ON THE INFLUENCE OF THE BETWEEN-THE-TURNS THERMAL INSULATION ON THE DUTY OF A LARGE, LIQUID-COOLED PULSED COIL*

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Introduction

The use of pulsed coils cooled by cryogenic liquids to produce high magnetic fields is nothing very new. J. D. Cockcroft[1] and P. Kapitza[2] described such devices using liquid air almost 50 years ago. The size, complexity, and expense of the machines being built in large research establishments throughout the world is, however, something new. Furthermore, future machines will almost certainly be even larger and more costly. Because of their enormous capital and operating costs, it is certainly desirable to keep the cooling time between "shots" as short as possible in order to minimize the cost of data acquisition.

The maximum permissible current in a pulsed magnet coil will usually be determined by the maximum permissible temperature increase which in turn depends on the power supply, the cross-sectional area of the conductors, and the specific heat of the conductor material. The time between pulses or the time needed to cool the coil back to its original temperature is more complicated to calculate. The obvious variables include the thermal properties of the coolant as well as those of the conductor. In addition, the velocity of the fluid and the size and shape of the coolant passages play important roles. More subtle is the influence of the electrical insulation between the turns of the coil. If the layer of electrical insulation is thin or ineffective as a thermal insulation, the coil will tend to a uniform temperature throughout and no moving cold front will be established. Hence, heat will be removed rather sluggishly. If, on the other hand, the turns are well insulated from each other, a moving cold front is set up and efficiently sweeps the heat out of the conductor. The primary purpose of this paper is to provide a clear and quantitative picture of the effect described above. The toroidal field coils of the ORMAK machines will be used as an illustration, but the discussion is applicable to any liquid-cooled coil made from hollow conductors.

Before the actual results of the investigation are presented, some of the pertinent details of the analysis will be briefly discussed.

Details of Analysis

Geometry

A cross section of an ORMAK toroidal field coil is shown in Fig. 1. These coils were fabricated by joining two six-turn assemblies or pancakes of hollow conductors. The crossover between pancakes was on the outside of the coil and is shown schematically in Fig. 2. The pancakes themselves were fabricated by winding two layers of conductors with a crossover on the inside of the coil. The conductor material is oxygen-free, high-conductivity copper, and the insulation is composed of fiberglass tape impregnated with epoxy.

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Idealization

From the beginning of the investigation, it was clear that numerical methods would be required. Hence, the turns were idealized as a series of lumps or discrete elements. The solid part of each turn was assigned ten elements as was the fluid region on the inside of each turn. The heat flow paths associated with the j^{th} lump of the first turn are shown schematically in Fig. 3. Note that heat can flow into or out of the element in the tangential, radial, or axial direction as well as into the fluid. The heat lost to the fluid will depend on the film coefficient, h_c, and the area of the coolant passage. The other thermal conductances shown in Fig. 3 depend on the conductivity of the copper and the insulating material as well as upon the area and length of the path.

The heat flow paths for the i^{th} fluid lump are shown in Fig. 4. For the investigation described in this paper, conductive heat transfer between neighboring fluid lumps was ignored.

Computational Procedure

Once the idealizations described above had been made, heat balance equations for the lumps were written and then rearranged for use with the so-called "explicit" numerical method for handling heat transfer problems.[3] In this method, the future temperatures (the temperatures at time t + Δt) of all lumps are found as explicit functions of current conditions and, where applicable, a generation term. After all "future temperatures" have been found, these temperatures become the new "present temperatures," and the process is repeated. There are strict stability requirements on the maximum permissible size of both the time step and the space step or lump size. These requirements are particularly well described by Dusinberre[3] but can be found in many texts devoted to numerical analysis.

Selection of Film Coefficient

The old and widely accepted correlation of McAdams[4] was used to evaluate h_c, the film coefficient:

$$\frac{h_c d}{k} = 0.023\,(N_R)^{0.8}\,(N_{Pr})^{0.4} \qquad (1)$$

where d is the diameter of the coolant passage, k is the thermal conductivity of the liquid, N_R is the Reynolds number, and N_{Pr} is the Prandtl number. The properties of liquid nitrogen were taken from a voluminous report written for the U.S. Air Force by the Cryogenic Engineering Laboratory of the National Bureau of Standards.[5]

Material Properties

Within the temperature range of liquid nitrogen, both the electrical resistivity and the specific heat of copper are strongly dependent on temperature. Inspection of the data in Ref. 5 suggested the following linear equations as being applicable for the region between 65 and 115 K:

$$c_p = 0.00207\,T + 0.044 \qquad (2)$$

and

$$\rho = 0.0074 - 0.37 \quad (3)$$

where c_p is the specific heat of copper in j/g-K, ρ is the resistivity in μΩ-cm, and T is temperature in K.

Results

The temperature profiles shown in Fig. 5 were calculated on the assumption that the electrical insulation shown in Fig. 1 is a perfect thermal insulator. The coil, initially at 80 K, was heated for 1 sec by a pulse of the form:

$$I = 13{,}000\,(1 - e^{-3.08\,t}) \quad (4)$$

where I is in amperes and t in seconds. Equation (4) agrees rather closely with measurements of a typical ORMAK pulse. The first lines to inspect in Fig. 5 are the flat ones for the short times, 1 and 2 sec. By the end of the 1-sec current pulse, the temperature of the liquid nitrogen has only risen by 4 K. Clearly for the liquid nitrogen velocity of 1 m/sec assumed in the analysis there is not enough heat transfer from the copper into the nitrogen to have any important influence on the peak temperature reached by the copper. (Note that the cold liquid nitrogen coming in does not have time to play any real role during the pulse.) Following the end of the pulse, the temperature of the nitrogen and copper tend toward an equilibrium temperature of 92 K in regions remote from the inlet. This equilibrium is reached after approximately 3 sec. Meanwhile, a moving cold wave is being set up in the entrance region. This wave moves down the conductor and efficiently extracts the heat of the pulse and carries it out at the downstream.

If the insulation between turns is very thin or ineffective as a thermal insulator, no cold wave is established. This case is shown in Fig. 6. Note that the temperature profiles for 1 and 2 sec are the same as those in Fig. 5 but that by 1 min the profiles are very different. Instead of a moving cold wave, a stationary wave is established. Furthermore, most of the metal to liquid heat transfer takes place within the first two turns. Thus, to be removed from the system, heat must be conducted into the first few turns where it is picked up by the liquid and then carried back again into the downstream turns from whence it came and finally out of the coil. Inspection of the profiles shows that in some parts of the coil the liquid nitrogen is actually heating the copper. The wiggles in the copper profiles are caused by the drop in temperature which occurs every time the coil passes the entrance region where 80 K liquid nitrogen is entering.

By the time 3 min have elapsed, the copper and nitrogen profiles are so close together as to be almost indistinguishable. At this point the remaining heat in the system is removed very slowly indeed. This point is illustrated more clearly in Fig. 7 where the temperature of the hottest lump in the coil is plotted as a function of time. Note that for very small times the temperature drops quickly as the nitrogen and copper approach an equilibrium temperature. For the well insulated case, the curve flattens out until the arrival of the cold wave at which time the temperature drops quickly. For the poorly insulated case represented by 0.05 cm of insulation, the temperature of the hottest spot initially drops quickly, then more gradually, and finally slowly on an exponential tail.

Improved Design

An inspection of Figs. 1 and 7 suggests several methods of improving the rate of heat removal.

1. First, and most obvious, where space permits one could simply make the insulation thicker. In particular, the insulation between pies could be made wedge-shaped. Thus, the complete coil assembly of four pies would not be a cylinder but a section from a torus.

2. Rather than bonding the insulation to the copper by impregnation, the insulation could consist of independent layers. The gaps between layers, particularly in an evacuated system, would provide a vastly improved barrier to heat flow. Clearly, this option would require some testing to make sure that fretting of the insulation during pulsing would not cause an electric failure.

3. Finally, a search could be made for a better type of insulation. Perhaps some highly anisotropic substance such as mica might improve the quality of the insulation if space requirements do not permit thicker insulation.

References

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Figure Captions

Fig. 1 Cross section of an ORMAK toroidal field coil. Conductor is OFHC copper and insulation is fiberglass tape impregnated with epoxy.

Fig. 2 Schematic of winding sequence of an ORMAK coil. Two internal and one external crossovers are implied. The numbers refer to "lumps" used in numerical calculations.

Fig. 3 Heat flow paths for a lump in the first turn of the first pie. Note that the most general lump will have six nearest neighbors. The tube represents the fluid and the rectangles represent the conductors.

Fig. 4 Heat flow paths for a typical fluid lump. Arrows imply that heat is transferred by the motion of the liquid not by conduction.

Fig. 5 Temperature profiles at selected times for the perfectly insulated case in an ORMAK toroidal field coil. Fluid velocity was 90 cm/sec; the film coefficient was 0.28 W/cm^2-K.

Fig. 6 Temperature profiles for an ORMAK toroidal field coil with 0.05 cm of epoxy-impregnated fiberglass insulation between turns. Other conditions identical with Fig. 5.

Fig. 7 Temperature histories for the hottest spot in an ORMAK toroidal field coil for various assumed thicknesses of insulation.

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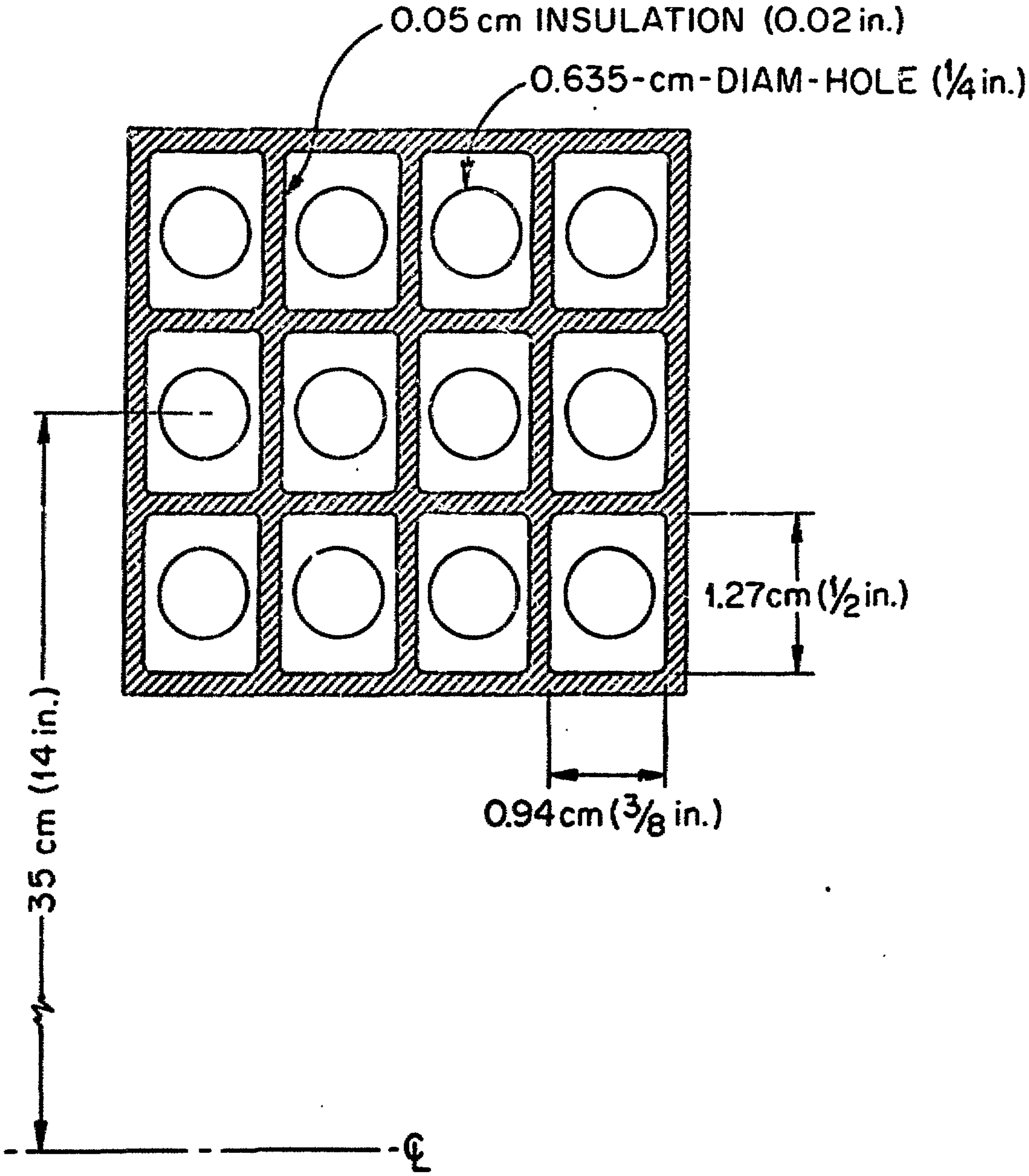

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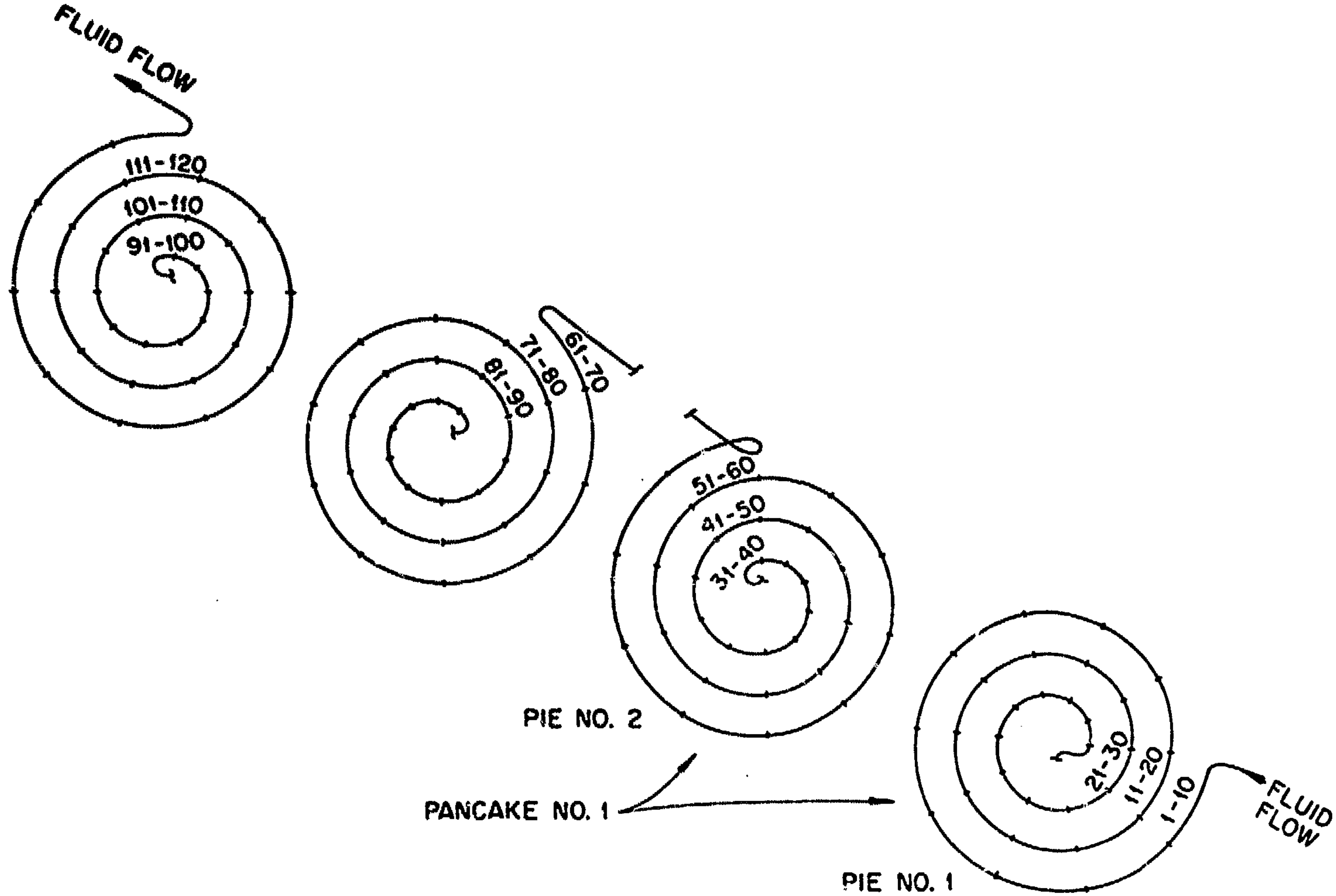

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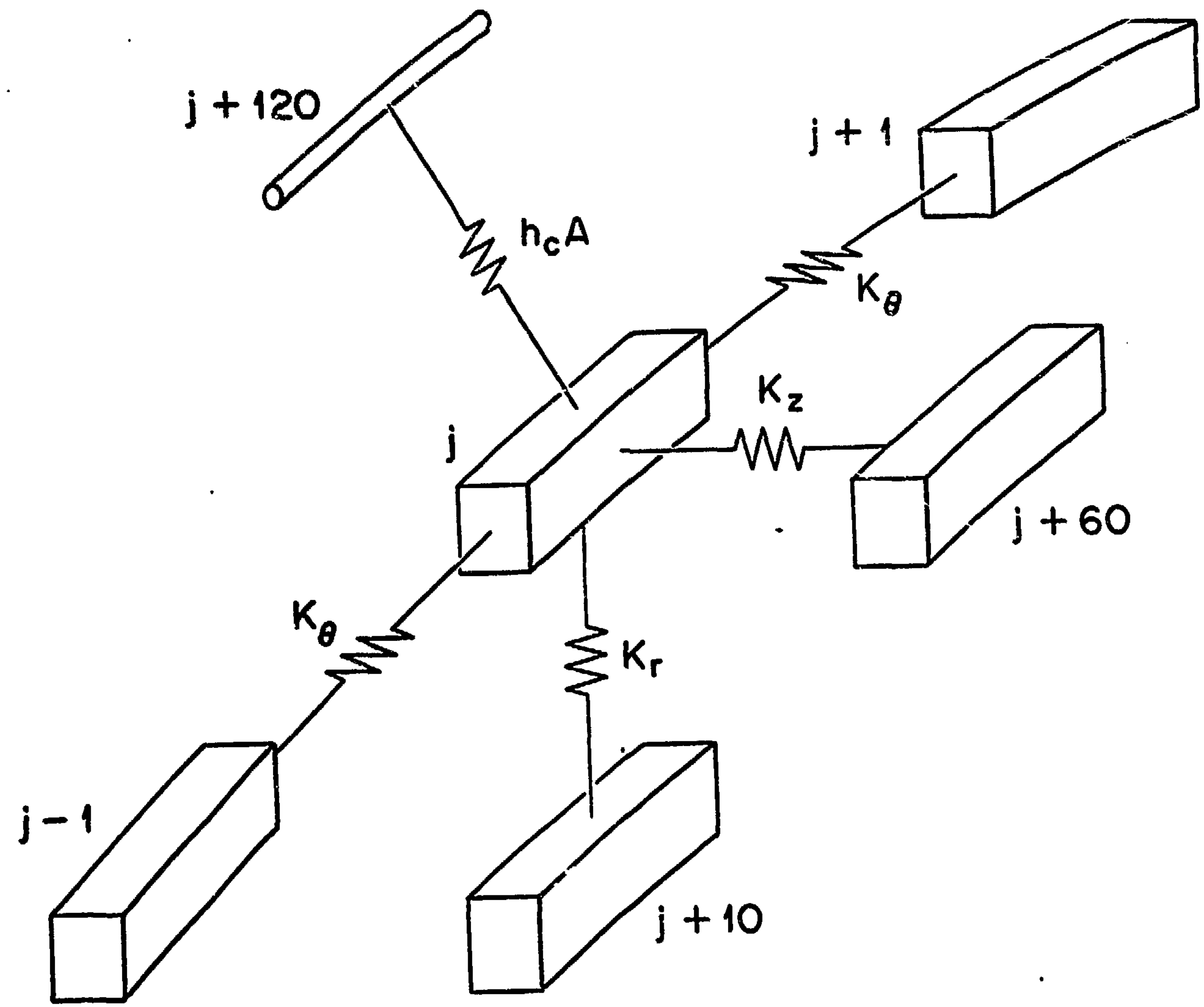

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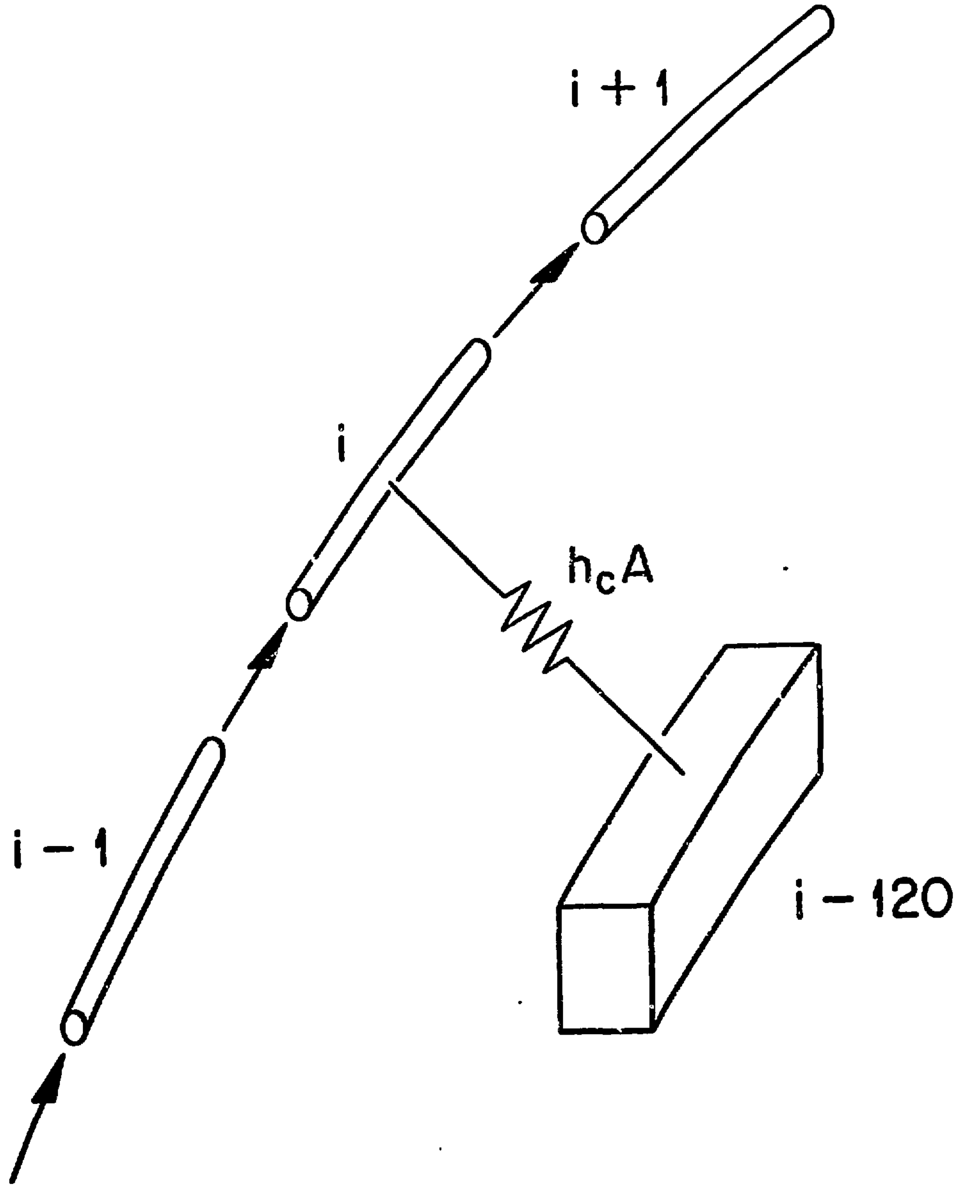

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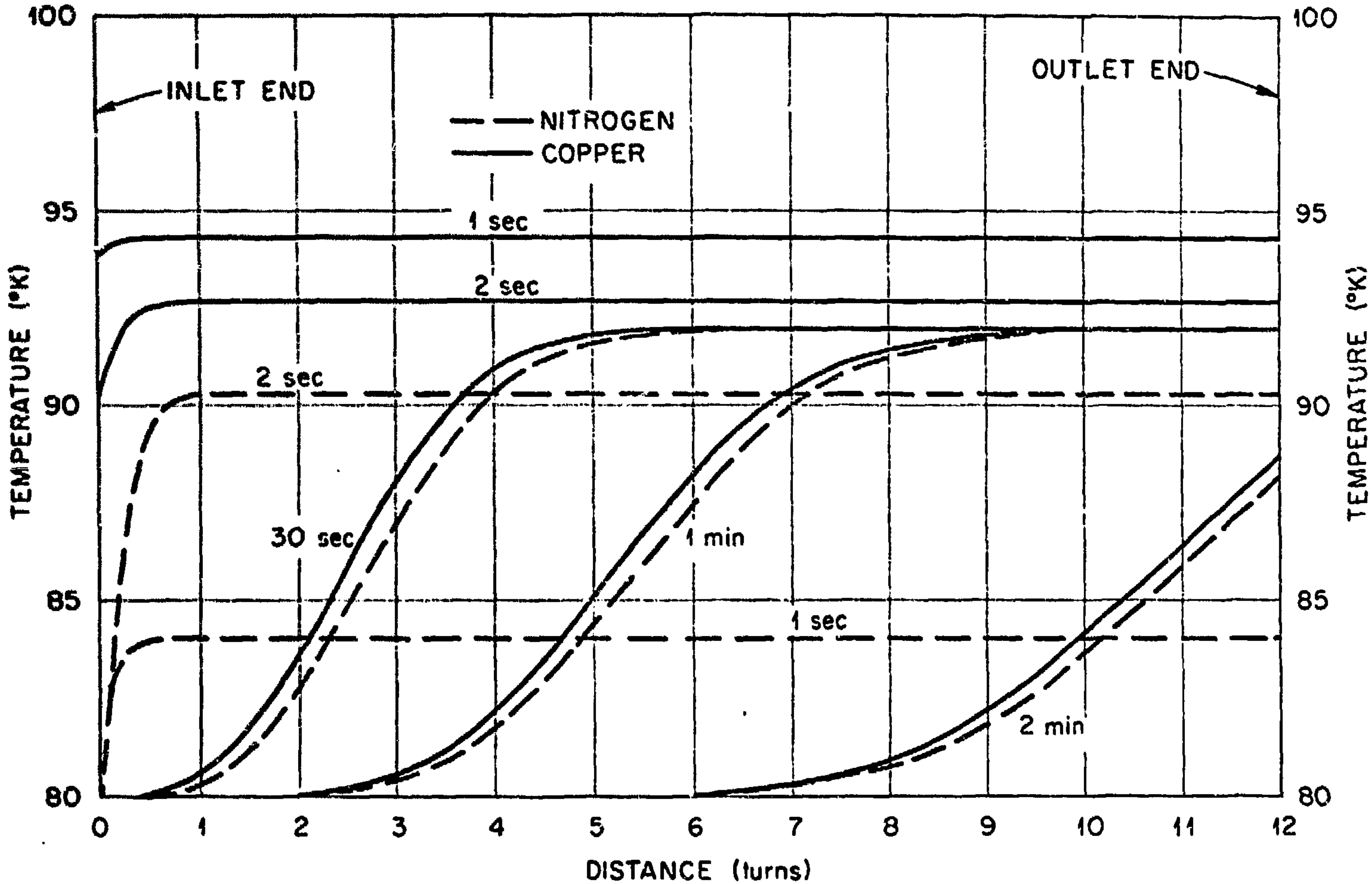

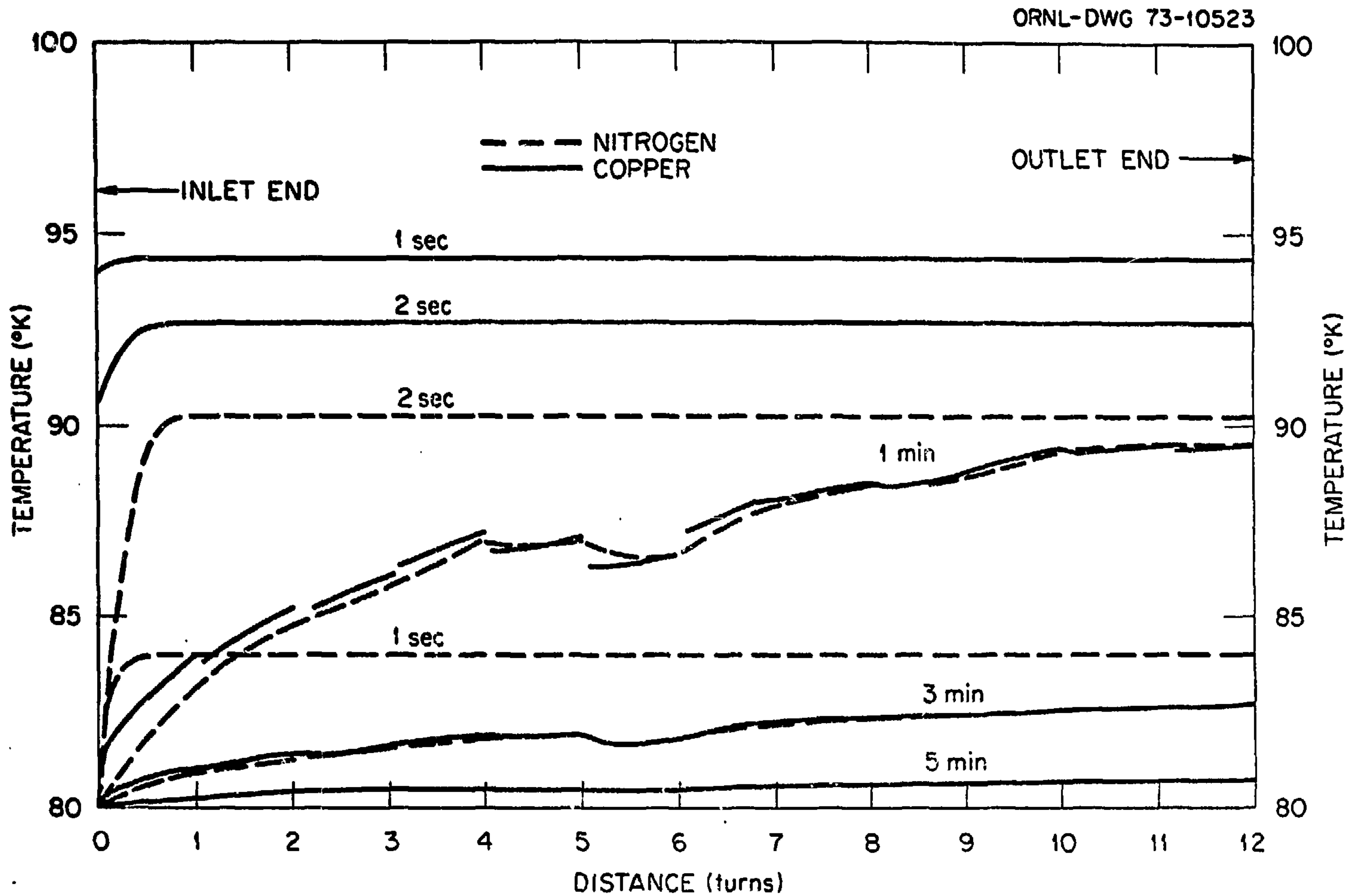
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NITROGEN
COPPER
INLET END
OUTLET END
1 sec
2 sec
2 sec
1 min
1 sec
3 min
5 min
TEMPERATURE (°K)
TEMPERATURE (°K)
DISTANCE (turns)
100
95
90
85
80
0
1
2
3
4
5
6
7
8
9
10
11
12

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