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System Dynamic Analyses on the JKJ Mercury Target and Cold Moderator Systems

Toshio Takahashi*, Masanori Kaminaga, Hidetaka Kinoshita, Tomokazu Aso, Katsuhiro Haga, Ryutaro Hino

Japan Atomic Energy Research Institute,
Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan
*E-mail: takahashi@cat.tokai.jaeri.go.jp

Abstract

The temperature responses of major points in a mercury target cooling system and in a cold moderator system of JKJ were simulated by the analytical code MATLAB (SIMULINK).

As a result, it was made clear that non-control of mercury temperature is the best way to control the mercury target cooling system. If the mercury temperature of the system is controlled by the PID control system using an outlet temperature of heat exchanger, the PID control system shows the characteristics of an on-off control system, and the temperature cannot be controlled.

Analytical results also showed that mercury temperature remained below the boiling point of 356℃ under 0.1MPa during a transient at one cooling pump trip.

Analytical results for the cold moderator system showed that the outlet temperature of cold moderator vessels could be kept within a temperature range of 1k during steady-state conditions.

1. Introduction

In a mercury target cooling system, the temperature of the mercury rises due to spallation reaction between the proton beam and the mercury. It is necessary to keep the mercury temperature in the system below the boiling point in order to maintain system safety during normal operation, as well as during both transients and accidents.

In a cold moderator system, the temperature of the liquid hydrogen rises through high-energy neutron heating. When the temperature of liquid hydrogen rises, the performance of its neutronic characteristics deteriorates.

Therefore, it is important to understand temperature response in the mercury target cooling system and in the cold moderator system. In the current operation plan for the proton beam induced from the accelerator in the facility, after 80 pulses appear in the frequency of 25 Hz, 4 pulses will be lost at the target in order to deliver these pulses to the 50GeV proton synchrotron.

The temperature responses of major points in the mercury target cooling and in the cold moderator systems were simulated by the analytical code MATLAB (SIMULINK) for both normal operation and operational transient conditions.

As a result, it was made clear that the mercury temperature never reached the boiling point in the target cooling system during operational transient conditions, and non-control of mercury temperature was the best way to control the system. If the mercury temperature of the system is controlled by the PID control system using an outlet temperature of heat exchanger, the PID control system shows the characteristics of an on-off control system, and the temperature cannot be controlled.

Analytical results for the cold moderator system showed that the outlet temperature of the cold moderator vessels could be kept within a temperature range of 1k during steady-state conditions without temperature control.

2. System description and analytical model

2.1 System Description

The system diagram of the mercury target cooling is shown in Fig. 2.1.1. The mercury target cooling system consists of three sub-systems; a primary mercury loop; a secondary water loop; and a tertiary water loop. During normal operation condition, two circulation pumps are operated at 50 % capacity in each sub-system.

The system diagram of the cold moderator is shown in Fig. 2.1.2. Supercritical hydrogen is refrigerated by a helium chiller and three units of cold moderator vessels are cooled in series. A multiplex pipe of helium, vacuum and hydrogen is used near the entrance of the cold moderator vessels.

2.2 Analytical Model

An analytical model based on the relations of each temperature was developed for the mercury target cooling system, including the transfer function of each heat exchanger, the delay time of the fluid and the transfer function of the expansion tank.

The following operating conditions can be analyzed by the analytical model; normal operation; proton beam off; one or both primary mercury circulation pump unit(s) trip; one or both secondary and tertiary water circulation pump unit(s) trip; and temperature responses of primary and secondary cooling system due to cooling tower outlet temperature or cooling capacity changes.

In the analytical model of the cold moderator system, the following items were considered; the transfer function including the multiplex pipe; the helium chiller and gas separation or expansion tank; time delay of the fluid; the radiation heat from the surface of liquid hydrogen pipe; and the neutron irradiation heating at cold moderator vessels and pipe near the cold moderator vessels. The following operating conditions can be analyzed by the model; normal operation; proton beam off; one or both liquid hydrogen circulation pump unit(s) trip; and temperature responses due to helium chiller unit capacity changes.

The analytical model can simulate two proton beam operation cases; proton beam off periodically; and random proton beam off around every three seconds.

3. Simulation result

3.1 Start-up period

In normal operation, the proton beam is injected into the target as shown in Fig. 3.1.1. The time response of the target vessel inlet temperature is shown in Fig. 3.1.2 during the start-up period. The target vessel inlet temperature rises about 27℃ due to spallation reaction, and 1,550 seconds after the beginning of the proton beam injection, the mercury temperature reaches 95% of its final value. In this case, the period of the pulse loss of the proton beam is the only dominant parameter that affects mercury temperature rise inside the target vessel. After target vessel outlet mercury temperature reaches the steady-state condition, it changes from 48℃ to 73℃ (temperature difference 25℃) periodically, which is shown in Fig. 3.1.3. On the other hand, the target vessel inlet mercury temperature change is restricted to fluctuation of 1℃ by the time lag of the first order element of the expansion tank installed in the system.

The liquid hydrogen temperature response of the cold moderator vessels during the start-up period is shown in Fig. 3.1.4. After reaching the steady-state condition, the temperature of liquid hydrogen in cold moderator vessels can be kept within the temperature range of 20.0±0.4K, 20.9±0.4K, 21.7±0.4K for the first, second and third moderator vessels respectively, at the outlet of each vessel.

The temperature responses in case of the random proton beam off around every three seconds are shown in Fig. 3.1.5 and 3.1.6.

3.2 Proton beam off

In this analysis, it was assumed that the proton beam was shut off during steady-state operation as shown Fig. 3.2.1. The response of the target vessel inlet mercury temperature during the transient is shown in Fig. 3.2.2. Heat generation in the target vessel stops with the shut off of the proton beam, and mercury temperature drops 10℃ about 160 seconds after the proton beam off.

The response of liquid hydrogen temperature of cold moderator vessels in this transient is shown in Fig. 3.2.3.

The temperature responses in case of the random proton beam off around every three seconds are also shown in Fig. 3.2.4 and 3.2.5.

3.3 One primary mercury circulation pump unit trip

The responses of the mercury temperatures are shown in Fig. 3.3.1 and Fig. 3.3.2 for target vessel inlet and outlet, for the case of one pump unit being tripped in the mercury loop. The highest mercury temperature during the transient was calculated to be less than 130℃, and it is far less than the boiling point (356℃) of mercury. Therefore, there is no need to send a proton beam trip signal from the viewpoint of mercury boiling prevention.

The temperature responses for the case of random proton beam off around every three seconds with one pump unit trip are also shown in Fig. 3.3.3 and 3.3.4.

3.4 One liquid hydrogen circulation pump unit trip

The response of liquid hydrogen temperature in the cold moderator is shown in Fig. 3.4.1 for the case of one pump unit in the liquid hydrogen loop. In this case, the base temperature of liquid hydrogen rises 6.5K, and the temperature change width also increases, from 0.8K to 1.6K.

3.5 One secondary or tertiary water circulation pump unit trip

The responses of the target vessel inlet mercury temperature are shown in Fig. 3.5.1 and 3.5.2 for the cases of one pump unit being tripped in either the secondary or tertiary water circulation loop. Because the highest mercury temperature was calculated to be less than 90℃ in each case, there is no need to send a proton beam trip signal from the viewpoint of mercury boiling prevention.

The temperature responses for the case of random proton beam off around every three seconds are shown in Fig. 3.5.3 and 3.5.4.

3.6 Cooling tower temperature change

The response of the target vessel inlet mercury temperature is shown in Fig. 3.6.1. In this transient, ±5℃ temperature change was assumed at the cooling tower outlet, as shown in Fig. 3.6.2. When the temperature of the cooling tower changes with low frequency, the mercury temperature simply follows suit, and a ±5℃ temperature change effects a similar change of temperature in the mercury system.

3.7 Variation of helium chiller inlet helium temperature change

The response of liquid hydrogen temperature is shown in Fig. 3.7.1 for the case of helium temperature increasing 1k at the helium chiller inlet, as shown in Fig. 3.7.2. Liquid hydrogen temperature follows the change in temperature of the helium chiller, and base temperature of liquid hydrogen increases 1K.

3.8 Temperature control

The response of the PID controller output signal (MV value) of the mercury temperature control system is shown in Fig. 3.8.1, and the response of the target vessel inlet mercury temperature is shown in Fig. 3.8.2. In this case, the secondary coolant flow rate was controlled in order to keep constant temperature at the primary heat exchanger outlet. PID parameters used in the calculation are 3 for the P value, 0 for the I value, 0 for the D value, and 60℃ for the set point. As shown in Fig. 3.8.2, it is impossible to control the mercury temperature. The PID control system shows the characteristics of an on-off control system. It shows the same action even if PID values are varied, because heat input changes as much as 650kW and the change in the width of the beam power cannot be controlled.

4. Concluding remarks

The temperature responses of major points in the mercury target cooling system and in the cold moderator system during normal operation and during operational transient conditions were simulated by using MATLAB. As a result, it was made clear that non-control of mercury temperature was the best way to control the mercury target cooling system. Analytical results also showed that the mercury temperature remained below the boiling point of 356℃ under 0.1MPa during a transient at one cooling pump trip.

Analytical results for the cold moderator system showed that the outlet temperature of cold moderator vessels could be kept within the temperature range of 1k during steady-state condition.

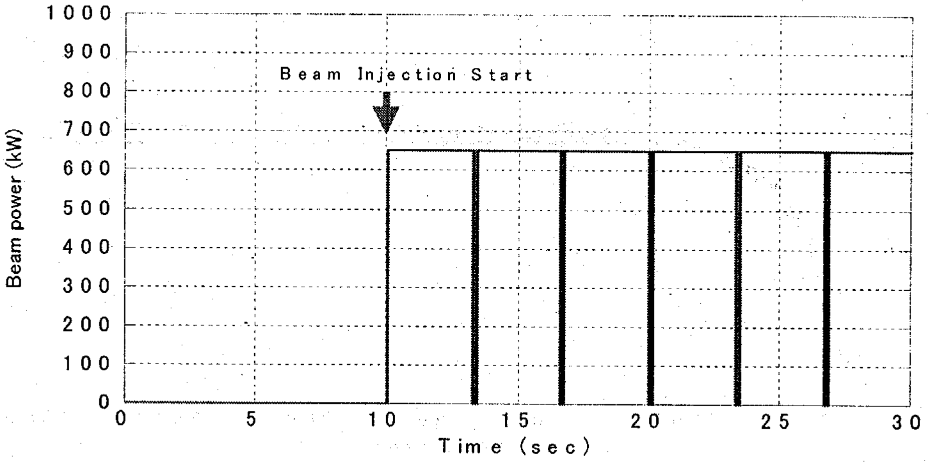

Fig. 3.1.1 Beam power during start-up period

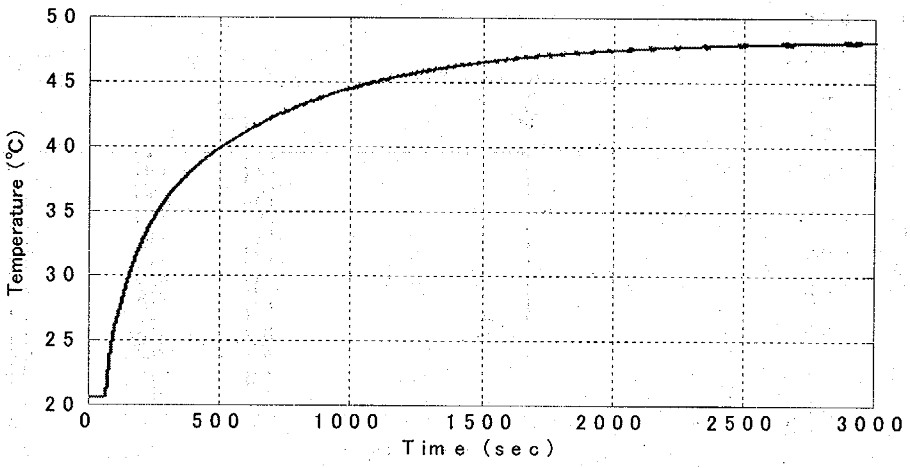

Fig. 3.1.2 Response of the target vessel inlet mercury temperature during start-up period

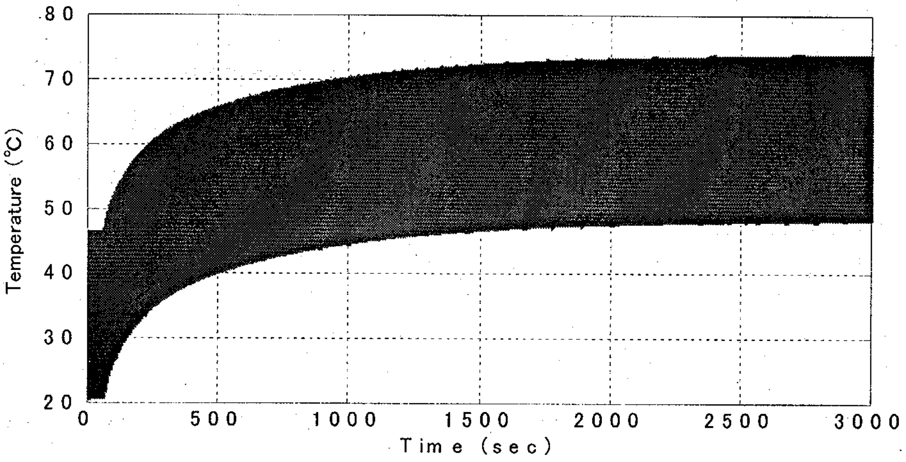

Fig. 3.1.3 Response of the target vessel outlet mercury temperature during start-up period

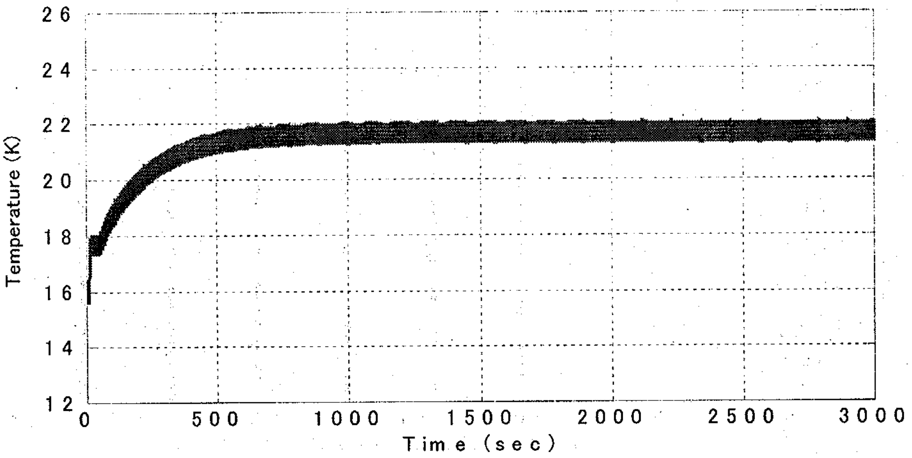

Fig. 3.1.4 Response of liquid hydrogen temperature in 3rd-moderator during start-up period

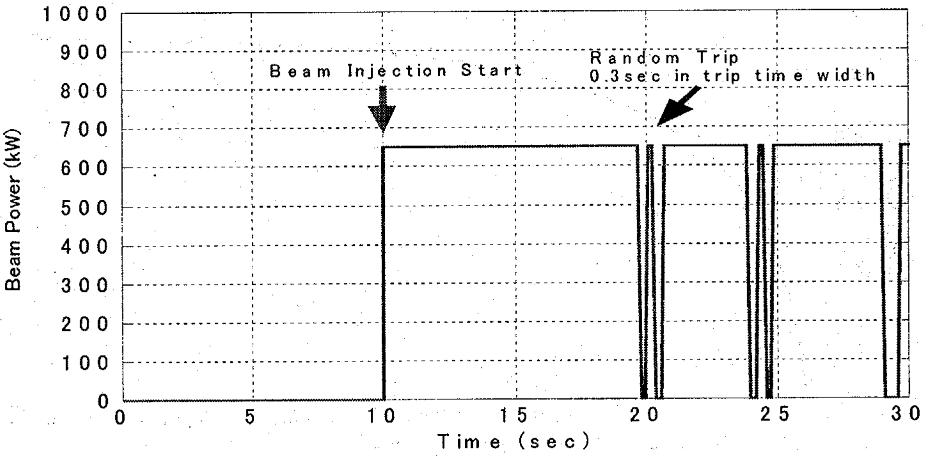

Fig. 3.1.5 Beam power during start-up period with random proton beam off around every three seconds

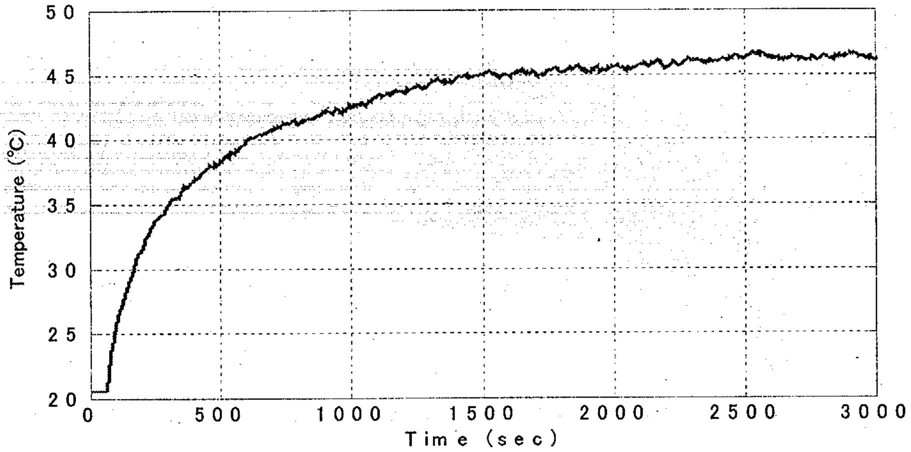

Fig. 3.1.6 Response of the target vessel inlet mercury temperature during start-up period to random proton beam off around every three seconds

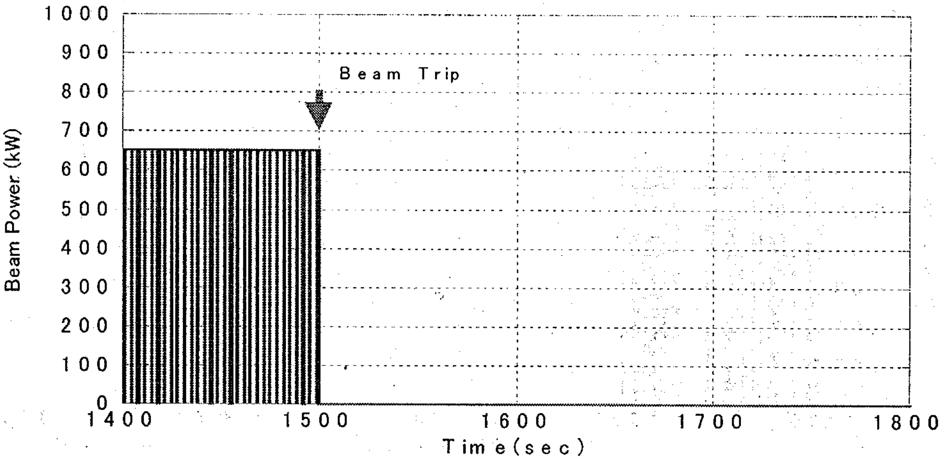

Fig. 3.2.1 Beam power with proton beam shut off

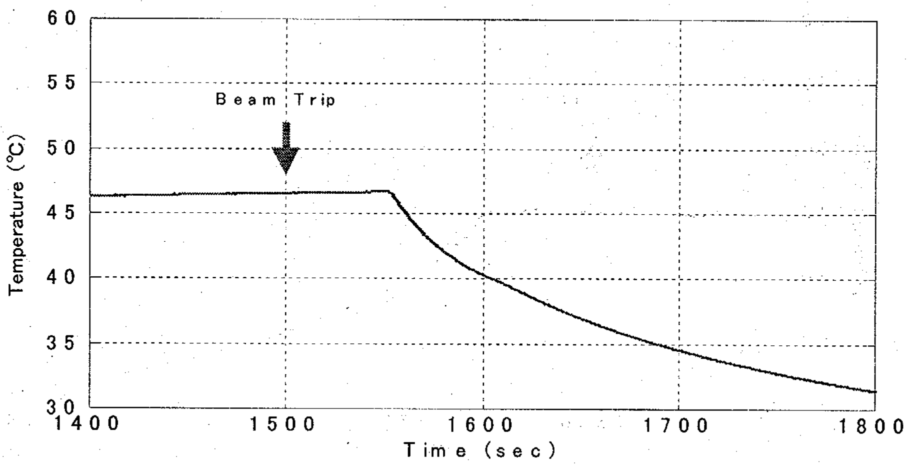

Fig. 3.2.2 Response of the target vessel inlet mercury temperature to proton beam shut off

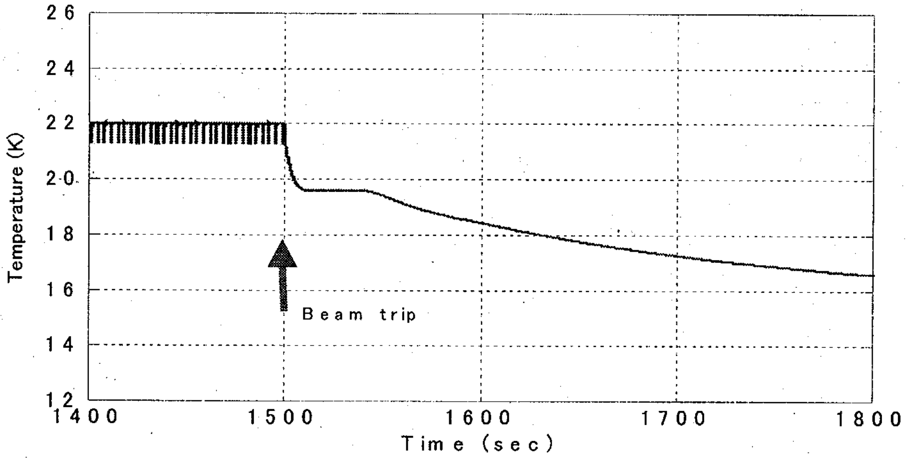

Fig. 3.2.3 Response of liquid hydrogen temperature in 3rd-moderator to proton beam shut off

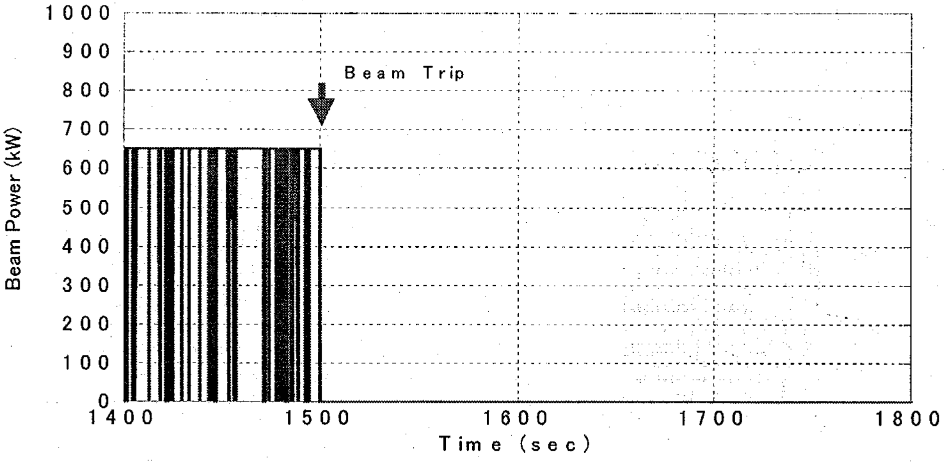

Fig. 3.2.4 Beam power at random proton beam off in the case of proton beam shut off

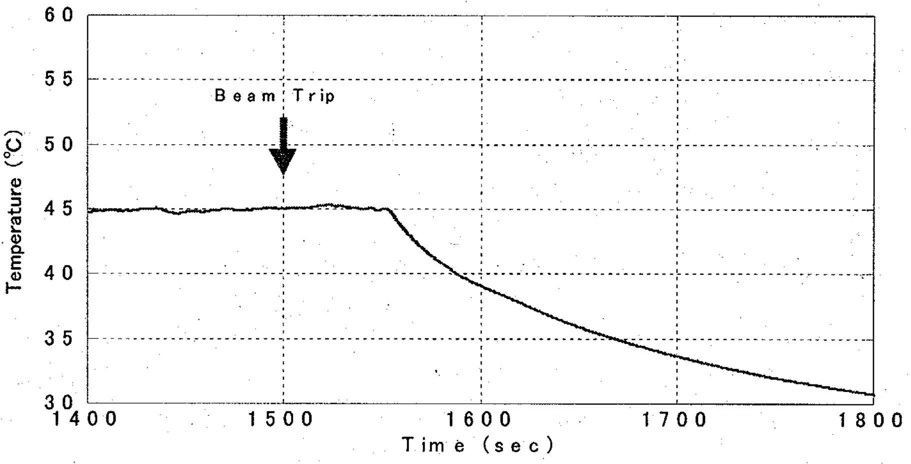

Fig. 3.2.5 Response of the target vessel inlet mercury temperature to random proton beam off in the case of proton beam shut off

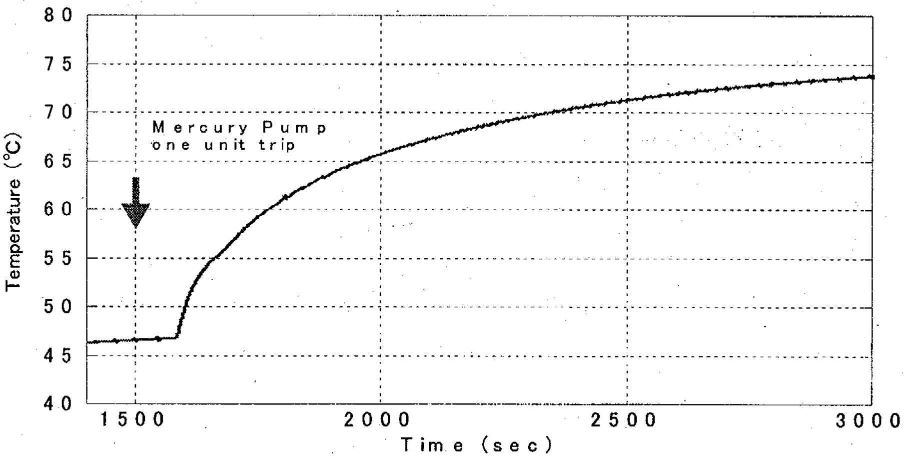

Fig. 3.3.1 Response of the target vessel inlet mercury temperature to one primary mercury circulation pump unit trip

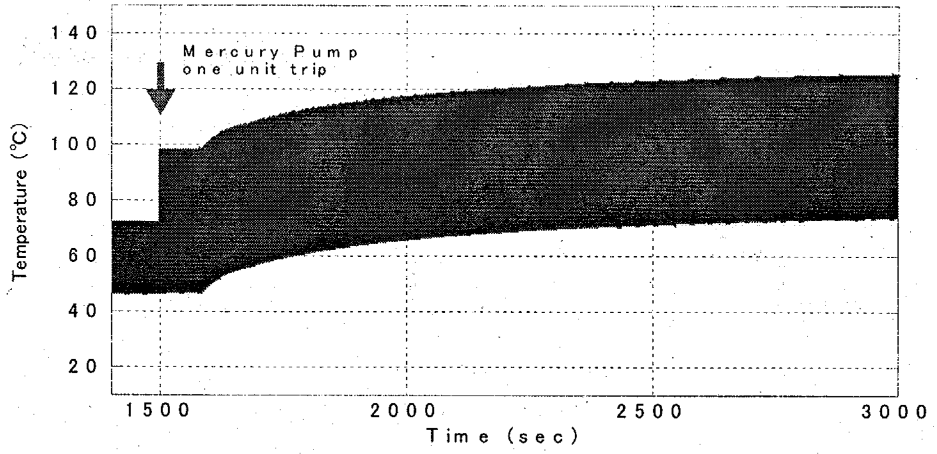

Fig. 3.3.2 Response of the target vessel outlet mercury temperature to one primary mercury circulation pump unit trip

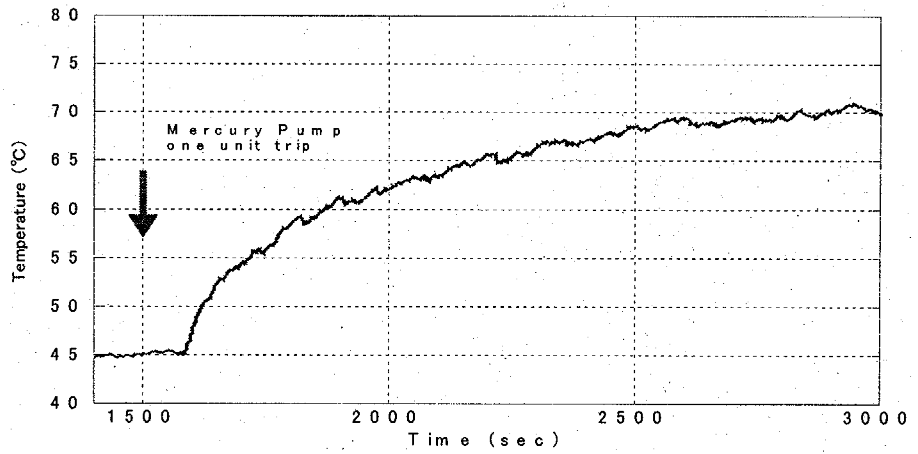

Fig. 3.3.3 Response of the target vessel inlet mercury temperature to one primary mercury circulation pump unit trip for random proton beam off

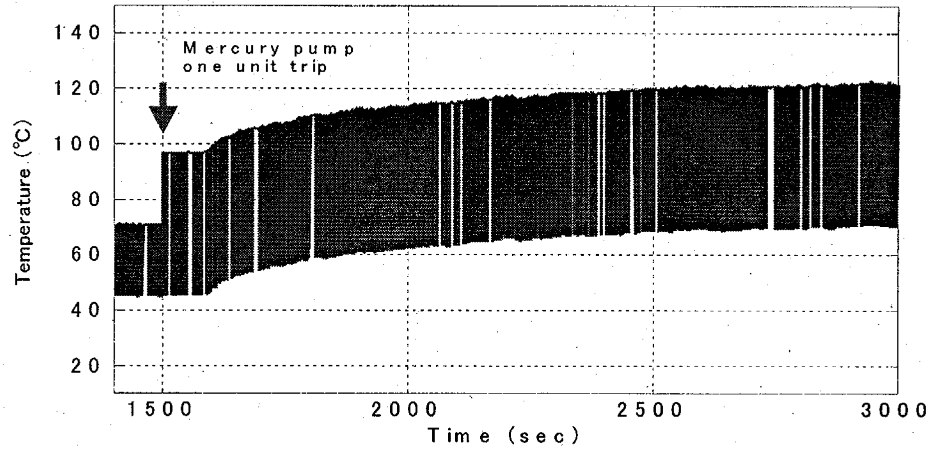

Fig. 3.3.4 Response of the target vessel outlet mercury temperature to one primary mercury circulation pump unit trip for random proton beam off

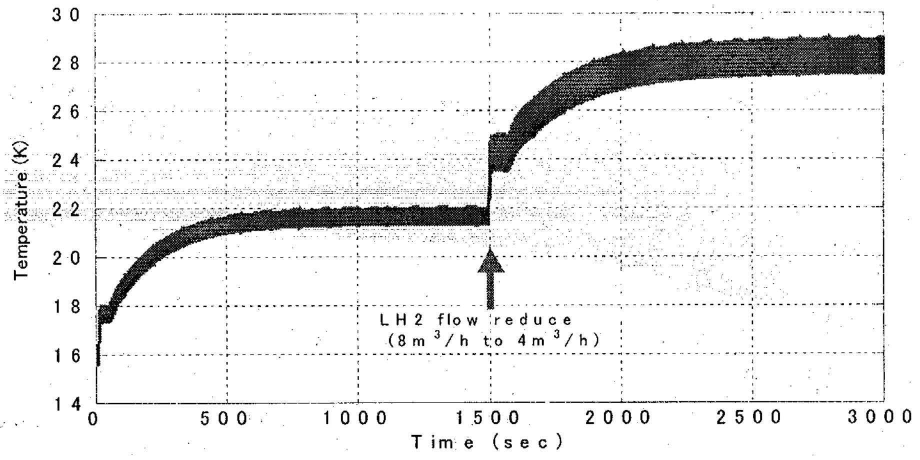

Fig. 3.4.1 Response of liquid hydrogen temperature in 3rd-moderator to one liquid hydrogen circulation pump unit trip

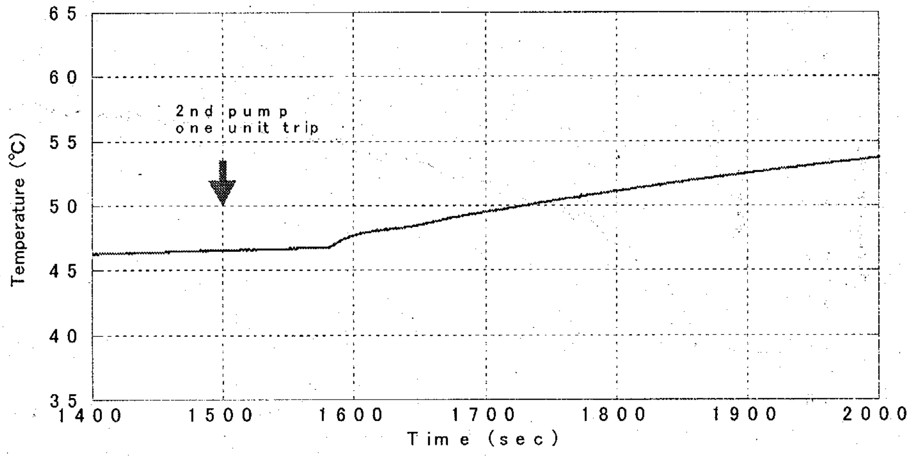

Fig. 3.5.1 Response of the target vessel inlet mercury temperature to one secondary water circulation pump unit trip

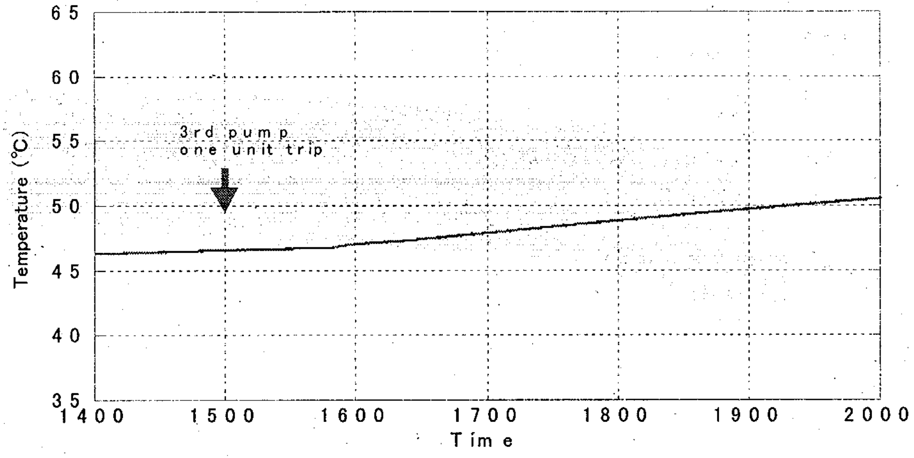

Fig. 3.5.2 Response of the target vessel inlet mercury temperature to one tertiary water circulation pump unit trip

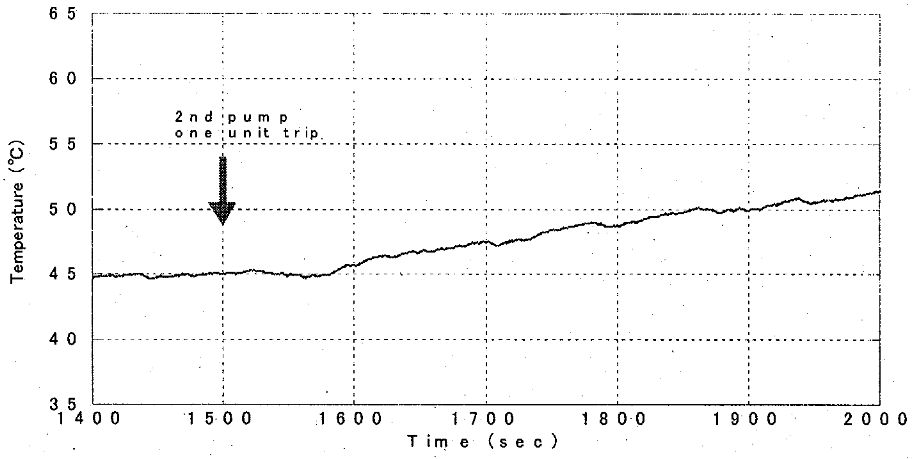

Fig. 3.5.3 Response of the target vessel inlet mercury temperature to one secondary water circulation pump unit trip for random proton beam off

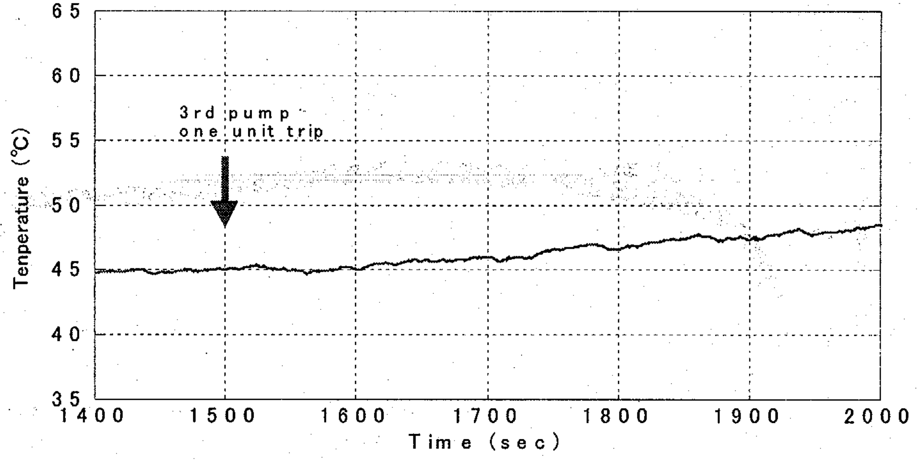

Fig. 3.5.4 Response of the target vessel inlet mercury temperature to one tertiary water circulation pump unit trip for random proton beam off

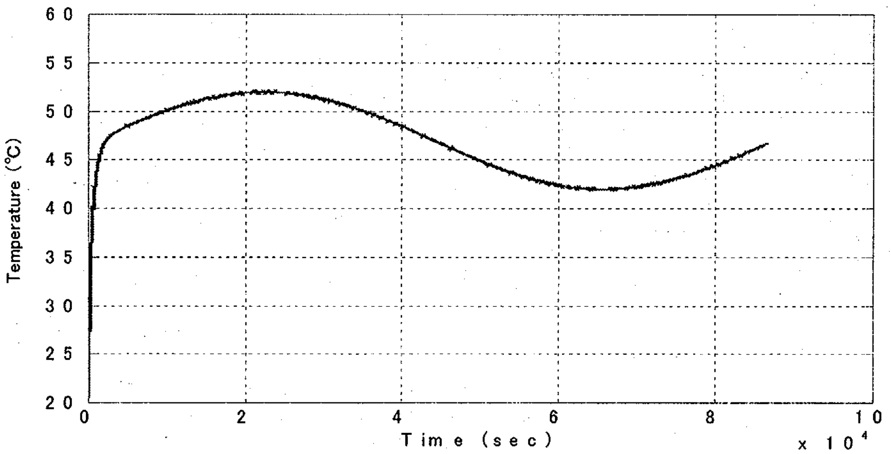

Fig. 3.6.1 Response of the target vessel inlet mercury temperature to cooling tower temperature change

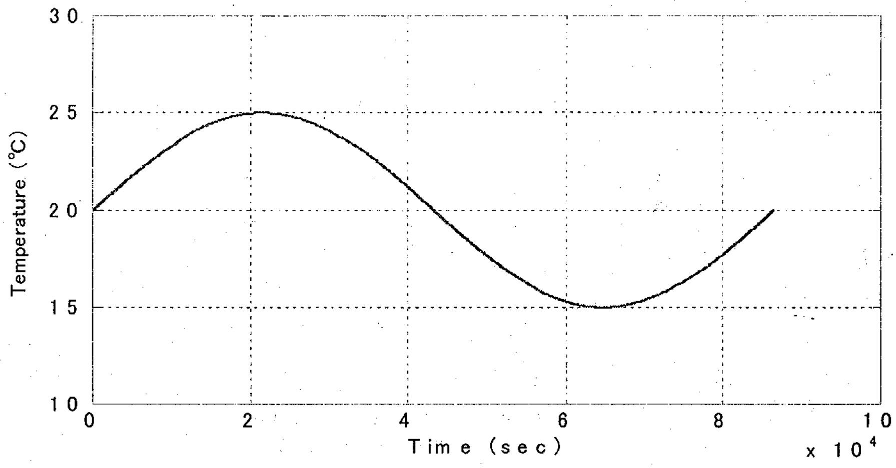

Fig. 3.6.2 Cooling tower outlet temperature change assumed

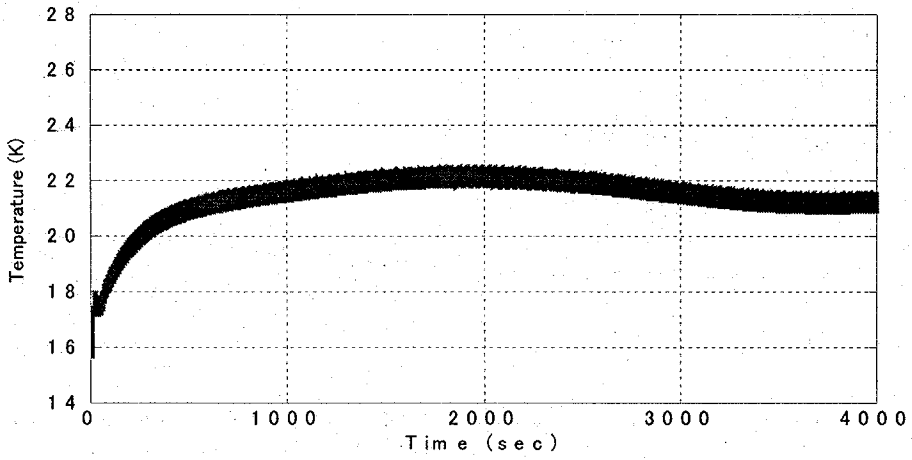

Fig. 3.7.1 Response of liquid hydrogen temperature in 3rd-moderator to chilled helium temperature change

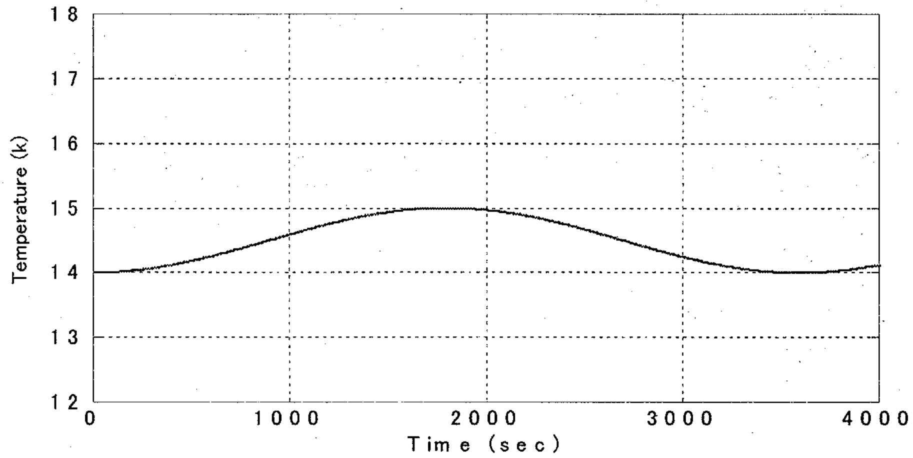

Fig. 3.7.2 Chilled helium temperature change assumed

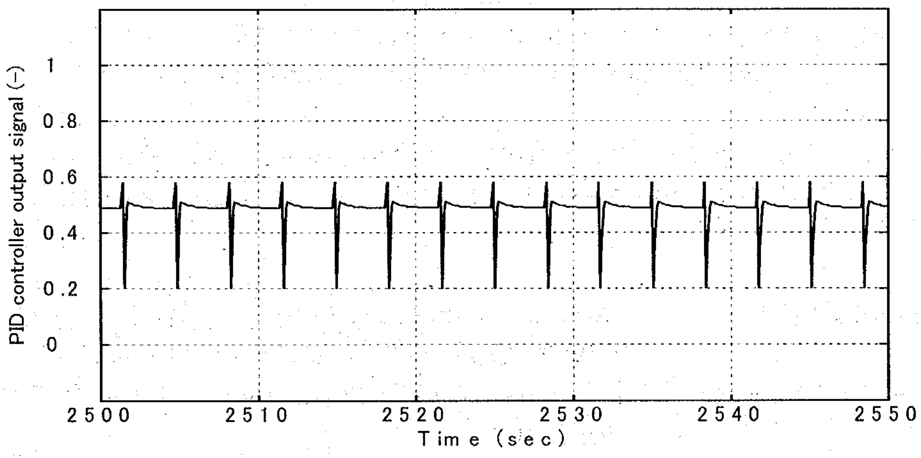

Fig. 3.8.1 Response of the PID controller output signal (P=3,I=0,D=0)

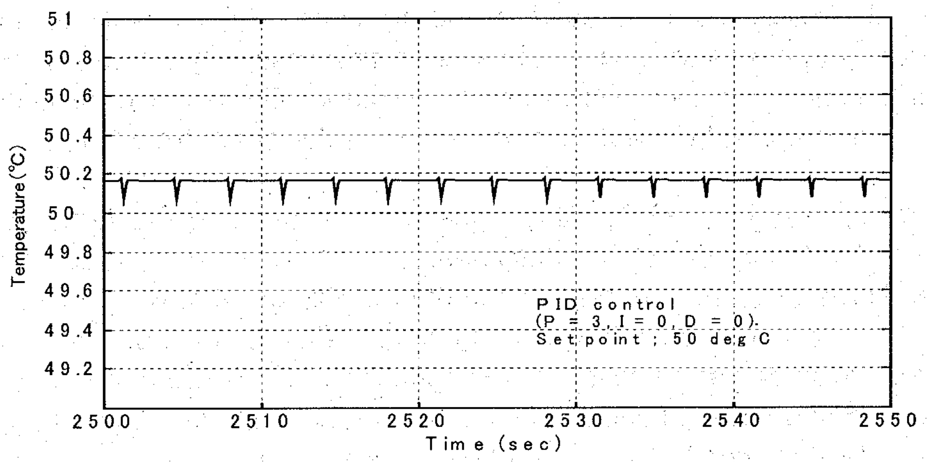

Fig. 3.8.2 Response of target vessel inlet mercury temperature in case of the PID control