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STUDY OF ELECTRIC PHENOMENA IN ENERGY DUMPING OF LCT COIL

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In IEA-LCT coil, electric phenomena in energy dumping were studied analytically and experimentally.

Protection resistance of the Japanese LCT coil is chosen as 0.1 Ω considering the quenching voltage, so that temperature rise of the coil is no problem.

Energy dumping characteristic of the six-coil system is calculated under different conditions. It is concluded that simultaneous dumping of all the coils with the equivalent resistance values of protection is necessary.

Flashover voltage tests of the model in 4.2 K liquid helium, 4.2 K gas helium and 4.2 K boiling helium show margin in practical quenching voltage of the coil.

Keywords; Coil Quenching, Energy Dumping, Coil Protection, Superconducting Magnet, Insulating Voltage, Insulating Spacer, Temperature Rise

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[*] On leave from Hitachi Wire and Cable Ltd.

LCTコイルのエネルギーダンピングに伴う電気的現象に関する検討

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（1980年1月30日受理）

現在，設計および製作を進めているIEA－LCTコイルについて，コイル・クエンチに伴う電気的諸問題を解析的および実験的に検討した。

わが国が製作するヘリウム浸漬冷却コイルでは，耐電圧の面からクエンチ保護抵抗0.1Ω選定し，それでコイル温度上昇の面でも問題がないことを確認した。

6個組合せコイル試験では1個のコイルがクエンチした場合，他の全てのコイルもダンプする必要があり，その場合でも，コイル保護抵抗が互いに大きく相異するとダンプ電圧の上昇を招き，好ましくない。

ダンプ時発生電圧に対する巻線スペーサの絶縁耐力については，パンケーキ間絶縁を模擬した試験試料を製作し，液体ヘリウム，気体ヘリウム，ならびに液体ヘリウム中に気体ヘリウム気泡が発生した状態で絶縁破壊試験を行ない，実コイルについてはかなりの裕度があることが判明した。

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IEA-LCT (Large Coil Task) has been started since 1977. In this project the six large scale superconducting magnets built by four international participants will be assembled at ORNL (Ork Ridge National Laboratory), where experimental coil tests are planned.[1)]

In this project JAERI has been fabricating a pool-cooling coil with edge-wise pancake windings of Nb-Ti conductor.[2)]

This report describes calculation and experimental studies on electric phenomena due to energy dumping of LCT coil.

Table 1 shows the main parameters of the Japanese LCT coil.

2. Choice of the Resistance Value for the Japanese LCT Coil Protection

In this report, calculation is executed with the assumption that six coils have the same electric constants as those of the Japanese LCT coil. Electric parameters of the Japanese coil are listed in Table 2. With the coil arrangement shown by Fig. 1, the whole energy E_1 of No.1 coil is

$$E_1 = \frac{1}{2} L_0 I_1{}^2 + M_1 I_1 I_2 + M_2 I_1 I_3 + M_3 I_1 I_4 + M_2 I_1 I_5 + M_1 I_1 I_6$$

Calculated results are later summarized in Table 4 (Sec. 5.1), where 100 % current of each coil is assumed to be 10 kA.

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We take the next conditions for LCT coil.

(1) By ORNL LCT specification, the temperature rise of conductor during coil dumping shall be lower than 80 K in case of the Normal Operation, 100 K in case of the Extend Test (ALT, A etc.).

(2) The Japanese LCT coil is operated by pool cooling system, so that a high voltage is not acceptable. The maximum voltage between the terminals should be below 1 kV.

Thus we chose 0.1 Ω of protecting resistance of the Japanese LCT coil.

3. Analysis of Current and Voltage during LCT Coil Dumping

3.1 General Solutions for Six Coil System

Currents of the coils during coil dumping, I_1, I_2, ... I_6 are generally written by the next expression.

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$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_6 \end{bmatrix} = \begin{bmatrix} I_{11} & I_{12} & \cdots\cdots & I_{16} \\ I_{21} & I_{22} & \cdots\cdots & I_{26} \\ \vdots & \vdots & & \vdots \\ I_{61} & I_{62} & \cdots\cdots & I_{66} \end{bmatrix} \begin{bmatrix} \exp(p_1 t) \\ \exp(p_2 t) \\ \\ \exp(p_6 t) \end{bmatrix} \qquad (1)$$

Coefficients I_{11}, I_{12} .... I_{66} shall be determined through unknown coefficient method by later equations (4) ∿ (9), and

P_1, P_2, ... P_6 are roots of the next sixth equations.

$$\begin{vmatrix} L_{11}p+R_1 & L_{12}p & \cdots\cdots & L_{16}p \\ L_{21}p & L_{22}p+R_2 & \cdots\cdots & L_{26}p \\ \vdots & \vdots & & \vdots \\ L_{61}p & L_{62}p & & L_{66}p+R_6 \end{vmatrix} = 0 \qquad (2)$$

Where L_{11}, L_{12}, etc. are coefficients of induction in the six coil system and R_1, R_2, etc. are protection resistances which are independently connected to that coils.

$R_k = 0$ in the equation (2) corresponds to no dumping of No. k coil. Equation (2), as far as $R \neq 0$, is transformed to the next eigen value equation.

$$\begin{vmatrix} \frac{L_{11}}{R_1} - \frac{1}{-p} , & \frac{L_{12}}{R_1} & \cdots\cdots & \frac{L_{16}}{R_1} \\ \frac{L_{21}}{R_2} , & \frac{L_{22}}{R_2} - \frac{1}{-p} & \cdots\cdots & \frac{L_{26}}{R_2} \\ \vdots & & & \\ \frac{L_{61}}{R_6} , & \frac{L_{62}}{R_6} & & \frac{L_{66}}{R_6} - \frac{1}{-p} \end{vmatrix} = 0 \qquad (3)$$

Coefficients I_{11}, I_{12}, ... I_{66} are determined by the following 36 simultaneous equations.

$$\begin{bmatrix} P_1L_{11}+R_1 & P_1L_{12} & \cdots\cdots & P_1L_{16} \\ P_1L_{21} & P_1L_{22}+R_2 & & P_1L_{26} \\ \vdots & \vdots & & \vdots \\ P_1L_{61} & P_1L_{62} & & P_1L_{66}+R_6 \end{bmatrix} \begin{bmatrix} I_{11} \\ I_{21} \\ \\ I_{61} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} P_2L_{11}+R_1 & P_2L_{12} & \cdots\cdots & P_2L_{16} \\ P_2L_{21} & P_2L_{22}+R_2 & & P_2L_{26} \\ \vdots & \vdots & & \vdots \\ P_2L_{61} & P_2L_{62} & & P_2L_{66}+R_6 \end{bmatrix} \begin{bmatrix} I_{12} \\ I_{22} \\ \vdots \\ I_{62} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} P_3L_{11}+R_1 & P_3L_{12} & \cdots\cdots & P_3L_{16} \\ P_3L_{21} & P_3L_{22}+R_2 & & P_3L_{26} \\ \vdots & \vdots & & \vdots \\ P_3L_{61} & P_3L_{62} & & P_3L_{66}+R_6 \end{bmatrix} \begin{bmatrix} I_{13} \\ I_{23} \\ \vdots \\ I_{63} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} P_4L_{11}+R_1 & P_4L_{12} & \cdots\cdots & P_4L_{16} \\ P_4L_{21} & P_4L_{22}+R_2 & & P_4L_{26} \\ \vdots & \vdots & & \vdots \\ P_4L_{61} & P_4L_{62} & & P_4L_{66}+R_6 \end{bmatrix} \begin{bmatrix} I_{14} \\ I_{24} \\ \vdots \\ I_{64} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} P_5L_{11}+R_1 & P_5L_{12} & \cdots\cdots & P_5L_{16} \\ P_5L_{21} & P_5L_{21}+R_2 & & P_5L_{26} \\ \vdots & \vdots & & \vdots \\ P_5L_{61} & P_5L_{62} & & P_5L_{66}+R_6 \end{bmatrix} \begin{bmatrix} I_{15} \\ I_{25} \\ \vdots \\ I_{65} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} I_{11} + I_{12} + \cdots\cdots\cdots\cdots + I_{16} \\ I_{21} + I_{22} + \cdots\cdots\cdots\cdots + I_{26} \\ \vdots \\ I_{61} + I_{62} + \cdots\cdots\cdots\cdots + I_{66} \end{bmatrix} = \begin{bmatrix} I_{10} \\ I_{20} \\ \\ I_{60} \end{bmatrix} \tag{9}$$

Where I_{10}, I_{20}, ... I_{60} are currents just at the moment of the beginning of dumping in No.1, No.2, ... No.6 coil respectively.

Terminal voltage of each coil is given by the multiplication of each current and the protection resistance of that coil.

3.2 Simultaneous Dumping Whole Coils with the Same Dumping Time Constant

The normal resistance value in the superconducting winding is practically neglected in comparison with the protection resistance value R_p.

The discharge currents I of all coils with the same dumping constant are expressed by

$$I = I_o \exp\left(-\frac{R_p}{L} \cdot t\right)$$

I_o : Initial current (A)
t : Time after initiating discharge (sec)
$L = L_1 + 2M_1 + 2M_2 + M_3$
$= 2.972$ H
$R_p = 0.1\ \Omega$
$L/R_p = 29.72$ sec.

Accordingly, the time constant of the system is 29.72 sec.

3.3 Current Characteristic with Different Dumping Resistance

As an example with different dumping resistances, calculations of the dumping current have been performed with the arrangement of Fig. 1, where the different resistances are alternatively connected. Because it may be expected that there exist plain effected modes in current by each other.

The numerical solution I of dumping current of No.1 coil for two typical cases are given as following.

Case I; $R_1 = 0.1\ \Omega$, $R_2 = 0.25\ \Omega$

$I_1 = 10\{1.3766 \exp(-0.03812t) - 0.3766 \exp(-0.1268t)\}$ kA

Case II; $R_1 = 0.1\ \Omega$, $R_2 = 1\ \Omega$

$I_1 = 10\{1.3886 \exp(-0.04046t) - 0.3886 \exp(-0.478t)\}$ kA

Examples of these two cases are shown in Fig. 2. If the difference of the coil protection resistance is so large as shown in an example for the

Case II, the dumping current value of the coil which has the smaller resistance is increased over the initial current. In order not to have large current value than the initial value, the smaller difference value between R_1 and R_2 is preferable.

3.4 Current Characteristic of No Dumping Coil in Case of Dumping of a Neighbouring Coil

The current characteristic of no dumping coil is here calculated on the case of dumping of a neighbouring coil in order to check the worst condition of no operation of circuit breaker. The current $I_1(t)$ of no dumping coil is shown by the following equation,

$$I_1(t) = (1 + \frac{M}{L}) \cdot I_1(0) - \frac{M}{L} \cdot I_2(0)e^{-\frac{R_2}{L}t}$$

where L/R_2 is the time constant of the neighbouring coil. If the time after the dumping is sufficiently long. The second term of the above equation diminishes.

A numerical value is presented here on the example of LCT test "ALT A" where the test coil of 110 % current is not dumped and a neighbour is dumped.

$$\begin{aligned} I_1(\infty) &= (1 + \frac{0.390}{2.141}) \times 11 \text{ kA} \\ &= 13 \text{ kA} \end{aligned}$$

If two neighbouring coils are dumped without opening of the circuit breaker of the test coil, the current value of the test coils is more than 13 kA. Such a high value is above the stable operational current calculated by thermal equation.$^{2)}$ Consequently all six coil should be absolutely discharged in any quenching case.

4. Experimental Measurement of Breakdown Voltage in Coil Quenching

4.1 Insulating Configuration of the Japanese LCT Coil and ORNL Specification

In the Japanese LCT coil winding, the roughed surfaces of the conductor is separated with fiber reinforced plastics of 3 mm thickness for the purpose of electric insulation. On the other hand ORNL specification of insulation for LCT coil are summarized as follows.$^{1)}$

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(1) The coil insulation resistance shall be a minimum of 100 kΩ between conductor and ground at 4.2 times the quench voltage dc when measured in air at ambient conditions.

(2) The insulation resistance of layer-to-layer or pie-to-pie shall be a minimum of 100 kΩ when tested by applying a voltage of 4.2 times the voltage which will appear between adjacent layer or pies.

(3) The coil shall withstand a potential of 3 times the voltage of quench rac, root-mean-square, 60 Hz, applied for one minute between the conductor and ground. This requirement shall be met for ambient conditions with the coolant volume filled with He gas at a pressure of 1±0.1 atmosphere.

4.2 Experimental Procedure

The insulation model specimens simulating to pie-to-pie insulation, shown in Fig. 3 were set up in He dewar, a series of voltage breakdown test were carried out.

An appearance of the model and the roughed surface electrode are shown in Fig. 4. The FRP (fiber reinforced plastic) spacers with 3 mm thickness are used as insulators, and two kinds of cooling surface with smooth surface and roughed surface of THERMO EXCELL$^{3)}$ (commercially named) are used as electrodes.

The surfaces of spacers were polished by emery paper before setting up into the electrodes. In the experiments two types of voltage DC (+,-) and AC rms (50 Hz) are applied. Breakdown in any case arose on the surface of FRP spacer. The voltage is applied between conductor models in 4.2 K Liq, He, 4.2 K Gas He, room temperature Gas He and room temperature Air. The model specimen in 4.2 K Gas He is prepared such that the level of Liq He is at the center of spacer insulating vertical channel.

In order to investigate breakdown voltage in the condition of boiling He, the Liq He was heated up with a 100 W heater in the bottom of the model specimen. Thus He bubbles were floating up in the insulating channel and in this condition a voltage was applied between conductors. Photographs of the experiment with and without heating are presented in Fig. 5(a) and 5(b) respectively.

4.3 Experimental Results

The experimental results of breakdown voltage tests are summarized in Table 3.

Main conclusions of the breakdown voltage tests are followings.

(1) THERMO EXCELL surface decreases 50 % of the flashover voltage of FRP spacer in comparison with that of smooth cooling surface in 4.2 K Gas He.

(2) The flashover voltage of 3 mm thickness spacer in 4.2 K He is at least DC 10 kV, which has large clearance for the quenching voltage 1 kV/20 layers i.e. 50 V.

(3) The insulating strength in Liq He of 3 mm thickness spacer is about DC 20 kV.

(4) Boiling of He decreases the insulating strength in Liq He, but the insulating strength with boiling He is considerably higher than that of Gas He. (dielectric constant ε in Liq He = 1.049)

(5) The rms of AC breakdown voltage is in any case in this experiment about 50 % of DC breakdown voltage.

(6) The value of scattering in AC breakdown voltage is smaller than that in DC breakdown voltage.

(7) On the insulating configuration it would be noticable that the breakdown voltage in Gas He is extremely low at the room temperature,

5. Temperature Rise of Conductor due to Coil Quenching

5.1 Temperature Rise in the Case where the Whole Conductor is changed into Normal State

In the case where whole length of winding is changed into normal stage, the energy dissipation in the winding with the external resistance 0.1 Ω is as following.

$$196.8 \times 10^6 \text{ J} \times \frac{0.0294\Omega}{0.1\Omega + 0.0294\Omega} = 44.71 \times 10^6 \text{ J}$$

In the above calculation the constant value of substrate resistance at 77 K is applied. For simplicity it is assumed that the whole energy is exhausted only in the winding.

The energy consumption per unit weight of winding is

$$(44.71 \times 10^6)\text{J} \div (20.9 \times 10^3)\text{kg} = 2139 \text{ J/kg}.$$

From the enthalpy of copper the temperature rise is 56 K.

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In such a way the temperature rise of each extended test is calculated and summarized in Table 4.

5.2 Hot Spot Temperature of Conductor with Fixed Cold Ends

During the resistive voltage across the coil terminals at coil quenching is lower than the detection voltage, the circuit breaker for protection does not operate.

When a comparatively short normal zone is limited and temperature rise is progressive, there may be an excess temperature rise of conductor by insufficiency of the generating voltage.

In fact such conditions are most probable when a short normal zone is limited by both cold ends with enough replenishment of liquid He.

The temperature of a conductor are calculated with the one-dimensional heat conduction equation (10).

$$m \cdot C(T) \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \{\lambda(T) \cdot \frac{\partial T}{\partial x}\} + Q - \frac{P}{A} H \qquad (10)$$

$$Q = \rho(T) \cdot \{\frac{I(t)}{A}\}^2$$

$$H = 0 \quad (|x| \leq \ell/2)$$

$$T = 4.2\ \mathrm{K} \quad (|x| \geq \ell/2)$$

where

T : Temperature of conductor at the point (x,t)
x : Coordinate of situation along conductor length
t : Coordinate of time
ρ : Specific resistivity of copper
C : Specific heat of copper
λ : Heat conductivity of copper
Q : Heat generation rate by current
H : Heat dissipation factor
P : Periphery of conductor section
A : Section area of conductor
I : Current of conductor
ℓ : Dry zone length
m : Specific gravity of conductor

For simplicity the next conditions are assumed in order to keep the estimation safe.

(1) A dry zone of conductor is due to vapor locking etc.

(2) Enough replenishment of liquid He prevents dry zone length from progressing.

(3) Enough replenishment of liquid He keeps the both ends of the dry zone at the constant temperature of 4.2 K.

(4) There is no heat dissipation from surface of the dry zone conductor.

The main parameters of the Japanese LCT coil are shown in Table 2.

Then calculation procedure with Crank-Nicolson method and the computer code are written in the Appendix.

The calculated results are given in Table 5 and in Fig. 6. If the dry zone length is less than 0.7 m, the temperature is saturated without detection of which voltage is 80 mV. The hot spot temperature reached at the maximum value when the dry zone length is 0.7 m, and it is 165 K. Figure 7 shows an example of the temperature distribution along the conductor of dry zone of 0.8 m in length. As conclusion in this section it can be said that the maximum temperature rise is attained to across the conductor length of 0.7 m, so that their is no anxiety of thermal stress in the winding.

6. Conclusion

Several electric problems due to quenching of the Japanese LCT coil are picked up and examined by calculation and experiment.

The conclusions of this report are listed as followings.

(1) The protection resistance 0.1 Ω of the Japanese LCT coil is chosen in view of the voltage below 1 kV and the temperature rise below 80 K at coil quenching.

(2) The analysis of current dumping with six coil system proves that the whole coils should be simultaneously dumped at quenching of any coil with the condition of equivalent resistance value.

(3) The insulating strength in the winding with rough surface in the Japanese LCT coil has enough margin for practical quenching voltage.

(4) The temperature rise of the Japanese LCT coil at quenching is calculated as 60 K in the case where the whole winding is normalized, and as 165 K in the case where local winding is normalized.

For simplicity the next conditions are assumed in order to keep the estimation safe.

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The conclusions of this report are listed as followings.

(1) The protection resistance 0.1 Ω of the Japanese LCT coil is chosen in view of the voltage below 1 kV and the temperature rise below 80 K at coil quenching.

(2) The analysis of current dumping with six coil system proves that the whole coils should be simultaneously dumped at quenching of any coil with the condition of equivalent resistance value.

(3) The insulating strength in the winding with rough surface in the Japanese LCT coil has enough margin for practical quenching voltage.

(4) The temperature rise of the Japanese LCT coil at quenching is calculated as 60 K in the case where the whole winding is normalized, and as 165 K in the case where local winding is normalized.

Dumping current analysis with six practical coils and insulating configuration study between winding and vessel are being continued for the purpose of more precise design study.

Acknowledgement

The participation of the stuffs of Superconducting Magnet Laboratory to the discussion is hereby aknowledged.

Reference

1) UCC-ND; Technical Specification No. TS14700-01 (Nov. 1976).
2) S. Shimamoto, et al.; Japanese Design of a Test Coil for the Large Coil Task, Paper to 8th Symp. on Engineering Problems of Fusion Research (Nov. 1979).
3) T. Torii, et al.; The Use of Heat Exchangers with THERMOEXCELL's Tubing in Ocean Thermal Energy Power Plants, ASME Publication 78-WA/HT-65 (Dec. 1978).

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Table 1 Main Parameters of the Japanese LCT Coil

Item	Value
Coil Bore	2.5 m × 3.5 m
Maximum Operational Field	8.0 T
Ampere Turns	6.76×10^{6} AT
Operational Current	10.21 kA
S.C. Material	Nb-Ti
Conductor	Rough Surface Copper Stabilizer Soldered Cable Superconductor
Winding	Edge Wise, 2 Grading 20 Double Pancake
Weight	39 ∿ 40 ton

Table 2 Electric Parameters of the Japanese LCT Coil

Item	Value
Coil Winding Weight	20.9 ton
Substrate Resistance	0.0133 Ω at 4.2 K (6×10^{-10} Ωm)
	0.0294 Ω at 77 K (13.3×10^{-10} Ωm)
Inductance	L_0 = 2.141 H
	M_1 = 0.390 H (No.1 - No.2)
	M_2 = 0.129 H (No.1 - No.3)
	M_3 = 0.084 H (No.1 - No.4)
Conductor Current	100 % = 10 kA

Table 3 FRP Flashover Voltage ; 3 mm, 1 atm

Insulating Media	Temp.	THERMO EXCELL C*		Smoothed surface	
		DC	AC rms	DC	AC rms
Liq He	4.2 K	19.8 kV	10.1 kV	20 kV	11.6 kV
Boiling He in Liq He	4.2 K	15.1	8.9	20	11.6
Gas He	4.2 K	10.8	4.8	19.7	9.4
Gas He	15 °C	1.08	0.59	1.16	0.6
Air	15 °C	5.24	3.12	9.98	4.16

* Height of saw-teeth : 1.2 mm, Interval of saw-teeth: 0.8 mm

Table 4 Magnetic Energy of No.1 Coil and Temperature Rise of ORNL Test Sequences

Test	I_1	I_2	I_3	I_4	I_5	I_6	E_1	Temperature Rise
Normal Op.	100 %	80 %	80 %	80 %	80 %	80 %	196.8 MJ	56 K
ALT A	110 %	90 %	90 %	90 %	90 %	90 %	248.9 MJ	60 K
ALT B	100 %	100 %	100 %	100 %	100 %	0 %	210.8 MJ	57 K
ALT C	140 %	0 %	0 %	0 %	0 %	0 %	209.8 MJ	57 K

Table 5 Calculated Results

L (m)	T_1 (K)	t_1 (sec)	T_h (K)	t_h (sec)
0.1	---	---	6.56	0.06 ∿
0.2	---	---	12.4	0.4 ∿
0.4	---	---	48.5	42 ∿
0.5	---	---	58.4	100 ∿
0.6	---	---	88.2	650 ∿
0.7	163.8	183.6	165.6	190
0.8	149.1	87.1	160.5	100
1.0	127.8	52.2	156.5	74
1.2	111.5	39.7	153.0	70
1.4	98.6	32.4	148.3	68
1.5	93.7	30.0	146.1	70
1.6	89.4	27.8	144.0	70
1.8	80.0	23.2	136.4	72
2.0	74.5	20.7	133.3	76

L ; Dry Zone Length
T_1; Temperature corresponding to V_1=80 mV
t_1; Time corresponding to V_1=80 mV
T_h; Maximum temperature over all time
t_h; Time corresponding to maximum temperature

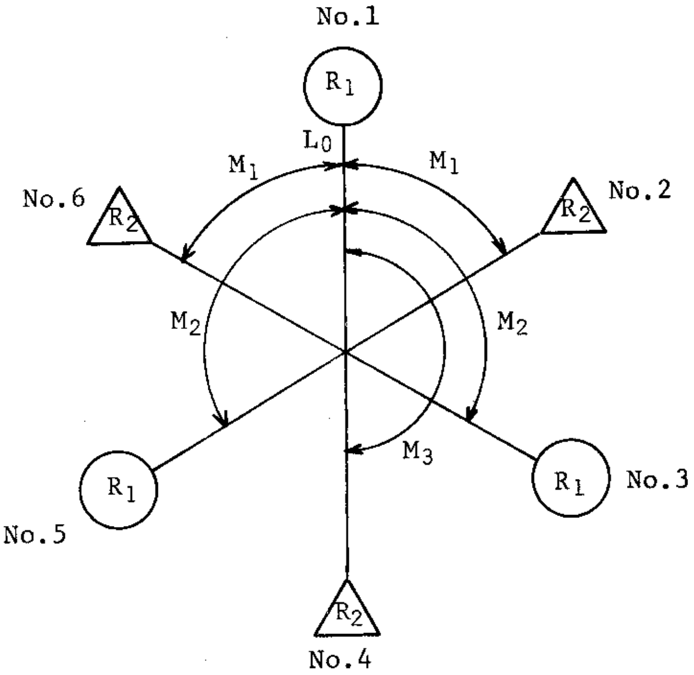


Fig. 1 Coil Arrangement with Alternatively Different Dumping Resistance

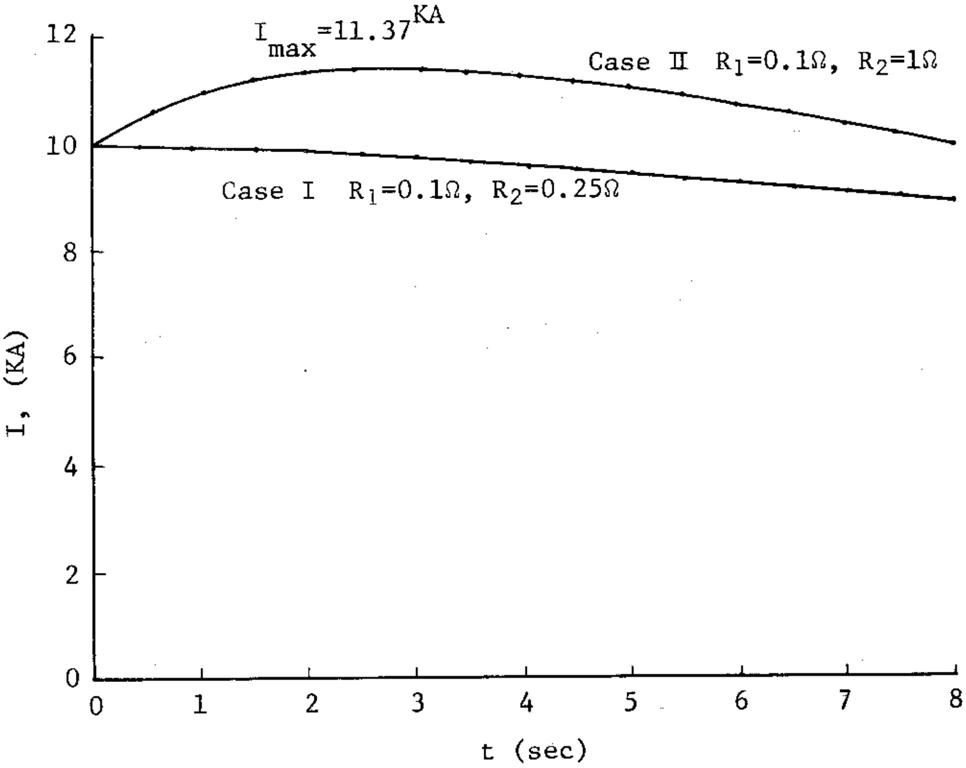


Fig. 2 Dumping Current Characteristics with Different Dumping Resistors

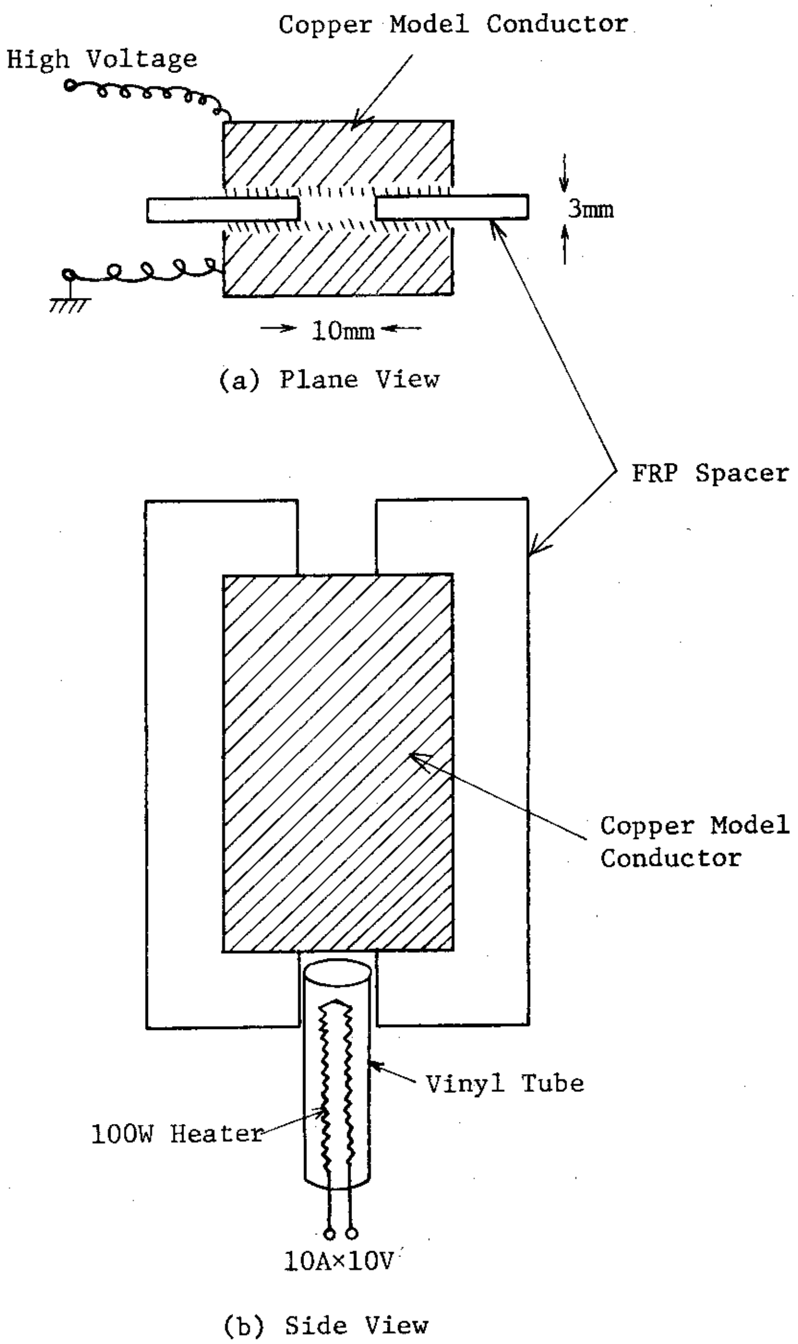
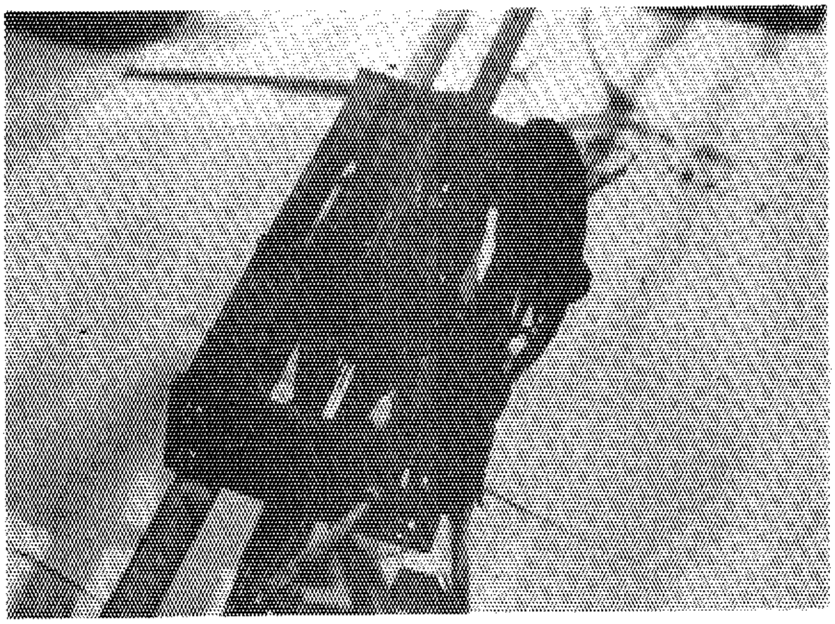
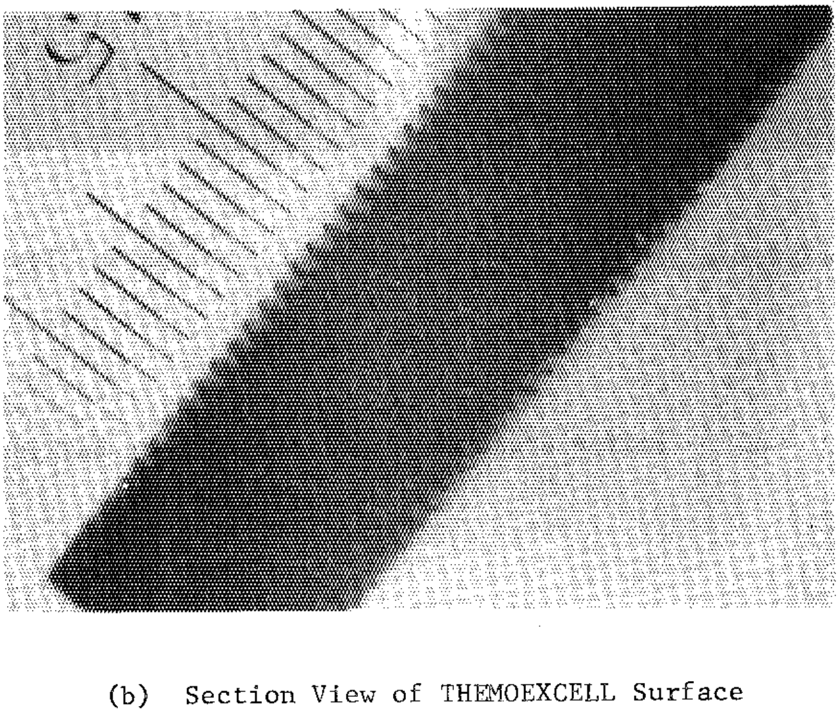


Fig. 3 Configuration of Test Sample

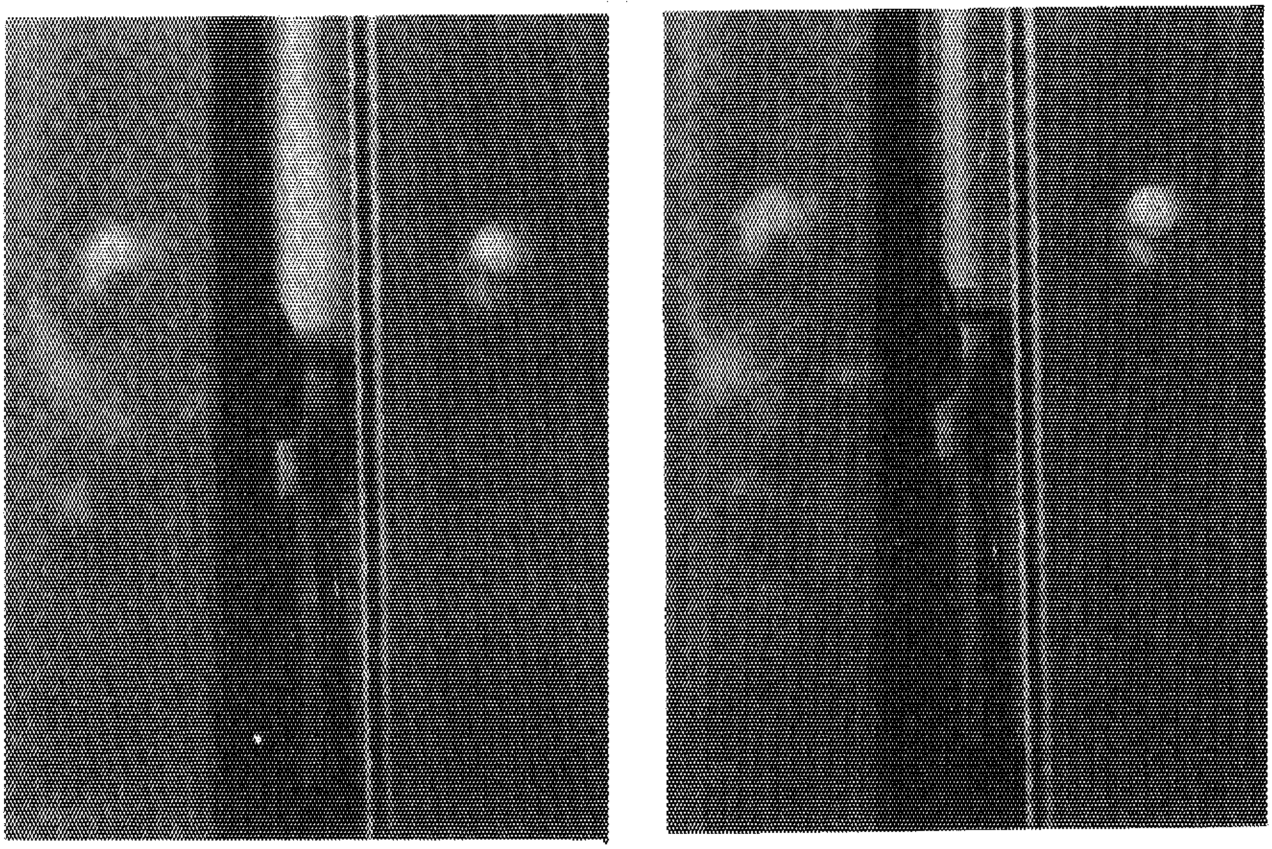


(a) Sample and Sample Holder



(b) Section View of THEMOEXCELL Surface

Fig. 4 Sample of Breakdown Voltage Test



(a) Herium bubbles in Liquid Helium (b) No bubbling in Liquid Helium

Fig. 5 Helium Conditions with and without Bubbles

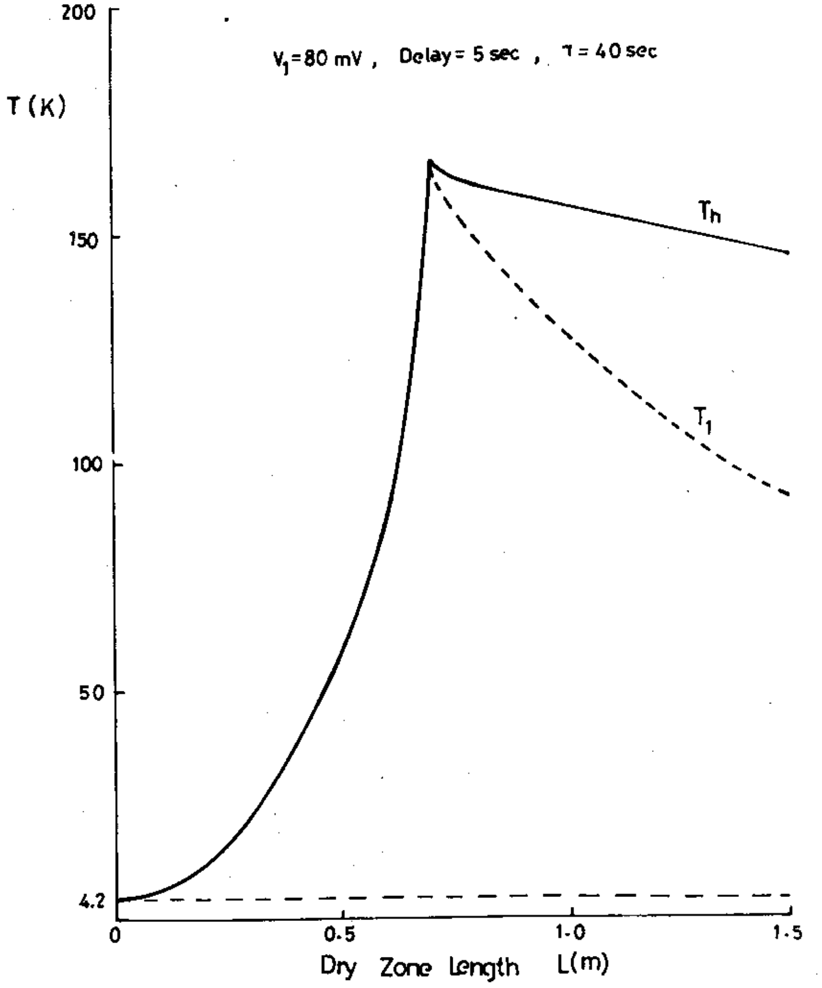


Fig. 6 Maximum Temperature in Relation with Dry Zone Length

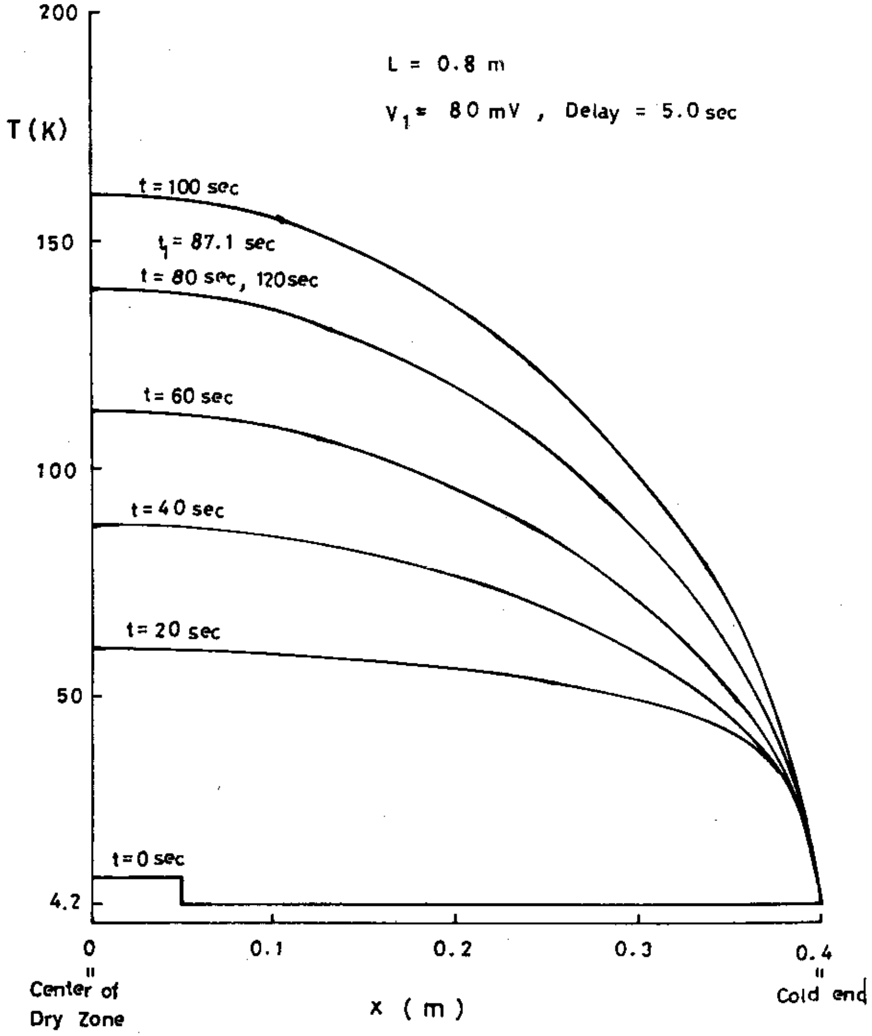


Fig. 7 Temperature Distribution along a Conductor by 0.8 m Dry Zone Length

Appendix Computer Code for Calculation of Hot Spot Temeprature of Conductor due to Coil Quenching

The differential equation (10) is transferred to the difference equation (11) with Crank-Nicolson method.

$$\begin{aligned}\frac{m\cdot C(T)}{\Delta t}(u_{i,j+1}-u_{i,j}) &= \frac{1}{2}\{\lambda(T)\cdot\frac{u_{i-1,j+1}-2u_{i,j+1}+u_{i+1,j+1}}{\Delta x^2} \\ &\quad + \lambda(T)\cdot\frac{u_{i-1,j}-2u_{i,j}+u_{i+1,j}}{\Delta x^2}\} \\ &\quad + \frac{1}{4}\cdot\frac{\partial\lambda(T)}{\partial x}\{\frac{u_{i+1,j+1}-u_{i-1,j+1}}{\Delta x}+\frac{u_{i+1,j}-u_{i-1,j}}{\Delta x}\} \\ &\quad + Q(T)-\frac{P}{A}H(T,x)\end{aligned} \tag{11}$$

$u_{i,j}$, $i\cdot\Delta x$ and $j\cdot\Delta t$ in the equation (10) are respectively $T(x,t)$, x and t in the equation (11).

Now $Q(T)$ is generated by the current which is constant until that the terminal voltage of the coil is below the detection voltage V_1 and dumped with the dumping time constant τ after a delay time t_1.

Furthermore the equation (11) is transformed to the gradualing expressions in the code.

In that code the symbols concerning "IN PUT" are as followings, and numerics are used in MKS unit.

DX; x, HFLG; ℓ ; Dry zone length, DSEC; Δt, FTIME; Calculated last time, AREA: A, PEFF; P, CUR; I(0), GRAV; m,

IP; Full mesh number of initial dry zone length

IS; Spaced mesh number for recording the solution along the dry zone length

IKM; Division number for recording the solution along the dry zone length

SECS; Spaced time for recording the solution

INPUT DATA SHEET

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IBJOB DECKNAME

備 考

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12345678901234567890123456789012345678901234567890123456789012345678901234567890
  0.01      0.3       0.1       1000.0  0.000265   0.0536    10220.0   8920.0
    DX       HFLG      DSEC     FTIME      AREA      PEFF      CUR       GRAV


         1         3        10   10.0
    IP        IS       IKM       SECS
12345678901234567890123456789012345678901234567890123456789012345678901234567890
```

共通E 1 7 3

* 73～75：DATAID / 76～80：SEQUENTIAL NUMBER

```
      FACOM 230-75 M7 FORTRAN-IV H COMPILER  (OPT2,CP)    SOURCE PROGRAM LIST  -790420-(V02,L14)  DATE  79.10.22/15:23    PAGE   2

ISN   ST-NO                 SOURCE PROGRAM                                                   SEQUENCE

      C       CHOUDENDOU K.OKA, 1979,10,2,  TEMP DSTRIBUTION ALONG CONDUCTOR
  1           DIMENSION UA(1000),UB(1000),TMP(1000),UU(1000),A(1000),B(1000) ,
             1C(1000),D(1000),ALPH(1000),S(1000)
  2           DIMENSION ALTT(10),RHOO(10),HHTT(10),CCUU(10)
  3           DIMENSION DLTX(10),SAHEN(10),UHEN(10)
  4           READ (5,1001) DX,HFLG,   DSEC,FTIME,AREA,PEFF,CUR,GRAV
  5      1001 FORMAT(8F10.0)
  6           READ (5,1002) IP,IS,IKM,SECS
  7      1002 FORMAT(3I10,F10.0)
  8           SECP=SECS
  9           QJ=0.0
 10           HEATM=14000.0
 11           TB=4.2+1.2
 12           DET=TB-4.2
 13           XP=IP*DX
 14           DX2=DX**2
 15           VDX2=2.0*DX**2
 16           VDSEC=2.0*DSEC
 17           WDX=4.0*DX
 18           IM=HFLG/DX
 19           IKM=IM/IS
 20           JM=FTIME/DSEC
 21           CA=(CUR/AREA)**2
 22           PA=PEFF/AREA
 23           WRITE(6,2000) DX,HFLG,DSEC,FTIME,AREA,PEFF,CUR,PA
 24      2000 FORMAT(/1H ,3X,       40HDX,HFLG,DSEC,FTIME,AREA,PEFF,CUR,PA
             18E11.4)
 25           WRITE(6,2009) CA,GRAV,IM,JM,IP,IS,IKM,SECS
 26      2009 FORMAT(/1H ,3X,       40HCA,GRAV,IM,JM,IP,IS,IKM,SECS
             12E11.4,5I11,E11.4)
 27           DO 25 I=1,IM
 28           IF(I.GT.IP) GO TO 26
 29           UA(I)=10.0
 30           GO TO 27
 31        26 UA(I)=4.2
 32        27 CONTINUE
 33        25 CONTINUE
 34           UAZ=UA(1)
 35           DO 15 IK=1,IKM
 36           I=15*IK
 37        15 UU(IK)=UA(I)
 38           WRITE(6,2001)
 39      2001 FORMAT(/1H ,3X,       30HINITIAL CONDISION ( 0.0 SEC ) ,)
 40           WRITE(6,2002) UAZ,(UU(IK),IK=1,IKM)
 41      2002 FORMAT(/1H ,3X,11F11.4)
 42           J=0
 43         5 CONTINUE
 44           DO 20 I=1,IM
 45        20 TMP(I)=UA(I)
 46           I=1
 47           ZI=I
 48           X=ZI*DX
 49           T1=UAZ
 50           T2=UA(2)
 51           T=UA(I)
 52           ALT=AL(T)
 53           ALT2=AL(T2)

      FACOM 230-75 M7 FORTRAN-IV H COMPILER  (OPT2,CP)    SOURCE PROGRAM LIST  -790420-(V02,L14)  DATE  79.10.22/15:23    PAGE   3

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 54           ALT1=AL(T1)
 55           DALXT=(ALT2-ALT1)/(2.0*DX)
 56           QT=CA*RHO(T)
 57           IF(X.GT.XP) GO TO 40
 58           HT=0.0
 59           GO TO 42
 60        40 HT=H(T)
 61        42 CONTINUE
 62           D(1)=ALT/VDX2 *(UA(2)-2.0*UA(1)+UAZ)+DALXT/WDX*(UA(2)-UAZ)+QT
             1-PA*HT+GRAV*CCU(T)/DSEC*UA(1)
 63           A(1)=ALT/VDX2-DALXT/WDX
 64           C(1)=ALT/VDX2+DALXT/WDX
 65           B(1)=GRAV*CCU(T)/DSEC+ALT/DX2
 66           S(1)=D(1)
 67           ALPH(1)=B(1)-A(1)
 68           CCUU(I)=CCU(T)
 69           ALTT(I)=ALT
 70           RHOO(I)=RHO(T)
 71           HHTT(I)=HT
 72           DLTX(I)=DALXT
 73           CONTINUE
 74           DO 30 I=2,IM-1
 75           ZI=I
 76           X=ZI*DX
 77           T1=UA(I-1)
 78           T2=UA(I+1)
 79           T=UA(I)
 80           ALT=AL(T)
 81           ALT1=AL(T1)
 82           ALT2=AL(T2)
 83           DALXT=(ALT2-ALT1)/(2.0*DX)
 84           QT=CA*RHO(T)
 85           IF(X,GT,XP) GO TO 50
 86           HT=0.0
 87           GO TO 52
 88        50 HT=H(T)
 89        52 CONTINUE
 90           D(I)=ALT/VDX2 *(UA(I+1)-2.0*UA(I)+UA(I-1))+DALXT/WDX*(UA(I+1)-
             1UA(I-1))+QT-PA*HT+GRAV*CCU(T)/DSEC*UA(I)
 91           A(I)=ALT/VDX2-DALXT/WDX
 92           C(I)=ALT/VDX2+DALXT/WDX
 93           B(I)=GRAV*CCU(T)/DSEC+ALT/DX2
 94           ALPH(I)=B(I)-A(I)*C(I-1)/ALPH(I-1)
 95           S(I)=D(I)+A(I)*S(I-1)/ALPH(I-1)
 96           IF(J ,GT,2 ) GO TO 91
 97           IF(I ,GT,9 ) GO TO 91
 98           DLTX(I)=DALXT
 99           CCUU(I)=CCU(T)
100           ALTT(I)=ALT
101           RHOO(I)=RHO(T)
102           HHTT(I)=HT
103        91 CONTINUE
104        30 CONTINUE
105           UB(IM)=4.2
106           DO 33 I=1,IM-1
107           II=IM-I
108        33 UB(II)=(S(II)+C(II)*UB(II+1))/ALPH(II)
```

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FACOM 230-75 M7 FORTRAN-IV H COMPILER  (OPT2,CP)    SOURCE PROGRAM LIST  -790420-(V02,L14)  DATE  79.10.22/15:23    PAGE   4

ISN  ST-NO                 SOURCE PROGRAM       ( FTMAIN )                        SEQUENCE

            CONTINUE
            UBZ=UB(1)
            IF(J .GT.2 ) GO TO 92
            DO 37 I=2,9
            SAHEN(I)=GRAV*CCUU(I)/DSEC*(UB(I)-UA(I))
            UHEN(I)=ALTT(I)/VDX2*(UB(I+1)-2.0*UB(I)+UB(I-1)+UA(I+1)-2.0*UA(I)
           1+UA(I-1))+DLTX(I)/WDX*(UB(I+1)-UB(I-1)+UA(I+1)-UA(I-1))
           2+CA*RHOO(I)-PA*HHTT(I)
         37 CONTINUE
            SAHEN(1)=GRAV*CCUU(1)/DSEC*(UB(1)-UA(1))
            UHEN(1)=ALTT(1)/VDX2*(UB(2)-2.0*UB(1)+UBZ+UA(2)-2.0*UA(1)+UAZ)
           2+DLTX(1)/WDX*(UB(2)-UBZ+UA(2)-UAZ)+CA*RHOO(1)-PA*HHTT(1)
         92 CONTINUE
            J=J+1
            PJ=J
            SEC=DSEC*PJ
            IF(J .GT.3 ) GO TO 93
            WRITE(6,2004) SEC
            WRITE(6,2005) UAZ,(UA(I),I=1,10)
            WRITE(6,5001)(A(I),I=1,9)
            WRITE(6,5001)(B(I),I=1,9)
            WRITE(6,5001)(C(I),I=1,9)
            WRITE(6,5001)(D(I),I=1,9)
            WRITE(6,5001)(S(I),I=1,9)
            WRITE(6,5001)(ALPH(I),I=1,9)
            WRITE(6,5001) (CCUU(I),I=1,9)
            WRITE(6,5001) (ALTT(I),I=1,9)
            WRITE(6,5001) (RHOO(I),I=1,9)
            WRITE(6,5001) (HHTT(I),I=1,9)
            WRITE(6,5001)(SAHEN(I),I=1,9)
            WRITE(6,5001) (UHEN(I),I=1,9)
       5001 FORMAT(/1H ,14X,10E11.4)
            WRITE(6,2005) UBZ,(UB(I),I=1,10)
         93 CONTINUE
            IF(SEC.GE.SECP) GO TO 300
            GO TO 309
        300 CONTINUE
            QJ=QJ+1.0
            SECP=QJ*SECS
            DO 16 IK=1,IKM
            K=IS*IK
         16 UU(IK)=UB(K)
            WRITE(6,2004) SEC
       2004 FORMAT(/1H ,1X,F8.3)
            WRITE(6,2005) UBZ,(UU(IK),IK=1,IKM)
       2005 FORMAT(/1H ,3X,11E11.4)
        309 CONTINUE
            IF(J.GT.JM) GO TO 6
            DO 34 I=1,IM
         34 UA(I)=UB(I)
            UAZ=UBZ
            GO TO 5
          6 CONTINUE
            STOP
            END


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      C     CCU(T) ; (J/KG/K) ; R=(AL(T)/DX**2)/(GRAV*CCU(T)/DSEC)
            FUNCTION CCU(T)
            IF(T.GT.40.0) GO TO 601
            CCU =0.95312E-3*T**3
            GO TO 609
        601 IF(T.GT.80.0) GO TO 602
            CCU =3.6*(T-40.0)+61.0
            GO TO 609
        602 IF(T.GT.100.0) GO TO 603
            CCU =2.45*T+9.0
            GO TO 609
        603 IF(T.GT.150.0) GO TO 604
            CCU =1.12*T+142.0
            GO TO 609
        604 IF(T.GT.200.0) GO TO 605
            CCU =0.42*T+247.0
            GO TO 609
        605 CCU =0.38*T+255.0
        609 CONTINUE
            RETURN
            END


FACOM 230-75 M7 FORTRAN-IV H COMPILER  (OPT2,CP)    SOURCE PROGRAM LIST  -790420-(V02,L14)  DATE  79.10.22/15:23    PAGE   6

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      C     AL(T) ; (W/M/K)
            FUNCTION AL(T)
            AL=76.77*T**0.88
            RETURN
            END


FACOM 230-75 M7 FORTRAN-IV H COMPILER  (OPT2,CP)    SOURCE PROGRAM LIST  -790420-(V02,L14)  DATE  79.10.22/15:23    PAGE   7

ISN  ST-NO                 SOURCE PROGRAM                                         SEQUENCE

      C     RHO(T) ; (OHM-M)
            FUNCTION RHO(T)
            RHO =0.0
            IF(T.GT.5.8) GO TO 700
            GO TO 709
        700 IF(T.GT.80.0) GO TO 701
            RHO =4.66E-15*T**3+6.0E-10
            GO TO 709
        701 RHO =0.7E-10*(T-50.0)+6.0E-10
        709 CONTINUE
            RETURN
            END

FACOM 230-75 M7 FORTRAN-IV H COMPILER  (OPT2,CP)    SOURCE PROGRAM LIST  -790420-(V02,L14)  DATE  79.10.22/15:23    PAGE   8

ISN  ST-NO                 SOURCE PROGRAM                                         SEQUENCE

      C     H(T) ; (W/M2)
            FUNCTION H(T)
        801 H =0.0
        809 CONTINUE
            RETURN
            END
```