# Transmission Loss of Prospective Power Transmission Model System Integrated under Superconducting Environment

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*Abstract*— **We have developed a "Prospective Power Transmission Model System Integrated under Superconducting Environment", abbreviated to PROMISE, with the transmission capability of 6kV-1000kVA. The PROMISE consists of a superconducting transformer (SC-Tr), a superconducting fault current limiter (SC-FCL) and a superconducting power cable (SC-power cable). These components are cooled down at liquid helium (LHe) temperature, 4.2K, in a cryostat with a volume of 854 ℓ. The paper indicates a computing procedure of a total heat leak $P_{leak}$ into the cryostat and discusses transmission losses of the superconducting electric power system, which evaporate the LHe. $P_{leak}$, core loss $P_{core}$ of the SC-Tr and a.c. loss $P_{ac}$ in the superconductor were measured in the PROMISE to be 43W, 180W and 50W, respectively. The measured $P_{leak}$ agreed with the theoretical one. In the superconducting power transmission system, the power to operate the refrigerator for liquefying the evaporated helium must be taken as the transmission loss. If the penalty factor was 500, the transmission loss was estimated to be 137kW and took 13.7% of the transmission capability in the PROMISE.**

## I. Introduction

A superconducting power transmission system is expected in the future as a system with a large transmission capability. However, such a system requires a refrigerator to liquefy a coolant like helium, vaporizing due to heat leak, core loss of a superconducting transformer, a.c. loss in a superconductor and so on. The power consumed in the refrigerator might be so large as to reduce the advantages of the application of the superconducting technology to the electric power system.

Many researches and thermal measurements for superconducting power apparatus have been carried out [1]-[3]. However, few researches have been reported in superconducting transmission system composed of several superconducting elements. We have developed a " Prospective Power Transmission Model System Integrated under Superconducting Environment", abbreviated to PROMISE with a transmission capability of 6kV-1000kVA [4]. The PROMISE consists of a superconducting transformer (SC-Tr), a superconducting fault current limiter (SC-FCL), a superconducting power cable (SC-power cable) and a long scale cryostat to enclose these elements and to cool down them to liquid helium (LHe) temperature, 4.2K.

The present paper discusses the transmission loss including the power consumed in the refrigerator for the prototype superconducting electric power system. To estimate the transmission loss, we measured (1)total heat leak $P_{leak}$ into the cryostat, (2)core loss $P_{core}$ of the SC-Tr and (3)a.c. loss $P_{ac}$ in the PROMISE. As to $P_{leak}$, we established a numerical calculation procedure. Furthermore, taking future technological advances into consideration, we estimated how much the transmission loss of the PROMISE may be reduced.

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## II. Heat Leak

### A. Structure of Cryostat

Fig. 1 shows a cross-sectional view of the cryostat of the PROMISE. The cryostat is composed of three sections : (1) substation (SC-Tr and SC-FCL) section, (2) cable section and (3) terminal section. The LHe vessel is made of stainless steel and has a large volume of 854ℓ. The LHe vessel is surrounded by a vacuum insulated container with a pressure of $10^{-4}$ Pa for the purpose of heat insulation. In the vacuum insulated container, a liquid nitrogen ($LN_2$) cooling shield is installed. In each LHe vessel for the substation and terminal section, five baffles are arranged below the top flange to avoid radiant heat coming from the flange. The superconducting power elements are connected with current leads spanning the temperature interval between the liquid helium and room temperature.

### B. Measurement

Until now, we have carried out seven cooling experiments in the PROMISE. Fig. 2 indicates the height of the LHe surface level as a function of time elapsed from the beginning of the injection of LHe at the last experiment. As can be seen in Fig. 2, the LHe level decreases at the rate of 2.0mm/min, i.e. 1.0ℓ/min at 21 hour. At this time, neither the a.c. loss of the SC wire nor the core loss of SC-Tr were generated, because no current passed through superconducting apparatuses of the PROMISE. Thus, the LHe is evaporated only by the heat leak into the cryostat from the room temperature region. The total heat leak was measured to be 43W.

### C. Calculation

In calculating the total heat leak into the cryostat, we take into account five kinds of heat leaks as listed below

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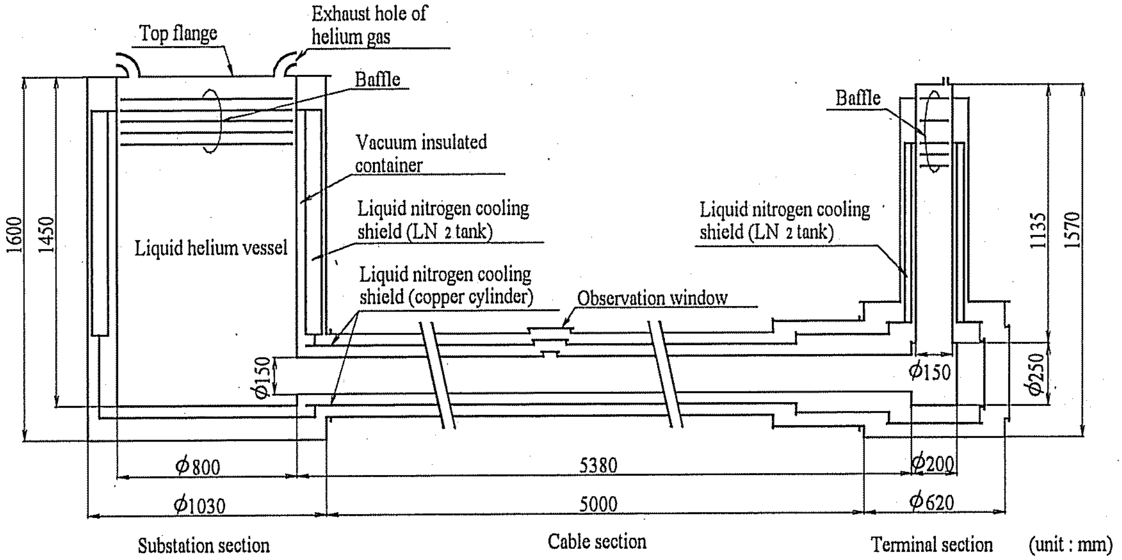


Fig. 1. Cross-sectional view of cryostat of PROMISE.

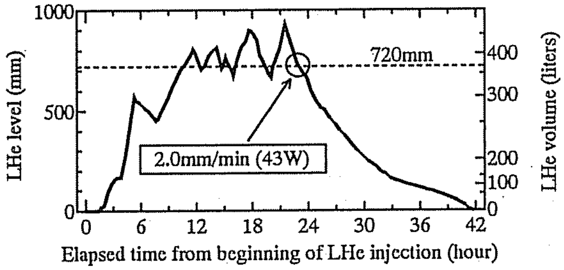


Fig. 2. Time variation in height of LHe surface level in PROMISE.

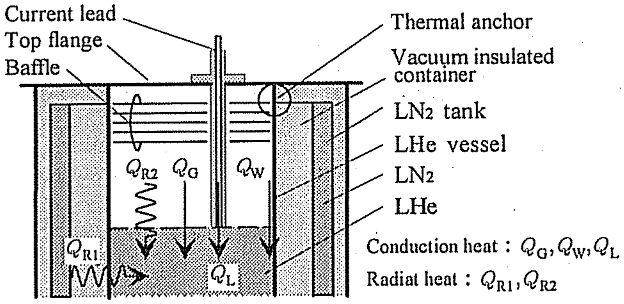


Fig. 3. Heat leak paths into LHe in PROMISE.

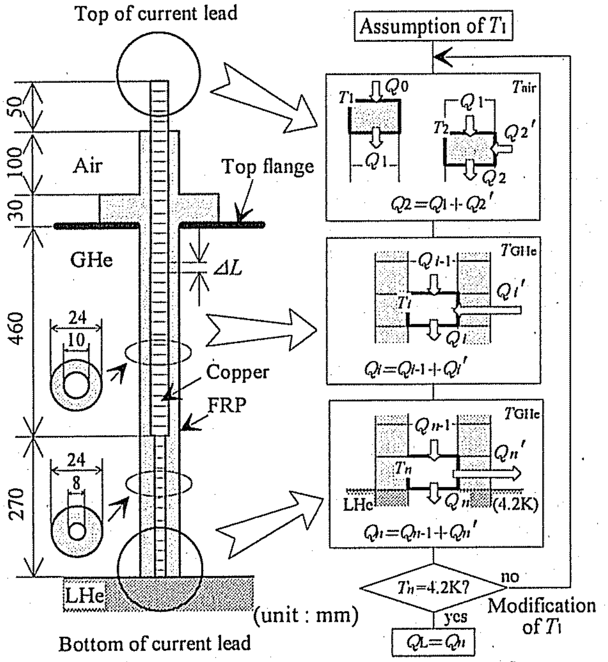


Fig. 4. Simulation of heat conduction through current lead.

(1)heat conduction through current lead : $Q_L$, (2)heat conduction through helium gas : $Q_G$, (3)heat conduction along wall of the LHe vessel : $Q_W$, (4)radiant heat from the $LN_2$ cooled shield : $Q_{R1}$ and (5)radiant heat from the top flange in the LHe vessel : $Q_{R2}$. These heat leaks are summarized in Fig. 3 .

*1) Heat conduction through the current lead:* Fig. 4 shows the geometric shape of the current lead used in the substation section. The current leads are made of copper and enveloped by fiber-reinforced plastics(FRP) for electrical insulation except for the upper 50mm long portion. Due to the low heat transfer of the FRP, the temperature of the current lead may differ from that of the peripheral gas around the FRP. We developed a calculation method for estimating the temperature distribution along the current lead and derived the heat conduction through the current lead. In the calculation, a joule heating in the current lead was neglected because our current lead has a sufficient fat diameter. Fig. 4 also demonstrates a model of the heat conduction process. The current lead is partitioned into "$n$" elements with a thickness $\Delta L$. The elements are numbered by letters "1", "2", $\cdots$and "$n$" in direction from top to bottom. Into the "$i$"th element with a temperature of $T_i$, the heat $Q_i'$ comes through its lateral surface. This heat is expressed by

$$Q_i' = h\pi D_1 \Delta L(T_{gas} - T_i) \quad (1)$$

for the upper portion without the FRP, and by

$$Q_i' = \frac{2\pi\Delta L}{\frac{1}{\lambda_{\rm FRP}} ln\frac{D_2}{D_1} + \frac{2}{hD_2}} (T_{\rm gas} - T_i) \qquad (2)$$

for the lower portion surrounded by the FRP, where $h$ is the heat transfer coefficient, $D_1$ is the diameter of the current lead, $D_2$ is the outside diameter of the FRP, $\lambda_{\rm FRP}$ is the thermal conductivity of the FRP and $T_{\rm gas}$ is the temperature of the peripheral gas. The calculation of $h$ was based on natural convection [5].

The heat $Q_{i-1}$ is conducted from the element "$i-1$". As a result, the heat $Q_i(=Q_{i-1}+Q_i')$ goes into the next element "$i+1$" under no load condition. This heat conduction $Q_i$ is produced by the temperature gradient. Thus the following equation for the temperature is derived :

$$T_{i+1} = T_i - \frac{4Q_i\Delta L}{\pi D_1^2 \lambda_{\rm Cu}} \qquad (3)$$

where $\lambda_{\rm Cu}$ is the thermal conductivity of the copper. In this way, $T_{i+1}$ can be calculated from $T_i$ using (1)-(3).

By assuming the temperature $T_1$ at the top of the current lead to be a certain magnitude as a boundary condition, a set of the temperature $T_2$, $T_3$, $\cdots$ and $T_n$ is obtained. If $T_n$ does not agree with 4.2K, $T_1$ is modified slightly and then the above estimation is repeated again. When $T_n$ is in agreement with 4.2K, we take $Q_n$ as the heat conduction $Q_{\rm L}$.

Cooling tests in the PROMISE under no load condition enabled us to find out that the temperatures $T_{\rm GHe}$ of the helium gas just under the bottom baffle and the top flange were 10 K and 250K, respectively, as shown in Fig. 5 with filled circles. Assuming that the helium gas has the temperature distribution represented by the broken line in Fig. 5, we estimated the temperature profile along the current lead in the substation section as shown by a solid curve in the figure.

The heat conduction $Q_{\rm L}$ per single current lead is calculated to be 5.0W and 5.7W for the substation and the terminal section, respectively. In the PROMISE, we arranged six current leads in the substation section and two in the terminal section for experimental convenience. Consequently, the total heat conduction $Q_{\rm L}$ along the eight current leads is estimated to be 41.0W.

*2) Other heat conduction:* Heat conduction between the high temperature $T_{\rm H}$ and low one $T_{\rm L}$ is generally expressed as follows :

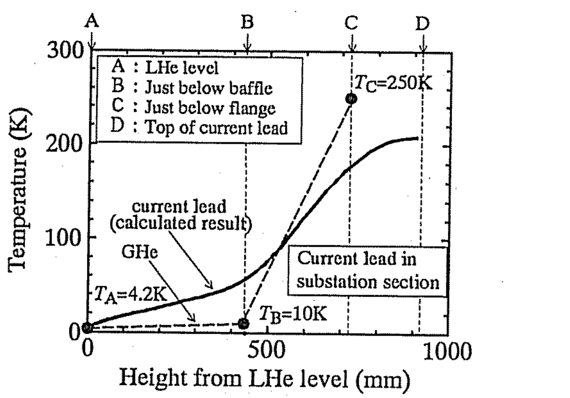


Fig. 5. Temperature distributions of current lead and gas helium layer as a function of height from LHe surface level.

$$Q = \frac{S}{L}\int_{T_{\rm L}}^{T_{\rm H}} \lambda \, dT \qquad (4)$$

where $S$ is the cross-sectional area for heat conduction, $L$ is a geometrical length between two points and $\lambda$ is the thermal conductivity of material. In the case of PROMISE, the heat conduction $Q_{\rm G}$ from the helium gas layer to the LHe is evaluated to be 0.09W by setting $T_{\rm L}=4.2$K and $T_{\rm H}=10$K, which is the temperature just under the bottom FRP baffle.

On the other hand, as shown in Fig. 3, the LHe vessel has a thermal anchor, which is assumed to have a temperature of 80K almost equal to the $LN_2$ temperature. In consideration of the thickness of the wall in the LHe vessel, the heat conduction $Q_{\rm W}$ along the wall is estimated to be 0.04W.

*3) Radiant heat:* The radiant heat $Q_{\rm R1}$ from the $LN_2$ cooling shield and $Q_{\rm R2}$ from the top flange are evaluated on the basis of Stefan-Boltzmann law. As shown in Fig. 1, the $LN_2$ cooling shield mainly consists of the $LN_2$ tank and the copper cylinder. The temperature of the $LN_2$ tank and the copper cylinder are found from the measurement to be 80K and 100K, respectively. As a result, the total radiant heat $Q_{\rm R1}$ is calculated to be 0.4W. The temperature just under the bottom baffle was measured to be 10K. Thus total radiant heat $Q_{\rm R2}$ in both substation and terminal sections proved to be $2.0\times10^{-4}$W.

*4) Total heat leak:* Summing of $Q_{\rm L}$, $Q_{\rm G}$, $Q_{\rm W}$, $Q_{\rm R1}$ and $Q_{\rm R2}$ enabled us to obtain a total heat leak of 41.5W. The calculated value is in good agreement with the measured one of 43W. It is also found that the heat conduction $Q_{\rm G}$ through current leads takes above 98% of the total heat leak.

## III. Core Loss of SC-Tr

In the PROMISE, the core of the SC-Tr is immersed in LHe for the simplicity of design. Therefore, the LHe is vaporized by the core loss induced in the excited SC-Tr. To reduce the loss, an accumulated strip of a high-level grain oriented silicon steel is used as the core. A no-load test was performed to estimate the core loss under the condition with voltage of 6kV$_{\rm rms}$ at the high-voltage side. The high-voltage side of the SC-Tr was opened and 60Hz voltage was applied to the low-voltage side. Fig. 6 shows waveforms of the excitation voltage and current when the voltage of 6kV$_{\rm rms}$ was induced at the high-voltage side. From the waveforms of the voltage and the current, the core loss was measured to be about 180W.

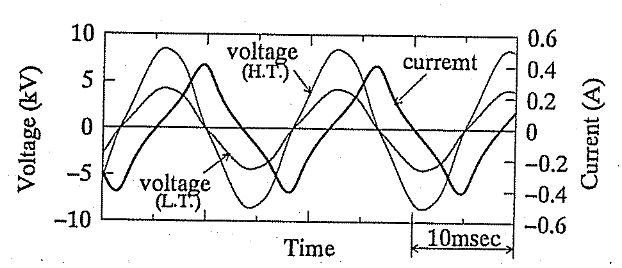


Fig. 6. Excitation voltage and current waveforms in no-load test of SC-Tr (magnetic flux density : 1.72T).

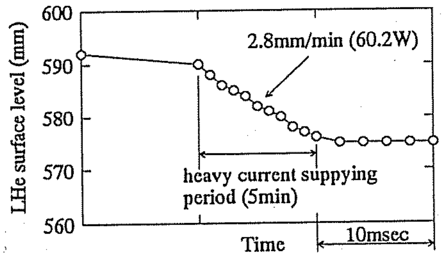


Fig. 7. Time variation of LHe surface level on short-current test.

## IV. A.c. Loss

To estimate the a.c. loss in the windings of the SC-Tr, a short-circuit test was performed, in which a current of 150 $A_{rms}$ was supplied through the high-voltage side. Fig. 7 shows the time variation of the LHe level measured around the current supplying period. In this experiment, since only the substation section in Fig. 1 was used as the cryostat, the decreasing rate of the LHe level under no current condition, i.e. the heat leak was smaller than that in Fig. 2.

The a.c. loss in the SC-Tr is measured to be about 50W by removing the decreasing rate corresponding to the heat leak and core loss from the overall value measured in the short-circuit test. The measured value corresponds to 62.5kW/m$^3$. This estimation disregards the eddy current loss in the cryostat, because magnetic field analysis suggests that the magnetic flux density at LHe vessel walls under heavy current is less than $5 \times 10^{-4}$T.

As compared to the SC-Tr, the SC-power cable is supposed to have very small a.c. losses because the SC-power cable is exposed to lower magnetic field and has a smaller volume of superconductor. This assumption is confirmed by the fact that no increase in bubble generation was observed near the SC-power cable during the actual power transmission tests.

## V. Transmission Loss of Superconducting Power System

The sum of $P_{leak}$, $P_{core}$ and $P_{ac}$, 273W, is regarded as the net loss of the PROMISE when transmitting the power of 1000kW at the voltage of 6kV. However, in the case of a superconducting transmission system, the power of refrigerators is so large that it should be taken into account as a transmission loss. Assuming that the refrigerator requires the power of 500W to liquefy the helium gas vaporized from the LHe by the heat of 1W, the transmission loss of the PROMISE is estimated to be 137kW and takes 13.7% of the transmission capability.

The transmission loss may be reduced due to future technological advances. In case of the PROMISE, the conduction heat through the current leads was estimated to take above 98% of total heat leak. The PROMISE has eight current leads for convenience to change the connection between apparatuses in the experiment. However, in the practical operation of a superconducting power transmission system, only four current leads (two current leads of sending end and two current leads of receiving end) are required. Total heat leak may be half of the current value. Furthermore, as compared with the copper current lead in the PROMISE, a current lead using Bi based high $T$c superconductor reduces the heat leak by ten times. In this case, the total heat leak may be about 2W.

TABLE I
Transmission Losses in PROMISE

| Loss | Current value | Prospective value |
|---|---|---|
| Heat leak | 43W | 2W |
| Core loss | 180W | – |
| A.c. loss | 50W | 5W |
| Total | 273W | 7W |
| Refrigerator power | 137kW | 3.5kW |

The core loss of the superconducting transformer has no relation to the evaporation of the LHe if the core is placed under the normal temperature outside of the cryostat or an air-core autotransformer is used. The a.c. loss in the superconductor may be reduced by the decreasing the filament diameter. A superconducting cable whose a.c. loss is 1/10 of that of the cable for the PROMISE has been developed.

Table I summarizes current values of losses in the PROMISE and ones expected by future technical advances. From Table I, it is found that the transmission loss may be reduced to 3.5kW, and takes 0.35% of transmission capability. It corresponds to 1/40 of current value.

## VI. Conclusion

The transmission loss of the prospective superconducting power transmission model system (PROMISE) was investigated. The heat leak into the cryostat, the core loss of the superconducting transformer and the a.c. loss in the superconductor was measured to be 43W, 180W and 50W, respectively. As to the heat leak, we also carried out the numerical simulation to confirm that the calculated value agreed with the measured one and the conduction heat through current leads took above 98% of the total heat leak.

Taking into account the power of the refrigerator to liquefy evaporated helium, we found that the transmission loss of the PROMISE was 137kW and took 13.7% of transmission capability. However, it is pointed out that the transmission loss was supposed to be reduced to 0.35% due to future technological advances.

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