 138.00 PRINT " "
 139.00 GS
 140.00 PRINT " "
*141.00 PRINT "FIG."
:%end
```