IEEE TRANSACTIONS ON MAGNETICS, VOL. 28, NO.1, JANUARY 1992

Development of High Current Vapor-Cooled Current Leads for Large Superconductor Critical Current Measuring

T. Mito, K. Takahata, N. Yanagi,
S. Yamada, J. Yamamoto

National Institute for Fusion Science,
Furo-cho, Chikusa-ku,
Nagoya 464-01 Japan

T. Uede, K. Sakaki, I. Itoh
Y. Yasukawa, K. Ueda

Fuji Electric Co., Ltd.
Yurakucho 1-chome, Chiyoda-ku,
Tokyo 100 Japan

Abstract- Several programs to develop superconducting magnets for Large Helical Device (LHD) are under way at the National Institute for Fusion Science in Japan. The development of large scale superconductors for use in superconducting magnets is an important goal of these programs.

To measure the critical current of such large scale superconductors we have to supply a very high current of up to 100 kA. For this purpose we have developed very large current capacity, vapor-cooled current leads.

As a first step in this development we have made and tested a pair of current leads with a short-time rated current of 30 kA. We have also developed an analytical program to calculate the time dependent characteristics of vapor-cooled current leads and compared the results of our calculations with the experimental results obtained with 30 kA current leads.

Based on the results of first-step development, we have made short-time rated-current 100 kA current leads and successfully operated them up to 75 kA, the maximum current capacity of existing electrical power supplies.

This report describes the development of vapor-cooled current leads, the test results obtained with them and a comparison of their measured and calculated characteristics.

I. INTRODUCTION

Superconduting wires having a large current capacity are increasingly used in superconducting coils for fusion devices for instance those found in the Large Helical device (LHD), [1], [2] presently being constructed by the National Institute for Fusion Science. When measuring the critical current of superconducting wires for LHD, a large current of about 100 kA is required.

Therefore, the National Institute for Fusion Science and Fuji Electric have developed a current lead with a very large current capacity of about 100 kA.

Current leads used to measure critical currents are different from current leads for superconducting coils. The former must feed a given current only when measurements are being made. It is desirable to suppress heat loss as little as possible when measurements are not being made (non operating time). In other words, it is desirable to feed a given large current into a superconducting wire through a small current capacity current lead.

When designing normal current leads, steady state characteristics are analyzed to determine the proper current lead size. But, in the case of current leads used to measure critical currents, a transient analysis is required to confirm current lead characteristics, when a large current flow for a short time.

However, analysis of the transient characteristics of current leads takes a very long time even with a super computer, unless the calculation model is simplified. This means, there are many problems for practical applications.

We have pursued the following three development goals:

- Experimental verification of operation at 100 kA,
- Confirmation of the size of short-time currents from the results of steady state analyses,
- Experimental verification of accuracy of transient analysis program.

This development was performed in two steps. In the first step, current leads with a 12 kA continuous rating and 30 kA short-time rating were manufactured for experiments and, in the second step, current leads having 100 kA of short-time rating were manufactured. Second-step current leads were based on the results of the first step development. During second step testing, the maximum rated current of 75 kA available from the existing power source was supplied to the leads. An assessment of the test results indicates that the current leads are able to carry currents of up to 100 kA.

II. DESIGN AND NUMERICAL ANALYSIS

A. Design

A test was conducted using Cable-in Conduit type current leads [3], [4], after much experience with continuous rated currents of up to 30 kA.

In the first step, current leads rated at 12 kA (continuous rating), capable of operating for 5 minutes after interruption of the cooling gas flow, were designed.

The size of the leads is nearly at the limit of the results obtainable with a steady state analysis at 30 kA, within the range of cooling gas flows obtainable with the equipment used. We used the transient analysis calculation described in the next section of this paper to determine whether a 30 kA short-time current is possible.

The current leads manufactured in the first step successfully carried a short-time current of 30 kA. Based on the experimental results obtained in the first step, current leads rated at 100 kA were designed in the second step. The maximum continuous rated current of those leads was nearly at the limit of the results obtainable with a steady state analysis at 100 kA, within the range of cooling gas flows obtainable with the equipment used. We used the transient analysis calculation described in the next section to determine whether a 100 kA short-time current is possible.

The specifications of the current leads used in first and second test steps are shown in Table I. The configuration of the Step-2 test lead is shown in Fig. 1.

TABLE I
DESIGN PARAMETERS OF TESTED CURRENT LEADS

	Step-1 Test	Step-2 Test
Type	Cable-in-Conduit	Cable-in-Conduit
Rated Current		
(1) Short Term	30 kA	100 kA
(2) Continuous	12 kA	40 kA
Break Down Voltage	1 kV AC	1 kV AC
Length of Cooling Path	1990 mm	1700 mm
Cross-sectional Area of Conductor	1244 mm^2	2699 mm^2
Helium Void Fraction	20 %	20 %
Period of Operation after Cooling Flow Interruption (at Continuous Rated Current)	5 min	3 min

0018-9464/92$03.00 © 1992 IEEE

B. Transient analysis

We prepared two transient analysis programs. One is a detailed calculation program and the other a simplified calculation program. The difference between these programs is that, in the simple calculation program, the conductor temperature was assumed to be equal to the temperature of He gas because of the excellent thermal transfer coefficient of the current leads. Therefore, we eliminate thermal transfer. In this way, the calculation time can be reduced to 1/200 of that required with the detailed calculation program.

Accordingly, the simple calculation program was used for the transient analysis.

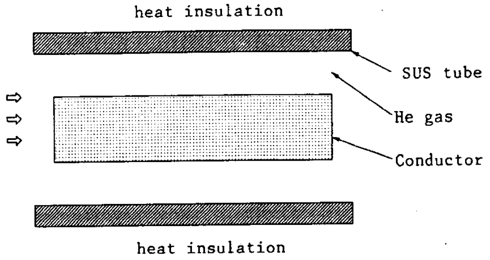
1) Analytical model:

During analysis, the conductor and He gas were regarded as primary objects, and the thermal exchange that took place between them was calculated with an average thermal transfer coefficient.

- Assumption

Mass flow of He gas is constant.
Pressure is 1 ata (constant).
The thermal conductivity in the He gas energy equation is neglected because its value is very small compared with He gas heat transfer coefficient.
The conductor temperature is fixed on both sides of the conductor.
Outlet gas temperature is calculated with the detailed calculation program.

- Model



The calculation model, shown in the above diagram, is based on the fact that heat is transferred through the He gas and to the outer wall of the SUS tube.

- Basic equation

* Conductor energy conservation equation

$$\frac{\partial}{\partial t}(A_C\rho_C C_C T) = \frac{\partial}{\partial X}\left(A_C\lambda_C\frac{\partial T}{\partial X}\right) + \frac{\rho_{ce}}{A_C}(I(t))^2 - hf(T-\theta) \tag{1}$$

* He gas energy conservation equation

$$\frac{\partial}{\partial t}(A_g\rho_g C_g\theta) + \dot{m}_g\frac{\partial}{\partial X}(C_g\theta) = \frac{\partial}{\partial X}\left(A_g\lambda_g\frac{\partial \theta}{\partial X}\right) + hf(T-\theta) \tag{2}$$

where A (m^2): Sectional area
ρ ($\mathrm{kg/m^3}$): Density
C (J /kgK): Specific heat
ρ_{ce} (Ω m): Specific resistance
λ (W /mK): Thermal conductivity
h ($\mathrm{W/m^2K}$): Heat transfer coefficient
f (m): Cooling perimeter
$\dot{m}_g$ (kg/s): He gas mass flow
I (A): Current
T (K): Conductor temperature
θ (K): He gas temperature
X (m): Distance
t (s): Time

Subscript "c" denotes conductor and "g" denotes He gas.

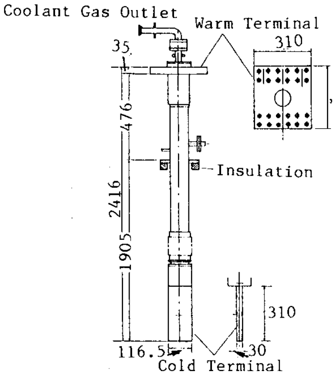


Fig. 1. Outline of Step-2 Current Lead having 100 kA Short-Time Rated Current

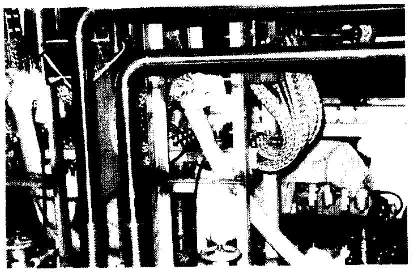


Fig. 2. View of Step-2 Current Leads During 40 kA Operation

- Simplified equation

In equations (1) and (2), conductor temperature is equal to He gas temperature, so the current leads were analyzed with the following equation.

$$(A_C\rho_C C_C + A_g\rho_g C_g) + \frac{\partial T}{\partial t} + \dot{m}_g\frac{\partial}{\partial X}(C_g T) = \frac{\partial}{\partial X}\left(A_c\lambda_c\frac{\partial T}{\partial X}\right) + \frac{\rho_{ce}}{A_c}(I(t))^2 \tag{3}$$

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Testing devices

During testing, one set of two current leads manufactured under the same design conditions was used.

Fig. 2 shows the test conditions for the Step-2 current lead test.

B. Experimental results

1) Continuous operation characteristic

Fig. 3 shows the steady state characteristics of Step-1 current leads. As shown in this figure, the thermal loss of Step-1 current leads is less than 1.2W/kA under rated self-cooled conditions (12 kA continuous rating). The leads can be used with a continuous current of 22 kA.

Similarly, the thermal loss of Step-2 current lead is less than 1.2W/kA at 40 kA (continuous rating), under self-cooled conditions.

During operation at the continuous rated current, after interruption of the cooling gas flow, the Step-1 current leads can be used for at least 5 minutes and the Step-2 current lead for at least 3 minutes.

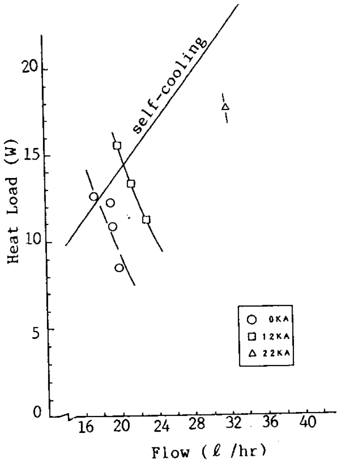


Fig. 3. Experimental Results for the Heat Load at Cold Terminal of Step-1 Current Leads

2) Transient operation characteristics

Figures 4(a) and 4(b) show the results obtained during short-time operations at 22 kA and 30 kA with the Step-1 current leads. Fig. 4(c) shows the results obtained during short-time operation at 75 kA with the Step-2 current leads.

Figures 4(a), 4(b) and 4(c) also show the results of analyses done with the transient analysis program.

The current changing rate is set at 30 kA/200 sec in accordance with the actual critical current measurements shown in Fig. 4(a) and 4(b), and at 75 kA/300 sec shown in Fig. 4(c). The peak-hold time is 310 sec (Fig. 4(a)), 200 sec (Fig. 4(b)) and 600 sec (Fig. 4(c)). Before operating, sufficient cooling gas was obtained with the heater.

C. DISCUSSION

1) Operation at 100 kA during the Step-2 test; 40 kA (continuous rating) current lead:

Operation was conducted at currents up to 75 kA, the maximum current capacity of existing power supplies. The capacity of power supplies will be increased to 100 kA in the future.

A comparison between Figs. 4(a), 4(b) and 4(c) shows the following.

- The voltage in Fig. 4(c) is similar to that in Fig. 4(a). The voltage in Fig. 4(c) is about 50 mV after 10 minutes of peak hold, which means, there is a sufficient voltage margin for longer operation.
- Voltage rises slowly during the first 5 minutes of peak hold, as it does in Fig. 4(a), but rises rather sharply thereafter.
- The temperature rise at the warm terminal of the current lead during 75 kA operation at Step-2 current lead is similar to that of 30 kA operation of Step-1 current leads, rather than 22 kA operation. This is the reason why the voltage rises sharply after 5 minutes of peak hold in Fig. 4(c).

Judging from the above,our conclusions are as follows.

- Since the ratio of 12 kA to 22 kA is the same as that of 40 kA to 75 kA and the voltage rise patterns are similar in both cases, we assume that the voltage rise patterns represented by the ratios 12 kA to 30 kA and 40 kA to 100 kA are also the same.
- The temperature rise at the warm terminal of the current lead shown in Fig. 5 is similar to that of Step-1 current leads during 30 kA operation. One of the reasons for this is that the power source is connected to the warm terminal of the current lead with 2 busbars so the rated current flowing into one side of the warm terminal is 50 kA, which produces the same conditions as an operating current of 100 kA. The current flowing into the other side of the warm terminal is 25 kA. Therefore, joule heat on the 50 kA side due to the connection of the busbars to the warm terminal is the same as that during operation at 100 kA. The value for joule heat obtained in this case is larger than that obtained whin current is flowing evenly into both side of the warm terminal.

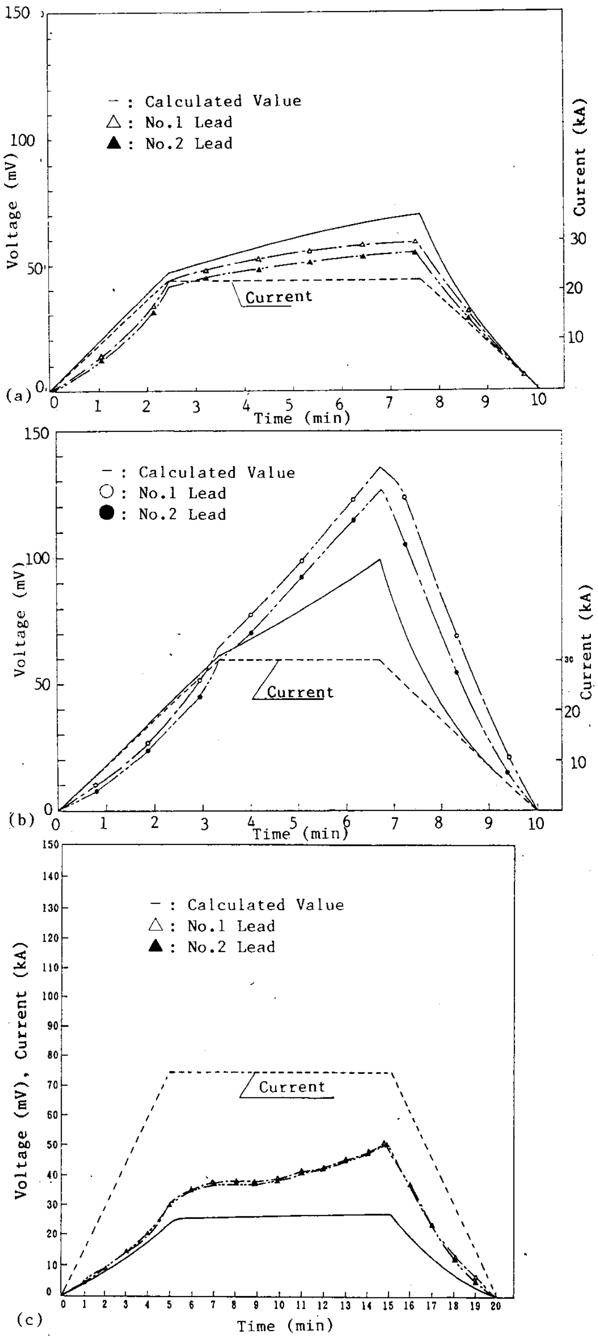


Fig. 4. Transient Characteristics of (a) Step-1 Current Leads at 22 kA Operation, (b) Step-1 Current Leads at 30 kA Operation and (c) Step-2 Current Leads at 75 kA Operation.

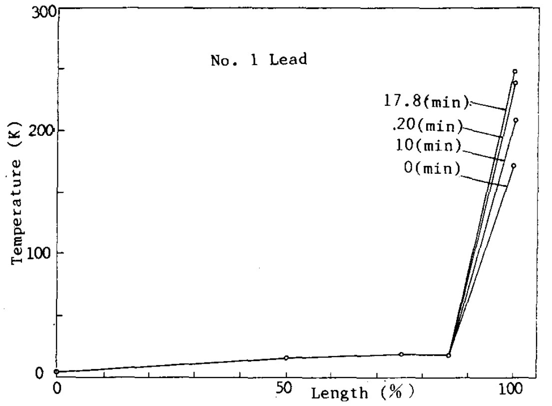


Fig. 5. Temperature Distributions of Step-2 Current Lead During 75 kA Operation

Another reason for the temperature rise at the warm terminal is that the current density of the current lead in the Step-2 test is a little larger than that of the current lead in the Step-1 test. Therefore, more heat is generated around the warm terminal of the Step-2 current leads than that of the Step-1 current leads.

- As shown in Fig. 4(c), the peak-hold time during operation at 75 kA is more than 10 minutes.

If operating time is inversely proportional to the heat generated or the square of the current, the value for operating time at 100 kA will be 1/1.8 . Even when the value is increased to 1/2, about 5 minutes of operating time is available. Even when joule heating at busbar connections and the warm terminal increases by 60%, and the temperature rises, 2-3 minutes of operation is still possible. So, operation at 100 kA is possible for the time required for critical current measurement.

2) Short time current assumed from the results of steady state analysis

In designing the current leads, a final design parameter was set up on the basis of the results of steady state and the transient analyses.

A steady state analysis can basically be done within the flow rate range shown in II. A.

As a result, the ratio of the continuous rated current to the maximum short-time operating current has been determined to be 2.5:1. This means that a current lead 1/2.5 times as small as that designed for continuous operation at the maximum current can be used.

In the Step-1 test, the allowable operating time at the continuous rated current after cooling gas flow interruption is 5 minutes. In the Step-2 test, it is 3 minutes. The difference in operating time is due to the fact that the total length of the Step-2 current leads is shorter than that of the Step-1 current leads.

Judging from the experimental results obtained, a maximum short-time current can be used for operation in either case, but it is better to provide an operating time of a little longer than 3 minutes from the viewpoint of convenient use of the current lead.

When operating at the maximum short-time current, it is necessary to take full consideration not only of the current lead but also of busbars connections.

If a longer peak-hold time is desired, not only the specifications of the current lead but also the temperature rise on the busbars must be considered. Judging from the experimental results obtained, the design criteria set up this time are considered reasonable.

3) Transient analysis program:

Voltage variations obtained from transient analysis are compared with the experimental results in Figs. 4(a), 4(b) and 4(c) shows that the analytical value is a little larger than the experimental value.

In Figs. 4(b) and 4(c), the experimental value is larger than the analytical value, showing a considerable difference for the following two reasons.

- In the simple calculation program of the transient analysis, it is assumed that the conductor temperature is equal to the cooling gas temperature. This assumption applies to a current lead having a good heat transfer, but does not apply to a current lead with a large void factor in the vicinity of the warm terminal of a current lead. This is verified by the fact that the analytical value is relatively close to the experimental value when the temperature variation at the warm terminal is small. However there is a considerable difference between the analytical value and the experimental values when the temperature variation is large as shown in Fig. 5.
- In the transient analysis, process variables are important. The process variables involve variations in the flow of cooling gas. The analysis of this phenomenon was based on the assumption that the cooling gas flow which normally changes is constant. The change in the flow is closely related to the characteristics of the system and hence the heat value transferred from the current lead does not always increase the flow. In some cases, the flow decreases even when the heat value increases.

  Therefore, the change in the flow is an important factor in determining the transient characteristics. So, such an analysis should be based on conservative assumptions.
- Considering the above two points, an analysis using the transient analysis program should be done so that the results of the study can be correlated with a steady state analysis program.

  The problem of the difference in the temperatures of the cooling gas and conductor can be avoided when calculations are done with the detailed program. However, changes in the cooling gas flow cannot be calculated reliably even with the detailed program.

VI. CONCLUSION

We have developed a current lead capable of carrying a short-time 100 kA current for measuring the critical current of superconducting wire.

The result of this development are as follows.

- It has been experimentally confirmed that a current as large as 100 kA can be supplied with a Step-2 current leads.
- The relation between the rated current and the short-time current is such that a short-time current about 2.5 times as large as the rated current can be used for the time required for Ic measurements.
- It has also been confirmed that an analysis using a transient analysis program is useful to verify stable operation with a large short-time current.

REFERENCES

[1] O. Motojima, "Design status of superconducting large helical device, "IEEE Transactions on Magnetics, Vol. 27, No. 2, pp. 2214-2219.

[2] J. Yamamoto, O. Motojima, T. Satou, T. Mito, and LHD Design Group, "Superconducting coil design for large helical device," IEEE Transactions on Magnetics. Vol. 27, No. 2, 2220-2223.

[3] E. Tada et al., "Development of high-current vapor-cooled current leads for fusion devices, "Advances in Cryogenic Engineering Vol. 31, pp. 225-233.

[4] E. Tada et al., "Development of 30-kA vapor-cooled current leads for fusion devices," Proceedings of the Eleventh International Cryogenic Engineering Conference, pp. 528-532.