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ANALYSIS OF SWEEPING HEAT LOADS ON DIVERTOR PLATE MATERIALS*

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by

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Abstract

The heat flux on the divertor plate of a fusion reactor is probably one of the most limiting constraints on its lifetime. The current heat flux profile on the outer divertor plate of a device like ITER is highly peaked with narrow profile. The peak heat flux can be as high as 30-40 MW/m^2 with full width at half maximum (FWHM) is in the order of a few centimeters. Sweeping the separatrix along the divertor plate is one of the options proposed to reduce the thermomechanical effects of this highly peaked narrow profile distribution. The effectiveness of the sweeping process is investigated parametrically for various design values. The optimum sweeping parameters of a particular heat load will depend on the design of the divertor plate as well as on the profile of such a heat load. In general, moving a highly peaked heat load results in substantial reduction of the thermomechanical effects on the divertor plate.

1. Introduction

The heat flux on the divertor plate of a magnetically confined fusion reactor is probably one of the most limiting constraints on its lifetime. High heat loads as much as 30-40 MW/m^2, with full width at half maximum (FWHM) in the order of a few centimeters, are expected on the divertor plate of a device like ITER. Sweeping the plasma separatrix point magnetically along the divertor plate is one of the options proposed to accommodate high heat loads and/or to reduce the thermomechanical effects of a given heat load. During the sweeping process, each location on the divertor plate will experience mini-periodic cycles in both the heat and the particle fluxes. These mini-cycles are superimposed on the main reactor on-and off-cycles. The mini-cycles will result in additional temperature fluctuations which may have the effect of reducing the divertor fatigue life. On the other hand, sweeping substantially reduces the temperature rise in the structural material which greatly enhances the component fatigue life.

The computer code A*THERMAL-2 [1] is used in this study for the thermal analysis of the divertor plate due to a moving heat source. The analysis can be done for any divertor structure composed with several layers of different materials. The temperature history at any point on the divertor structure can be calculated as a function of sweeping parameters and various reactor conditions for any layer of material. The work presented in this paper assumes a divertor plate constructed from a 1 cm carbon-fiber-composite armor bonded to a 3 mm copper alloy which is the heat sink material. The required sweeping parameters for a particular heat load to reduce the surface as well as the interface temperatures to an acceptable level can easily be obtained from the code. The input heat flux profile on the divertor plate can be described by either a histogram or by analytical functions [2]. The sweeping wave can also have different time profiles. In this study sweeping is done linearly in time and starts from the origin.

Carbon-fiber-composite (CFC) is still seriously considered as an armor material for the initial phase of operation in fusion devices for several reasons. One reason is the extensive operating experience in current large tokamaks which indicates a strong preference for low z materials. Another reason is that CFC have demonstrated excellent thermomechanical properties against thermal shocks during abnormal events like disruptions and runaway electrons. In additions, CFC can be designed to achieve high thermal conductivity and irradiation resistance. The CFC used in this analysis is the CX-2002U composite which is currently available commercially.

2. Thermal analysis

The heat flux profile per unit area on the outer plate of a double null divertor used in this analysis can be described as [3]

$$h = h_1 e^{x/\lambda_1} + h_2 e^{x/\lambda_2} \qquad x \le 0 \tag{1}$$

and

$$h = h_3 e^{-x/\lambda_3} + h_4 e^{-x/\lambda_4} \qquad x \ge 0 \tag{2}$$

where x is the origin. The total power to the outer divertor plate, P_T, can then be given by

$$P_T = 2\pi R \sum_{i=1}^{4} \lambda_i h_i \tag{3}$$

where R is the major radius of the reactor. The parameters h_i and λ_i are determined from the total power expected toward the divertor plate as well as from different engineering, physics, and safety factors.

Fig. 1 shows two different heat flux profiles considered in this analysis that have the same total power on the divertor plate. The peak heat flux in normal operation on the inclined divertor plate include estimated physics and engineering peaking factors for uncertainties in asymmetries and geometrical alignment, power variation, and for engineering safety considerations. The uncertainties in the scrape-off layer (SOL) width may also contribute to the peaking factor by narrowing the profile as shown in Fig. 1, such that the total power to the divertor plate remains the same. The resulting peak heat flux value in a device like ITER can be as high as 40 MW/m^2 with a full width at half hight of only 4-5 cm. There is not any available material that can withstand such high heat fluxes over extended periods of time. Because of this narrow peaked nature of the heat flux, a modest movement around the origin can substantially reduce the effective heat flux on the divertor to an acceptable level from material performance points of view. The maximum acceptable surface temperature for a graphite-based material is assumed to be about 1400 K in order to avoid runaway erosion by self-sputtering at plasma edge temperatures up to 100 eV.

It was recently recommended for a device like ITER, based on physics considerations, that the sweeping frequencies of the heat load are given such that the sweeping distance times the sweeping frequency should be about 3 Hz.cm. It was further recommended, due to design configuration and space limitations, that the sweeping in ITER be done within a distance of ±15 cm from the origin. Fig. 2 shows the surface temperature variation at three different locations on the divertor surface during one complete sweeping cycle of ±15 cm distance and 0.2 Hz frequency. This temperature profile is repeated every period t = 1/frequency (i.e. every 5 seconds for this frequency) during the main on-cycle of the reactor. If for example the duration of the main on-cycle of the reactor is 200 S, there will be 40 additional mini-cycles in this case. The near edge location, where the maximum temperature is expected to occur, is defined as one-half of the FWHM distance to the left of the edge location. The edge location is where the sweeping heat load is reversed back toward the center of the sweeping. The temperature profile within the sweeping cycle varies substantially at each location on the divertor plate. For example the profile at the center of the sweeping starts at high temperature because of the original location of the peak heat load. As the sweeping progresses and the peak heat load moves away from the center, the temperature at the center decreases drastically because the heat load decreases exponentially. Then the temperature at the center starts increasing as the heat load reverses at the edge of the sweeping going back passing through the center to the other left edge and back again to the original location prior to sweeping. The profile near the edge has a double hump and has the maximum expected temperature because the maximum heat load passes twice through this location in very short time as it reverses at the edge.

Figure 3 shows the spatial distribution of the maximum temperature occurred at each point along the divertor plate. Again it can be seen that the highest temperature occurs near the edge location. One should point out that these maximum temperatures occur at different time as the heat load moves along the divertor plate. It can also be seen that all the maximum temperatures at every location on the divertor plate exceed the 1400 K limit set to avoid runaway erosion. This means that the sweeping parameters of ±15 cm distance and 0.2 Hz frequency are not sufficient enough for the narrow peaked heat flux profile shown in Fig. 1. For the less peaked heat flux distribution, with the same power content but without the scrape-off uncertainty factor, the surface temperature rise is always much less than that of the peaked profile as shown in Fig. 4 as an example for the center position temperature profile.

The effect of increasing the sweeping frequency on the armor surface temperature is shown in Fig. 5. Increasing the sweeping frequency from 0.1 Hz to 10. Hz will reduce the maximum surface temperature by about a factor of 2. Not only the higher sweeping frequency reduces the peak surface temperature, it also reduces the temperature change (ΔT) within the sweeping cycle. This is more important for the heat sink substrate structure because it reduces the thermal stresses and fatigue damage. Figure 6 shows the corresponding copper substrate surface temperature rise for the different sweeping frequencies. Although a higher sweeping frequency increases the total number of the stress and fatigue cycles on the structural material, it substantially reduces both the temperature and the temperature change within these cycles. For example, increasing the frequency from 0.1 Hz to 1.0 Hz will increase the number of cycles by a factor of 10 (this is in addition to the total main reactor on-and off-cycles) but it reduces the ΔT from 400 K to only a few degrees. This will overall result in an increase in the fatigue lifetime.

The near edge maximum surface temperature as a function of the sweeping distance for different sweeping frequencies is shown in Fig. 7. The required sweeping distance for each sweeping frequency such that to keep the maximum surface temperature at 1400 K is also shown. To keep the sweeping frequency at 0.2 Hz, one should sweep the heat load at ±25 cm from the origin. However, if one can sweep the heat load at a frequency of 1.0 Hz, the sweeping distance need only be ±14 cm. The decision whether to use higher sweeping frequencies or larger sweeping distances should be based on several factors such as the required sweeping power, design constraints, space limitations and other factors.

The effect of the sweeping frequency on the predicted maximum temperature at near the edge location is shown in Fig. 8 for two different sweeping distances. Large reductions in the armor surface temperature is predicted by increasing the sweeping frequencies up to 1.0 Hz. Further increase in the sweeping frequencies does not substantially reduce the temperature and may require large power supply. However, longer sweeping distances always result in large temperature reduction because of the narrow nature of the predicted heat flux distribution on the divertor plate. In addition longer sweeping distances may have other advantages such as spreading both sputtering and disruption erosion over larger areas. This will result in as much longer lifetime for the divertor plate.

3. Conclusion

Sweeping the heat loads over the divertor plate may be required and necessarily to mitigate and reduce the effects of the highly peaked heat fluxes. Higher sweeping frequencies and longer sweeping distances substantially reduce the resulting armor and substrate surface temperature. Lower temperatures also allow the use of thicker armor and coating materials which tend to increase the erosion lifetime. The maximum temperature during sweeping will roughly occur about one-half the FWHM (of the heat flux) to the left of the sweeping edge. Longer sweeping distances have the additional advantage of spreading disruption and sputtering erosion over larger areas thus substantially increasing the divertor lifetime.

References

[1] A. Hassanein, J.Nucl. Mater. 122 & 123 (1984) 1453.
[2] A. Hassanein, Fusion Technology Vol. 19, (1991) 1724.
[3] S.A. Cohen, Personal Communications.

Figure Captions

Fig. 1. Heat flux profile with different peaking factors.

Fig. 2. Surface temperature variation during sweeping at different locations.

Fig. 3. Maximum surface temperature occurred along the divertor plate.

Fig. 4. Surface temperature variation for different heat flux profile.

Fig. 5. The effect of different sweeping frequencies on the armor surface temperature.

Fig. 6. The effect of different sweeping frequencies on the substrate structure.

Fig. 7. Maximum armor surface temperature as a function of sweeping distance.

Fig. 8. Maximum armor surface temperature as a function of sweeping frequency.

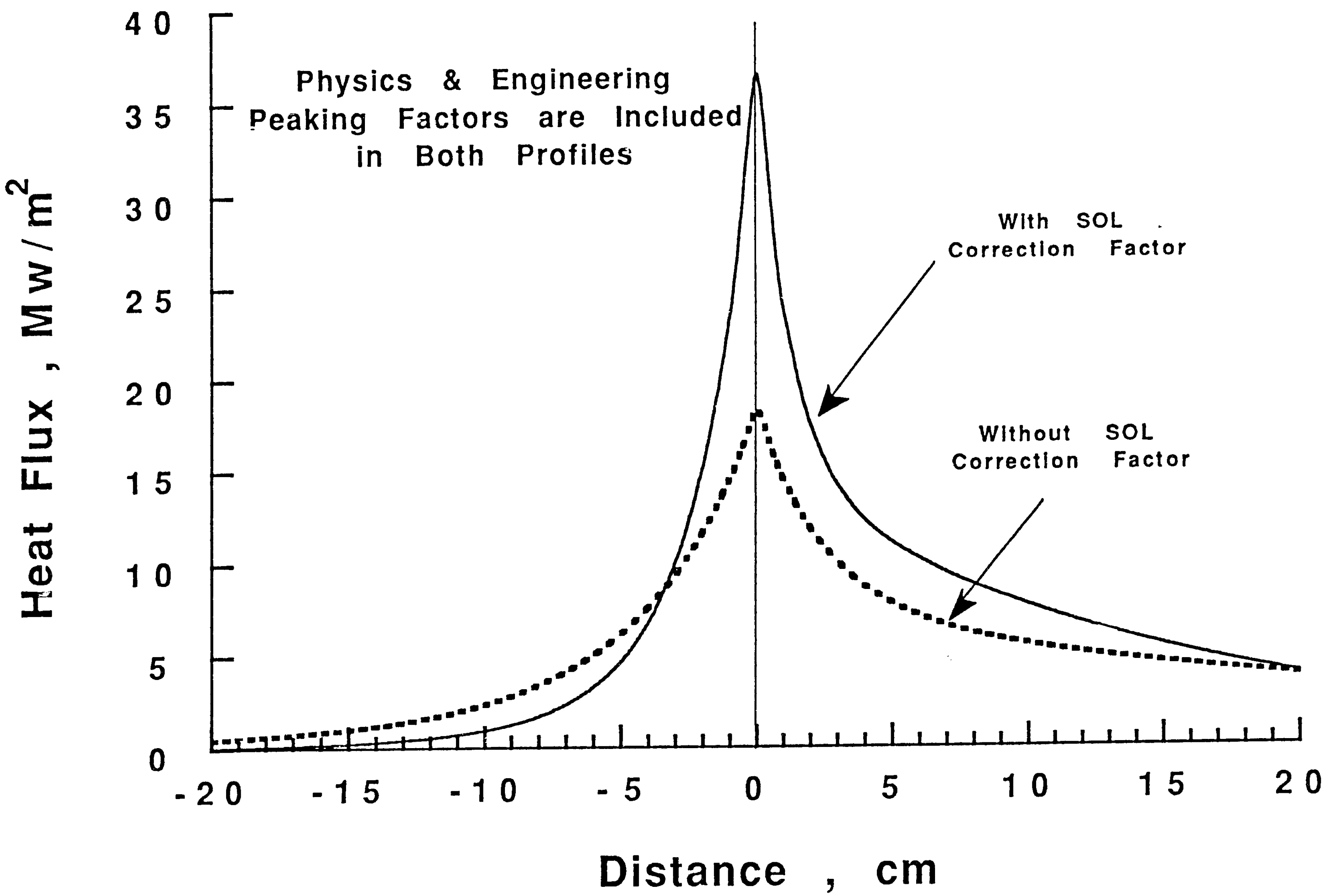

Physics & Engineering
Peaking Factors are Included
in Both Profiles
With SOL
Correction Factor
Without SOL
Correction Factor
Heat Flux , Mw/m2
Distance , cm
40
35
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 1

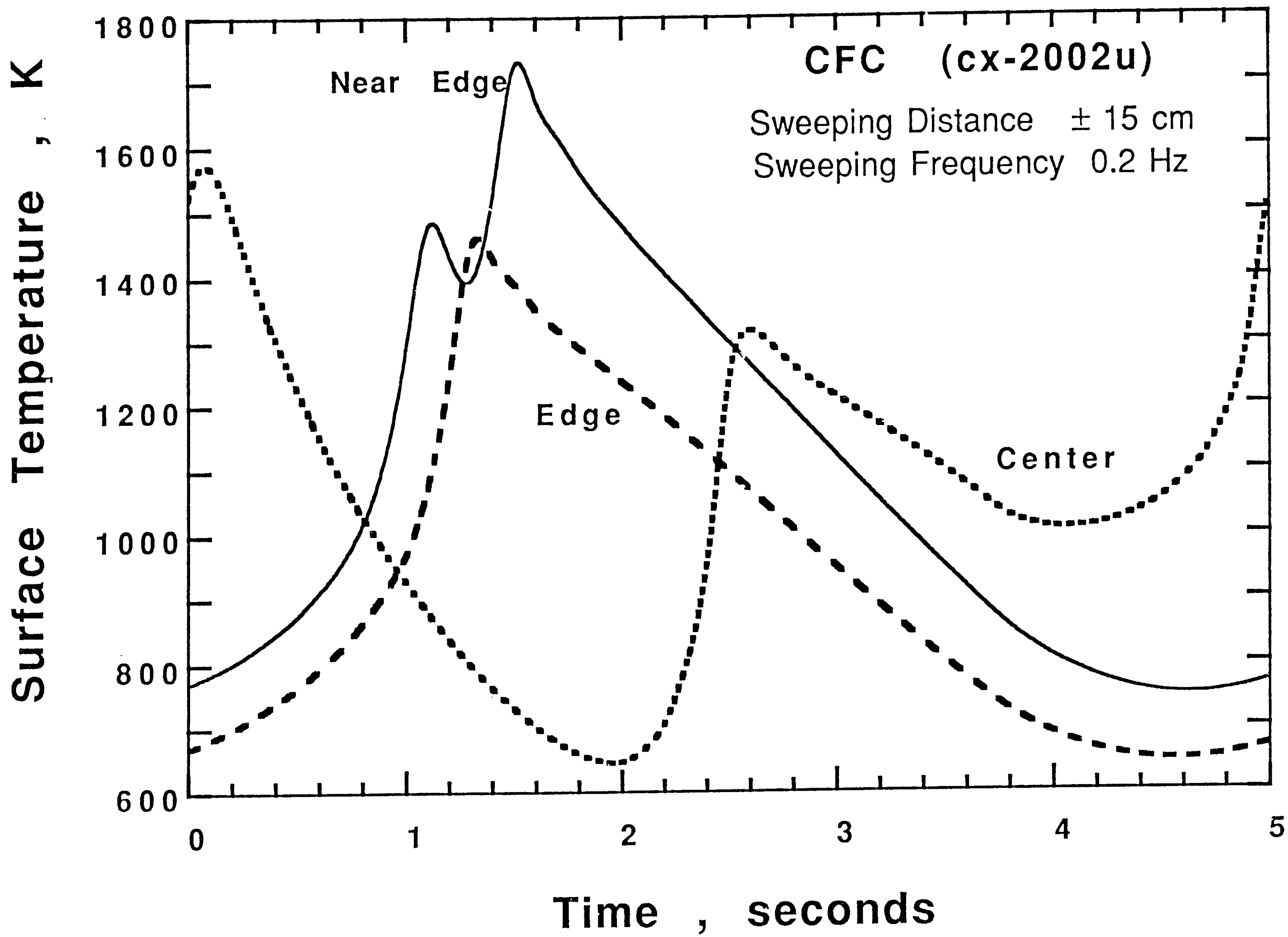
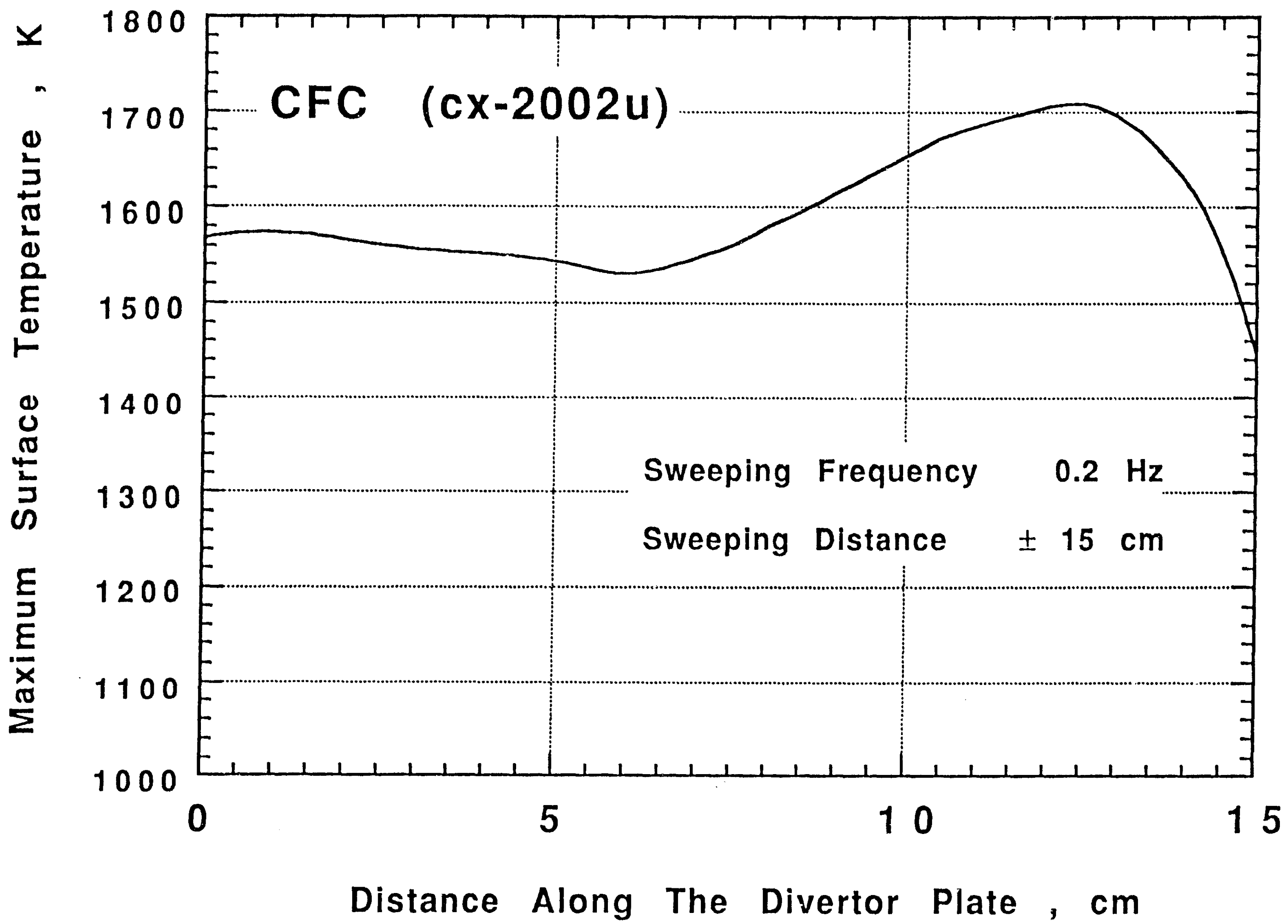

CFC (cx-2002u)
Sweeping Distance ± 15 cm
Sweeping Frequency 0.2 Hz
Near Edge
Edge
Center
Surface Temperature , K
1800
1600
1400
1200
1000
800
600
0
1
2
3
4
5
Time , seconds

Figure 2



CFC (cx-2002u)
Sweeping Frequency 0.2 Hz
Sweeping Distance ± 15 cm
Maximum Surface Temperature , K
1800
1700
1600
1500
1400
1300
1200
1100
1000
0
5
1 0
1 5
Distance Along The Divertor Plate , cm

Figure 3

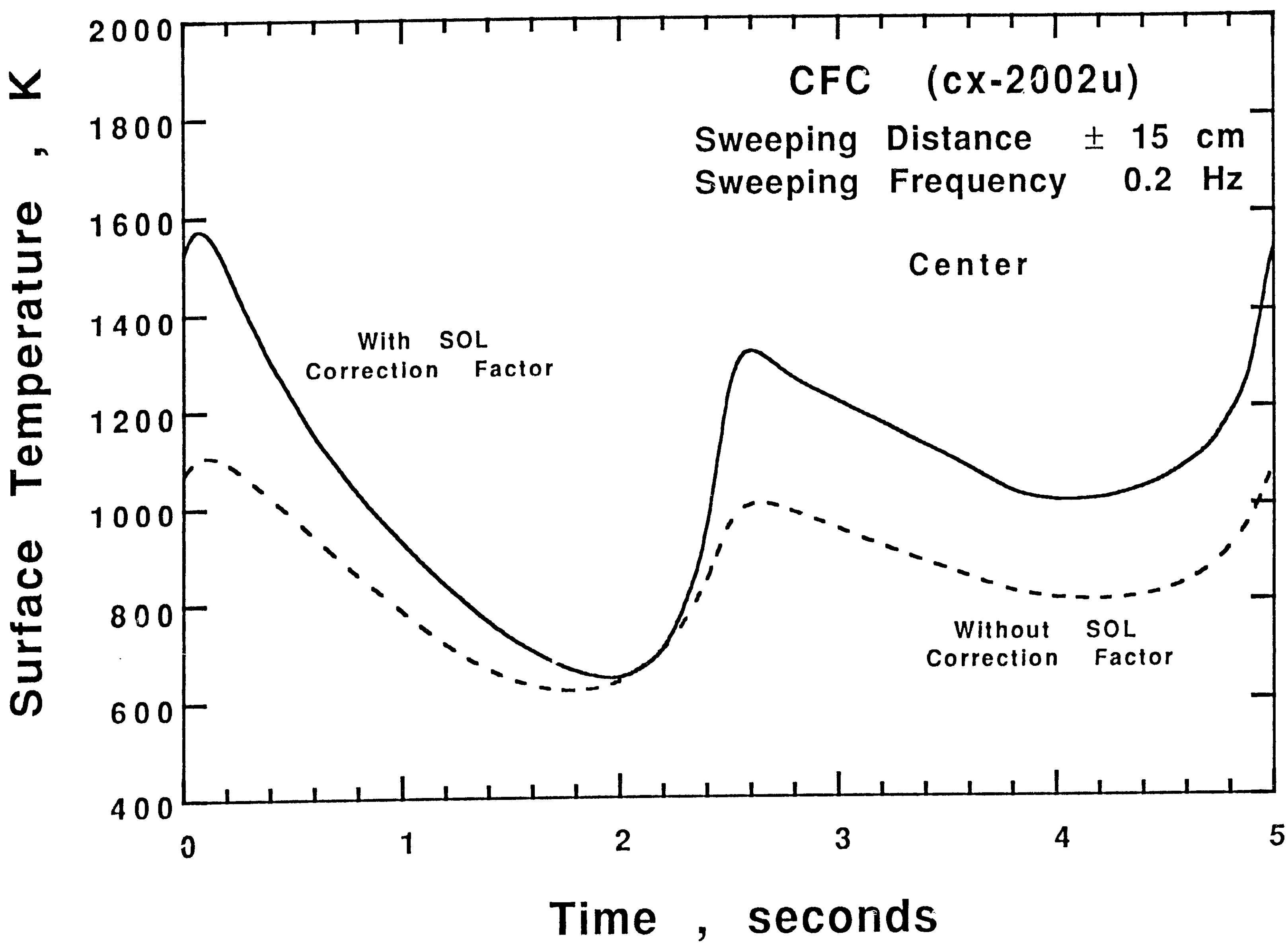
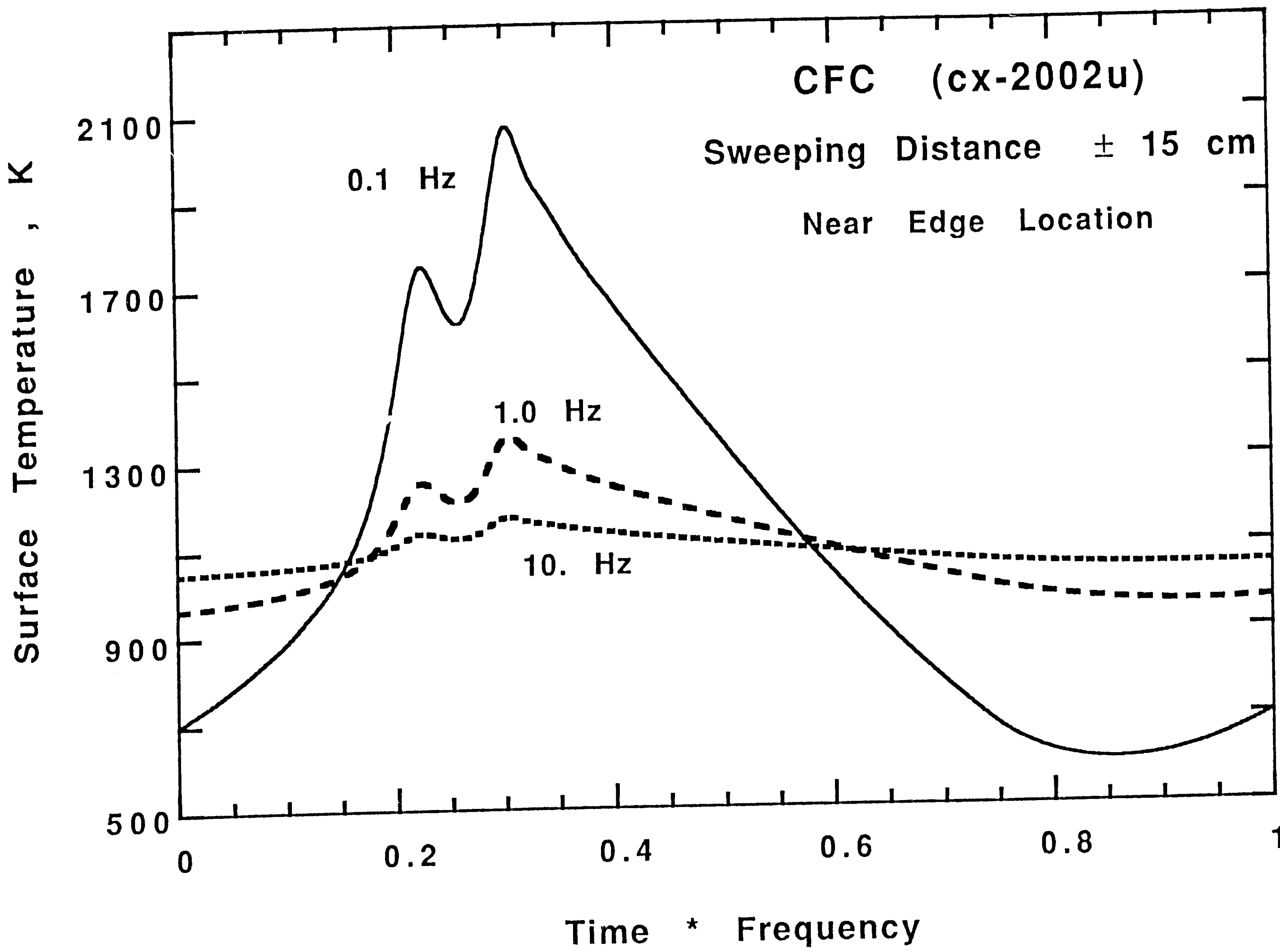

CFC (cx-2002u)
Sweeping Distance ± 15 cm
Sweeping Frequency 0.2 Hz
Center
With SOL Correction Factor
Without SOL Correction Factor
Surface Temperature , K
2000
1800
1600
1400
1200
1000
800
600
400
0
1
2
3
4
5
Time , seconds

Figure 4



CFC (cx-2002u)
Sweeping Distance ± 15 cm
Near Edge Location
0.1 Hz
1.0 Hz
10. Hz
Surface Temperature , K
2100
1700
1300
900
500
0
0.2
0.4
0.6
0.8
1
Time * Frequency

Figure5

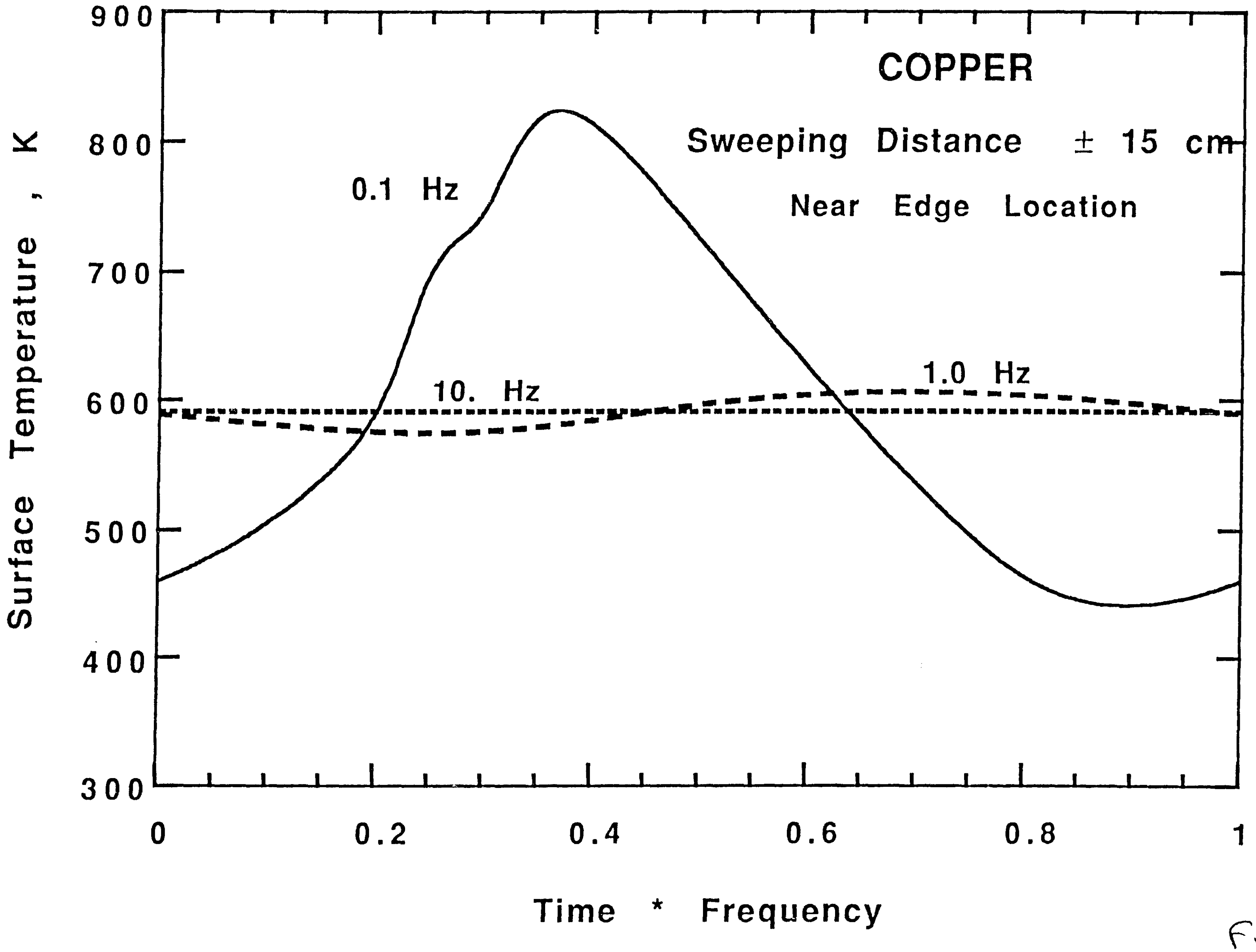

COPPER
Sweeping Distance ± 15 cm
Near Edge Location
0.1 Hz
10. Hz
1.0 Hz
900
800
700
600
500
400
300
Surface Temperature , K
0
0.2
0.4
0.6
0.8
1
Time * Frequency

Figure 6

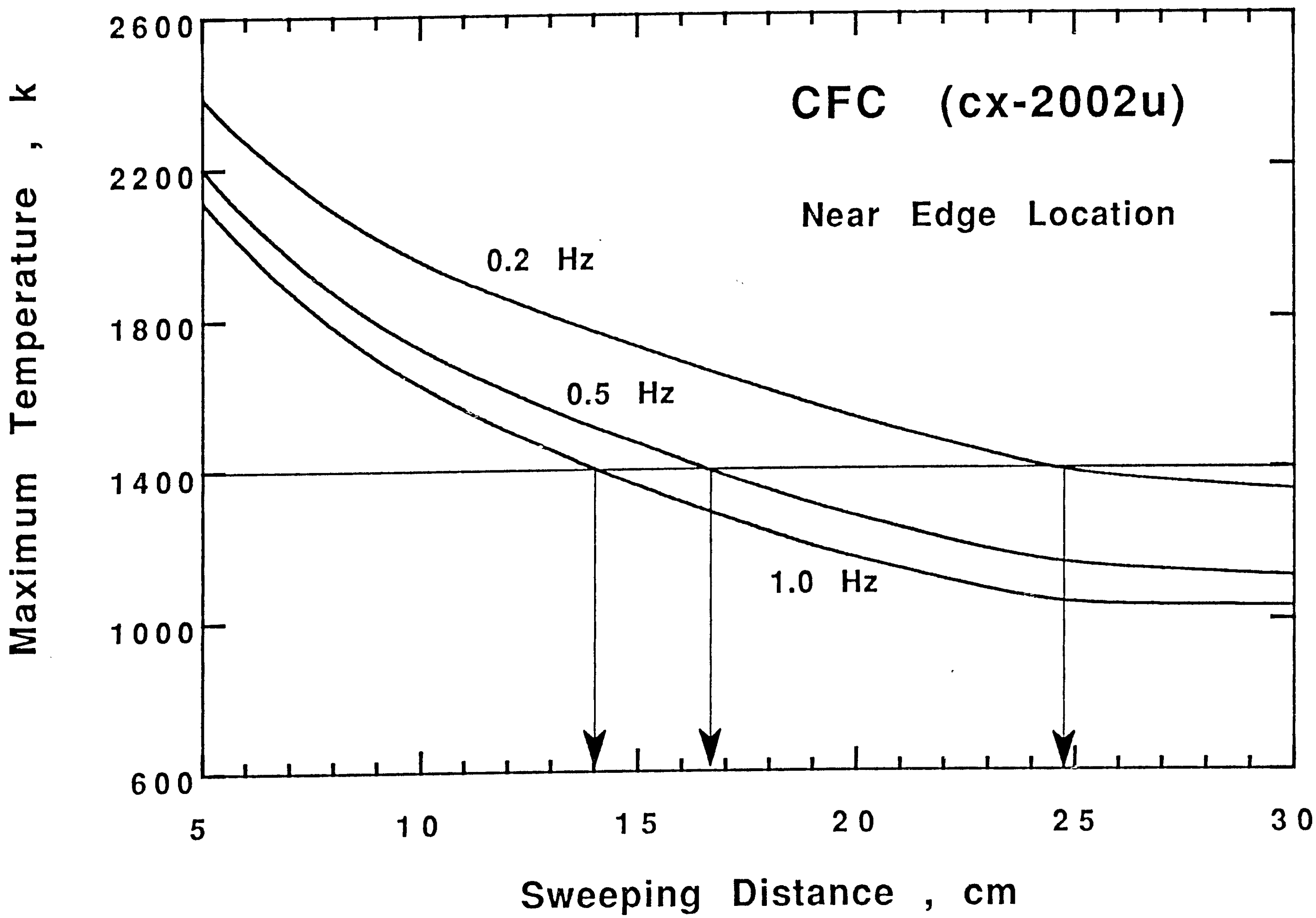

CFC (cx-2002u)
Near Edge Location
0.2 Hz
0.5 Hz
1.0 Hz
2600
2200
1800
1400
1000
600
5
10
15
20
25
30
Maximum Temperature , k
Sweeping Distance , cm

Figure 7

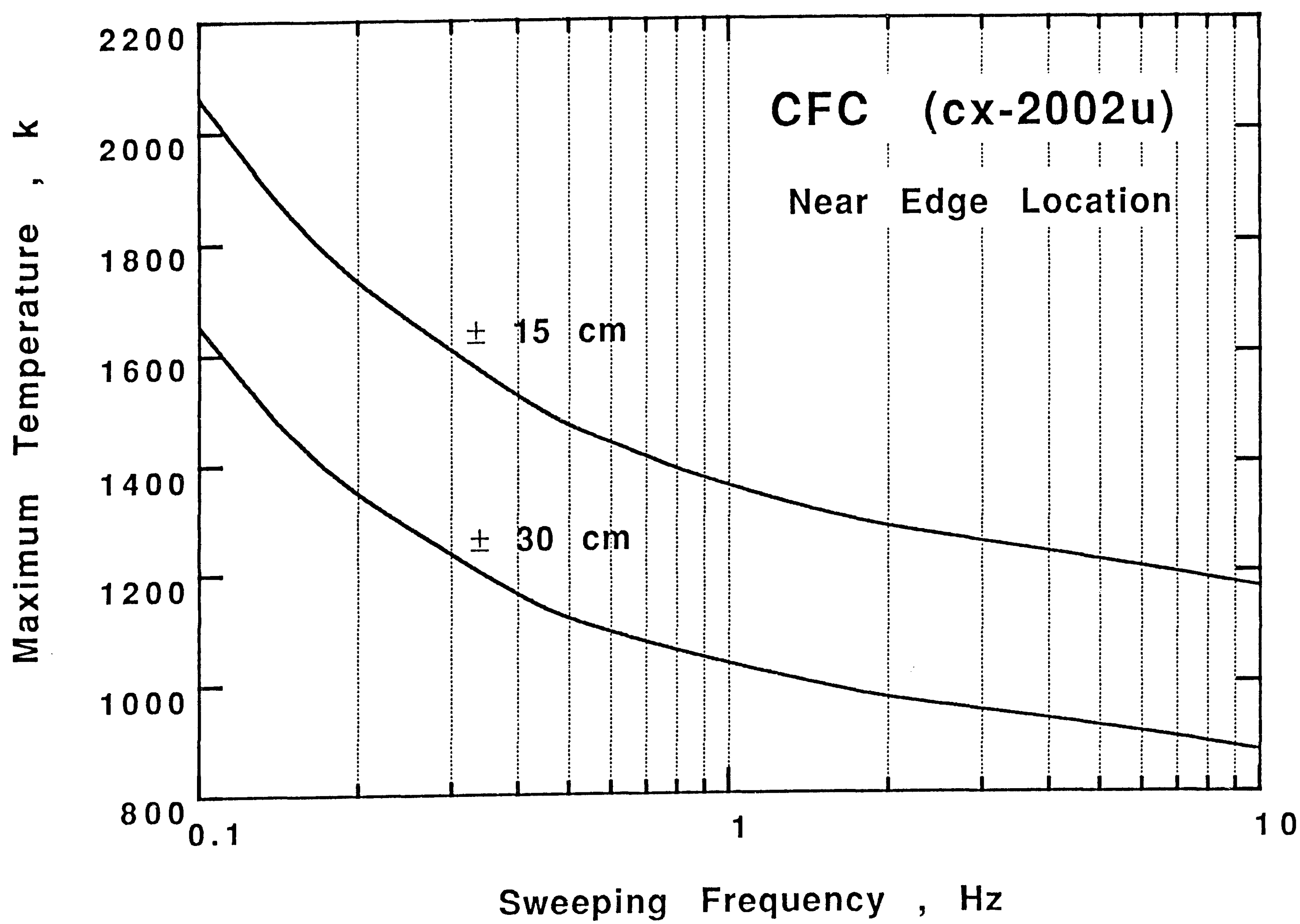

CFC (cx-2002u)
Near Edge Location
± 15 cm
± 30 cm
2200
2000
1800
1600
1400
1200
1000
800
Maximum Temperature , k
0.1
1
10
Sweeping Frequency , Hz

Figure 8

END

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