

OSCILLATING LIMITER CONCEPTS*

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Abstract

An oscillating multiple limiter concept for tokamak fusion reactors has been conceived and reported in this note. The limiters consist of half circle or short arc segments in the poloidal direction. They are oscillated locally in the scrape-off layer. Each limiter will be alternately in contact with the plasma for 50 ms or less at an interval of 0.5 sec. It has been shown that the limiter can be subjected to a transient heat load as high as 10 kW/cm^2 during the exposure time and can be cooled by water or helium in 0.5 sec during the off-time. Only a few cm of movement is needed. A simple driving mechanism is also proposed.

1.0 Introduction

In the major tokamak devices the limiters are often damaged by high heat load from the plasma. The heat load tends to concentrate on a small local area. The problem will become more severe for a power producing reactor because the heat load would be much higher. The present major devices such as ISX-B, Alcators, PLT, PDX and Doublet have a total heat load in the range of hundreds of kW to 6 MW. Doublet III will reach 18 MW and TFTR will have 40 MW. The heat load for a prototypical reactor will be about 200 MW for 1000 MW of thermal power (1). Therefore, limiters will be subjected to a very high heat load if the plasma is not diverted.

Lately there is emphasis on mechanical divertors or pumping on a limiter. The first criterion for such a method to work is to be able to design a reliable limiter which can survive the high heat load of the plasma. To spread the heat uniformly a limiter of large surface area which closely matches the boundary of the plasma is necessary. A toroidal bumper or belt limiter has been discussed by many groups. However, there is still a peaked local heat load even on a limiter surface perfectly matched to the plasma boundary. Thus, a uniform heat load condition is almost impossible to achieve, let alone the other abnormal operations, such as disruptions or run-away electrons. We have found that an oscillating limiter system is a possible answer for solving the high heat load problem. The unsteady heat transfer analyses show that a cooled surface can sustain a much higher heat load under transient conditions.

2.0 Oscillating Limiter Concept

As has been discussed in the introduction, local heat is very difficult to avoid. A large surface limiter system covers more than fifty percent of the first wall. It is also very difficult to replace any damaged part. Remote controlled maintenance is necessary which will greatly reduce the machine availability. Therefore, it is important to find a method to design a feasible local limiter which can sustain the heat load and can be replaced with reasonable ease. We thus discovered that the oscillating limiter method might be the solution.

A straight forward oscillating limiter concept can be illustrated by Fig. 1, which is the cross-sectional view of a tokamak plasma. The end of the limiter driving shaft is attached to a spring. The limiter can be driven by a cam shaft. Such a limiter system is closely in analogue to the piston system of an internal combustion engine. Only one segment is in contact with the plasma while all the others are back near the wall. The half circle limiter system is illustrated by Fig. 2. The lower picture shows the top view of the tokamak. The upper figures are the expanded plasma cross-sections at AA and BB. The limiters at AA are in contact with the plasma. They will be subjected to a transient heat for 50 ms or less and thus called exposure period. The limiters at BB and

other locations are away from the plasma and will be cooled by water or helium and thus called cooling period which is 0.5 sec. The limiters are driven by a simple mechanism on the top and bottom. When the shafts are pushed in, the limiter pair will be separated from the plasma. On the other hand, the limiter pair will move toward the plasma when the shafts are pulled away. Since there is only 2 cycles per sec for each limiter pair, the driving mechanism would be simple. The thermal hydraulic analyses for water and helium cooling are as follows. The heat transfer problems in the transient exposure period and cool down period can be treated separately. During the exposure period the heat load is very high and time is short so that we can conservatively and conveniently neglect the heat removal by the coolant. The surface temperature rise can be calculated from (2)

$$\Delta T = 4q \frac{\delta}{\lambda} \sqrt{F} \sum_{n=1}^{\infty} \operatorname{ierfc} \frac{(2n-1)}{2\sqrt{F}}. \quad (1)$$

Here $F = \frac{q\tau}{\delta^2}$, $a = \frac{\lambda}{\rho c_p}$ and λ is the heat conductivity, ρ is the density, C_p is the specific heat, δ is the wall thickness of the limiter and τ is the exposure time. We choose Mo as the sample material. Other materials with high melting point will work equally well as long as they meet other requirements, such as low Z and erosion resistance. For sputtering, erosion and protection against disruption and run-away electrons, the wall thickness is chosen to be no less than 3 mm. We also assume that the heat load of 10 kW/cm² which is reasonable for both TFTR and prototype reactors. This means that the needed limiter area is 0.33 m² for reactors which can be easily designed. The surface temperature rising would be $\Delta T = 1410^\circ\text{C}$ for 50 ms and 25 ms respectively. The average temperature rises are 554°C and 277°C. The question is now whether it can be cooled in 0.5 sec during the cooling down period by either water or helium. Since the cooling of helium is of great interest because it is safe, we will use helium cooling as a sample case to analyze the thermal characteristics. The analysis method using water as coolant is similar.

During the cooling down period, the limiter has been moved back 5 cm where the heat load will be reduced by a factor of nearly two orders of magnitude because of the exponential decay in heat flux from the plasma boundary (3). This heat load can be neglected as compared with the cooling rate. A reasonable choice of the helium pressure is 60 atm and the mean velocity would be 400 m/sec. Assuming the equivalent diameter of the cooling path is $d_{eq} = 2\text{cm}$, then Prandtl number $\simeq 0.72$, Reynolds number $= \frac{\rho v d}{\mu} = 1.1 \times 10^6$, and the Nusselt number $\text{Nu} = 0.023 \times (\text{Re})^{0.8} (\text{Pr})^{0.4} \simeq 1373$. The heat transfer coefficient becomes

$$a = \frac{\text{Nu} \lambda}{d} = 1.37 \text{ Watt/cm}^2 \cdot ^\circ\text{k}$$

To remove the total heat within 0.5 sec, the average heat transfer rate is

$$q_{av} = 0.5 \text{ kW/cm}^2.$$

Thus the mean temperature difference between the helium and the wall is 364°C. The thermal characteristics for both water and helium cooling are shown in Figs. 3 and 4 and tabulated in Table 1. Figure 3 shows the input heat as function of time. The design points are indicated by the arrows. Figure 4 shows the temperature variation during the exposure (on) and cooling down (off) periods. The maximum temperature is well below the melting point. The limiter can be cooled down in 0.5 sec. The temperatures cooled down to 764°C and 200°C for He and water coolants respectively. Cooling down to lower temperature is not necessary and is not efficient. This temperature range is close to that of the environment inside the reactor chamber. The cooled down temperature is higher and the exposure time is shorter for He because of the much lower heat transfer coefficient.

3.0 Conclusion

We can draw a definitive conclusion from this preliminary analysis. The oscillating limiter concept is feasible for a tokamak reactor, using either water or helium as a coolant. The advantage is that the helium can be used as coolant so the danger of water leakage can be eliminated. The limiters are at discrete local positions, thus easy maintenance is possible. Further investigation of fatigue problems, detailed mechanical and maintenance design studies are warranted.

Table 1

Thermal Characteristics of the Oscillating Limiters Designed
Using near TFTR Parameters

TFTR Parameters

thermal power	$W = 40 \text{ MW}$	first wall loading	13 W/cm^2
major radius	$R_o = 2.48 \text{ m}$	first wall area	110 m^2
minor radius	$a = 0.85 \text{ m}$	wall total loading	$15 \times 110 \times 10^4 = 20 \times 10^6 \text{ W}$
plasma current	$I_p = 1 \text{ MA}$	limiter loading	$40 - 20 = 20 \text{ MW}$
mean temperature	$T = 6 \text{ keV}$	limiter max. heat load	10 kW/cm^2
area of each limiter	$0.2 \text{ m}^2 = 0.8 \text{ m} \times 0.25 \text{ m}$		

Thermal Characteristics

material of limiters	Mo	Mo
thickness of limiters	3 mm	3 mm
exposure time	50 msec	25msec
max. surface temperature	1640°C	1764°C
coolant:	water	Helium
average wall temperature rise	553°C	277°C
velocity:	10 m/s	400 m/s
cooling period:	0.45 sec	0.475 sec
total limiters number	10	20

Figure Captions

- Fig. 1. Cross-sectional view of toroidal plasma with simplified oscillating limiter system. The limiter surface is in contact with plasma sequentially following the movement of the controlled rods. There are four sets or more of such limiters distributed around the torus.
- Fig. 2. A simplified diagram of a separated oscillating limiter system. The pictures on the top show the cross-sectional views at AA and BB in the figure at the bottom which shows the top view of tokamaks. Each limiter touches the plasma for a short time, then retreats several cm for a longer time to cool down.
- Fig. 3. Thermal characteristics of the oscillating limiters. The upper curve is the maximum surface temperature of plates as a function of thickness δ under transient heat load q . Here $a = \frac{\lambda}{\rho c_p}$ is the physical property of the materials, the ratio of surface temperature rise to the input heat, and t is the exposure time. The lower curve shows the typical history of surface temperature of limiter in a working cycle using water or helium as coolant.

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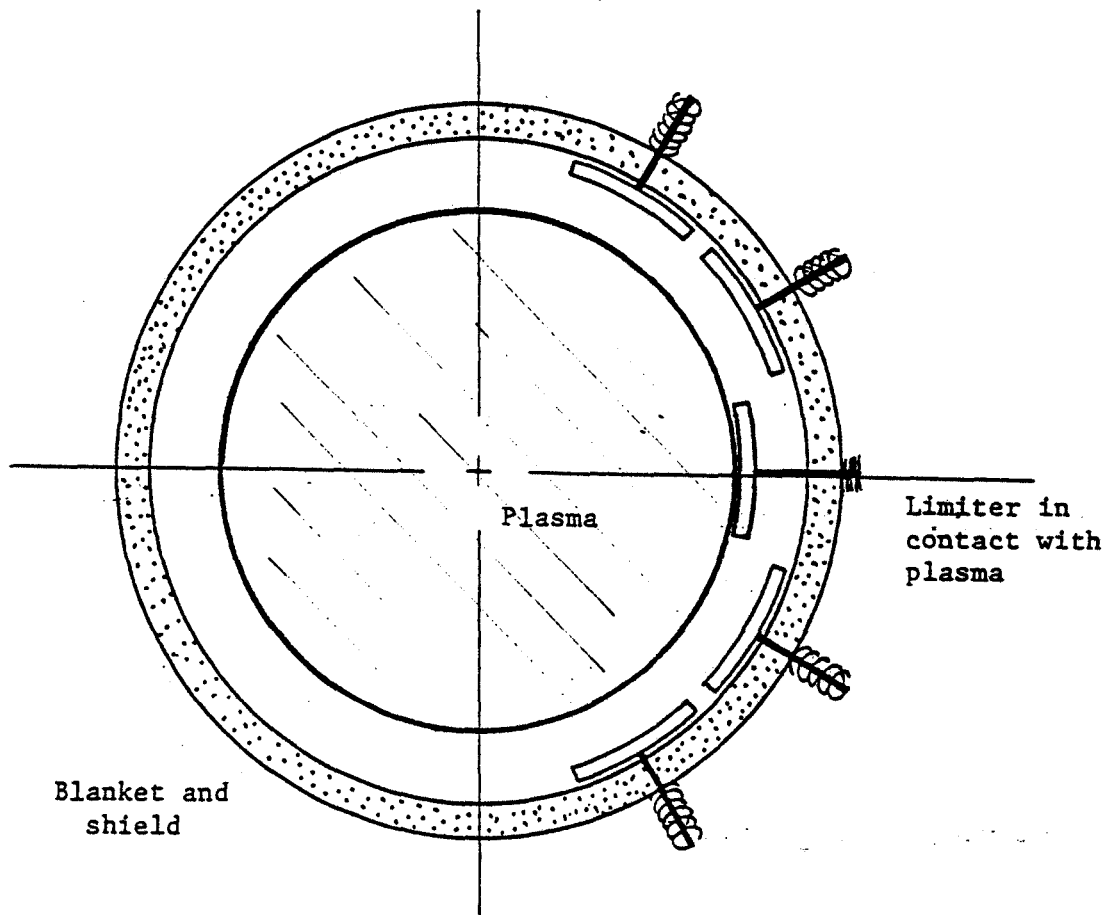


Fig. 1. Cross-sectional view of toroidal plasma with simplified oscillating limiter system. The limiter surface is in contact with plasma sequentially following the movement of the controlled rods. There are four sets or more of such limiters distributed around the torus.

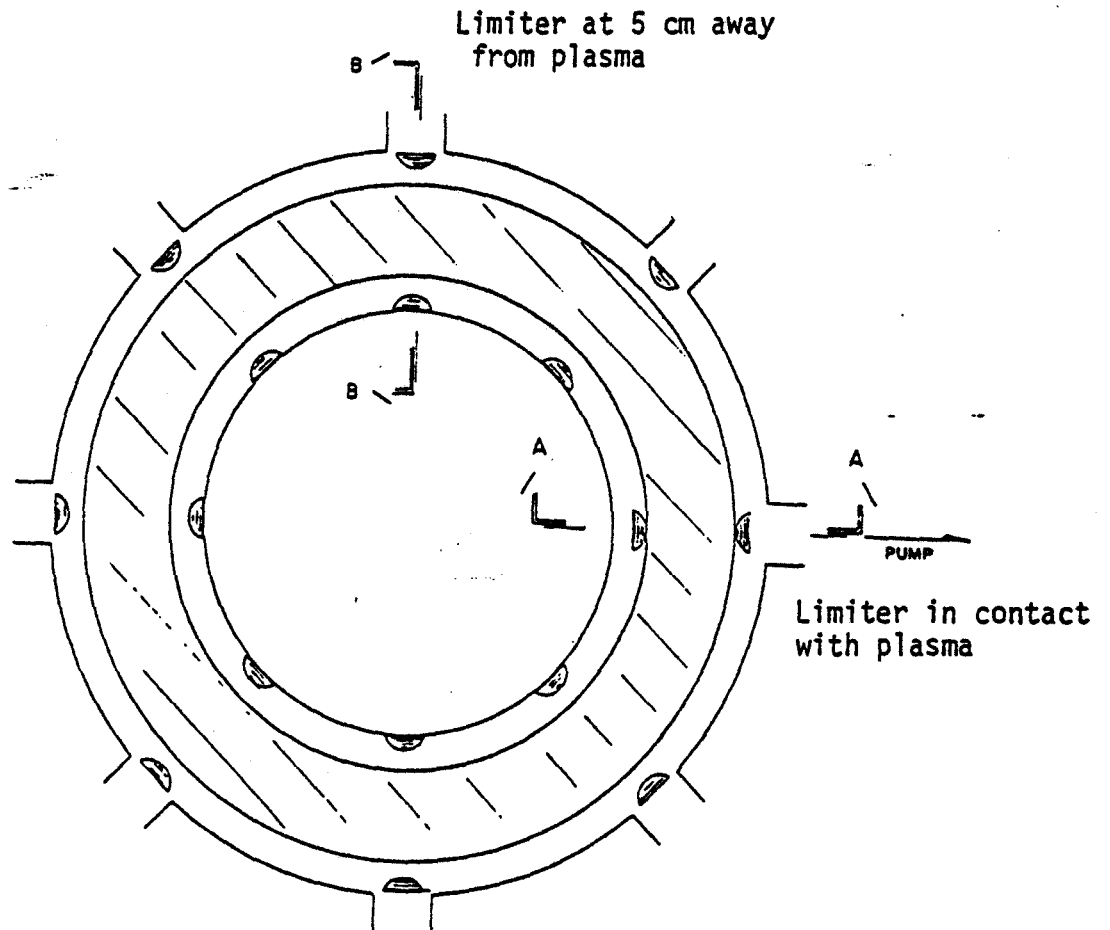
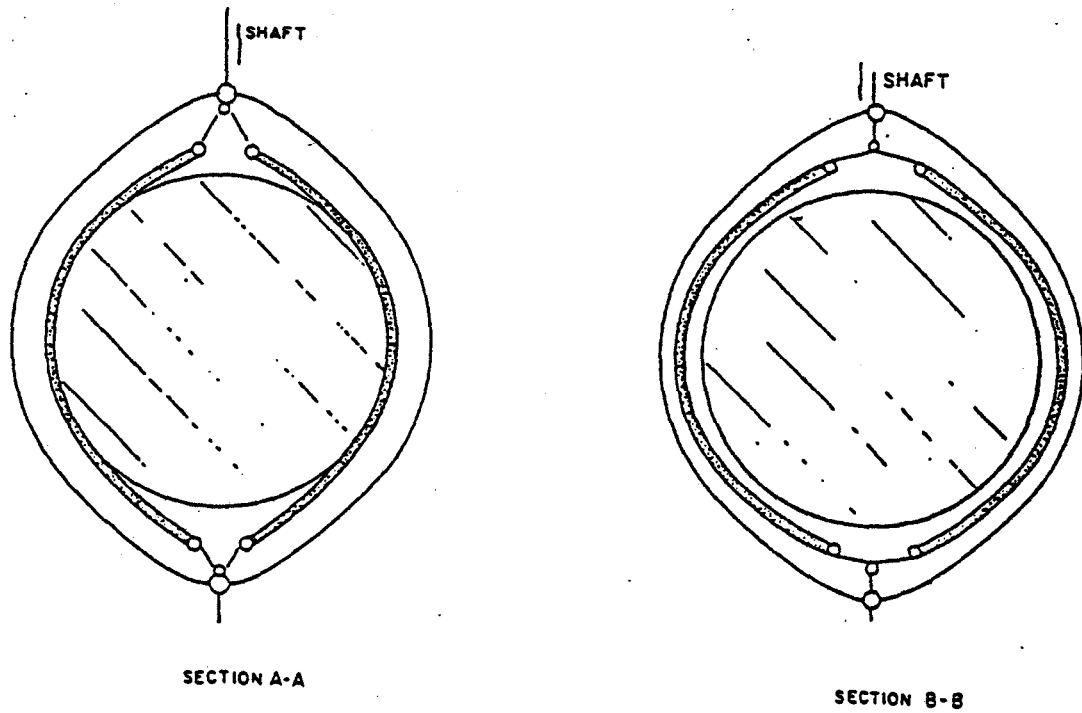


Fig. 2. A simplified diagram of a separated oscillating limiter system. The pictures on the top show the cross-sectional views at AA and BB. The figure at the bottom shows the top view of a tokamak. Each limiter touches the plasma for a short time, then retreats several cm for a longer time to cool down while being actively cooled.

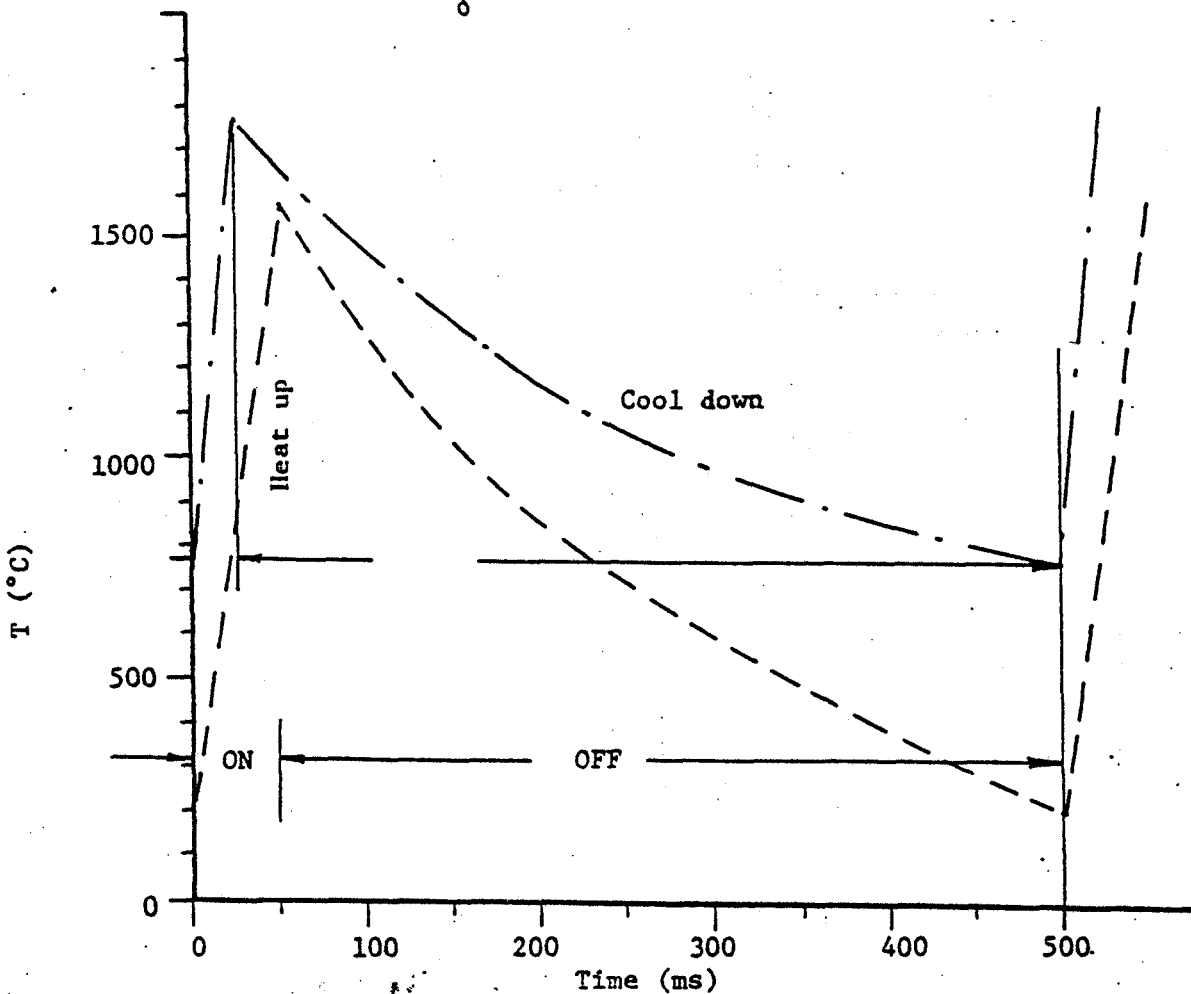
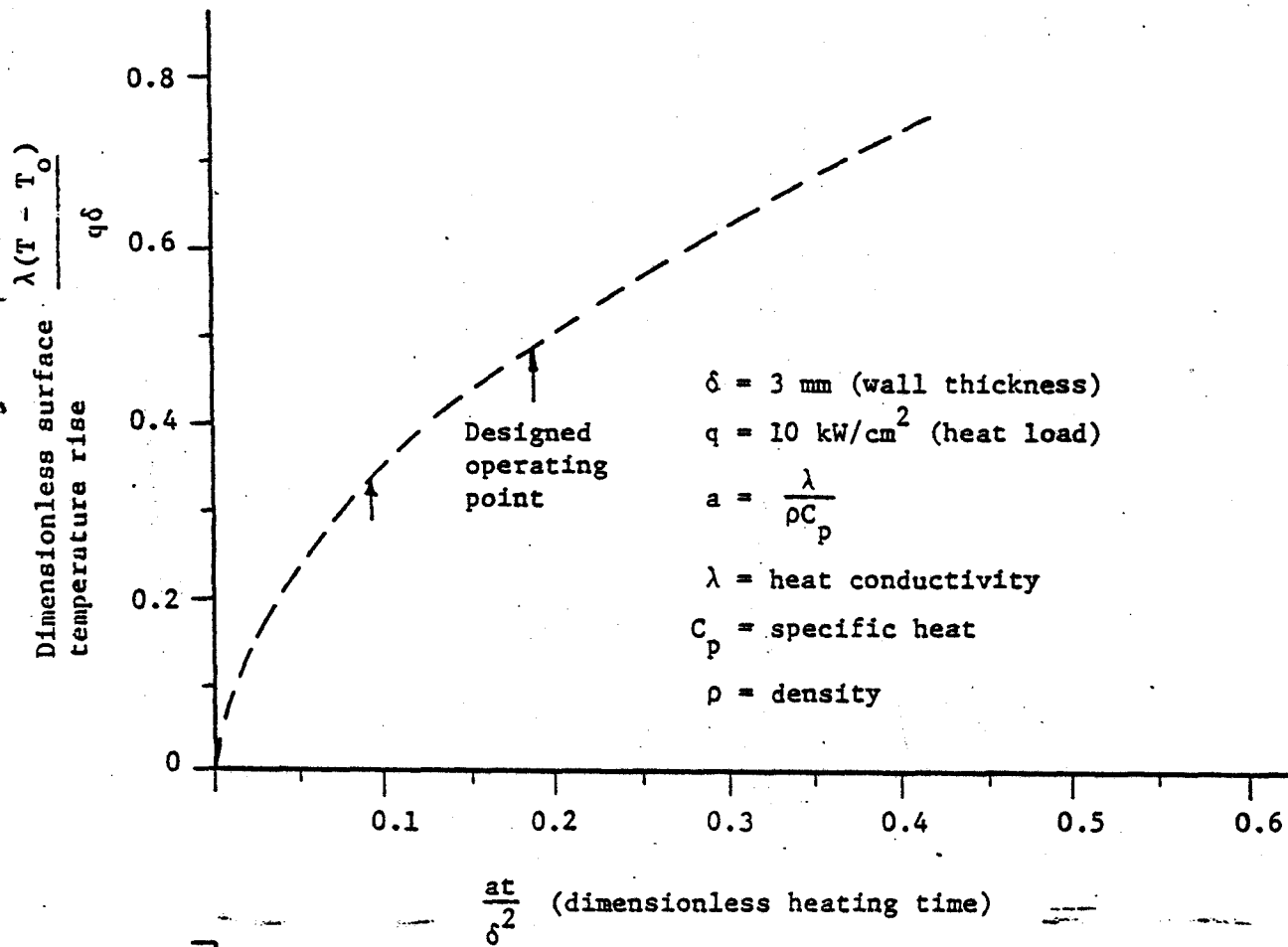


Figure 3 Thermal characteristics of oscillating limiters.