LIMITER CALORIMETRY AT THE W VII-A STELLARATOR

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(February 1978 (in English)

Abstract

During stationary series of discharges in the W VII-A stellarator differing fractions of the ohmic input power are found to be deposited as heat at the limiter. This heat is localized predominantly at the radial outside limiter segment which is touched by the long side of the magnetic surface. The total limiter yield amounts to 20 % of the ohmic power; at negative helix polarity,values of 15 and 3 % are found at the upper outside and lower inside limiter segment of W VII-A. These numbers are averages from a data set of 70 observations taken in W VII-A between the end of March and August 1977. For these data the dependence of the limiter yield on the toroidal field, the external rotational transform, as well as on plasma parameters is either weak or masked by the scatter of the results. A variation of the plasma position during a discharge series can be seen in a corresponding change of the heat loads of the two limiter segments touched by the long side of the shifted magnetic surfaces.

The temperature increase of the cooling air of the four limiter segments is observed. The time constant of the W VII-A limiter calorimetry is about 10 minutes. The estimated thermal radiation of the limiter appears to be less than 10 % of the power deposited to the limiter.

Introduction

In the study of the confinement properties of a toroidal system, such as the W VII-A stellarator, the measurement of radial profiles of density, temperature and radiation yields local information regarding the transport of energy and particles. These results are supplemented by bolometric measurements in W VII-A. Further information towards a complete energy balance is obtained by calorimetry at the limiter.

In the W VII-A stellarator this is performed during stationary pulse series by observing the temperature increase of the limiter cooling air. Incomplete spatial performance of the W VII-A limiter is seen. Therefore, the calorimetric data obtained at the W VII-A limiter and corrected for thermal radiation are a lower limit of the charged particle energy losses at the plasma edge in W VII-A.

The present report starts with a description of the W VII-A limiter. Then some details of the limiter calorimetry are discussed for stationary and transient conditions. Experimental data covering stationary series of discharges during the period between March 25 and August 12, 1977 are given. The Appendices contain some material constants of molybdenum and some results of further studies of transient limiter phenomena.

W VII-A Limiter

Fig. 1 shows a cross-section of the W VII-A limiter plane, along with a set of computed magnetic surfaces. They correspond to a pure stellarator field at a rotational transform of $\iota_o = 0.23$. Due to the torus curvature a slight radial inward offset exists between the centre of the magnetic surfaces and the centre of the torus.

Further technical details of the W VII-A limiter and the relevant dimensions are discussed along with Fig. 1A. The W VII-A limiter consists of four molybdenum segments of 5.6 cm^2 cross-section, covering approx. 4 quarter circles in the poloidal direction at a bending radius r_B = 14 cm. Bending of straight pieces of sintered molydenum to these dimensions is difficult, but was made possible by the supplier. Stainless steel support rods are brazed to the molydenum segments by means of a gold-nickel alloy.

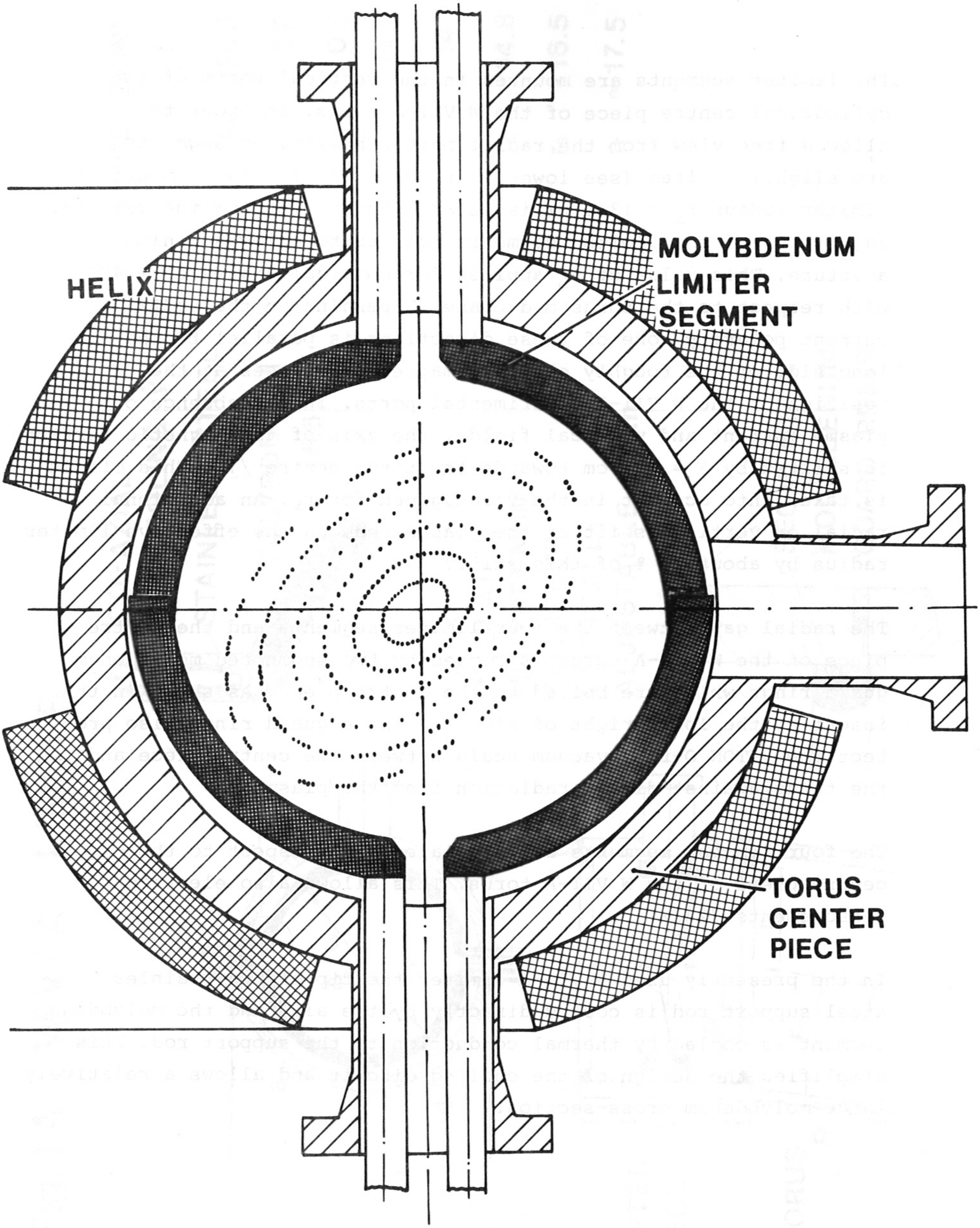


FIG.1 W VII A LIMITER PLANE

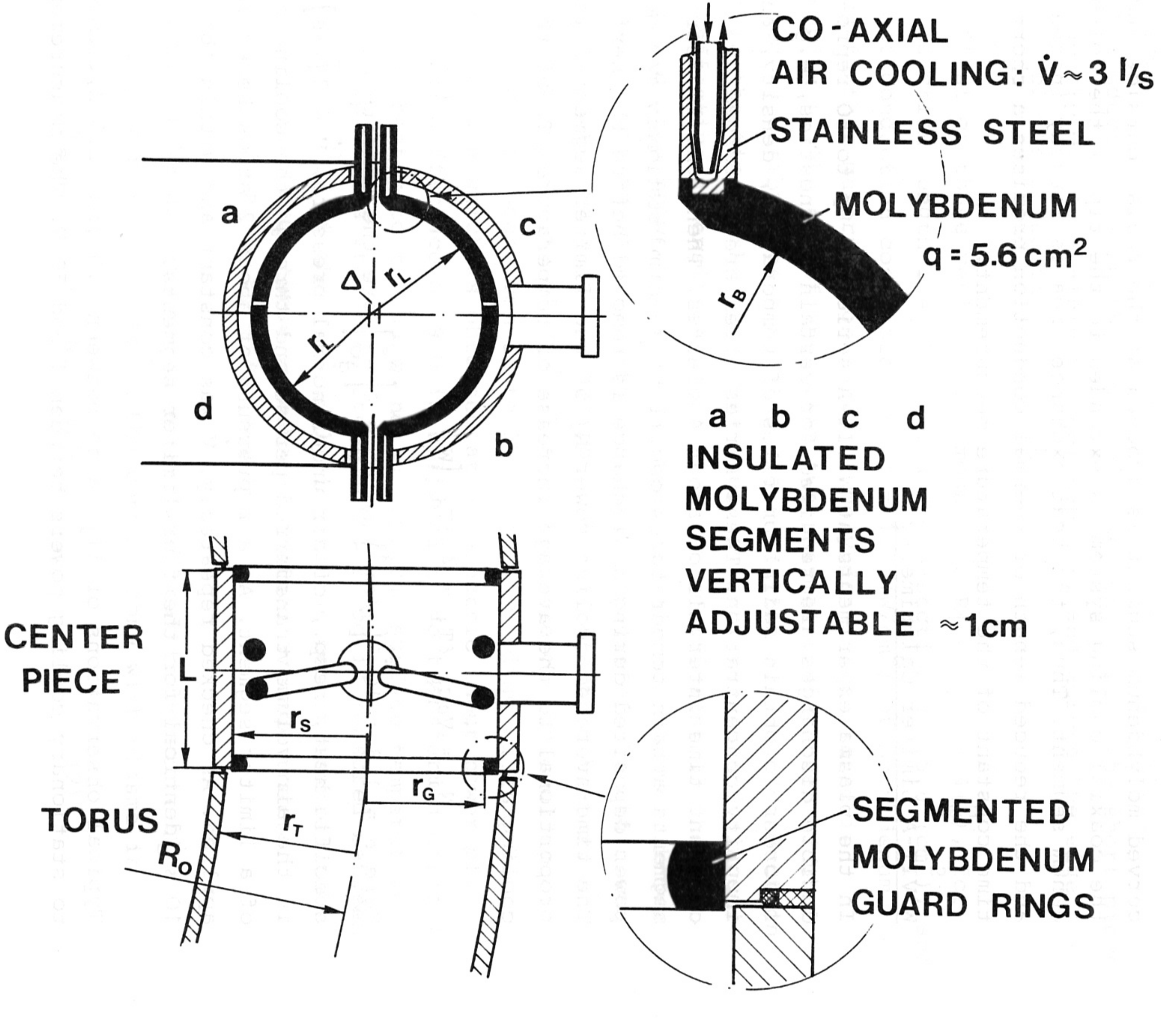
The limiter segments are mounted in the vertical ports of the cylindrical centre piece of the W VII-A torus. In order to allow a free view from the radial port, the limiter segments are slightly tilted (see lower left part of Fig. 1A). An effective limiter radius r_L = 13.2 cm is established by setting the vertical adjustment of the limiter segments such as to allow a minimum aperture. This value of r_L applies for poloidal angles of $\pm$ 45° with respect to the torus mid-plane. Depending on the helix current polarity, one of these directions is parallel to the long side of the roughly elliptic magnetic surfaces at the position of the W VII-A experimental ports. In the absence of plasma current and vertical fields, the axis of the magnetic surfaces is shifted by Δ = 0.6 cm towards the torus centre /1/. This offset is taken into account in the value given for $r_{\perp}$. An additional radial or vertical shift of the plasma reduces the effective limiter radius by about 70 % of this shift.

The radial gap between the four limiter segments and the centre piece of the W VII-A torus is closed by two segmented molybdenum guard rings which are bolted to the centre piece. As shown in the insert at the lower right of Fig. 1A, these guard rings also protect the VITON O-ring vacuum seals between the centre piece and the torus against direct radiation from the plasma.

The four limiter segments are insulated with respect to the centre piece of the W VII-A torus. This allows also electric measurements /2,3/.

In the presently used W VII-A limiter the tip of the stainless steel support rod is cooled directly by the air, and the molybdenum segment is cooled by thermal conduction to the support rod. This simplifies the design of the cooling circuit and allows a relatively large molybdenum cross-section.

Fig. 1 A   W VII A   LIMITER



DIMENSIONS (cm)

R_O	200
L	27
Δ	$\approx$ 0.5
r_L	13.2
r_B	14
r_G	14.8
r_S	16.5
r_T	$\approx$ 17.5

A thin-walled stainless steel tube coaxial with the support rod supplies the cooling air. The long distance between the cooled tip of the support rod and the contact region of the plasma as well as the large enthalpy of the limiter segments cause a thermal time constant of $\lesssim$ 10 minutes.

A second limiter version is prepared for W VII-A. The curved molybdenum segment is grooved at the radial outside and the coaxial cooling system is extended to the tip of the molybdenum segment. Thus, the heat exchange area is largely increased and the reduced length of thermal conduction promises a short time constant of the temperature measurement.

W VII-A Limiter Calorimetry

In the plasma experiments at W VII-A series of up to 50 reproducible discharges are required for certain diagnostics, e.g. in order to obtain radial profiles of temperature, density, and impurity concentration. These series often are performed at constant time intervals of about 4 minutes. Then, the limiter segments attain temperatures oscillating around stationary averages. The power deposited during a discharge is removed before the next one. The time-averaged cooling power N_i of the limiter segment i is proportional to the average increase of temperature δT_i of the cooling air.

$$N_i = \dot{V} \rho c_p \; \delta T_i = 4 \; \delta T_i \; [W] \qquad (1).$$

Here $\rho = 1.3 \cdot 10^{-3} [g/cm^3]$ and $c_p = 1 \left[\frac{W_s}{g^o}\right]$ are the density and specific heat, resp., of air under normal pressure, $\dot{V} = 3\,[l/s]$ is the air volume transferred per second through the cooling duct of a limiter segment. An air pressure of about 2 atmospheres is applied. As checked repeatedly, $\dot{V}$ was constant and within about 10 % identical for the four limiter segments.

Typical observations of δT_i range between 0.3 and 12.5 K, corresponding to stationary cooling powers between 1 and 50 W. The measurement of such small temperature differences requires some precautions regarding disturbing influences. This will be discussed below with the experimental results.

Under stationary conditions the difference between the local time-averaged peak temperature T_s of a limiter segment and the average temperature T_o of the cooling air is proportional to the cooling power N_i via the sum of three thermal resistances: heat conduction along the molybdenum segment, along the short piece of the tip of the stainless steel support, and across the edge sheath of the streaming cooling air.

The first of these resistances amounts to $R_1 = \frac{l}{q\lambda} = 1.4 (\frac{o}{W})$, for a conduction length l = 10 (cm), a cross-section q = 5.6 (cm^2), and a heat conduction coefficient of $\lambda = 1.3$ (W/cm^o) of molybdenum. Some further material constants of molybdenum are listed in Appendix A. The sum of the other two thermal resistances is obtained by calibration since the cross-section for heat conduction within the tip of the stainless steel support varies and since the effective dimension and the transfer coefficient of the heat exchange area between stainless steel and air are not well known. This calibration is done with a separate module of the stainless steel support rod which is equipped with an electric heater. At an air transfer rate of $\dot{V}$ = 3 l/s an increase of the cooling air temperature is seen from 25 to 37°C, corresponding to a cooling power of 48 W which is obtained at an electric input power of 57 W. The difference of 9 W is believed to be transferred directly from the heater to the surrounding air. The surface temperature at the tip of the stainless steel support rod is measured between 104 and 123 °C, if the air supply is via the center coaxial tube of the system. From these numbers a combined average thermal resistance $(R_2+R_3) = 1.7$ (^{o}/W) results.

With the above numbers the time-averaged peak temperature T_s of a limiter segment close to the contact zone with plasma is

$$T_s = T_o + 3.1\, N_i \quad (K) \qquad (2),$$

where T_o = 300 K will be taken as the average temperature of the cooling air and N_i is the observed cooling power in Watt.

The power radiated from the limiter surface is proportional to the emissivity ε of molybdenum. From literature /4,5/ values of $\varepsilon \approx 10$ % are given at a temperature of 1000 K. In the range T = 300 to 500 K ε decreases to 1 - 3 % for clean and to $\approx$ 5 % for oxidized samples /5/. For the W VII-A limiter material ε has not been measured. It is believed that $\varepsilon = 0.1$ is a reasonably conservative value, which would also take into account the roughness of the limiter surface. In order to estimate the stationary radiated power it is assumed that 2/3 of the limiter segment is at the temperature T_s, eq.. 2. Then the radiated power amounts to

$$N_r = \varepsilon A_r \sigma (T_s^4 - T_o^4) = 10^{-2}\left[\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4\right] \ [W] \qquad (3)$$

where A_r = 160 cm^2 is the radiating surface, T_o = 300 K, and $\sigma = 6 \cdot 10^{-8}$ $(W\ m^{-2} K^{-4})$ is the radiation constant.

The radiated stationary power N_r is small compared to the cooling power N_i. For the maximum cooling power of a single limiter segment $N_i \approx 63$ W which has been observed so far,+) equation 3 yields a radiated power of N_r = 5.5 W.

Transient Limiter Temperature

In W VII-A operated with ohmic heating the limiter temperatures are time-dependent due to the pulsed heat load. Instead of solving the time-dependent equations of heat conduction and thermal radiation for the exact limiter geometry, we list some quantities for plane geometry:

- the time constants of the limiter
- the adiabatic temperature increase per discharge
- the maximum surface temperature, and
- the radiated power connected with this maximum temperature.

Thermal conduction and radiation are treated separately. For the numbers to be given below, we will use the maximum heat load of N_i = 63 W as observed so far.

+) Discharges Nos. 6511-6516, 29.6.77 at B = 3.5 T, ι_o = 0.055

For the transient heat conduction in the molybdenum segment three time constants $\tau = x^2/a$ can be envisaged:
The first time constant τ_1 describes the adiabatic temperature increase of the limiter close to the contact zone with plasma; $x_1 = d/2 \approx 1$ cm, where d = 2.2 cm is the thickness of the molydenum segment. For the equipartition of temperature along the molybdenum segment, i.e. from the contact zone of the limiter with plasma towards the cooled or the warm end, $2x_2 = l \approx 10$ cm is to be taken. In order to describe the cool-down of the whole limiter segment after the discharges, a length $2x_3 \approx 2.5\ l$ is effective. Here we take a length $l_p \approx 5$ cm as the poloidal extension of the contact zone of the limiter segment with plasma. This value is indicated from side-on photography+) of the W VII-A plasma in the limiter region.

The thermal diffusion coefficient for molybdenum amounts to $a = 0.5\ cm^2/s$ for a temperature $300 \lesssim T \lesssim 600$ K. The three time constants $\tau_1 = 2$–3 s, $\tau_2 \approx 1$ min, $\tau_3 = 6$ min are long compared with the pulse time $t_p \lesssim 0.5$ s of the OH discharges.

In order to estimate the maximum adiabatic temperature rise δT_a in the contact zone of the limiter with plasma, we consider the upper limiter segment positioned at the radial outside as an extreme case . The discharges are characterized by an average Ohmic power of $P \approx 160$ kW, pulse length $t_p = 0.4$ s++) . From the evaluation of the data (to be described below) we find a fraction f = 26 % of the time-integrated Ohmic power to be deposited at this

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+) F. Rau, cover picture of the IPP Annual Report 1976

++) Note that for a given flux in the OH transformer, at constant plasma current, the product $P \cdot t_p$ is $\approx$ constant.

limiter segment. This power corresponds to an adiabatic temperature increase of the limiter segment:

$$\delta T_a = \frac{f \cdot P \cdot t_p}{l_p q \rho c} = 220 \text{ K} \qquad (4)$$

Here we use the cross-section $q = 5.6 \text{ cm}^2$ and the poloidal length $l_p = 5$ cm of the limiter interaction zone with plasma. Since thermal radiation and parallel heat conduction are neglected, eq. 4 is a conservative upper limit of the adiabatic temperature increase. For molybdenum, the density $\rho = 10.2 \text{ g/cm}^3$ and the specific heat $c = 0.27$ Ws/gK are found in the literature.

The time constant $\tau_1 = 2\text{-}3$ s characterizes this adiabatic temperature increase. An average adiabatic cooling power is obtained by

$$N_a = fP \cdot \frac{t_p}{\tau_1} \approx 7 \text{ kW} \qquad (5)$$

for this case. After a time $t \approx \tau_2$ the heat $f \cdot Pt_p$ then is spread along the whole limiter segment.

Visual inspection of the W VII-A limiter shows local melting zones, within a poloidal length of about 2 - 3 cm, mainly at the upper radial outside limiter segment. This does not contradict the much lower time-averaged temperatures stated above, but can be understood in terms of a transient surface heating which occurs only within a short interval of the order of $t \lesssim t_p$, during the OH pulse time t_p.

For linear geometry, the time-dependent equation of heat conduction yields a simple relationship between the increase of the peak surface temperature T_p and the pulse time t_p at a given power density F and a given initial temperature T_i, if thermal radiation is neglected:

$$T_p - T_i = \frac{2F}{C} t_p^{1/2} \qquad (6)$$

The constant $C = \sqrt{\pi \lambda c \rho}$ amounts to 3.4 $Ws^{1/2}cm^{-2}K^{-1}$ for molybdenum. If we identify T_p with T_m, the melting temperature, and take $T_i \approx T_s$ according to eq. (2), then a maximum power density

$$F_m(W/cm^2) = \frac{C}{2}(T_m - 3.1\ N_i[W] - T_o)t_p^{-1/2} \qquad (7)$$

is correlated with the observed stationary cooling power N_i of the limiter segment . For sake of simplicity, in eq. (7) we neglect the stationary radiated power N_r, eq. (3). With the numbers of the example inserted we obtain the maximum power density

$$F_m = 6.6\ kW/cm^2 \qquad (7a)$$

for a pulse time t_p = 0.4 s.

At a given fraction f of the Ohmic power P deposited onto the considered limiter segment, eq. (7) then yields the minimum size A_m of the contact area with plasma:

$$fP = F_m \cdot A_m \qquad (8)$$

The power N_{rm} radiated by the area A_m at the molybdenum melting temperature T_m is approximated by

$$N_{rm} \approx A_m \varepsilon \sigma T_m^4 = 200\ A_m\ (W) \qquad (9)$$

if an emissivity $\varepsilon = 0.5$ is taken. For the numbers of the example used before $fP = 42$ kW. Using $F_m = 6.6$ kW/cm^2, the area A_m amounts to 6.4 cm^2 and a radiated power of 1.3 kW results. As will be shown in Appendix B, the radiated power N_{rm} according to eq. (9) is a maximum of the radiated power if we keep ε and fP constant, vary the radiating area of the contact zone, and use eq. (6) in order to obtain the peak surface temperature. The radiated power N_{rm}, eq. (9) is much smaller than the applied pulse power Pf. Due to the simultaneously present and much larger adiabatic cooling power $Na \approx 7$ kW (eq. (5)) the true local peak radiated power

$$N_{rp} < N_{rm} \tag{10}$$

can be present only within a time $t_r \lesssim t_p$, the pulse time. Therefore, in the further evaluation of the data the small correction according to eqs. (9) and (10) is neglected.

Under differing conditions and less developped "state of art" of the plasma conditions, colour photographs of the W VII-A limiter have shown hot spots only in a very small number of discharges taken in the late summer of 1976.

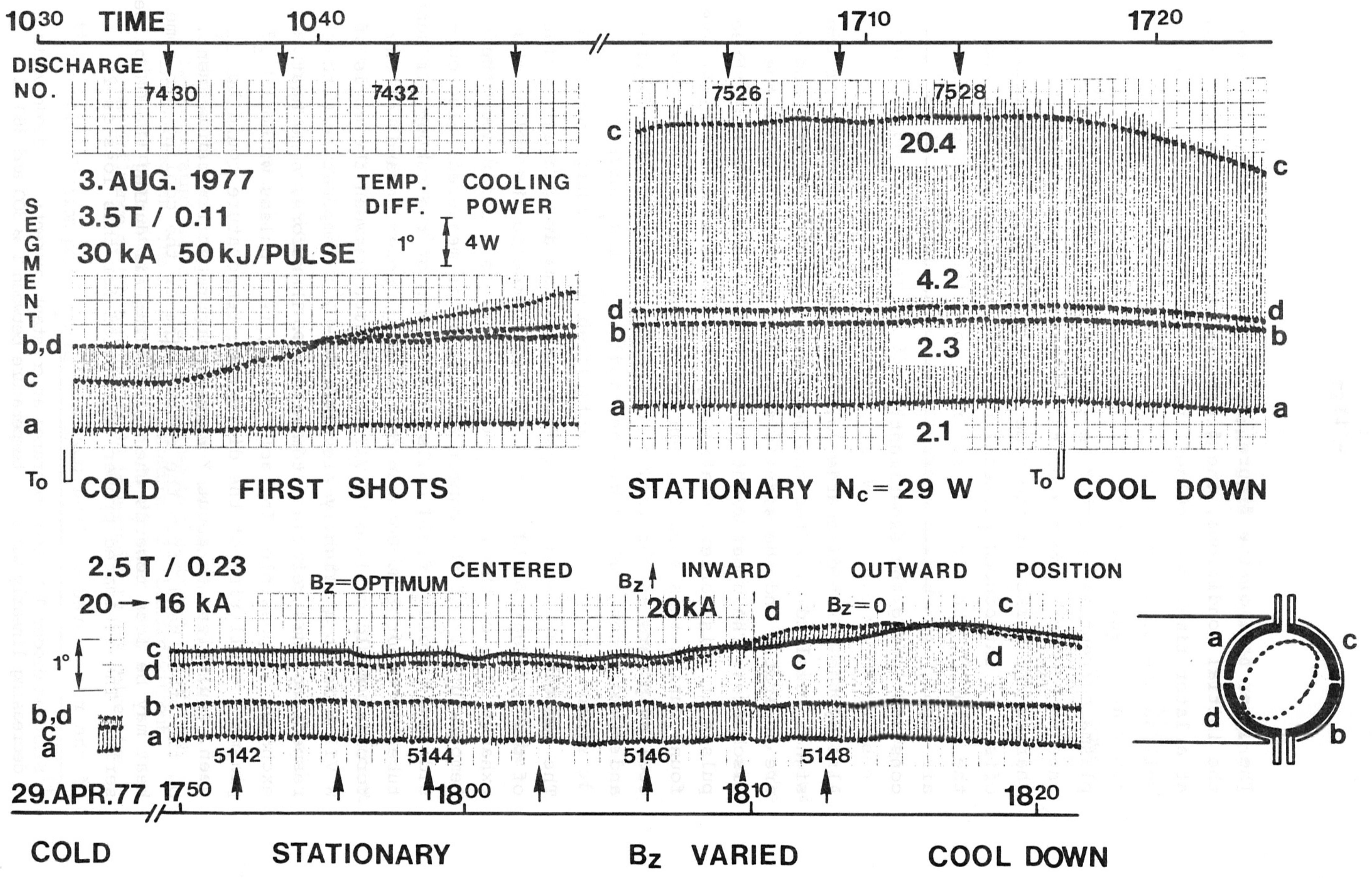
Some more studies of transient limiter temperatures are performed with the use of a RC network /6/ which models a W VII-A limiter segment. The details and some results are given in Appendix C.

Experimental Results and Discussion

Calorimetric measurements at the W VII-A limiter started by the end of February 1977. The present report covers the information obtained between March 25 and August 12, 1977.

Two examples of the temperature registration curves are given in Fig. 2. They are obtained on different days under differing conditions.

Fig. 2 WVII A LIMITER CALORIMETRY



The upper half of the figure is from August 3, 1977. It shows the initial conditions, the first discharges of this day, and, at a later time, some pulses under stationary conditions as well as the beginning of the cool-down. The toroidal field is 3.5 T at an external rotational transform ι_o = 0.11. The plasma current is constant in time at 30 kA, and the time-integrated Ohmic power amounts to 50 kJ per pulse. The discharges are marked at the time scale by arrows. An arbitrary offset is introduced between the different channels a-d, and the value of the air temperature T_o obtained at the common air supply. As checked several times, the value of T_o is constant during the experiment.

Already the first discharge No. 7430 causes an increase of the signal labelled c. After the second pulse, the traces d and b are separated and the signals rise continuously between the discharges. The upper right of the figure shows the last three pulses of this series. Stationary conditions at the limiter are found during this specific run for more than one hour. The cooling powers as obtained directly are entered in the figure and yield a total of 29 W.

The temperature sensors+) used at that time are placed outside of the toroidal field coils of W VII, close to the end of the exhaust line of the limiter cooling air. As a reference, the temperature T_o of the common air supply is measured, also outside the toroidal field coils. The length of the rubber air supply tubes is about 2 m. Because of the large power demands of the toroidal field coils of W VII, the region between the coils of W VII-A is at a slightly elevated (1 - 2^o) temperature with respect to this reference temperature. Therefore, some heat exchange is possible. In fact, during test pulses without plasma a small rise of the difference temperature could be seen, equivalent to about 1 W power input per limiter segment. On the other hand, from the return line of the cooling air some heat may be lost towards the surrounding air during the OH pulse series. The estimated proper correction for this loss is 25 % of the registered cooling power.

+) Silicium diodes 1 N 4005, operated at constant current; diode voltage decreasing linearly with temperature between T ≈ 300 and 380 K.

Therefore, for the limiter segment i, the corrected cooling power of the air system amounts to

$$N_c = 1.25\ N_i - 1 \quad [W] \qquad (11)$$

The sum of these corrected values depends on the total power ΣN_i observed. For the system of four limiter segments the corrections cancel for a total observed cooling power of 16 W.+)

For the data shown in the upper right half of Fig. 2, the total corrected power++) is 33.7 W at a total observed cooling power ΣN_i = 29 W. The main part (26 W) of this value is seen at the segment c which also requires the largest correction. The corrected values of segments d, a, and b are 4.4, 1.6, and 1.9 W, respectively. As indicated in the insert of Fig. 2, the limiter segments c and d are those towards which the long side of the magnetic surface is oriented.

In the upper right of Fig. 2, the beginning of the cool-down of the limiter segments after the end of the series can be seen. The quantitative description of the transient change of the temperature distribution along the molybdenum segment towards stationary cool-down is complicated and will not be discussed further.

The lower half of Fig. 2 shows a part of the registration taken on April 29, 1977, at a toroidal field of 2.5 T and an external rotational transform of t_o = 0.23. The plasma current is changed from 20 to 16 kA during the discharge. Nearly stationary conditions are established and the vertical field B_z is optimized.

+) The position of the temperature sensors has been changed recently. Two temperature sensors are placed close to the support rod of each limiter segment. The difference temperatures are obtained without the disturbing effect described above. On the other hand, a strong influence of the toroidal field is seen during its pulse time.

++) Thermal radiation power N_r, eq. 3, taken into account.

Beginning with discharge No. 5146 the conditions are changed: the plasma current is kept constant at I_p = 20 kA and the vertical field is varied in order to introduce a radial shift of the plasma. For two discharges B_z is increased. The corresponding inward offset is seen after a few minutes by an increase in the signal d (lower inside limiter segment) and a simultaneous decrease of the signal c. This behaviour is reversed again after the last discharge which is performed without vertical field. The plasma position is shifted radially outward, and the corresponding change in the heat distribution of the limiter segments c and d can be seen shortly afterwards.

From curves similar to those shown in Fig. 2 a data set of 70 observations +) has been obtained which cover the time between March 25 and August 12, 1977, for different plasma and machine parameters.

The total limiter yield $\sum_i f_i$ and successively the individual yields f_i are obtained by normalizing the observed and corrected cooling power N_c by the total Joule heat of the discharges:

$$(\sum_i f_i) \cdot \int_o^{t_p} P dt = \sum_i [(N_c + N_r) t_c + N_{rm} t_p] \qquad (12)$$

The quantities are defined as above. The term $N_{rm} t_p$ is neglected as a minor correction, but the stationary radiation power N_r is included in the evaluation of the limiter yields.

The observed values of the total limiter yield scatter markedly and range between 10 and more than 30 % of the ohmic heat of the discharges. Therefore, averages are given in this report for discharges, where the toroidal field B_o and the external rotational transform t_o are kept constant. These averaged heat balances are shown in Fig. 3. The symbol S indicates the total limiter yield, and the symbols A, B, C, D correspond to the segments a ... d as shown in Fig. 1.

+) Details available on request

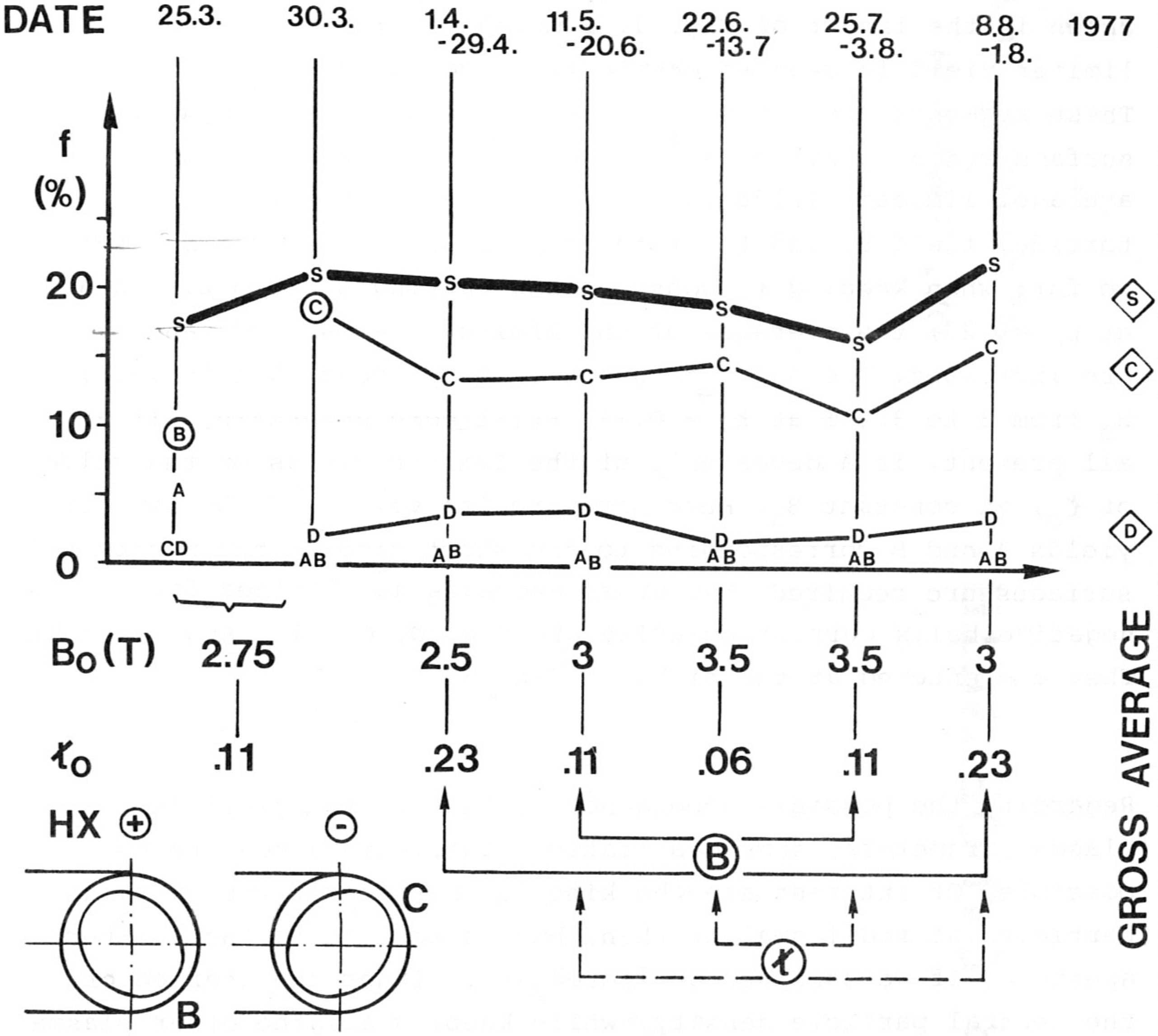


FIG. 3 WVII A LIMITER CALORIMETRY

AVERAGED HEAT BALANCE

$$f = \frac{\text{HEAT DEPOSITED AT LIMITER}}{\text{JOULE HEAT PER PULSE}}$$

A...D : LIMITER SEGMENT, S: SUM

A change of the polarity of the W VII-A helix current changes the orientation of the long side of the magnetic surface, as shown in the insert of Fig. 3. Simultaneously, the largest limiter yield is seen to change from segment B to segment C. These segments are touched by the long side of the magnetic surface radially outwards+). No clear dependence of the averaged limiter yields S, C, and D on the variation of the toroidal field B_o and the rotational transform ι_o can be stated so far: when keeping ι_o constant and varying B_o from 2.5 to 3 T at ι_o =0.23, the averages of the limiter yields S, C, and D are increased. The opposite seems to be present when increasing B_o from 3 to 3.5 T at ι_o = 0.11. Still more uncertain, if at all present, is a dependence of the limiter yields on the value of ι_o, at constant B_o. Here more precise values of the limiter yields A and B corresponding to the short side of the magnetic surfaces are required. The gross averages as obtained for negative helix current polarity are S = 20, C = 15, and D = 3 %. They are entered at the right in Fig. 3.

Regarding the possible dependence of the limiter yield on plasma parameters, some qualitative statements appear to be possible. Of interest are the kinetic energies of the charged particles at radii smaller than, but comparable to the limiter aperture. If we consider an increase of either the charged or the neutral particle density, while keeping all the other plasma parameters constant, the limiter yields are expected to be reduced because of the increased energy losses towards the wall which are caused by the increased radiation and charge exchange. Experimentally, the plasma parameters are usually interdependent. Therefore, one might choose the average drift parameters

$$\bar{\xi} = V_{dr}/V_{th} \sim \frac{I_p}{a^2 \, \bar{u} \sqrt{T}}$$

in order to correlate the observed limiter yields with plasma parameters.

+) The change from (a single observation of) B = 10 % at positive helix polarity to a larger value of C = 15 % (averaged over different conditions) qualitatively agrees with the recently observed radial stray field in W VII-A which tends to shift the plasma upwards.

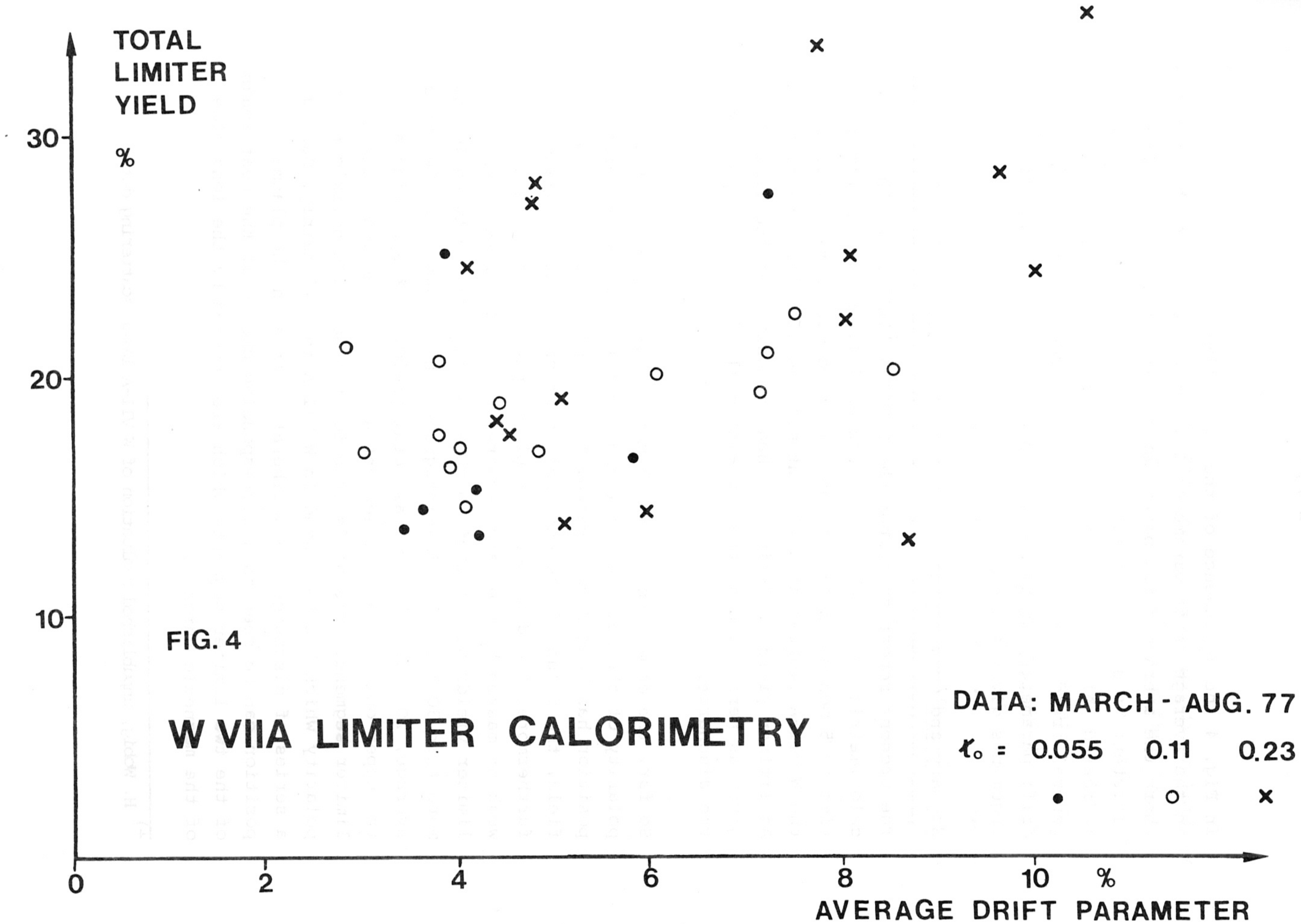


FIG. 4

W VIIA LIMITER CALORIMETRY

In Fig. 4 the dependence of the total limiter yield $f = \Sigma f_i$ on the average drift parameter $\overline{\xi}$ is shown for those observations where the average drift parameter is also available+). The different values of the external rotational transform ι_o are indicated. Although the limiter yields scatter largely, a general trend towards an increase at larger values of the drift parameter can be seen, in accordance to the qualitative arguments given above.

Summary and Conclusions

The present report describes the W VII-A limiter and the calorimetric method which has been used during an experimental time of 5 months in 1977 in an effort to obtain the yield of the W VII-A limiter at different machine and plasma parameters. As limiter yield we define the heat deposited at the limiter, given as percentage of the time-integral of the ohmic power of the discharge.

So far, the dependence of the limiter segment yield on the polarity of the helix current and the influence of the plasma position has been demonstrated. The dependence on the toroidal field, the value of the external rotational transform, and, furthermore, the dependence on plasma parameters appears to be weak or masked by the large scatter of the data. The total limiter yields of a set of 70 observations range between 10 and more than 30 % of the time-integrated ohmic power. In the gross average, 20 % are observed as total yield, 15 % appearing at the upper outside limiter segment and 3 % at the lower inside limiter segment. This holds true for the negative helix current polarity which has been used in W VII-A in 1977 mainly. During a series of discharges, a deliberate change in the plasma position can be seen as a corresponding change of the heat loads of the two limiter segments which are touched by the long side of the magnetic surface.

+) H. Wobig, unpublished evaluation of W VII-A laser scattering data.

Considering the stationary and transient temperature distributions in the limiter segment, and estimating the pertinent thermal radiation, one can neglect in the heat balance the power radiated by "hot spots" which can be present during a time comparable to the OH pulse duration of less than 1/2 s. The radiated heat due to the much lower stationary peak temperature - which is attained by a large fraction of the limiter segment and is characterized by a time constant of the order of 3 to 10 minutes - is taken into account in the evaluation of the limiter yield. This correction is less than 10 % of the observed cooling power, for the parameter range of W VII-A treated in this report.

Appendix A

Some material constants of molybdenum:

density	$\rho = 10.2\ g/cm^3$
specific heat	$c = 0.27\ Ws/gK$
thermal conductivity	$\lambda = 1.3 \cdot W/cm\ K$ for T = 300 - 600 K
thermal diffusivity	$a = \frac{\lambda}{\rho c} = 0.47\ cm^2 s$ for T = 300 - 600 K
melting point	$T_m = \sim 2900\ K$
emissivity+)	= 0.05 for T = 300 - 600 K; oxidized 0.1 for T = 1000 K
sputtering yield++) (atom/ion)	$S = 1.7\ 10^{-3}$ for H^+ at 1 keV $5 \cdot 10^{-3}$ for H_e^+ at 0.2 keV $1 \cdot 10^{-3}$ 0.1 keV
electron secondary emission++) (electron/electron)	g = 1.3 for $\bar{e}$ at 0.4 keV 0.8 0.1 0.4 0.03 0.1 0.01 0.1 for H^+ at 0.1 keV 0.7 for H_e^+ at 0.2 keV 0.7 0.1 0.3 for H_e^{++} at 0.2 keV 0.3 0.1

+) Handbook of Thermophys.Prof., Vol.I, Pergamon Press 1961

++) Atomic Data for Contr.Fus.Res., ORNL-5207, Vol. II (1977)

Appendix B

Hot-Spot Radiation of a Limiter Segment

As a numerical example for the radiated heat of a hot spot we take the discharges Nos. 6511 - 6516, where the ohmic input power P = 160 kW, the pulse time t_p = 0.4 s, the limiter yield of the segment c is f_c = 0.26 at an observed cooling power N_c = 63 W, and the cooling time between OH discharges t_k = 240 s. We assume the time of existence of a hot spot to be equal to the pulse time t_p and take as thermal emissivity ε = 0.5.

In the table below different sizes of hot spots are considered, ranging from a minimum value A_m = 6.4 cm^2 (eq. (8)) to an area 3 times as large. According to the 4th power relationship with temperature, the radiated power of this hot spot N_{hs} decreases rapidly when increasing the area. The reduced power density F determines the peak temperature T_p via eq. (6); the initial temperature $T_i \approx$ 500 K according to eq. (2).

A	F	$T_p - T_i$	$N_{hs} = 3\,A\left(\frac{T_p}{1000}\right)^4$
6.4	6.6	2450	1360
8	5.3	1960	880
10	4.2	1560	540
20	2.1	800	170
cm^2	kW/cm^2	K	W

Within a pulse time of 0.4 s the hot spot radiates approximately heat amounts ranging between 550 down to 70 J. These values are to be compared with the heat radiated during the cooling time t_K by the limiter segment at an average stationary temperature $T_s \approx T_i$ amounting to 1.3 kJ.

Consequently, the stationary radiation is taken into account in the evaluation of the data of this report, whereas the radiation of hot spots is neglected.

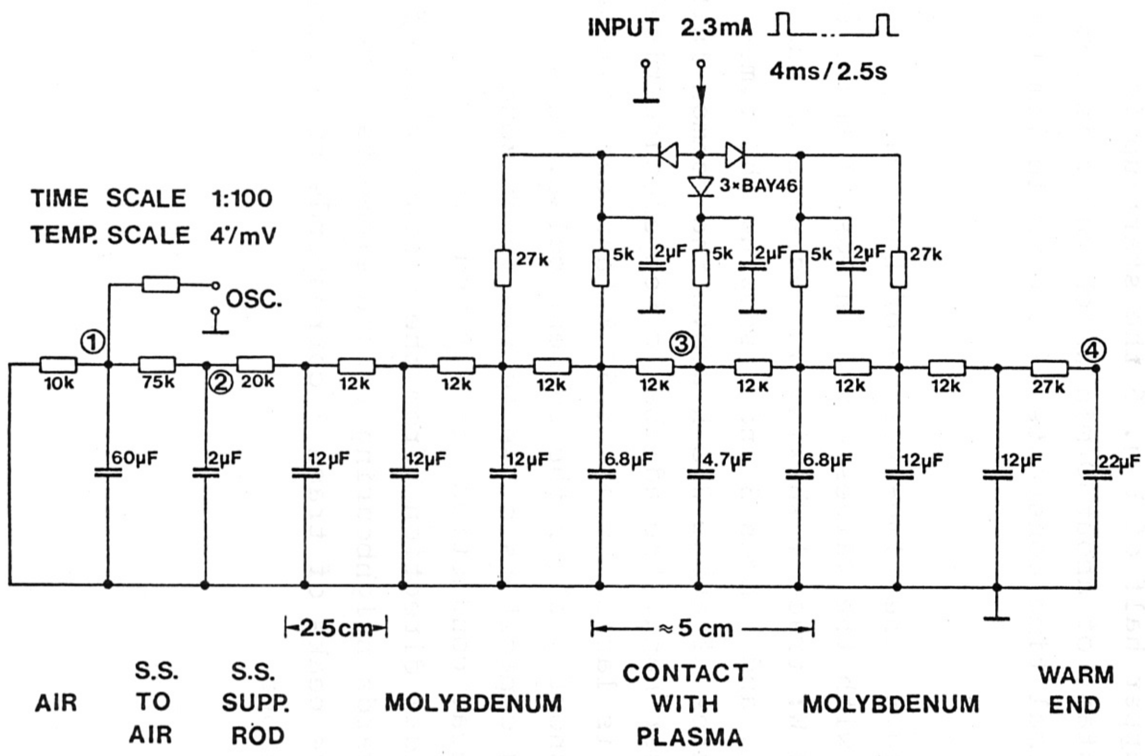
APPENDIX C

Electric Model for Transient Limiter Segment Temperature

In ref /6/ a method is described which enables one to study transient heat flow problems in complex geometry by comparatively simple RC networks, where C models the enthalpy and R the heat conduction of a volume element of the object to be studied. The transient heat load is represented by a current waveform, and the temperature by the resulting voltage which is measured at the desired grid points of the network.

In our study of the transient behaviour of a W VII-A limiter segment a scaling factor of 100 is used for time and pulses of 2.3 mA during 4 ms are chosen to correspond to Ohmic heating pulses of 10 kJ absorbed within an OH discharge of $t_p = 0.4$ s. The data of this example agree with those discussed earlier in this report and correspond to the discharges Nos. 6511 to 6516 of the W VII-A stellarator. The network describing a W VII-A limiter segment is shown in the left of Fig. 5. A limiter element 2,5 cm in length is represented by R = 12 kΩ and C = 12 μF. The OH power is taken to be distributed in the poloidal direction with a peaked center region of about 5 cm. This is modelled by the parallel pairs of input resistors (5 to 27 kΩ , resp.).

The current source is decoupled by diodes. Between the contact zone with plasma and the far end of the limiter segment the network grid can be coarse, R = 27 kΩ and C = 22 μF corresponding to a length of 5 cm of the limiter segment. The short piece of stainless steel support rod towards the heat exchange area is modelled by 20 kΩ and 2 μF. In series to it resistors of 75 kΩ represent the temperature difference across the boundary sheath of the streaming air and 10 kΩ are chosen to match the temperature increase of the cooling air at a transfer rate of 3 l/s. The comparatively large capacitor of 60 μF represents the enthalpy of the whole support rod plus the rubber air supply tubes.



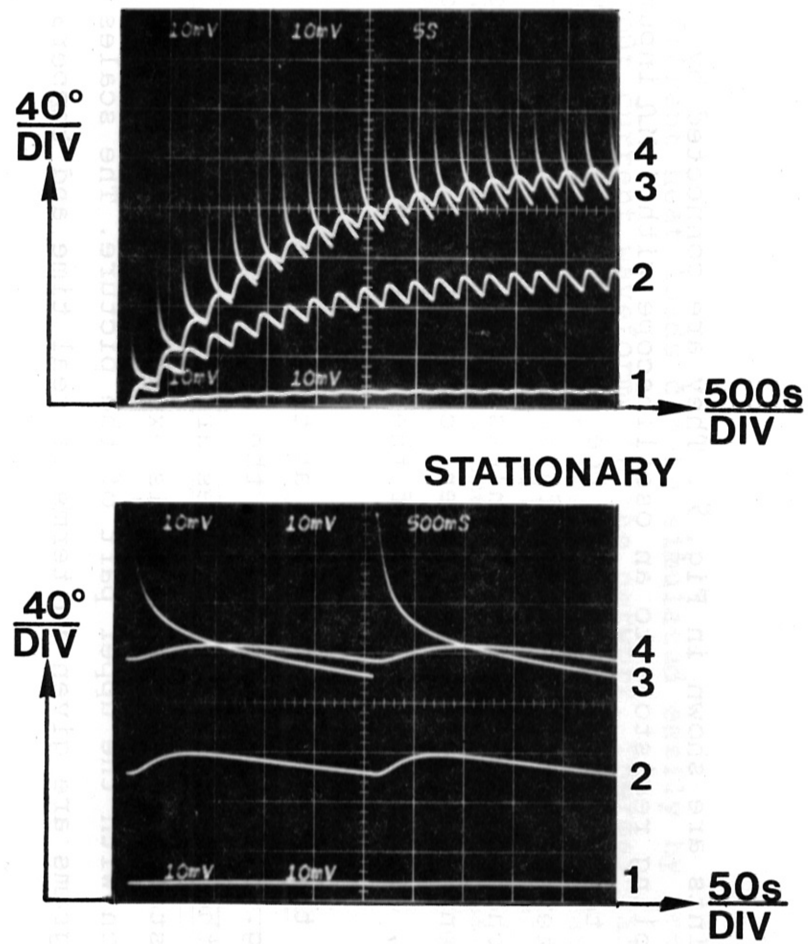


FIG. 5

TRANSIENT LIMITER TEMPERATURES - ELECTRIC MODEL

1 AIR
2 S.S. SUPPORT ROD
3 CONTACT WITH PLASMA
4 WARM END

Four test points are shown in Fig. 5 . They are connected by 10 MΩ decoupling resistors to an oscilloscope with 1 MΩ input, as shown at test point ①, which is the image of the air exhaust of the limiter segment. The three further test points refer to the heat exchange area of the stainless steel support rod, to a volume element of the limiter segment close to the contact zone with plasma, and to the warm end of the limiter segment.

Examples of the waveforms obtained at these test points are also shown in Fig. 5. In the upper half the start-up behaviour is shown, whereas in the lower half two pulses are to be seen during stationary state. Here, the sweep is expanded by a factor of 10 in comparison with the upper part of the picture. The scales of the oscillograms are given in terms of real time and temperature.

As can be seen in the upper half of Fig. 5 the start-up is governed by a time constant of about 10 min which value is comparable to τ_3, the thermal time constants of the whole limiter segment.

In the lower half of Fig.5 the time-average of the traces 1, 3, and 4 agree quite well with the values given in eqs. 1 and 2 of this report for N_i = 63 W: trace 1 showing an increase of the air temperature of 16 K, and traces 3 and 4 showing the time-averaged peak temperatures of about 200 K above the common initial temperature. On the other hand, the adiabatic temperature rise of δT_a = 220 K (eq. 4) is larger by about 60 % than the voltage peaks seen at trace 3 shortly after the current pulse. This is due to the neighbouring capacitors close to the input zone whereas in eq. 4 no heat conduction is assumed to be present in the poloidal direction from the contact zone of the limiter segment towards neighbouring volume elements. The rise-time of the voltage peaks of trace 3 corresponds to a time of 2 s $\approx \tau_1$, as given above.

Different heat loads can be simulated easily by appropriate input current waveforms in the network. Thermal radiation has not been included in the limiter network so far. It would be possible using voltage-dependent resistors and/or diodes which could model the relationship of radiated power proportional to T^4.

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