JAERI-Research
97-044

COOL-DOWN SIMULATION OF Nb_3Al INSERT AFTER DUMPING FOR COIL PROTECTION

July 1997

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編集兼発行　日本原子力研究所
印　　刷　㈱原子力資料サービス

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(Received June 2, 1997)

Nb_3Al Insert will be fabricated and tested in an Engineering Design Activity (EDA) for the International Thermonuclear Experimental Reactor (ITER). A large amount of heat is generated during dumping because of the induced eddy current of the thick stainless steel plate in which the conductor is embedded. The cool-down simulation of Nb_3Al Insert after dumping from 46kA with a decay time constant of 15 s and a quench detection time of 2 s was performed using the 0-dimentional quench simulation model, thin plate eddy current simulation model and the 2-dimentional cool-down simulation model. The conductor temperature and average temperature of the plate were calculated to be 103 and 21 K, respectively. In addition, the cool-down duration is evaluated to be about 1 h. We can conclude that the cool-down duration is enough short to successively carry out the experiment.

Keywords: Nb_3Al, ITER, Cool-down, Quench

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コイル保護のための遮断時のNb_3Alインサートの冷却解析

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（1997年6月2日受理）

国際熱核融合炉（ITER）の工学設計行動（EDA）の一環としてNb_3Alインサートが製作，試験される。その遮断時には，導体が埋め込まれているステンレス・プレートに発生する渦電流が原因となり，大きな発熱が生じる。電流値46kA，遮断時定数15秒，クエンチ検出時間2秒でNb_3Alインサートを遮断した後のクールダウン解析を，0次元クエンチモデル，薄板渦電流解析モデル，2次元冷却解析モデルを用いておこなった。導体温度とプレート温度はそれぞれ103K，21Kと計算された。また，冷却時間は約1時間となった。この解析より，冷却時間が1時間程度であるので，Nb_3Alインサートの試験を連続的に行えることがわかった。

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1. Introduction

The Engineering Design Activity (EDA) for the International Thermonuclear Experimental Reactor (ITER)[1] has carried out under collaboration with European Union, Japan, the Russian Federation and the United States ever since 1992. In this project, Central Solenoid Model Coil (CSMC)[2] will be fabricated and tested in CSMC Test Facility (CSTF)[3] at the Japan Atomic Energy Research Institute (JAERI). In addition, three single layer solenoid coil, CS Insert[4], TF Insert and Nb_3Al Insert[5] will be fabricated and tested at CSTF.

The ITER-TF conductor is embedded in a thick stainless steel plate to sustain the large electromagnetic force during the coil operation. A large eddy current was induced into the plate during the dumping of the TF coils, resulting in a large rise in the temperature of the plate. The long length conductor, for instance, the entire length of the conductor, is therefore heated from the plate during the dumping. It is consequently anticipated that the long-length conductor becomes normal state during the dumping. The conductor temperature and pressure rise may be quite high in this case. It is thought that such a high temperature and pressure rise will damage the conductor or insulation. It is then important to investigate the quenching degree during the TF coil dumping.

One of the major purposes of Nb_3Al Insert experiment is to simulate the quenching behavior of the TF coil. The stainless steel plate is then adopted as the structure in Nb_3Al Insert as shown Fig. 1. Since a large eddy current can be induced during the dumping of Nb_3Al Insert, we can simulate long-length thermal perturbation during the TF coil discharge by dumping Nb_3Al Insert. Major parameters of Nb_3Al Insert are shown in Table 1.

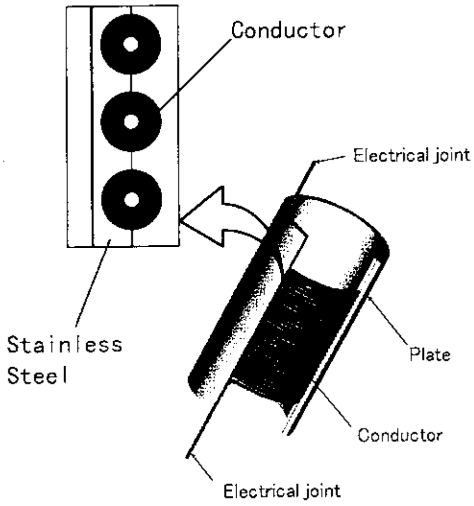

Fig. 1. Schema of Nb_3Al Insert.

Table 1. Major parameters of Nb_3Al Insert

Strand	Diameter	0.81 mm
	Cu/Non Cu ratio	1.5
	RRR	>100
	Surface	2 μm chromium plating
	Critical current density at 12 T	≈ 630 A/mm^2
Conductor	Number of strands	1152 (3×4×4×4×6)
	Outer diameter	42.5 mm
	Inner diameter	38.5 mm
	Outer diameter of sub-channel	12 mm
	Inner diameter of sub-channel	10 mm
	Void fraction	36% at cable space
	Jacketing material	SS (JN1HR)
Coil	Winding method	Layer winding
	Winding diameter	1430 mm
	Winding height	1870 mm
	Height of outer plate	2795 mm
	Number of turns	30
	Nominal current	46 kA
	Nominal field	13 T

The cooling should not be long to carry out the experiment successively. We consequently evaluate the temperature rise of the conductor and plate due to the conductor quench and eddy current in the plate during the dumping, and then, cool-down period is estimated using the calculated temperatures.

2. Simulation Model

The heat generation period at Nb_3Al Insert quench takes only a few ten seconds. On the other hand, it takes considerably longer time, such as more than 1 h, to cool Nb_3Al Insert after the quench. Therefore, the period of the quench of Nb_3Al Insert is negligible compared with the cool-down duration. In addition, it is much more difficult to simulate the coolant behavior during the dumping than the cool-down[6] period. In our model, the temperature rise due to Nb_3Al Insert dumping is evaluated, and then, a cool-down simulation is carried out using the calculated temperature for simplicity.

2.1.Quench simulation

The conductor quench is generally caused by the short length perturbation during a

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2.1.Quench simulation

The conductor quench is generally caused by the short length perturbation during a coil operation, but a long-thermal disturbance is applied to the conductor as a result of the generation of a large eddy current in the plate during the dumping as described previously. The long-length conductor may therefore become the normal state during the discharge. After the conductor temperature rises higher than the plate temperature, the heat produced in the conductor goes to the plate through the thermal interaction between them. However, in our model, the thermal interaction between them is ignored, for simplicity, in the calculation of the temperature rise. The temperature rise of the conductor during the quench is therefore evaluated to be higher than the actual. This assumption allows us to separately calculate the heat generation by the eddy current in the plate and the Joule heating of the conductor.

In our model, we assumed that the entire length conductor reaches the normal state from the beginning. This is the most pessimistic case. The conductor's temperature rise is therefore calculated with the 0-dimensional model, and then, governing equations are as follows:

$$\gamma_c A \frac{dT}{dt} = A_{st} Q \qquad (1)$$

$$\begin{cases} A = A_{st} + A_{He} + A_{con} & (2) \\ \gamma_c = \dfrac{\gamma_{st} A_{st} + \gamma_{He} A_{He} + \gamma_{con} A_{con}}{A} & (3) \\ Q = \dfrac{\rho_{Cu} I_t^2}{A_{st} A_{Cu}} & (4) \end{cases}$$

Where t [s] denotes time, T [K] becomes the conductor temperature, γ_c [J/m^3] the volumic specific heat of the conductor, A [m^2] the cross-sectional area of the conductor, Q [W/m^3] the joule heat generation rate in the strands, ρ_{Cu} [Ωm] the resistivity of the copper, and I_t [A] the transport current to the conductor. The subscripts *st, He, Con, Cu* are respectively for strands, helium, conduit and copper. γ_{st} is substituted by γ_{Cu} since the Nb_3Al's specific heat nearly becomes equal to that of copper and γ_{He} is calculated assuming the constant volume of the coolant.

The eddy current loss in the mandrel and the outer plate is calculated by the eddy current simulation code, ECTAS[7], in which a thin plate model is employed.

The conductor and plate temperature of Nb_3Al Insert are calculated for the series discharge with CSMC from 46kA with a time constant of 15 s with a quench detection time of 2 s, 1 s and 0.5 s.

2.2 Cool-down simulation

The conductor is cooled by supplying a coolant. The heat is conducted between the neighboring turns through the plate in Nb$_3$Al Insert. The heat conduction in them is therefore taken into account in our model. The governing equations are then fluid dynamics equations for the coolant, heat conduction equation for the strands and plate[6].

In the continuous equation of the coolant, the time derivative of coolant density ρ [kg/m^3] can be neglected since the coolant temperature slowly decreases during the cool-down. Consequently, we obtain,

$$\frac{\partial \dot{m}}{\partial \xi} = 0 \tag{5}$$

Where ξ [m] denotes spatial coordinate along the conductor and $\dot{m}$ [kg/sm^2] the coolant mass flow rate through a unit area.

In the coolant momentum equation, the inertia term can be ignored since the time derivative of $\dot{m}$ is small during the cool-down. The momentum equation for the coolant is as follows.

$$\frac{\partial p}{\partial \xi} = \frac{f\dot{m}^2}{2D_h\rho} \ . \tag{6}$$

Where p [Pa] denotes the coolant pressure, D_h [m] the hydraulic diameter and f the friction factor, respectively. The friction factor and density are calculated from the average coolant temperature and pressure . The average temperature is calculated by,

$$T_{ave} = \frac{\int_0^L T d\xi}{L} \ . \tag{7}$$

Where L [m] shows the conductor length. The average pressure is calculated from,

$$p_{ave} = \frac{(p_{in} - p_{out})}{2} \ . \tag{8}$$

The heat transfer performance between the strands and coolant is good because of the considerably long wetted perimeter. It allows us to assume an identical temperature between the coolant and strands. Thus, we obtain the following equation by combining the energy equation of the coolant and heat conduction equation of the strands[8].

$$\gamma_c A \frac{\partial T}{\partial t} - \lambda_{Cu} A_{Cu} \frac{\partial^2 T}{\partial \xi^2} + \left(\dot{m} c_p - A_{Cu} \frac{\partial \lambda}{\partial \xi} \right) \frac{\partial T}{\partial \xi} + hPe(T - \phi) = 0 \qquad (9)$$

Where ϕ [K] denotes plate temperature, c_p [J/kgK] the coolant specific heat, h [W/m^{2}K] the heat transfer coefficient between the conductor and plate and Pe [m] the wetted perimeter between them, respectively. Note the heat conduction of the conduit, coolant and superconductor is ignored in Eq. (9) since they are negligibly small in comparison with that of copper.

The plate temperature is supposed to be uniform in the radial direction, for simplicity. Then,

$$\gamma_p \frac{\partial \phi}{\partial t} - \frac{\partial}{\partial x}\left(\lambda_p \frac{\partial \phi}{\partial x} \right) - \frac{\partial}{\partial y}\left(\lambda_p \frac{\partial \phi}{\partial y} \right) - q = 0\,. \qquad (10)$$

Where x [m] denotes spatial coordinate in the circumference direction, y [m] the spatial coordinate in the vertical direction, as shown in Fig. 2. γ_p [J/m^3] and λ_p [W/mK] shows volumic specific heat and thermal conductivity of the plate. q [W/m^3] is the heat removal rate from the conductor to the plate.

The conductor and plate are discreted as shown in Fig. 2 and Eqs. (9) and (10) are solved by the finite differential method. q is calculated by Eq. (11) below when the grids of the plate are adjacent to the conductor,

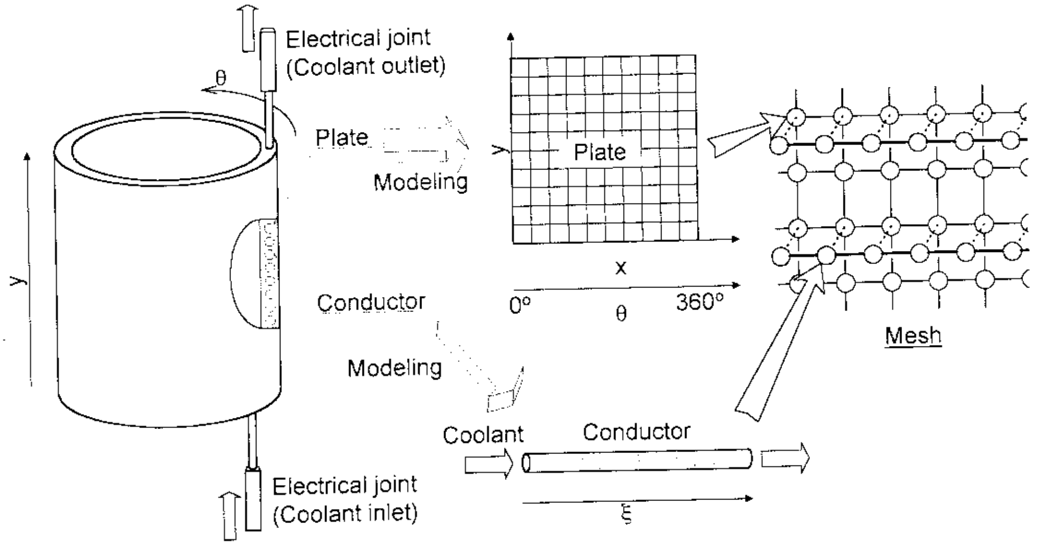

Fig. 2. Simulation model.

$$q = \frac{hPe(\phi - T)}{\eta \delta y} . \qquad (11)$$

Where η [m] and δy [m] show the effective thickness of the plate and discrete increment in the vertical direction, respectively. The effective thickness of the plate is defined by dividing the volume of the plate by the circumference length of the plate. If the grids of the plate are not adjacent to the conductor, no heat exchange between the conductor and plate can be assumed. The time discrete increment is 1 s. The number of grids of the conductor and on the plate are 493(ξ) and 17(x)×87(y), respectively.

The Nb_3Al Insert cool-down simulation is carried out for an inlet pressure of 0.6 MPa, a pressure drop of 0.1 MPa and a supplied coolant temperature of 4.5 K. The coolant flow rate is however supposed not to exceed a certain level of 10, 20 or 30g/s.

3. Results

Figure 3 shows the calculation results of the conductor temperature for a dumping from 46 kA and with a quench detection time of 2 s and a decay time constant of 15 s, respectively. The conductor temperatures for the other cases are listed on Table 2.

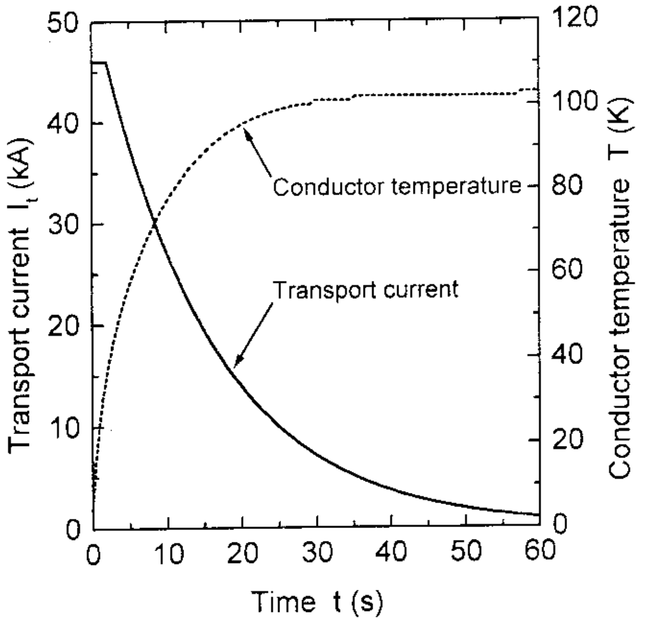

Fig. 3. Calculated conductor temperature for the dumping from 46 kA and with a quench detection time of 2 s and a decay time constant of 15 s.

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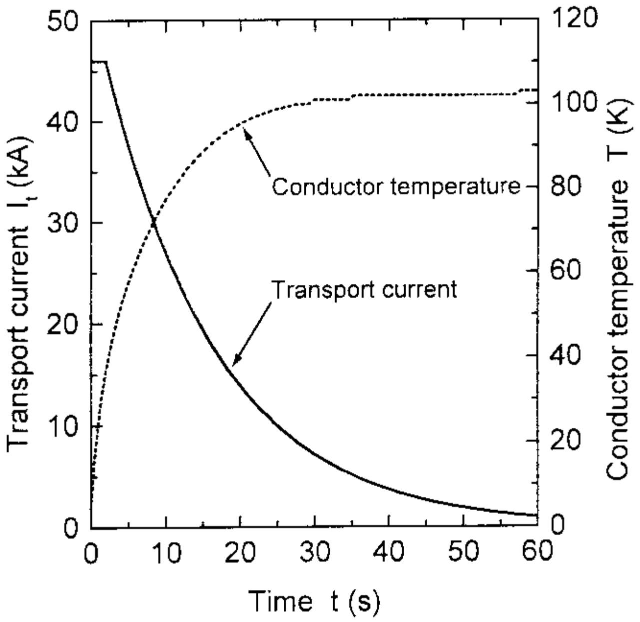

Fig. 3. Calculated conductor temperature for the dumping from 46 kA and with a quench detection time of 2 s and a decay time constant of 15 s.

Table 2　Summary of calculation results

Detection time (s)	Temperature of conductor (K)	Average plate temperature (K)	Mass flow rate limitation (g/s)	Cool-down duration (s)
2	103	21	10	4200
2	103	21	20	3700
2	103	21	30	3600
1	90	21	10	3600
0.5	83	21	10	3200

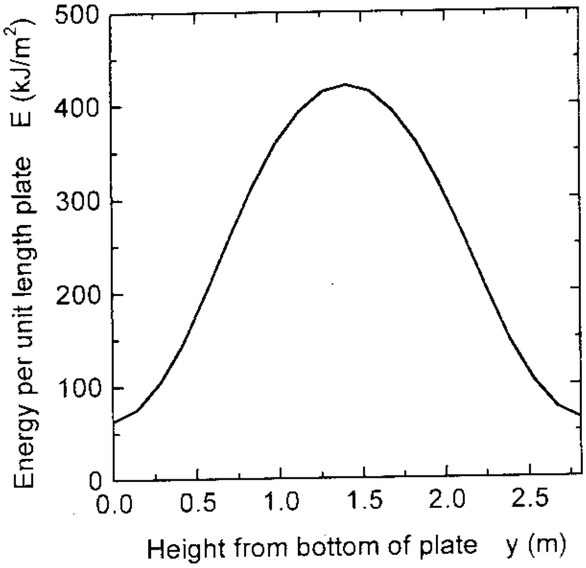

Fig. 4.　Heat energy of the unit length plate by eddy current loss in the plate as a function of the height from the bottom of the plate.

Figure 4 shows the heat energy generated by the eddy current in the plate.　The heat energy varies along the vertical axis.　The total eddy current in the plate is shown in Fig. 5 with the transport current to CSMC and Nb_3Al Insert.　The average plate temperature is also shown in this figure.　The average plate temperature is 21 K after the dumping with a time constant of 15 s.

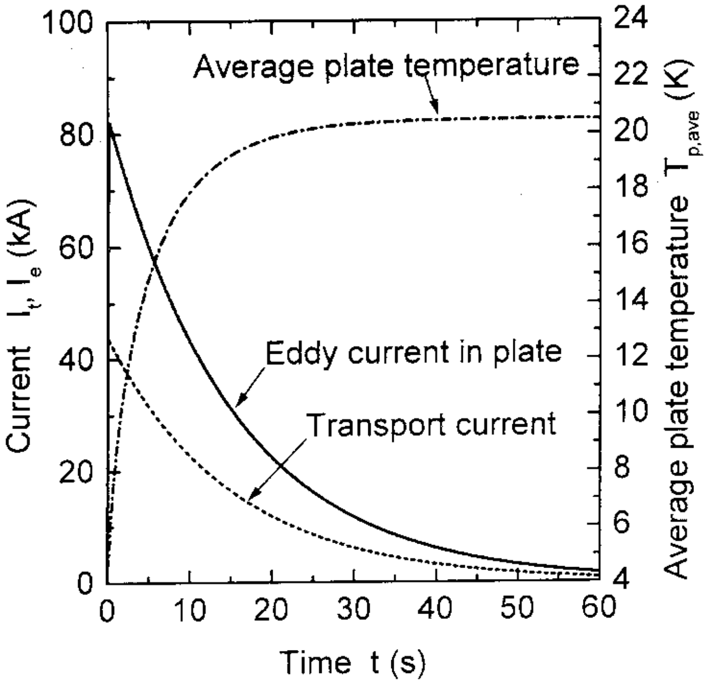

Fig. 5. Eddy current in the plate and average plate temperature. *t*=0 corresponds to the beginning of the dumping.

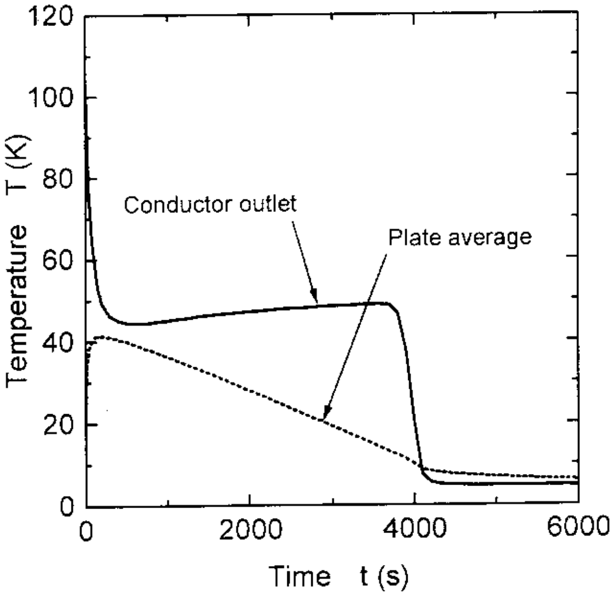

Fig. 6. Conductor outlet temperature and average plate temperature during the cooling after the dumping with a detection time of 2 s and a decay time constant of 15 s. The coolant flow rate is limited to be less than 10 g/s during the cool-down.

Figure 6 shows the calculated coolant outlet and average plate temperatures in case the initial ones are those shown in Figs. 3 and 5. The average plate temperature does not become 4.5 K even after 6000 s. This is because the temperature of the upper plate is still high at that time. However, we can start the coil charge since the temperature of the all conductor becomes the inlet coolant temperature of 4.5 K.

The evaluated cool-down durations are summarized in Table 2. The cool-down time takes 1 h and then seems to be acceptable. The difference in the cool-down duration among the cases of the maximum coolant flow of 10, 20 and 30 g/s is not so long as can be seen in Table 2. This is because the coolant flow can not reach the maximum until a certain time from the limitation of the pressure drop of 0.1 MPa as shown in Fig. 7.

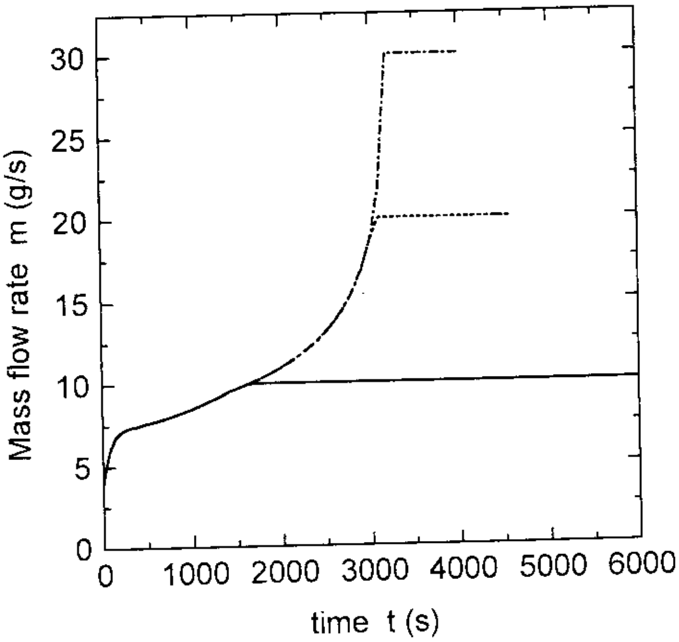

Fig. 7. Coolant mass flow rate in case the maximum is limited to less than 10, 20 and 30 g/s.

4. Conclusions

The cool-down period during the cooling after the Nb_3Al Insert dumping from 46 kA with a decay time constant of 15 s is evaluated using the 0-dimensinal quench simulation model, thin plate eddy current simulation model and 2-dimensional cool-down simulation model. The cool-down duration is estimated to be about 1 h and we

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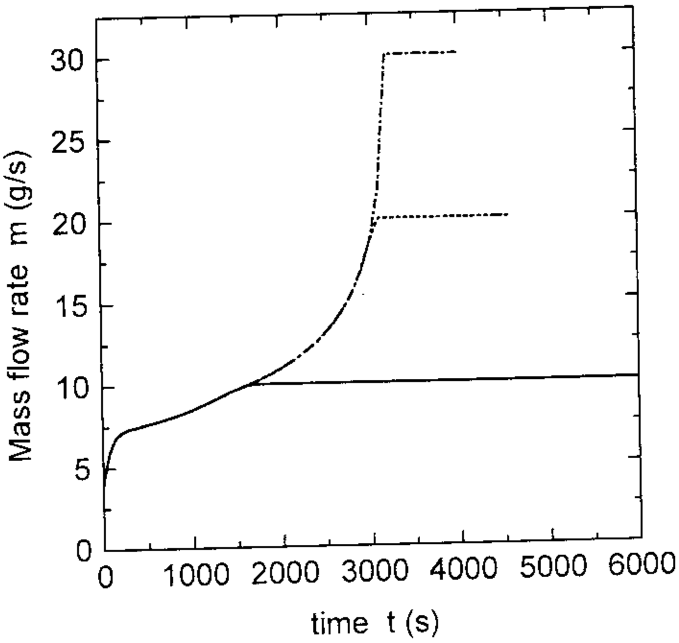

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