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**Westinghouse Electric Corporation
Fusion Power Systems Department**

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NEUTRAL BEAM HEATING OF THE TFTR VACUUM VESSEL PROTECTIVE PLATES

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Prepared by:
Daniel A. Sink

Approved by:

T. C. Varljen
Engineering Manager
TFTR Project

Approved by:

G. Gibson
Manager, Applied Physics
TFTR Project

Westinghouse Electric Corporation
Fusion Power Systems Department
Post Office Box 10864
Pittsburgh, Pennsylvania 15236

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ABSTRACT

The transmission of neutral beams through plasmas expected in the Tokamak Fusion Test Reactor (TFTR) has been investigated. An analytical expression for the transmission coefficient of a 120 keV deuterium beam through a tritium plasma was used and a model for the flux profile of the TFTR Neutral Beam System designed by LBL/LLL was developed and incorporated. The plasma is assumed to have a parabolic profile and is characterized by a major radius of 310 cm, a minor radius of 57 cm, and a central plasma density of $\geq 0.4 \times 10^{14} \text{ cm}^{-3}$. To protect the stainless steel vacuum vessel walls of the TFTR device, tungsten plates are located inside the vessel. The loading of the tungsten protective plates during normal operation is well below the neutral beam fluxes which would melt the tungsten. The TFTR Neutral Beam System will inject a total of 20 MW of 120 keV deuterium atoms from twelve sources, as well as approximately 12 MW of 60 keV deuterium atoms. The fluxes anticipated on the tungsten plates due to an unattenuated beam which would be incident at an angle of 45° are $\leq 6.5 \text{ kW/cm}^2$. The fluxes due to an attenuated beam are calculated to be $\leq 0.35 \text{ kW/cm}^2$. For the maximum injection time of 0.5 second, a fault condition in which the plasma was not formed at the time of injection could induce a surface temperature very near the melting point of tungsten. For the standard 0.1 second injection time anticipated for TFTR, a similar fault condition would not cause the temperature to rise to more than 2000 K which is well below the melting point (3640 K) of tungsten.

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INTRODUCTION

This report presents the results of a study into anticipated neutral beam energy fluxes impinging upon the walls of the TFTR Vacuum Vessel. The TFTR is presently designed to incorporate tungsten plates to protect the vessel walls, but the high-intensity beams expected to be used in TFTR are capable of melting materials having extremely high melting points. This study was undertaken to estimate the resultant neutral beam (NB) fluxes on the tungsten plates during normal operating conditions as well as during fault conditions in which the full NB power is deposited on the plates and to determine any potential problems.

This work is part of the analysis of the TFTR Conceptual Design¹ which represents a reference point in arriving at the TFTR Final Design. The Neutral Beam Injectors are still being designed and developed, so that the characteristics and properties of the beams produced are not known in detail. In order to carry out the analysis, a number of assumptions are required, but where possible the TFTR design, as presently conceived, was incorporated.

A very important aim throughout the analysis has been to provide results as meaningful as possible, and in addition, to remain biased on the pessimistic side of any approximations or assumptions made. This is particularly true in the determination of the NB characteristics, e.g., flux profiles. For this work it was arbitrarily decided to perform calculations using the Lawrence Berkeley Laboratory/Lawrence Livermore Laboratory (LBL/LLL) Neutral Beam Injection System² as opposed to the Oak Ridge National Laboratory (ORNL) System³. The decision was based entirely on choosing a specific system with a specific set of parameters. A similar analysis using the ORNL System would provide quite similar results. After choosing the particular NB System, additional assumptions are necessary, e.g., beam trajectories, focusing properties, peak densities, etc., and the guiding view adopted was to always be pessimistic.

This paper is divided into four sections as follows: 1) discussion of the transmission of neutral beams through a plasma, 2) the development of a model for the flux profile of the neutral beams, 3) the calculational results, and 4) discussion and conclusions.

NEUTRAL BEAM TRANSMISSION THROUGH A PLASMA

The TFTR has been designed¹ for neutral beam injection of deuterium beams into a toroid-shaped tritium plasma. The NB particles injected tangentially will be absorbed in the plasma during ionizing collisions with the plasma ions and electrons. The most important collisional interactions are charge exchange with the plasma ions, electron ionization of the neutrals, and triton ionization of the neutrals. The fast neutral atoms are trapped within the confining magnetic fields after being ionized and, as a result, the beam intensity I is attenuated along its path through the plasma according to the following equation:

$$I = I_0 e^{-D(s)} \quad (1)$$

where I_0 is the incident beam intensity (e.g., in units of kW/cm²), and $D(s)$ is the absorption decrement at a distance s along this path, i.e., the parameter s is the distance traversed by the neutrals through the plasma. The absorption decrement is given by

$$D(s) = \sigma_t \int_0^s n(x) dx \quad (2)$$

The total absorption cross section σ_t includes yields from charge exchange, triton ionization, and electron ionization. This integral can be evaluated as a function of the injection radius R_b (for tangential injection) and of the distance Z_b above the plasma equatorial plane. The plasma is assumed to have a parabolic density distribution, as shown in Fig. 1., and given by

$$n(x) = n_0 \left[1 - (x/a)^2 \right] \quad (3)$$

where n_0 is the central density, a is the minor radius of the plasma, and x is measured along the minor radius.

Figure 1. Parabolic Density Profile

Assuming a toroidal plasma with a major radius R_o , a minor radius a , and a parabolic profile, J. A. Rome and coworkers⁴ at ORNL derived the following expression (rewritten in this report for calculational purposes) for $D(s)$:

$$D(s) = D(R_b, Z_b) = \frac{8a}{15\lambda_o} \sqrt{2 \frac{R_o}{a}} (S + h)^{3/2} (3h - 2S) \quad (4)$$

where

$$S = \frac{R_o - R_b}{a} \quad (5)$$

$$h = \frac{\sqrt{a^2 - Z_b^2}}{a} \quad (6)$$

and

$$\lambda_o = (n_o \sigma_t)^{-1} \quad (7)$$

The absorption mean free path λ_o at maximum plasma density depends on the interaction cross section σ_t , and thus the beam energy E_b , where⁵

$$\sigma_t \approx 3.7 \times 10^{-14} E_b^{-1} \text{ cm}^2 \quad (8)$$

with E_b in keV.

The above expression for $D(R_b, Z_b)$ assumes a pencil beam (as opposed to a diffused beam). In addition, Eq. (4) is for the total absorption decrement of the beam after it has emerged on the "exit" side of the plasma. The geometry is shown in Figs. 2 and 3. Indicated in these figures are the values of the various TFTR parameters. These parameter values will be discussed in the section where the calculational results are presented. It should be noted that the expressions by J. A. Rome, et al.,⁴ are for a plasma containing no impurity ions which for the results presented in this report is a pessimistic assumption.

Figure 2. The Geometry of the LBL/LLL Neutral Beam Injection System and the TFTR Toroidal Plasma

Figure 3. Cross-sectional View of the Neutral Beam and Plasma Geometry

A MODEL FOR THE FLUX PROFILE OF THE NEUTRAL BEAMS

In the previous section, the NB transmission (absorption) as a function of the plasma density and beam trajectory was presented. Before such results can be applied to calculations of the NB loading of the vessel protective plates, the flux (current or energy flux) distribution of the beams injected into the vessel must be determined or, in this case, estimated. The following is a discussion of the model of the NB used for the calculations. As mentioned in the introduction, the LBL/LLL system is assumed and any assumptions used are believed to be on the pessimistic side so as to provide an upper limit to the NB flux at a given point of impingement on the tungsten plates.

Each source on a LBL/LLL injector emits an approximately uniform energy flux (current) over a 10 cm x 40 cm surface. There are three sources per injector and four injectors on TFTR. The three sources are arranged so that the centerline of each beam is in the equatorial plane of the toroidal vessel (and plasma column). The sources are spaced 50 cm apart and are aimed at three injection radii: $R_b = 250, 270, \text{ and } 290 \text{ cm}$. (Additional radii of injection are also included in the design, but are not considered in detail in this report.)

The required¹ NB power per source is 1667 kW (20 MW for the twelve-source TFTR system) of 120 keV neutral deuterium atoms. Thus the energy flux out of each source with an emitting area of 10 cm x 40 cm is 4.167 kW/cm^2 . Each beam is focused at or near a 40 cm x 70 cm entrance aperture to the vacuum vessel. The maximum flux at the focal plane can be estimated to be at the Langmuir limit⁶ given by:

$$\Phi_f^{(\max)} = \Phi_s \cdot \frac{E_b}{k\theta} \cdot \gamma_x \cdot \gamma_y \quad (9)$$

where the source flux Φ_s is 4.167 kW/cm^2 , $E_b = 120 \text{ keV}$, and the ion temperature $k\theta$ of the source plasma is estimated to be 4.5 eV. The geometric factors γ_x and γ_y are related

to the characteristics of the source. The factor γ_x is the ratio of the half-height of the source along the "x-axis" to the corresponding focal length. Similarly, γ_y is the geometric factor along the "y-axis". For the LBL/LLL source $\gamma_x = 5.24 \times 10^{-3}$ and $\gamma_y = 1.75 \times 10^{-2}$ where the x-axis is chosen along the 10-cm dimension, and thus

$$\Phi_f^{(max)} = 10.15 \text{ kW/cm}^2 \quad (10)$$

The maximum flux expected at the tungsten plates would be less than 10.15 kW/cm^2 . Since the details of the beam between the focal plane and the plates is not known, only an estimate of this maximum flux can be made. An estimate which is certainly on the pessimistic side would be one in which the beam was, for some reason, focused at the plates. Such a situation is unlikely, but assuming such a case, the flux at the plates which are at a distance $d \approx 13.5 \text{ m}$ from the source is

$$\Phi_d^{(max)} = \Phi_s \cdot \frac{E_b}{k\theta} \cdot \frac{x_o}{d} \cdot \frac{y_o}{d} \quad (11)$$

where x_o and y_o are the half-width and half-height of the source and x_o/d and y_o/d are the respective geometric factors associated with the source. Now $x_o = 5$ and $y_o = 20 \text{ cm}$, so that,

$$\Phi_d^{(max)} = 6.14 \text{ kW/cm}^2 \quad (12)$$

The actual angle of impingement for the neutral beam on the plates is $< 45^\circ$ ($\pi/4 \text{ rad}$), and an estimate of the maximum heat flux Φ_o on the plates is,

$$\Phi_o \leq \Phi_{d, \pi/4}^{(max)} = 4.34 \text{ kW/cm}^2 \quad (13)$$

The corresponding value of Φ_o for the ORNL system is 5.05 kW/cm^2 .

To estimate the upper limit of the flux $\Phi(r)$ at the wall as a function of the radius r from the central point of impingement, the following was done. Assuming that $\Phi(r) \leq \Phi_o$, and

that the beam profile will be circular at the wall so the e-folding width along each axis is the same, $\Phi(r)$ was maximized for each value of r . To do this a gaussian profile was assumed and parameterized as a function of r such that $\Phi(r)$ is maximum while the total beam flux is conserved. This results in a family of gaussians which has an envelope given by

$$\Phi(r) = \begin{cases} \Phi_o & r \leq r_o \\ \Phi_o \left(\frac{r_o}{r} \right)^2 & r \geq r_o \end{cases} \quad (14)$$

where $\Phi_o = 4.34 \text{ kW/cm}^2$, and $r_o = 11 \text{ cm}$. This profile, $\Phi(r)$, was assumed for each source.

The LBL/LL system has three sources per injector with each located in the equatorial plane of the device. The three sources are spaced 50 cm apart and each is aimed at a different injection radius, i.e., $R_b = 250, 270, 290 \text{ cm}$. The resulting profile in the equatorial plane and at the tungsten plates for an unattenuated beam from each source is shown in Fig. 4, where the distance t is measured from the center of the "270-cm" profile. The function $\Phi(r)$ given in Eq. (14) was assumed for each source.

An envelope of the three-source profile is also shown in Fig. 4. For purposes of calculating plasma-attenuated profiles, this envelope was adopted. The profile in the Z_b direction (perpendicular to the equatorial plane) was assumed to have a Z_b^{-2} dependence similar to the r^{-2} dependence of $\Phi(r)$. Approximating the t dependence (along the equatorial plane) by a Fermi Function (envelope in Fig. 4), the unattenuated neutral beam flux is analytically represented as follows:

$$\Psi(Z_b, t) = \frac{\Psi_o}{e^{(|t| - t_o)/\Delta t_o} + 1} \begin{cases} 1 & Z_b \leq Z_o \\ \left(\frac{Z_o}{Z_b} \right)^2 & Z_b > Z_o \end{cases} \quad (15)$$

where $\Psi_o = 5 \text{ kW/cm}^2$, $t_o = 70 \text{ cm}$, $\Delta t_o = 5 \text{ cm}$, and $Z_o = 11 \text{ cm}$.

Figure 4. The LBL/LLL Neutral Beam Profile at the Tungsten Plates for $Z_b = 0$ and $E_b = 120$ keV Where t is Along the Equatorial Plane

CALCULATIONAL RESULTS

Using the model developed in the previous section and Eq. (4) for the NB transmission function, the neutral beam loading of the tungsten plates protecting the stainless steel vacuum vessel wall on the TFTR device can be calculated. The attenuation T of the neutral beam through the plasma is given by

$$T(Z_b, R) = \frac{I_f}{I_i} = e^{-D(Z_b, R)} \quad (16)$$

The resulting flux density at the tungsten plates is given by

$$\psi_t(Z_b, t) = \psi(Z_b, t) T(Z_b, R(t)) \quad (17)$$

where

$$R(t) = R_{bo} - \frac{2}{5} t \quad (18)$$

and $R_{bo} = 270$ cm.

Equation (18) was determined from the geometry where the neutral beams are tangentially injected and then impinge the plates at an angle of 45° . As can be seen from this relation a change in radius of injection of 20 cm results in a change in the point of impingement on the plates of 50 cm.

Using the TFTR design parameters ,

$$\begin{aligned} E_b &= 120 \text{ keV} \\ a &= 57 \text{ cm} \\ R_o &= 310 \text{ cm} \end{aligned} \quad (19)$$

and a value of the central plasma density of $0.7 \times 10^{14} \text{ cm}^{-3}$, the attenuation T was calculated and the results are shown in Fig. 5. For $E_b = 120$ keV, and $n_o = 0.7 \times 10^{14} \text{ cm}^{-3}$, the absorption mean free path λ_o is 46.3 cm. The maximum damping decrement (minimum transmission coefficient) occurs at $R_b = 280$ cm,

Figure 5. The Neutral Beam Transmission T as a Function of the Injection Radius R_b for Several Injection Planes Z_b , and $n_o = 0.7 \times 10^{14} \text{ cm}^{-3}$

and $Z_b = 0$, and can be roughly estimated by⁴

$$D_{\max} \approx \frac{8a}{5\lambda_o} \sqrt{\frac{3R_o}{a}} \quad (20)$$

The transmission increases for $R_b < 280$ cm and for increasing Z_b . This increased transparency is a result of the decrease in path length through the plasma as well as the passage of the beam through the less dense portions of the plasma. This effect is particularly apparent on a plot of the relative plasma density, n/n_o , as a function of the distance along the beam path. Such plots are shown in Figs. 6-8.

To study the variation of T with the plasma density parameter n_o , calculations were made and the results are shown in Figs. 9 and 10 for $Z_b = 0$ and $Z_b = 35$ cm, respectively. As can be seen, the transmission at $Z_b = 0$ is generally well below 2% for $n_o \leq 0.5 \times 10^{14} \text{ cm}^{-3}$, and between 1% and 3% for $n_o = 0.4 \times 10^{14} \text{ cm}^{-3}$. For the case where $Z_b = 35$ cm, the transmission is as high as 40% for the beam traversing the lower plasma densities near $R_b = 250$ cm.

As can be seen from the transmission curves, the plasma is very transparent for lower n_o , large values of Z_b , and at the smaller injection radii. This result is supported further by calculations using Eq. (17), the transmission weighted by the neutral beam profile. These calculations are shown in Figs. 11-13.

Figure 11 shows the results for the loading in the equatorial plane ($Z_b = 0$) for two values of n_o , where $n_o = 0.7 \times 10^{14} \text{ cm}^{-3}$ parameterizes the expected plasma density and $n_o = 0.4 \times 10^{14} \text{ cm}^{-3}$ parameterizes the plasma at the lowest density anticipated during normal operations. Both curves peak at around $t = -62.5$ cm, corresponding to an injection radius R_b of 245 cm. Except in the vicinity of this peak, the flux at the plates is below 0.1 kW/cm^2 for $n_o = 0.4 \times 10^{14} \text{ cm}^{-3}$.

Figure 12 shows the results at $R_b = 245$ cm as a function of the distance above the equatorial plane for the same two values of n_o as shown in Fig. 11. For the smaller n_o value the flux oscillates about 0.25 kW/cm^2 , but never reaches higher than 0.35 kW/cm^2 .

Similar calculations are shown in Fig. 13 for $R_b = 270$ cm.

It is anticipated¹ that TFTR plasmas will be initiated having different parameters, i.e., R_o and a , than those used in the above calculations. In particular, a set of experiments are planned in which the neutral beams will be injected at $R_b = 200, 220$, and 240 cm, and into a plasma characterized by $R_o = 248$ cm and $a = 85$ cm. The neutral beam profiles will be the same as before, but the transmission coefficients will be different. These coefficients for the case $n_o = 0.7 \times 10^{14} \text{ cm}^{-3}$ are shown in Fig. 14. When compared to Fig. 5, these results indicate that the coefficients are generally much smaller than for the case where $R_o = 310$ cm and $a = 57$ cm. From this result it is believed that the neutral beam heating of the plates will be much less in the main case, and need not be discussed in more detail.

The discussion throughout this section has not considered the effects of the half-energy (60 keV) components of the NB arising from the neutralization of molecular ions out of the NB sources. This component will be strongly attenuated by the plasma and will not be "seen" by the plates during normal operations. It will contribute to the heating of the tungsten plates in the event that a fault condition arises in which the full NB power strikes the plates. The half-energy component will be discussed in more detail in the following section.

Figure 6. The Ratio n/n_o Along the Neutral Beam Path s for an Injection Radius $R_b = 250 \text{ cm}$ and Injection Plane $Z_b = 0$

Figure 7. The Ratio n/n_0 Along the Neutral Beam Path s for an Injection Radius $R_b = 270$ cm and Injection Plane $Z_b = 0$

Figure 8. The Ratio n/n_0 Along the Neutral Beam Path s for an Injection Radius $R_b = 290 \text{ cm}$ and Injection Plane $Z_b = 0$.

Figure 9. The Neutral Beam Transmission T as a Function of the Injection Radius R_b for $Z_b = 0$ and for Several Values of The Central Plasma Density n_o

Figure 10. The Neutral Beam Transmission T as a Function of the Injection Radius R_b for $Z_b = 35 \text{ cm}$ and for Several Values of the Central Plasma Density n_o .

Figure 11. Neutral Beam Loading in the Equatorial Plane of the Tungsten Plates for Two Values of n_o

Figure 12. Neutral Beam Loading at $t = 62.5 \text{ cm}$ ($R_b = 245 \text{ cm}$) as a Function of the Distance Z_b Above the Equatorial Plane

Figure 13. Neutral Beam Loading at $t = 0$ ($R_b = 270 \text{ cm}$) as a Function of the Distance Z_b Above the Equatorial Plane

Figure 14. The Neutral Beam Transmission T as a Function of the Injection Radius R_b for Several Injection Planes Z_b , $n_o = 0.7 \times 10^{14} \text{ cm}^{-3}$, $R_o = 248 \text{ cm}$, and $a = 85 \text{ cm}$

DISCUSSION AND CONCLUSIONS

Combining the results in the previous two sections with the thermal analysis⁷ of the TFTR vacuum vessel protective plates, the heating of the plates due to the neutral beam can be predicted. In the work⁷ by A. Y. Lee, a parametric study over a wide range of neutral beam fluxes was carried out to determine the maximum allowable flux (before surface melting occurs) during both normal and fault conditions. The results of that thermal analysis will now be used without going into the details of the analysis.

The maximum neutral beam flux expected on the tungsten plates for the 120 keV deuterium beam is $\sim 5 \text{ kW/cm}^2$ using the model developed in this report. For a NB injection lasting 0.5 s (the maximum injection time for TFTR), the change in surface temperature of the plating would be 2200 K if the total flux impinged the tungsten. This change would result in a temperature which is well below that for the melting point of tungsten which is 3640 K. Thus the protective plates would retain their integrity against melting even during a fault condition involving an injection into the vessel devoid of a plasma column.

There is the possibility that the fault condition indicated above could occur after a number of pulsing cycles (pulses 0.5 s in duration every 300 s). The resulting value of the surface temperature for such a fault condition is 2830 K for the plates "seeing" the highest NB flux. This temperature was obtained by assuming that the maximum energy flux after plasma attenuation is 0.35 kW/cm^2 (see previous section). From the thermal analysis, this flux causes an equilibrium surface temperature during a large number (≥ 15) of consecutive pulsing cycles of 630 K. Adding this temperature to a $\Delta\Theta = 2200 \text{ K}$ gives 2830 K.

A maximum NB flux of 5 kW/cm^2 being attenuated by the plasma to a level of 0.35 kW/cm^2 corresponds to an attenuation factor of 93% ($1 - \frac{0.35}{5}$). Using this as a characteristic value, the maximum NB flux tolerable for the current design of the tungsten protective plates is⁷ $\sim 6.5 \text{ kW/cm}^2$. The 5 kW/cm^2 flux does not take into account the expected 6 to 12 MW (twelve sources) of half-energy (60 keV) components of the injected beams.

Calculating the flux due to this component in the same way as for the full-energy component, one finds an additional flux of $\leq 1.5 \text{ kW/cm}^2$ at the plates. So that during a fault condition, $\leq 6.5 \text{ kW/cm}^2$ of flux will impinge upon the tungsten plates which is right at the maximum allowable level. During normal operation the attenuation of the half-energy component by the plasma will be essentially complete, i.e., 99.5% as compared to 93% for the 120 keV component.

As indicated in the previous paragraph, there is a potential problem arising from a set of conditions in which a fault takes place after a number of normal NB injections into a plasma of low density ($n_o = 0.4 \times 10^{14} \text{ cm}^{-3}$). In particular, this problem occurs for the NB injected at $R_b = 250 \text{ cm}$ and not at the other two radii (270 and 290 cm). At the higher densities ($n_o = 0.7 \times 10^{14} \text{ cm}^{-3}$) a similar fault condition would cause the plate surfaces, where the $R_b = 250 \text{ cm}$ beam impinges, to rise to 3370 K which is just below the melting point of tungsten.

As presently designed, the plasma having $R_o = 310 \text{ cm}$ and $a = 57 \text{ cm}$ will be accompanied by the injection of the NB for only 0.1 second. For this case the temperature rise due to a fault condition in which a plasma was not formed would be 1400 K. Even if such a fault occurs after a number of pulses the resulting surface temperature of the plates would be $< 2000 \text{ K}$ which is well below the melting point of tungsten.

This report has addressed the problem of the NB heat loading of the tungsten plates protecting the TFTR vessel walls. In addition to thermal problems, there are two additional problem areas which could result in difficulties associated with the operation of TFTR. First, the sputtering of the tungsten by the incident deuterons could contribute high levels of impurities into the plasma. Such impurities, having high Z values, should be well below a few hundredths of a percent for normal operation. Second, the tungsten plates are heated to a temperature of several hundred kelvin so that high outgassing rates of trapped molecules could result and contribute to the impurity levels of the plasma.

In summary, the resultant NB fluxes on the tungsten plates during normal operating conditions as well as during fault conditions have been calculated. All assumptions used in obtaining these results are believed to be on the pessimistic side, but as realistic as possible. The fluxes at the plates after attenuation by the plasma were calculated to be $\leq 0.35 \text{ kW/cm}^2$ resulting in an equilibrium surface temperature of $\leq 630 \text{ K}$. If a fault condition were to take place in which the full NB flux of $\leq 6.5 \text{ kW/cm}^2$ impinges upon the plates, the surface temperature would rise to 2900 K (m. p. of W is 3640 K). If this fault condition occurred after a number (≥ 15) of normal pulses where the plasma density was consistently low, then the plates would be heated to just below their melting point. The plates which receive the highest flux are those intercepting the NB injection at $R_b = 250 \text{ cm}$. This is the only fault condition investigated in which melting might occur. For an injection time of 0.1 s , the plates will be in no danger of melting even for the case of a fault following a large number of normal pulsing operations.

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