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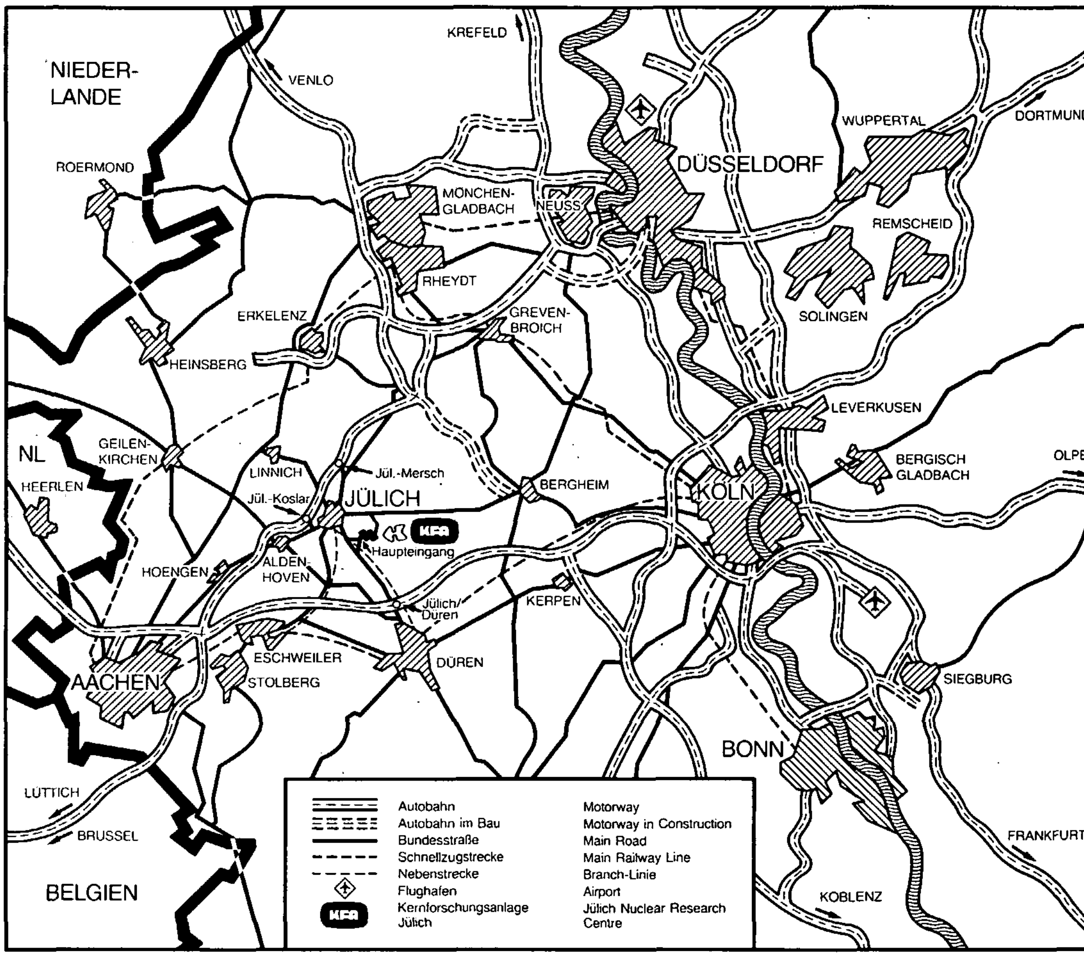

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Abstract

Materials of the First Wall in near-fusion plasma machines are subjected to a complex load system resulting from the plasma-wall interaction. The materials for their part also influence the plasma. Suitable materials must be available in order to ensure that the wall components achieve a sufficiently long dwell time and that their effects on the plasma remain small and controllable. The present report discusses relations between the plasma-wall interaction, the reactions of the materials and testing and examination methods for specific problems in developing and selecting suitable materials for highly stressed components on the First Wall of fusion reactors.

Contents

1. Introduction

Materials for the highly stressed components of the First Wall of fusion reactors are subject to plasma-wall interaction. This concept includes a series of load mechanisms which have a negative influence on both the plasma and the materials /1, 2/.

These mechanisms and the resulting changes and damage to the materials already limit the life of highly stressed components of the First Wall in those TOKAMAKs currently in operation. With the further approximation of TOKAMAKs to real fusion conditions in extended versions of present facilities - JET, JT 60, TFTR, TORE SUPRA -, and in particular in the next generation of machines - NET, DEMO, STARFIRE - the materials currently used in direct contact with the plasma will no longer be able to be applied: high-temperature metals and metallic alloys /3, 4/ - for example vacuum vessels and liners of stainless steel, limiters of Fe- or Ni-base alloys without protective layers against direct plasma-wall interaction - contaminate the plasma as middle-Z materials. Graphites /5, 6/ - currently frequently used for limiters and armor tiles - are damaged with respect to their thermal and mechanical properties by the high fluxes of the 14-MeV fusion neutrons and their geometrical dimensions changed. Furthermore, most graphites would probably have an unfavourable effect on "hydrogen recycling", i.e. the "scheduled" hydrogen adsorption and release.

Thin protective coatings applied externally to the components of the First Wall - e.g. TiC on graphite /7/ or TiN on INCONEL - would also probably hardly satisfy the necessary requirements on the materials, especially for limiters. It is therefore imperative to develop new materials with sufficiently good behaviour during plasma-wall interactions and moreover with good irradiation behaviour, and to test them in appropriate laboratory tests (out-of-pile), in plasma machines (TOKAMAK-in-pile), for example in the KFA TEXTOR TOKAMAK /8, 9/, and in a neutron flux, for example the HFR Petten.

The initial results of such studies show that thick low-Z coatings (sacrificial layers) on actively cooled substrate materials or optimized ceramic-metallic composite systems (CERMETs) are suitable as materials for the plasma contact on highly stressed components of the First Wall. A further promising concept consists of using thin protective coatings, which can be generated and regenerated in situ.

The materials, material tests and results of studies discussed in the following must ultimately - insofar as this does not involve materials for the vacuum vessel or the liner - also be considered from the aspect of active coolability of the respective component.

2. Plasma-Wall Interaction

The type and intensity of the plasma-wall interaction depends on the one hand on the component itself - vacuum vessel, liner, limiter -, but on the other hand also on the operating state of plasma. Interactive mechanisms affecting the vacuum vessel or, for example in the case of the TEXTOR TOKAMAK, the liner, under all operating conditions are

- continuous erosion (sputtering) /10, 11/ by high-energy neutron particles, ions and electrons,

- chemical interaction between the plasma and the First Wall, or its alloying constituents; a typical process is the reaction of hydrogen and carbon to methane (chemical sputtering) /12, 13/ at the surface of the graphite internals (limiter, armor tiles),

- erosion and evaporation of First-Wall materials by unipolar arcing /14/, and

- thermal fatigue /15/ by the pulsed transport of thermal energy in the case of TOKAMAKs.

The vacuum vessel or liner and active components of the First Wall, e.g. high-frequency antennas for the ion cyclotron resonance heating, ICRH, /16/, are protected by limiters /17, 18/ against direct plasma contact. This is particularly true of unstable plasma states or of plasma states with low particle densities. These thermally highly stressed components are subjected to the same interaction processes as the vacuum vessel and liner during normal operation of a fusion reactor.

However, the effects on the materials of the limiters are considerably more intensive even in normal operation since the main limiters (passive limiters or pump limiters) /19/ extend into the boundary layer of the plasma. During plasma instabilities or during plasma states with low particle densities the following can occur:

- thermal shock load through plasma disruption /20/ and

- thermal shock loads, material melting and evaporation through high-energy, so-called "run-away" electrons /21, 22/.

Furthermore, selective erosion or evaporation at the surface of the First-Wall components can cause changes which influence, for example, heat transfer or erosion behaviour. The same is true of the redeposition of evaporated material from a plasma, whereby surface layers of different chemical composition and/or different morphology can arise on the First Wall and its components.

In order to ensure that new materials for highly stressed components of the First Wall behave more favourably under the loads mentioned above than those previously used they must be tested and studied under conditions which are also realistic from the aspect of longer pulse duration and higher energy contents of the next generation of TOKAMAKs. The materials, material tests and test results presented in the following are therefore considered from this point of view and preferably for application for actively cooled limiters.

Some mechanisms of plasma-wall interaction are not taken into consideration in this discussion. They will be mentioned here but not further discussed in the course of this representation. These include:

- the short-term ability of the surface of the First Wall to store hydrogen which is favourable to a certain extent for stable plasma shots, especially for concluding the pulse without disruption (soft landing) /23/,

- influencing the material properties by implanting helium /24, 25/, the "ash" of fusion reactors, and finally

- changing the material properties by irradiation with high--energy fusion neutrons (14-MeV neutrons) /26/.

It must be noted that sources sufficiently intensive for 14-MeV neutrons will not be available in the foreseeable future. The necessary irradiation experiments must therefore in the interim be carried out in high-flux material test reactors, e.g. in the HFR Petten/Netherlands.

3. Plasma-Induced Material Damage

The structural changes and damage induced by near-fusion plasma in the materials of the First Wall of TOKAMAKs, depending on the operating state of the plasma, can be divided into individual processes, Fig. 1:

During normal operation of a plasma machine material is eroded from the First Wall and its components by neutral particles, ions and electrons, Fig. 2, 3. Unipolar arcs, microscopically small arcs, are formed between the plasma boundary layer and the surface of the components of the First Wall. They can move over the surface of the material vertically to the magnetic field lines. In doing so they locally melt and evaporate the material thus forming craters and chains of craters in the surface, Fig. 4, /31/. Molten material may be sputtered over adjacent sectors.

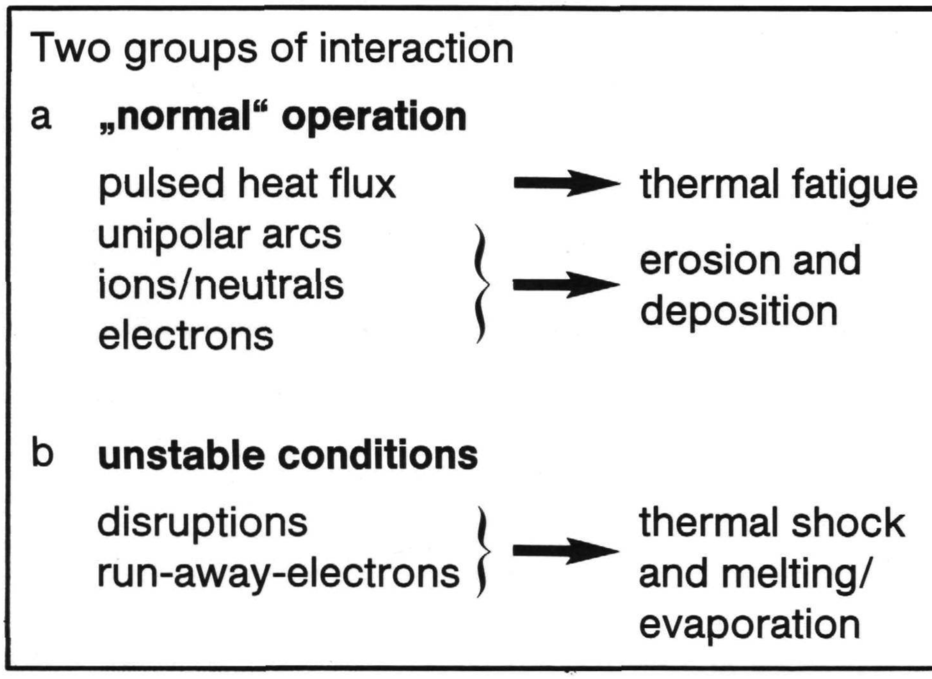


Fig. 1:
Classification of plasma states and effects on materials due to plasma-wall-interaction

Evaporated or eroded material from the First Wall can either be redeposited immediately or reaches the plasma, is transported in the plasma and deposited at other locations in the plasma chamber.

The pulsed energy flux of a TOKAMAK thus eventually leads to fatigue of the materials. Thus for example in TEXTOR the surface temperature of the poloidal main limiters can increase through plasma pulses from the lower equilibrium temperature of the order of magnitude of 300 - 400 °C at the beginning of an operating period to over 1000 °C and then drop again during the following pulse interval, Fig. 5a, /27/. The maximum surface temperature rises during a fairly long pulse sequence since with passive cooling the pulse intervals are not sufficient to cool the limiter down to the intitial state, Fig. 5b, /67/.

Disruptions or run-away electrons can occur during unstable plasma states. The run-away electrons can achieve energies of

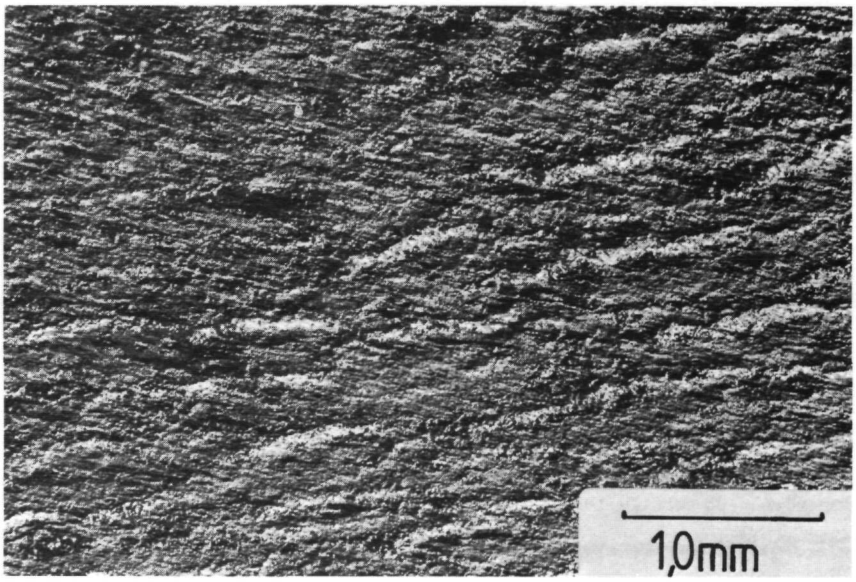


Fig. 2:
Surface area of INCONEL-600-limiter in TEXTOR after erosion by ions (ion drift side)

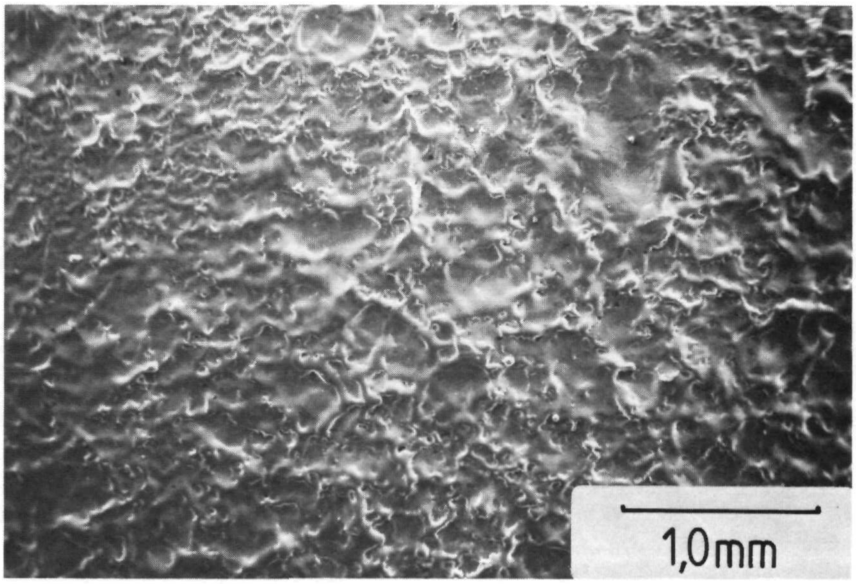


Fig. 3:
Surface area of INCONEL-600-limiter in TEXTOR after erosion by electrons (electron side)

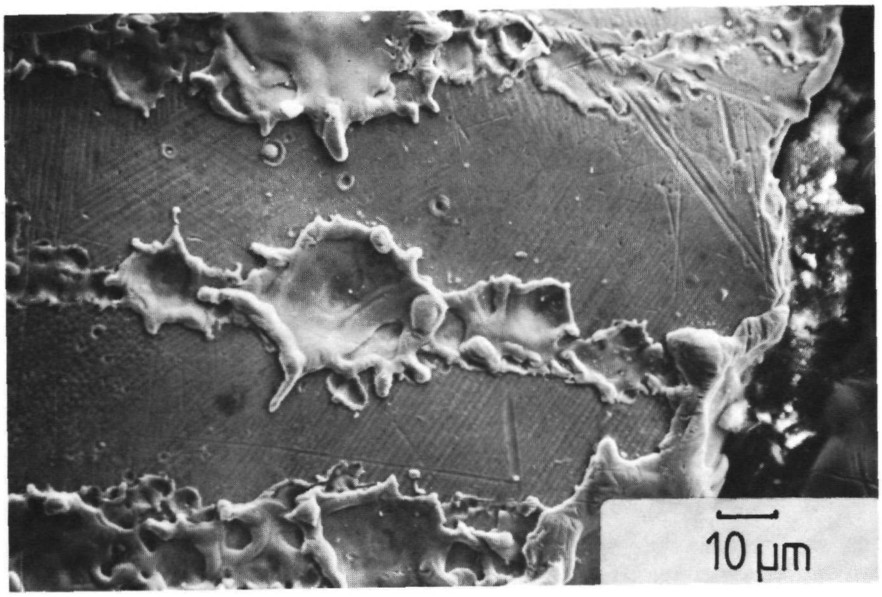


Fig. 4:
Arcing traces on the surface of an INCONEL-600-limiter after operation in TEXTOR

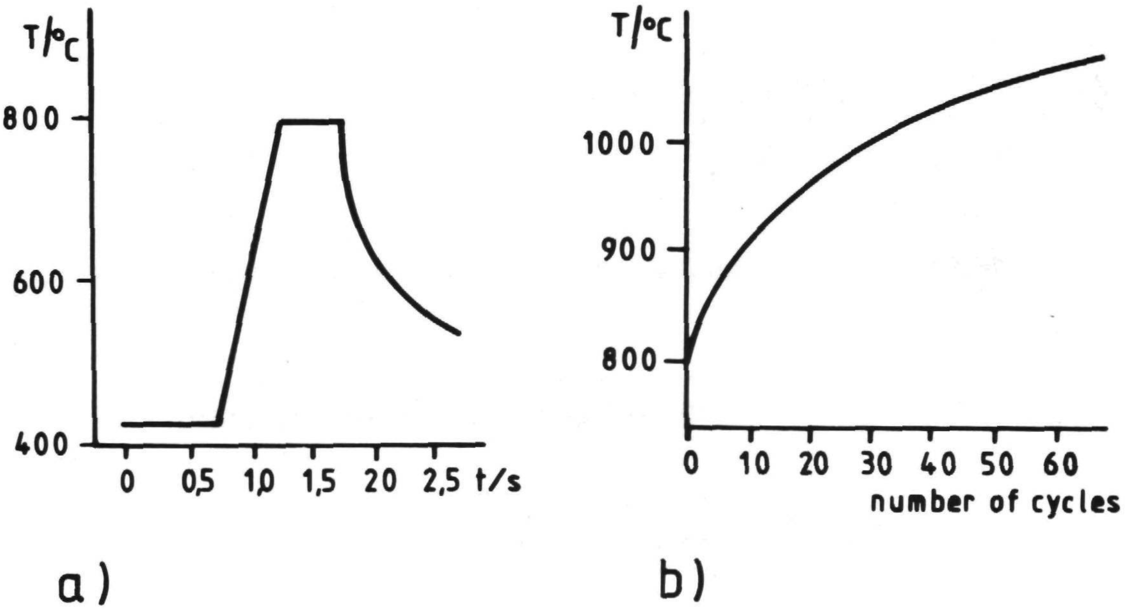


Fig. 5:
Surface temperature of a passively cooled metallic limiter,
a) during first plasma pulse
b) increase of peak temperature as a function of plasma pulses
- pulse duration 1.5 s, cool down time between pulses 300 s -.

several MeV by an acceleration during plasma states of low density /21/. They exert a load on the limiters and protective devices of the First Wall.

The plasma energy, or at least a large fraction of it, is shock deposited during plasma disruptions for the most part onto the inner limiters and protective devices /21, 22/. Due to the thermal shock loads, disruptions and run-away electrons cause considerable stresses in the material which can lead to cracking in the material surface, Fig. 6. Moreover, the material in the central area of high thermal load melts and evaporates. The melts are recrystallized, Fig. 7. Due to shock heating of the material and cooling immediately occurring by heat dissipation into the relatively cool surrounding material, recrystallization takes place without a perceptible heat affected zone resulting, Fig. 8.

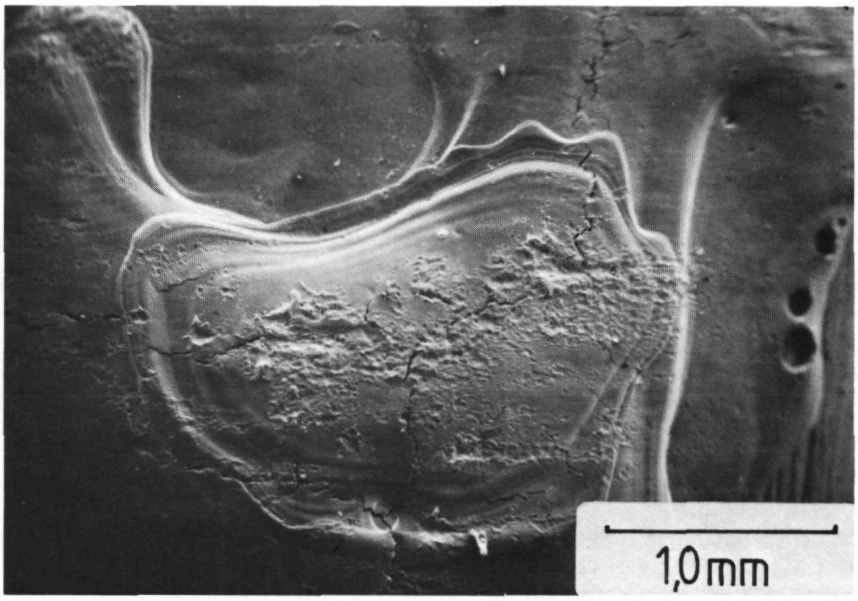


Fig. 6:
Molten surface area and cracks caused by thermal shock in an INCONEL-600-limiter from TEXTOR due to run-away-electrons

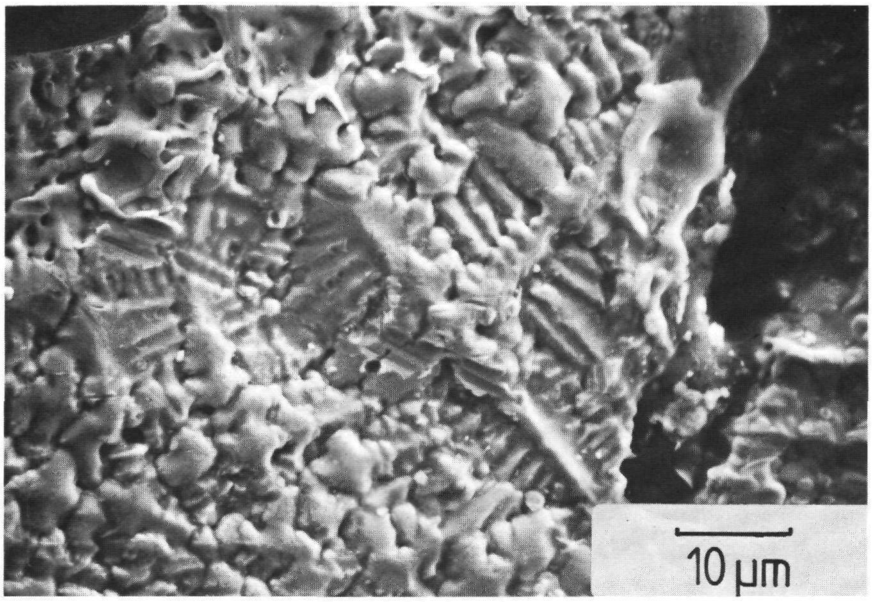


Fig. 7:
Recrystallized surface area of an INCONEL-600-limiter from TEXTOR after thermal shock melting

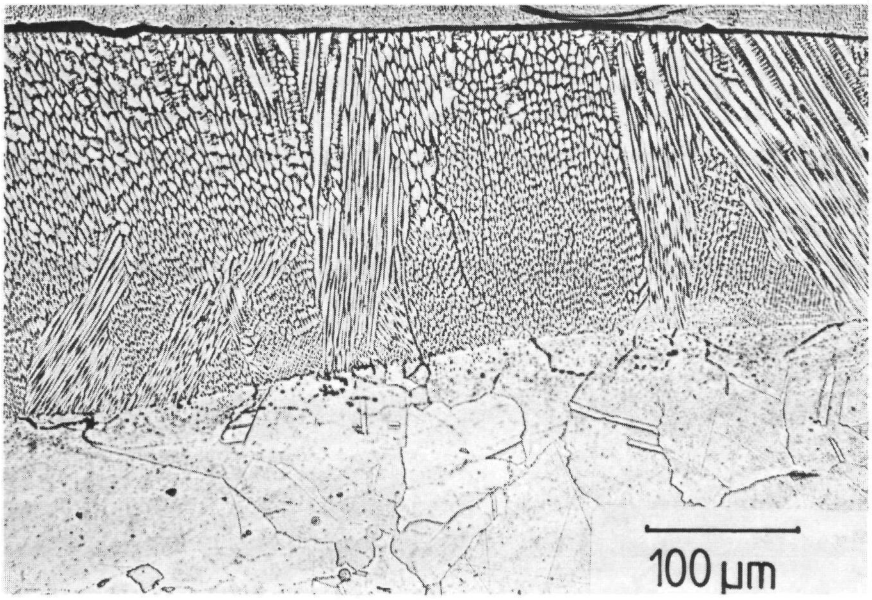


Fig. 8:
Metallographic section through recrystallized surface area after melting by thermal shock in TEXTOR

Erosion and evaporation transport material from the First Wall into the plasma. This material is redeposited on the First-Wall components in the form of droplets or thin layers /28, 29, 30/. If such a film is subsequently briefly heated, for example by loading due to unipolar arcing, then the film can agglomerate into droplets, Fig. 9, 10 /31, 32, 33, 66/. However, the re-deposited material can also penetrate into the material in regions of near-surface grain boundaries and cracks and "impregnate" them, Fig. 11, /66/. Both processes are depicted schematically in Fig. 12a. The droplets can be measured with respect to their geometrical parameters with the aid of a coupled system consisting of a scanning electron microscope and an automatic image analyzer. This is shown in Fig. 12b for the size distribution of the droplet volume.

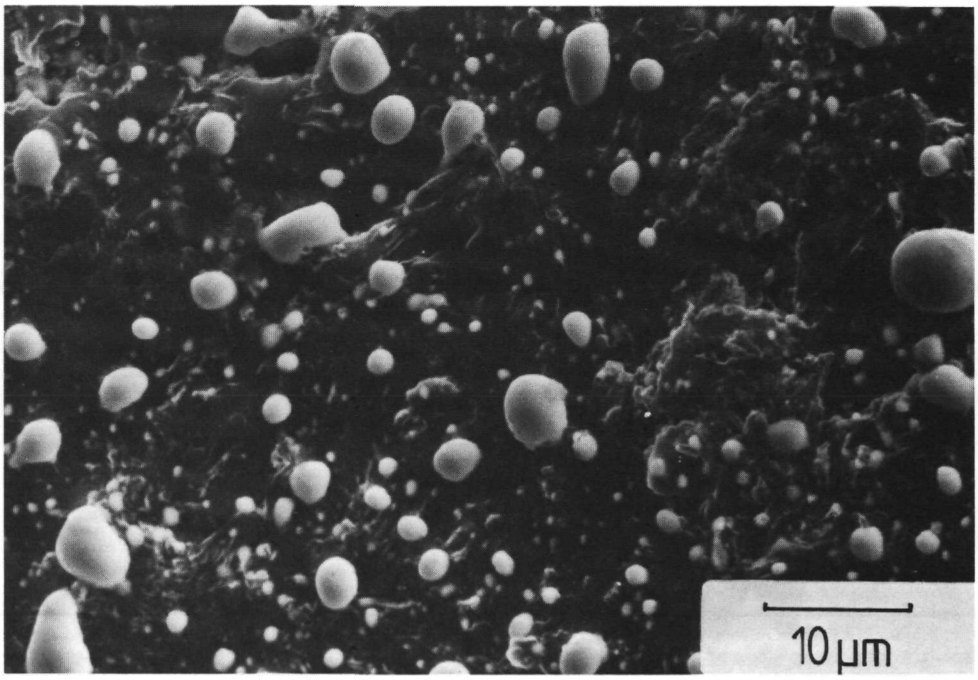


Fig. 9:
Metal droplets on the surface of a graphite sample (graphite type EK 98, Ringsdorff) after in-pile-test in TEXTOR

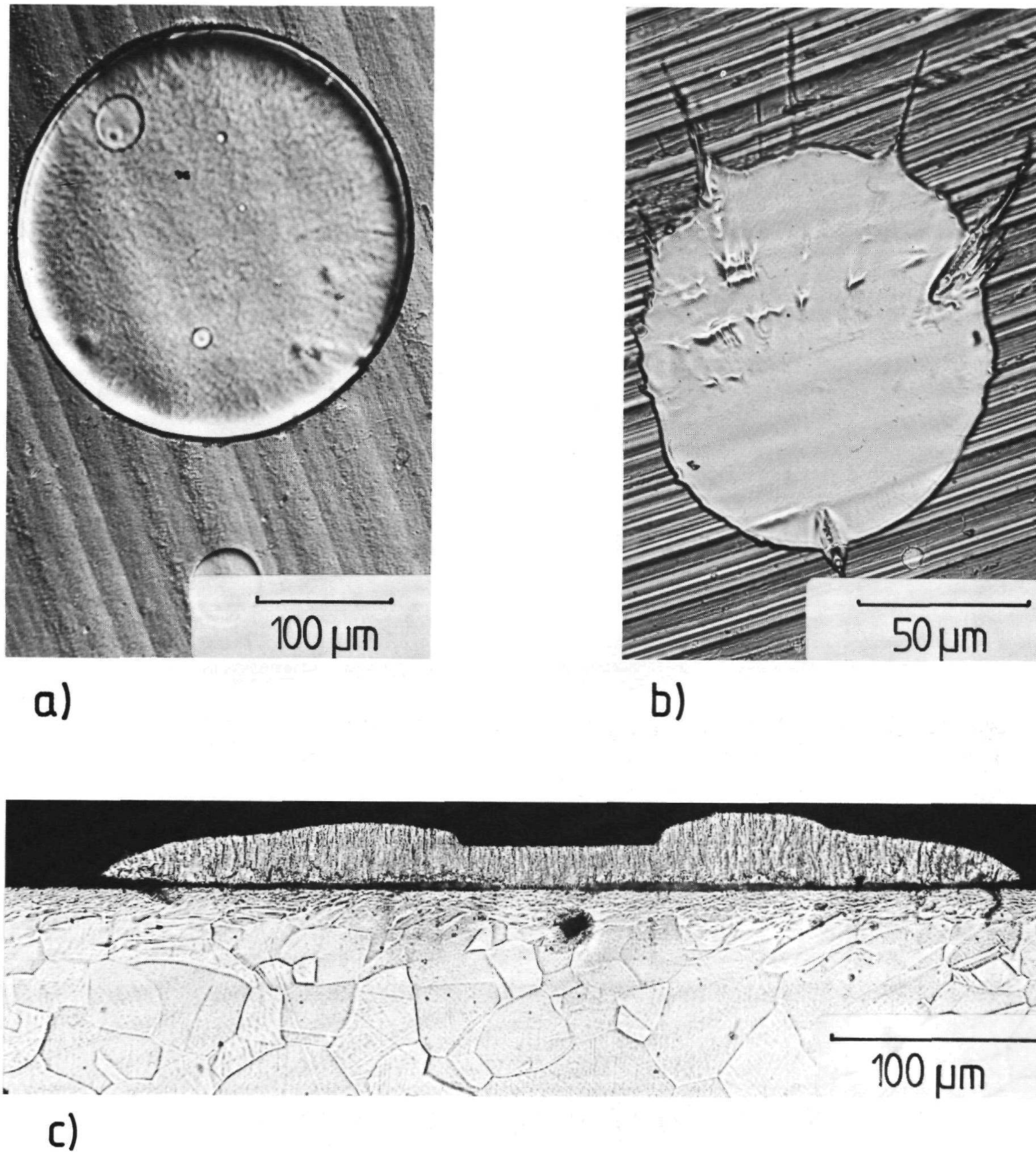
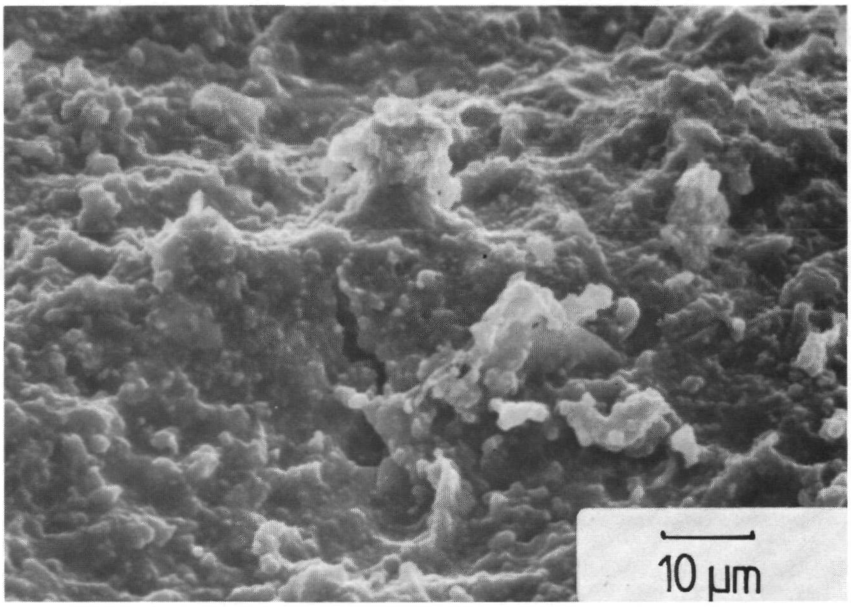
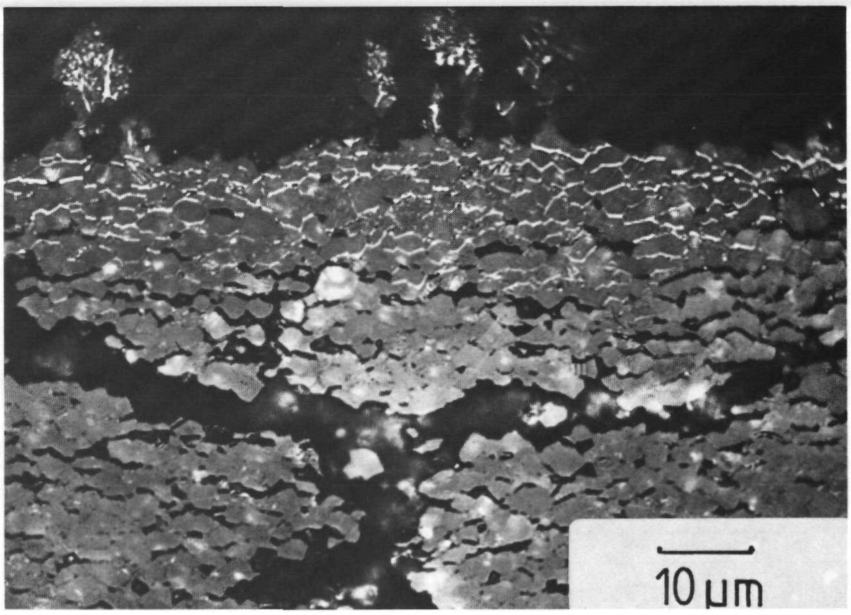


Fig. 10:
Metal droplets on long term samples in the first wall of JET (a,b) and etched metallographic section through such a droplet (c)

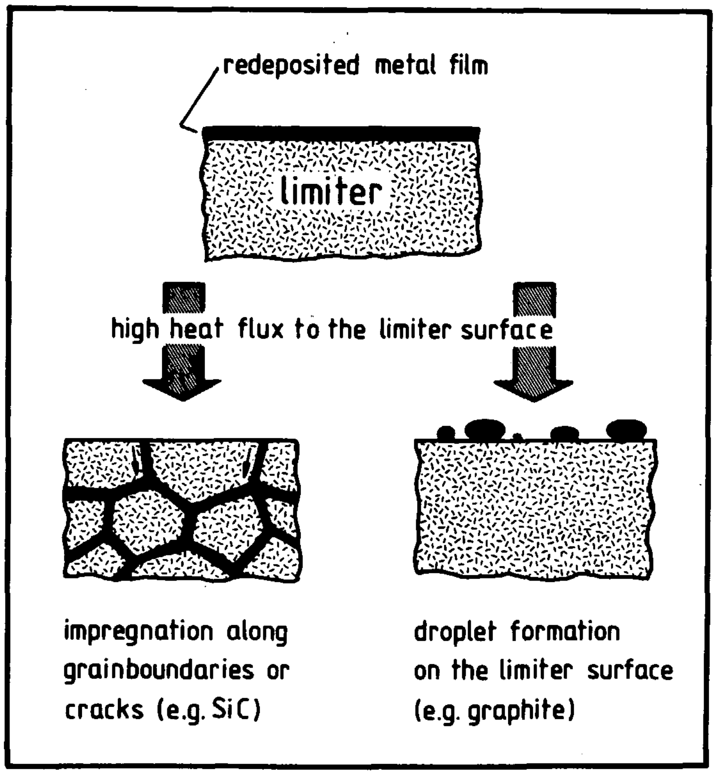


a)

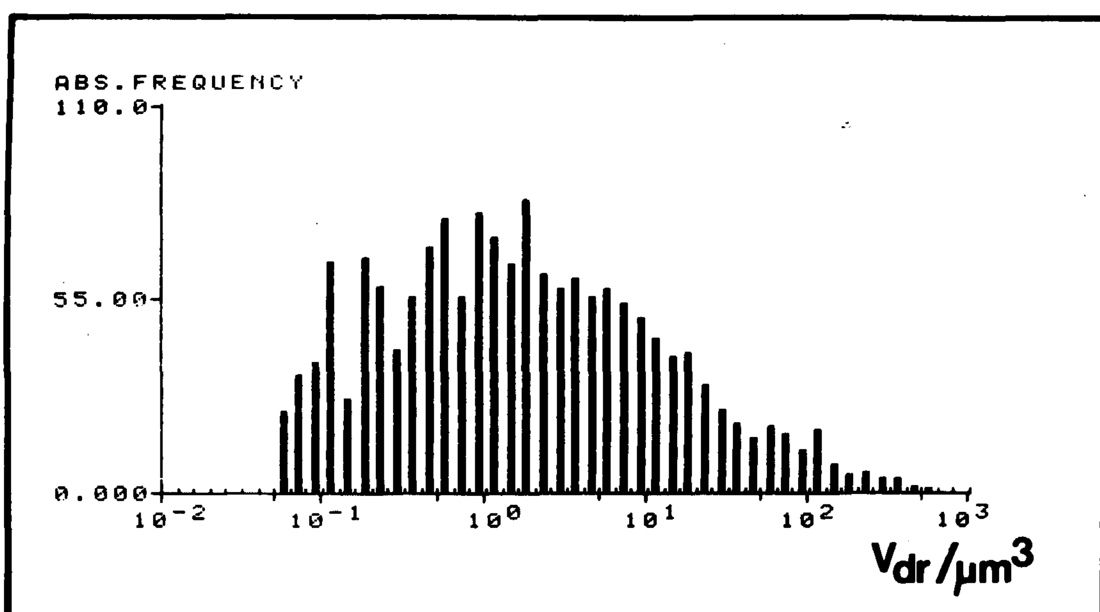


b)

Fig. 11:
Surface cracking and impregnation by redeposited metallic material in a SiC + 2 % AlN sample after in-pile-test in TEXTOR
a) SEM-image, front face
b) ceramographic cross section



a)



b)

Fig. 12:
Schematic figure of impregnation or droplet formation after deposition and heating of a surface film (a). Size distribution of redeposited droplets (b)

Which of the two processes occurs during heating of a redeposited film, either agglomeration or surface impregnation, may possibly depend on the interfacial tension between the film and substrate material, on the open porosity and surface cracking. Both processes have been realized in laboratory experiments. Particular attention was paid to the important role of interfacial tension for the occurrence of agglomeration. Details of this cannot be discussed within the framework of the present report. They are presented in a different publication /68/.

The thermal and mechanical properties of the material surfaces or near-surface regions of the First-Wall components are negatively changed by the described processes of plasma-wall interaction. Furthermore, damage to the material can also intensify the plasma-wall interaction. For example, metallic droplets deposited on the surface of a highly stressed component can cause accelerated local erosion. This can be seen by the severe erosion or etching zones caused by the flow of ions or neutron particles from the plasma to the First Wall in the immediate vicinity of the metal droplets. If the particle flow is aligned, for example in the region of a neutron beam injector (NBI), then the etching structures are also oriented. This is e.g. true of the accelerated erosion of TiC-coated graphite armor tiles at the location of the so-called "shine through" of an NBI, Fig. 13b. A "droplet model" serves to demonstrate the increased, oriented erosion /31/, Fig. 13c.

Large redeposited metal droplets can also be the starting point for increased occurrence of arcing. This was for example established on the JET graphite limiters, Fig. 14.

The erosion and evaporation of First-Wall materials do not necessarily affect all alloying constituents of the material used to the same extent /34, 35, 36/. Thus from titanium carbide layers used as protective coatings on graphite components (limiters, armor tiles) titanium is preferentially dissolved and transported into the plasma. The same is true of chromium from metallic alloys containing chromium, for example, Fe- and Ni-base alloys.

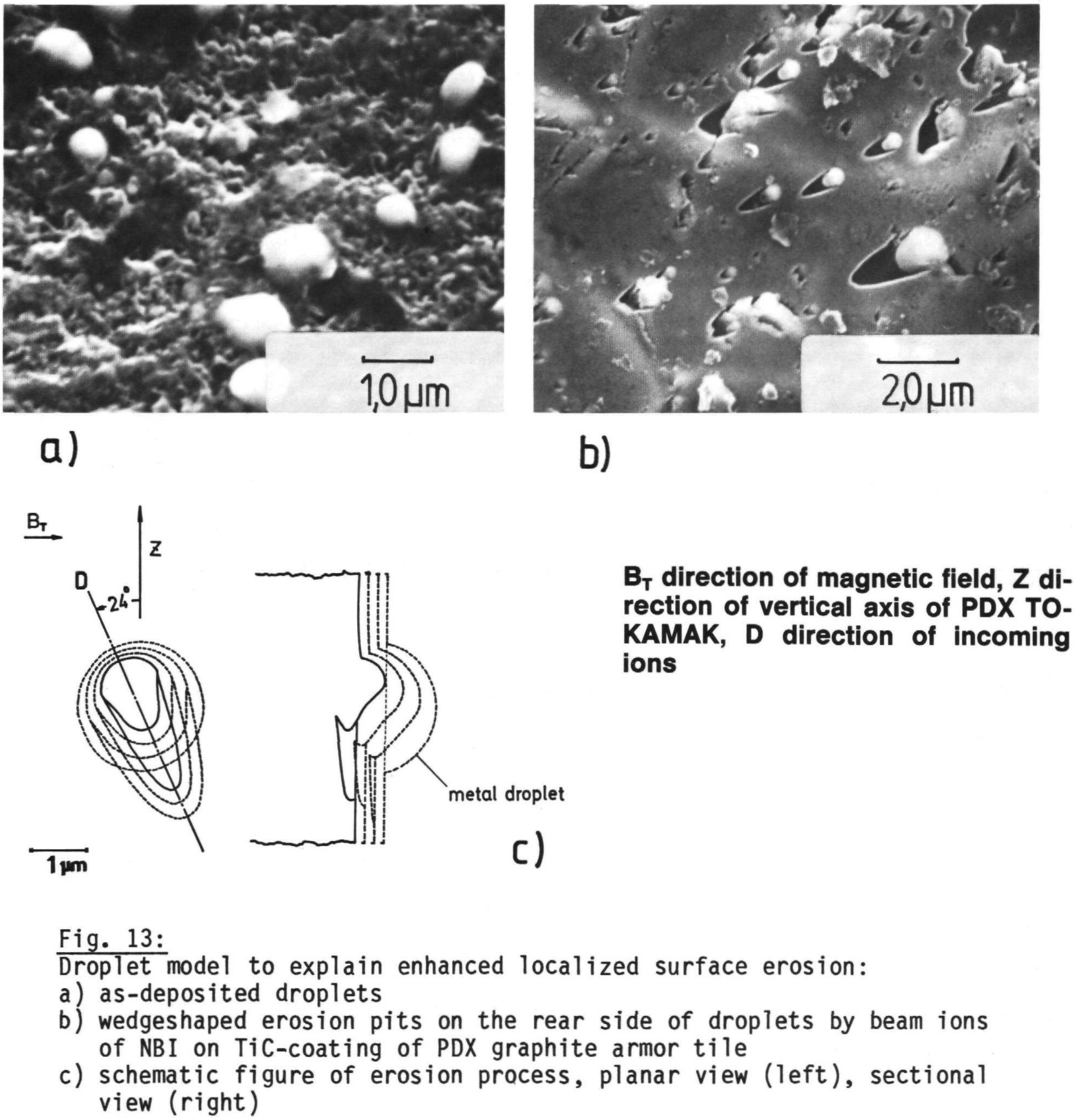


Fig. 13:
Droplet model to explain enhanced localized surface erosion:
a) as-deposited droplets
b) wedgeshaped erosion pits on the rear side of droplets by beam ions of NBI on TiC-coating of PDX graphite armor tile
c) schematic figure of erosion process, planar view (left), sectional view (right)

It cannot yet be said which factors influence such a preferential erosion of individual alloying constituents - thermal stability of the carbides, steam pressure of the metallic constituents,etc.

A deposition of metallic alloying constituents, such as chromium, from the plasma onto uncoated graphite components apparently leads to the formation of thin metal-metallic carbide films /37, 38, 39/. This could be the reason why the high graphite erosion rates originally expected do not occur in practice due to suppression of chemical sputtering.

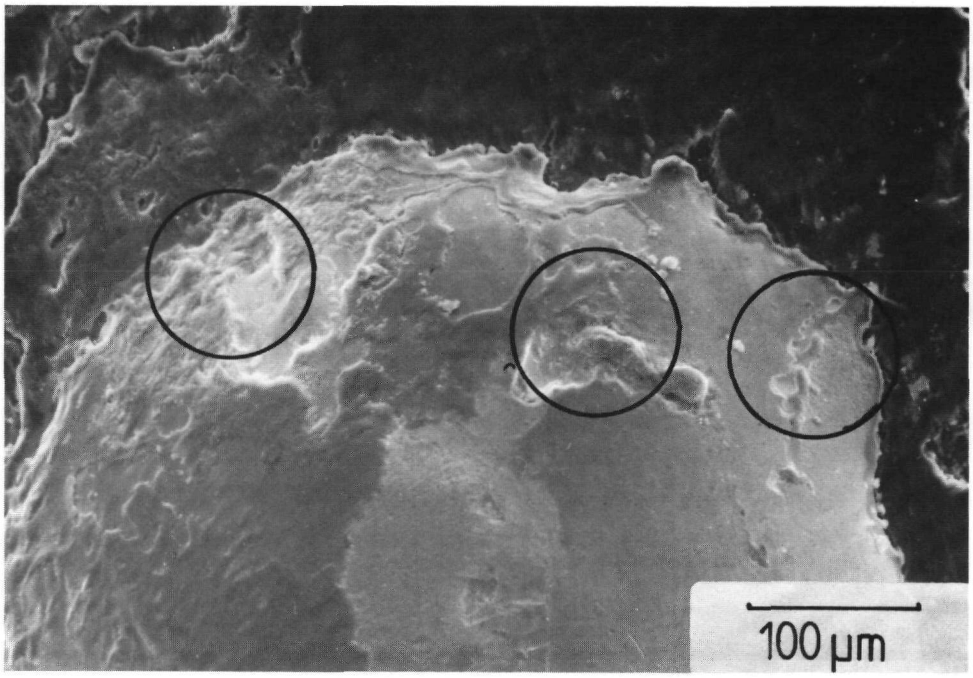


Fig. 14:
Metal droplet on the surface of a JET graphite limiter with arcing traces starting on it (marked by circles)

4. Materials for Highly Stressed Components of the First Wall

As discussed in detail, plasma-wall interaction damages the materials of the First Wall of TOKAMAKs operating at near fusion. The plasma is contaminated with impurities by erosion of the materials. The interaction processes and thus the plasma-induced materials damage are most severe in the case of the highly stressed components of the First Wall, i.e. for example the limiters.

Amongst others Ni- and Fe-base alloys and coated or uncoated graphites are currently used for limiters. Graphites, with and without protective coatings, are also used in fabricating other highly stressed components of the First Wall, such as armor tiles for shielding the inner wall of the torus against that part of the neutral particle beam penetrating the plasma (shine through). The externally applied protective coatings currently used are thin layers a few 10 µm in thickness. A typical example of this is TiC coatings on graphite limiters and armor tiles.

By the example of the originally unintentional formation of chromium carbide layers on graphite components it was demonstrated that extremely thin surface coatings can have a positive influence on plasma-wall interaction. This is at least true if the components thus coated "in situ" are not subjected to any extreme loads, such as through plasma instabilities. These thin protective coatings or films to be applied "in situ" /40, 41, 42/ have attracted special attention in recent years.

"In situ" does not here primarily mean "during the plasma shots", as is the case for the formation of the chromium carbide layer mentioned above. It rather means that suitable surface films can be deposited on the First Wall without opening the vacuum vessel, or can be fabricated in combination with chemical reactions at the surface of the components. These films are no more than a few 100 A in thickness. If reactive material is deposited, for example carbon or hydrocarbon groups during so-called "carbidization" in TEXTOR /40, 43/, the coating material can enter into a chemical compound with the substrate or wall material by means of a chemical reaction.

The necessary prerequisites for the effectiveness of in-situ coatings or the resulting compounds are firm adhesion of the layers to their substrates under all TOKAMAK operating conditions and erosion behaviour clearly superior to the uncoated material under plasma-wall interaction. In such cases these surface films can provide effective protection of the First Wall against erosion on the one hand and on the other hand protect the plasma against contamination. They can moreover have a favourable effect on hydrogen recycling.

However, in-situ coating is probably not sufficient for thermally highly stressed components of the First Wall, especially during unstable plasma states, i.e. under the effect of disruptions or run-away electrons. This is the more valid the higher the values of the plasma energy, plasma pulse duration and plasma density rise, that is the higher the power density at the surface of the components becomes. A suitable solution to these problems could possibly be thick coatings also applied and repaired in situ by appropriate methods such as low-pressure plasma spraying (LPPS).

Nevertheless, it must be noted that on the basis of experience with graphite in fission reactors /44/ the application of this material in fusion reactors appears very doubtful. The energetic neutrons of the fission reactors (max. 2 MeV) already impair all relevant properties of the graphites. For example, the thermal conductivity of a graphite is considerably reduced by the neutron-induced radiation damage, Fig. 15a. The radiation-induced changes in dimension, Fig. 15b, with their effects on the strength and adhesion to cooled metallic substrates must not be neglected either. These considerations possibly also apply to an increased extent to changes of material properties caused by high-energy fusion neutrons (max. 14 MeV).

A consideration of the neutron-induced property changes will possibly already become necessary for some TOKAMAKs currently in operation. In Europe, for example, this affects the extended version of JET and in the USA the TFTR. This will increasingly affect the next generation of facilities, e.g. the European NET machine.

By way of summary it can therefore be said that a new material with improved properties, especially for limiters, must fulfill, among other, the following conditions:

- Its thermal shock behaviour under bombardment by neutral particles, ions and electrons must, if possible, be as good as that of graphite.

- The thermal conductivity should be at least as high as that of graphite or of the metallic alloys previously used.

- A good heat-conducting or heat-transferring connection must be established between the material in direct contact with the hot plasma and the actively cooled substrate materials.

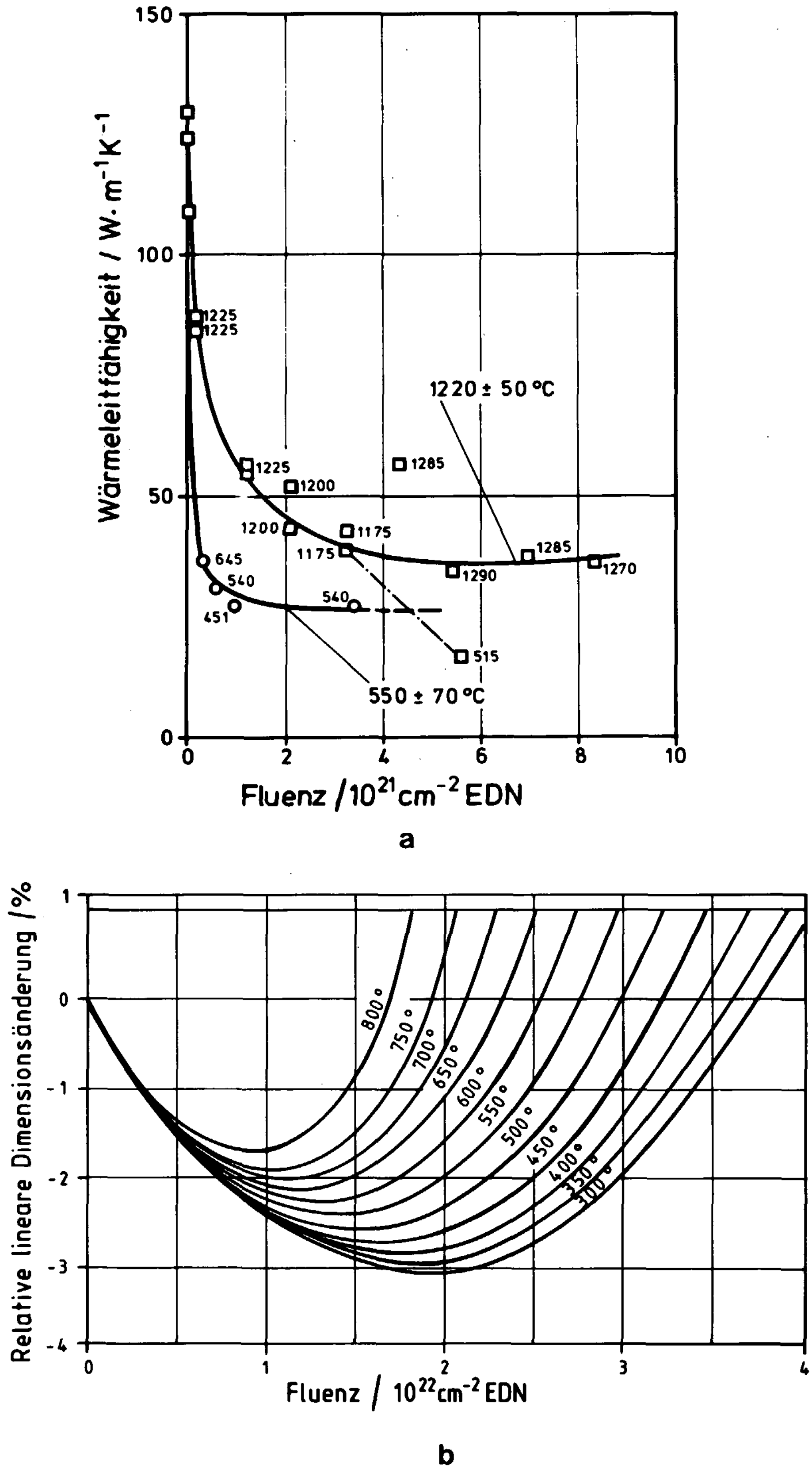


Fig. 15:
Neutron irradiation effects on graphites:
a) decrease of thermal conductivity (Gilsonite; therm. conductivity at room temperature)
b) relative dimensional changes (pitch coke graphite; parallel to grain orientation)

This joining layer must retain its good thermo-mechanical properties under the loads mentioned above.

- Material erosion into the plasma, the sputtering yield by physico-chemical processes during bombardment of the material surface with high-energy particles and erosion by unipolar arcing must be sufficiently small. This is particularly valid if medium- or high-Z materials are used.

- A possible interaction between the initial material and the redeposited material must not have a negative influence on the behaviour of the First Wall components.

- The new material must not store any large amounts of hydrogen for long periods of time or must be capable of being "sealed" against hydrogen by suitable coatings. Nevertheless, a sufficiently good short-term storage of hydrogen must be possible for the soft landing (hydrogen recycling).

- The incorporation of helium into the materials must not lead to inadmissably strong negative influence on material properties (blistering, material embrittlement).

- Finally, the irradiation behaviour of an improved material must be good with respect to erosion and thermal, mechanical and geometrical properties.

A very important task as part of the development of fusion reactor materials is the definition relevant to the problem of the concepts used such as "good properties", "good behaviour", "sufficiently small" etc. This means that within the framework of a kind of "material specification" both the different types of load, requirements on the materials, relevant material properties and meaningful testing and characterization methods must be determined quantitatively if possible, Fig. 16, /45, 46, 47, 48/.

The decisive task in the search for material for the First Wall of fusion reactors, especially for thermally highly stressed components of the First Wall, must therefore be aimed at selecting or developing material fulfilling the conditions listed above.

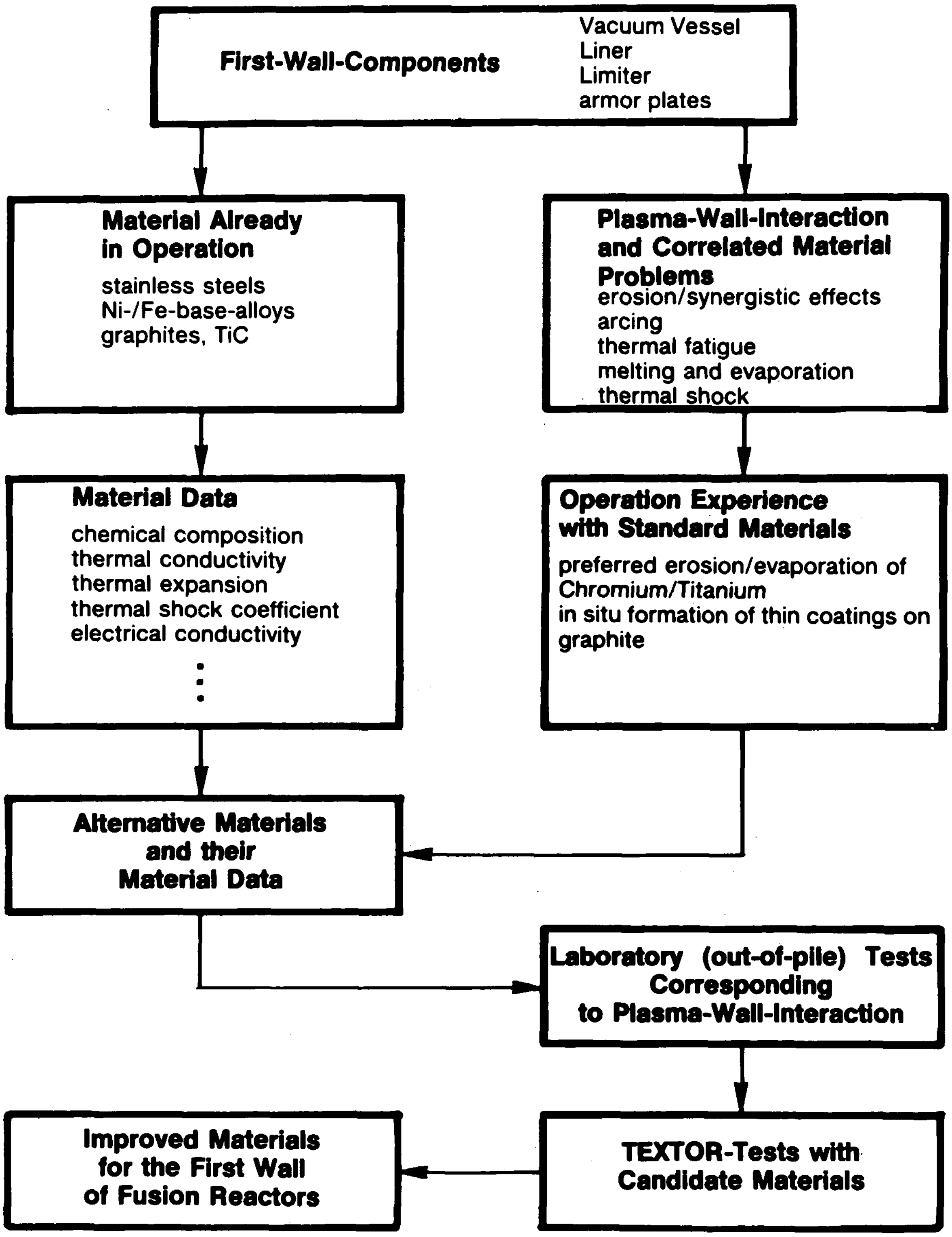


Fig. 16:
Plasma-wall-interaction and material specification system for materials for the first wall of plasma chambers of fusion reactors

5. Load Tests and Material Studies

The behaviour of possible new materials for the First Wall of fusion reactors, especially for highly stressed components, must be studied under realistic conditions. This means that suitable material tests must generate the energy deposition per unit area actually to be expected, namely both with respect to the load or pulse duration as well as with respect to the surface-power density. These conditions are compiled in Fig. 17 for several TOKAMAK's.

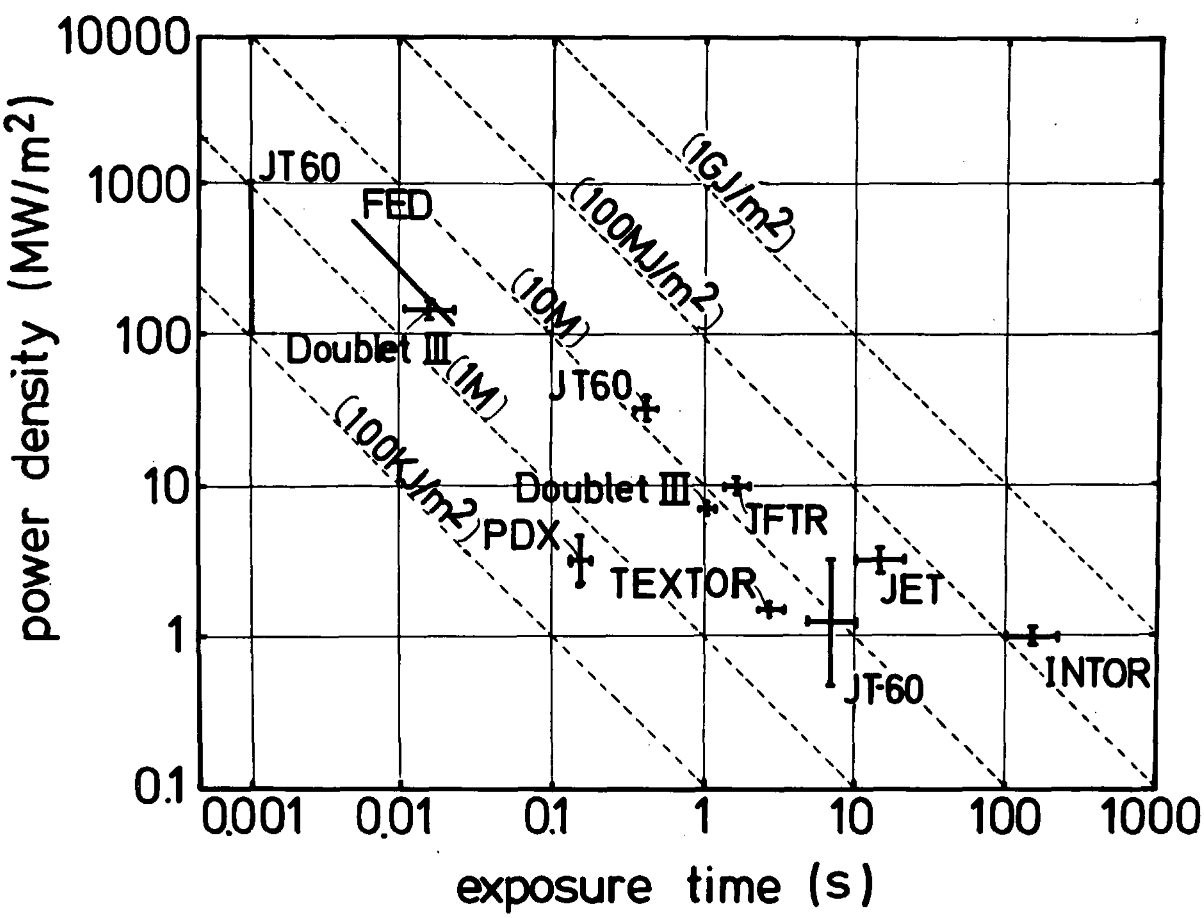


Fig. 17:
Graphic presentation of energy load (thermal, electron and ion radiation) to the limiter surface for different TOKAMAKs

Load testing of a candidate material must subject a material specimen to such types of process as occur in a TOKAMAK during plasma-wall interaction. Only then is the information obtained really reliable. In order to be able to carry out these studies in the laboratory the very complex collective load actually effective must be subdivided into individual processes, Fig. 18. Ideally each individual process would be realized in a specific test facility. In actual fact, however, a material specimen is subjected to several load mechanisms in the test facilities currently available. Nevertheless, an appropriate experimental procedure must ensure that the information gained is preferentially allocated to the individual process in question.

Load tests on materials in an "electron beam test" provide a particularly wide range of information about material behaviour under plasma-wall interaction /49, 50, 51/. On the one hand, the material specimens are loaded with high-energy electrons, i.e. one of the three particle fluxes from the plasma actually reaching the First Wall. On the other hand, the electron beam test has a large range of variation with respect to particle energy, surface power density, electron beam pulse duration and the number of pulses with which a material specimen is loaded.

An electron beam welding machine was used for the studies described here*, Fig. 19. For example, thermal shocks due to plasma disruption are simulated in experiments where each material specimen is loaded with one beam pulse each of suitable power density and duration (one-shot experiment), Fig. 20. From the point of view of the experimental procedure, the most important difference between the thermal shock test mentioned above and those tests simulating thermal shock by run-away

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* The authors wish to thank Dr R. Lison and Mr E. Sigismund from the Central Department of General Technology (ZAT) for implementing the experiments on their electron beam welding machine.

screening tests out-of-pile by applying relevant single load types to material samples

a) **for normal operation**

unipolar arcs	→	arcing machine, laser
other erosion	→	neutral beam injector test facility
pulsed heat flux	→	thermal cycling by thermal radiation, electron beam and/or neutral/ion beam t = 1...10 s T = 500...1000 K

b) **for irregular operation**

run away electrons disruptions	→	thermal shock by neutral/ion beam

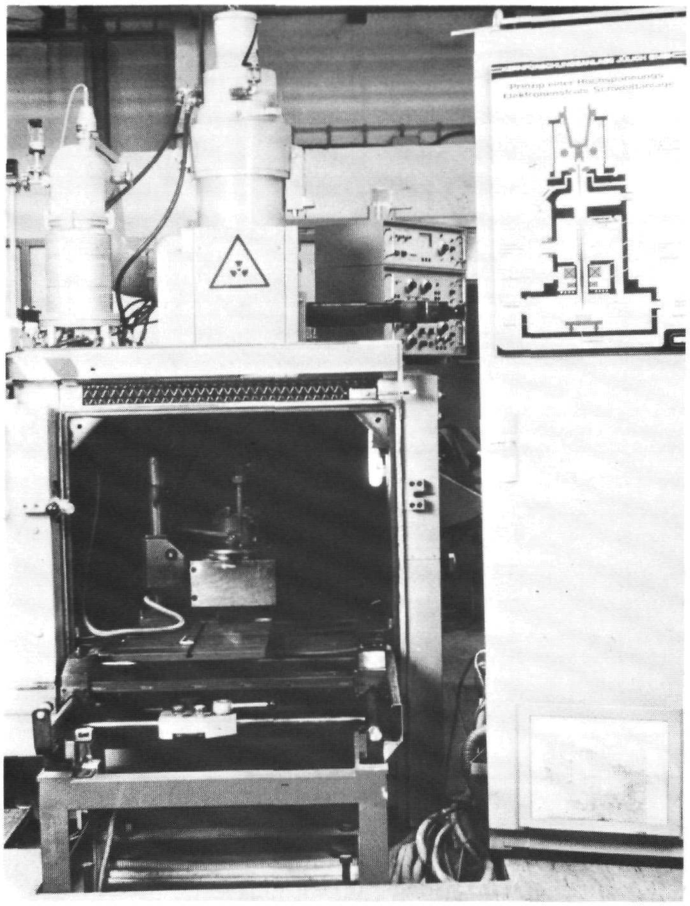
in-pile-tests in TEXTOR

a) screening tests	→	sandwich-limiter
b) final tests and tests of actively cooled limiters	→	limiter made of one material/ material system

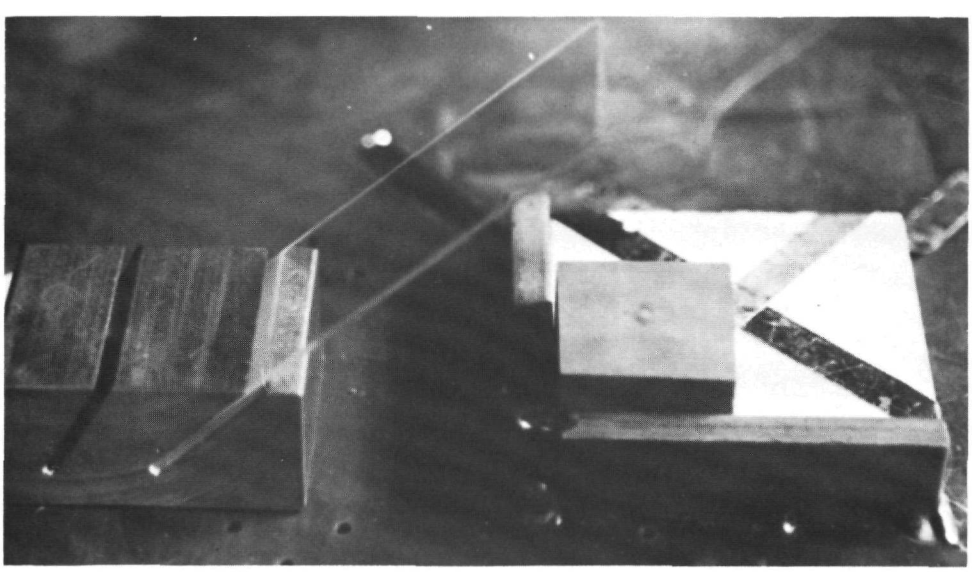
neutron irradiation tests

with candidate materials (in material test reactors like HFR Petten, BR 2 Mol)

Fig. 18:
Correlation between single loading types of plasma-wall-interaction and corresponding test facilities



a)



b)

Fig. 19:
Electron beam welding machine for thermal shock and thermal fatigue testing
a) overall view
b) sample stage with collector probe (glass disk) for evaporated/eroded material

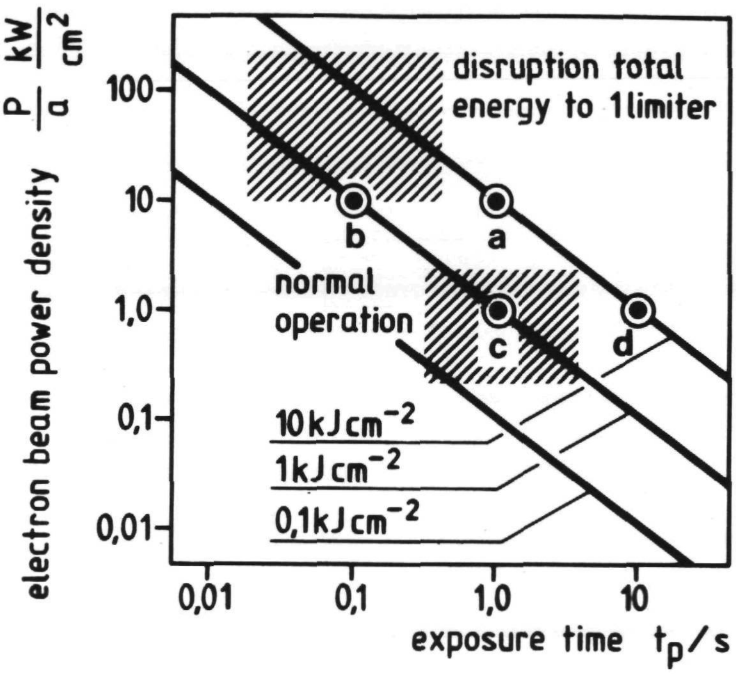


Fig. 20:
Electron beam power density vs. exposure time for three typical energy deposition densities for electron beam thermal shock tests. TEXTOR operation regions are shaded.

electrons is probably mainly to be found in the load duration. The effective duration of the disruptions seems to be about 20 . . . 100 ms and that of the run-away electrons could be shorter by a factor of ...100... .

The electron beam test is used to study the thermal fatigue of a material in multiple-shot experiments, i.e. in tests where the same specimen location is loaded with numerous individual beam pulses of suitable length and power density /52/. The specimen is loaded at the same ratio of pulse duration to cooling-down interval as is for example experienced by a limiter during pulsed TOKAMAK operation.

Part of the energy extraction of the plasma is effected by electromagnetic radiation. Due to the pulsed operation of a TOKAMAK, infrared radiation similarly loads the materials of the First Wall in a pulsed manner and is thus a further cause of thermal fatigue of the materials. This type of material load must also be realized by a necessary test facility, for example by using suffiently powerful infrared lamps /53, 54/. Corresponding experiments are currently in preparation.

The chemical analysis of material surfaces loaded in multiple-shot experiments permits statements to be made about the erosion behaviour of a material. If the studies are non-destructive, for example by means of energy-dispersive X-ray analysis (EDA) in a scanning electron microscope (SEM), then the same specimen can be analyzed after several beam pulses and then used again in the electron beam facility. A probe, namely an uncooled collector above the loaded specimen location, Fig. 19b, permits the eroded material to be chemically analyzed. Ideally the results of the measurements which generally have to be made by means of AUGER electron spectroscopy (AES)[*] due to the slight thickness of the layers deposited on the collector should be complementary to the results of the sample surface.

Comparative studies of this type are currently in progress.

In order to realize the material loads actually occurring in a TOKAMAK similar tests to those with the electron beam must be carried out, i.e. on thermal shock behaviour, thermal fatigue and erosion behaviour, also with a hydrogen-ion or neutral-particle beam /55, 56, 57/. A neutral beam injector test stand is available at the KFA for such studies. This facility generates an ion beam without using the neutralizer chamber. Material studies on this test stand are currently in preparation.

The extent to which the three types of load, electron, ion or neutral particle bombardment, influence each other, i.e. the extent to which synergistic effects are important and should be

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* We would like to thank Dr K.H. Besocke, Institute of Surface Research and Vacuum Physics, KFA Jülich, and Dr W. Koch, Institute of Physics, Technical University of Clausthal, for implementing the AES measurements.

taken into consideration if the individual results are extrapolated to behaviour during the complex, real plasma-wall interaction, is discussed elsewhere /58, 59, 60/.

A decisive step towards the selection of new, improved materials for the First Wall is finally in-pile tests in a TOKAMAK operating at near-fusion /61, 62, 63, 64/, for example in the KFA TEXTOR TOKAMAK which is primarily designed for studies of plasma-wall interaction /65/.

A sandwich limiter is used for in-pile tests in TEXTOR for a direct comparison of the behaviour of various materials (screening tests), Fig. 21. The sandwich limiter can be brought so close to the plasma that it takes over the function of the main limiter. It is incorporated in TEXTOR in the medium plane in the outer region, Fig. 22. This position ensures that during normal operation of the plasma it is loaded by all types of load, but during unstable plasma states mainly by run-away electrons. Due to

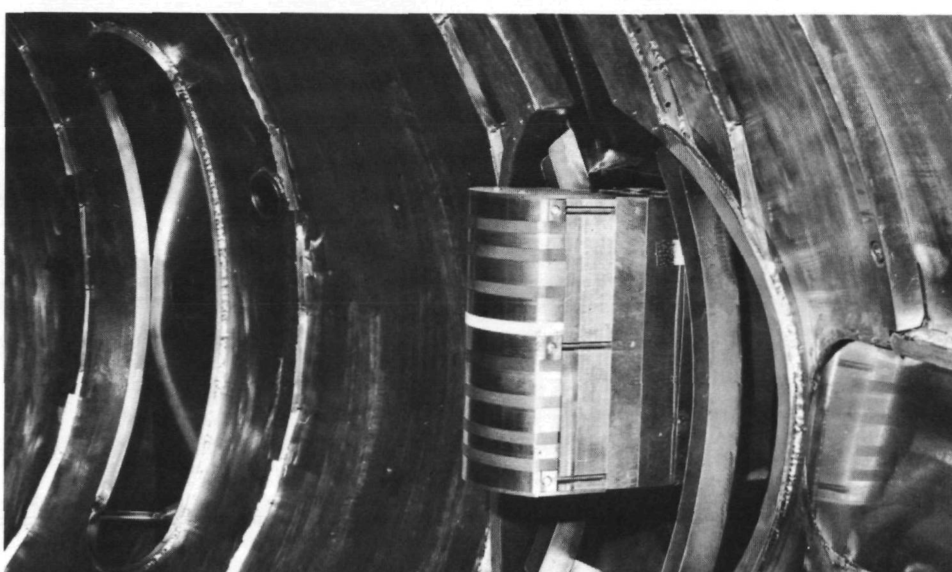


Fig. 21:
Sandwich test limiter in its position inside the liner in TEXTOR before operation

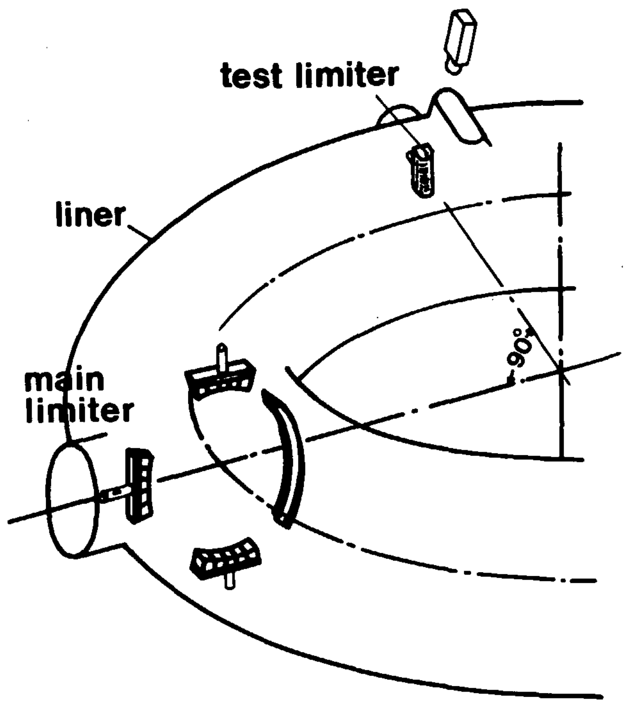


Fig. 22:
Schematic diagram of TEXTOR vacuum vessel with the position of main limiters and sandwich test limiter

the property of TOKAMAK plasmas of mainly depositing the plasma energy in the inner region of the vacuum vessel during disruptions, in the position indicated the sandwich limiter does not experience any or only slight loads through plasma disruptions.

Due to stable TEXTOR operation no run-away electrons have occurred during the previous application of the sandwich limiter as the main limiter.

As emphasized at the beginning, the behaviour of a material under neutron irradiation is of decisive significance in evaluating its applicability in fusion reactors. Corresponding experiments would have to be carried out with 14-MeV neutrons of sufficiently high flux densities. Such neutron sources are not yet available. In order to nevertheless obtain information about the irradiation behaviour of new materials recourse must be taken to material test reactors, i.e. fission reactors, with their - in comparison to the actual requirements - relatively soft neutron spectrum.

Neither is it possible in these reactors to realize He implantation in the material occurring simultaneously with neutron irradiation in a fusion reactor. However, if fusion reactor materials contain nickel or boron as the alloying elements then this process can be approximated via (n,α) reactions. Nevertheless, it must be ensured that the ratio characteristic of fusion reactors of helium implanted in the material to the damage caused, generally characterized as "ppm He to dpa", is at least achieved in the same order of magnitude.

Irradiation experiments in a high-flux reactor are being prepared for the ceramic materials and composite material systems found to be serviceable in laboratory experiments and TEXTOR tests.

6. Experimental Results and Conclusions

Work on developing and studying materials for the "thermally" highly stressed components of the First Wall of fusion reactors are being implemented and evaluated from two aspects:

- Specimens of material from First Wall components from TOKAMAKs already in operation are being studied. A picture of plasma-wall interaction is being compiled from the information thus obtained together with information from relevant publications. The main priority of all work discussed here is to be found on the material side of the plasma-wall combination. This section of the studies and their results is discussed in the previous chapters of the present report. The objective of this work does not ultimately only consist of improved knowledge of plasma-induced material damage but also in systemizing the interaction processes, the material damage thus caused and the requirements on First Wall materials. In the chapter on "Materials for Highly Stressed Components of the First Wall" this objective is characterized as the "specification" for the resulting load types, the materials and their properties, and the testing and characterization methods.

- New materials are being studied with respect to their suitability for First Wall materials on the basis of currently available knowledge concerning the type of load occurring and the reaction of materials previously used.

In this concluding chapter results of the material studies will be presented, insofar as they have not already been considered in the discussion of plasma-wall interaction and the material damage thus caused.

Up to now the electron beam facility has been mainly used in single-shot tests to examine the thermal shock behaviour of materials. To this end the pulse conditions were adapted to the thermal shock conditions in TEXTOR, Fig. 20. Series of experiments with specimens of different materials under constant pulse conditions (power density of the electron beam and electron beam pulse duration) permit a comparison to be made of the thermal shock behaviour of the various materials, Fig. 23. At a power density of 100 MWm^{-2} and the - realistic - pulse duration of 100 ms, point b) in Fig. 20, all materials represented still display useful thermal shock behaviour; graphite behaves best and the metallic alloy INCONEL 600 worst, already showing a comparatively large molten surface area. All materials clearly display more severe damage at the same power density but with a longer pulse duration of 1 s. A comparison of the four materials represented shows that damage is least for graphite and BN.

Ceramographic or metallographic sections through the damaged areas of specimens after thermal shock permit an evaluation of the course of damage in the specimen surface and in the interior of the specimen, Fig. 24. In the case of graphite, damage mainly results by erosion, Fig. 24 a). Individual, short cracks occur vertical to the surface of the specimen. An interesting fact is that the eroded graphite is at least partly redeposited on the specimen in the form of pyrocarbon with a high degree of order and marked orientation, Fig. 24 b). SiC displays severe cracking after thermal shock, not only the vertical cracks visible at the surface but also extensive cracks in the interior of the specimen parallel to the surface, Fig. 25 a). These latter can lead to chipping of large parts of the specimen surface. Finally the

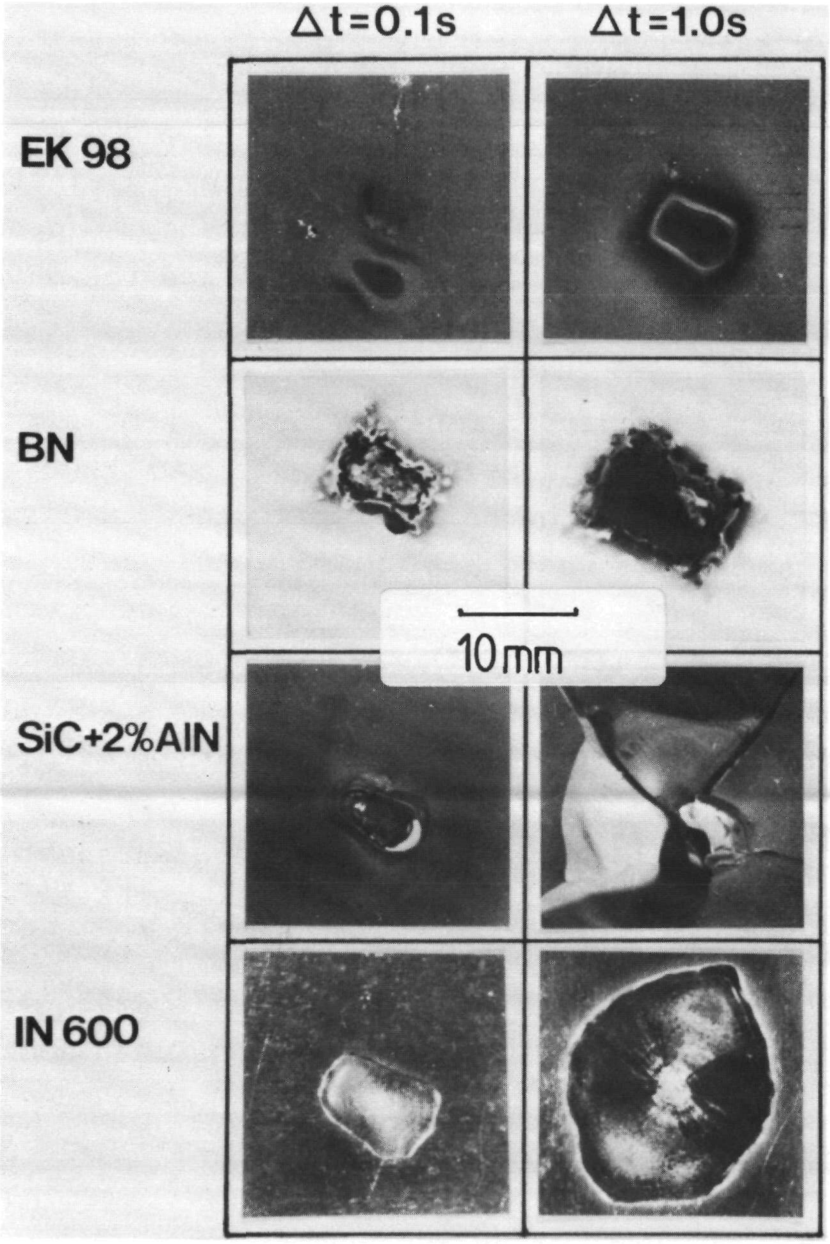
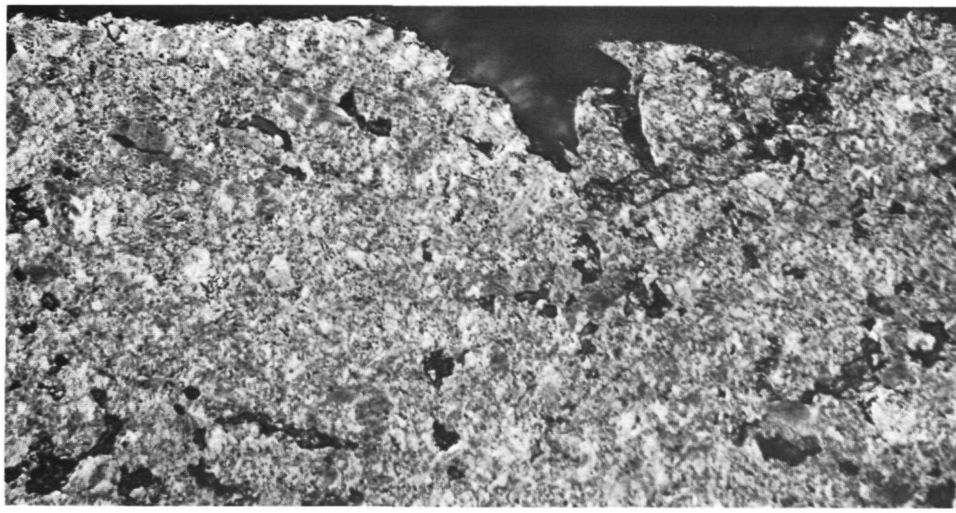


Fig. 23:
Morphology of the surface damage in different materials caused by electron beam thermal shock experiment; beam power density 100 MW m^{-2}

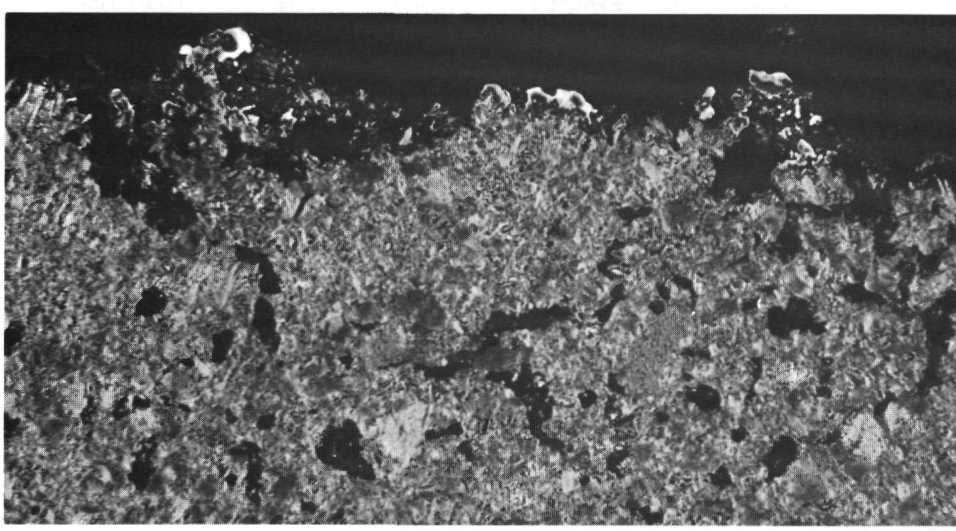
metallic specimen, Fig. 25 b), looks the same as the section of the "real" metallic limiter from TEXTOR shown in Fig. 8.

The materials studied to date and the evaluation of their behaviour in thermal shock tests and in-pile experiments in TEXTOR are compiled in Table 1.



a)

50 µm



b)

Fig. 24:
Metallographic section of different materials after thermal shock experiments:

a) eroded graphite surface with cracks (graphite EK 98, Ringsdorff)
b) eroded graphite surface, graphitic material is redeposited as pyrocarbon

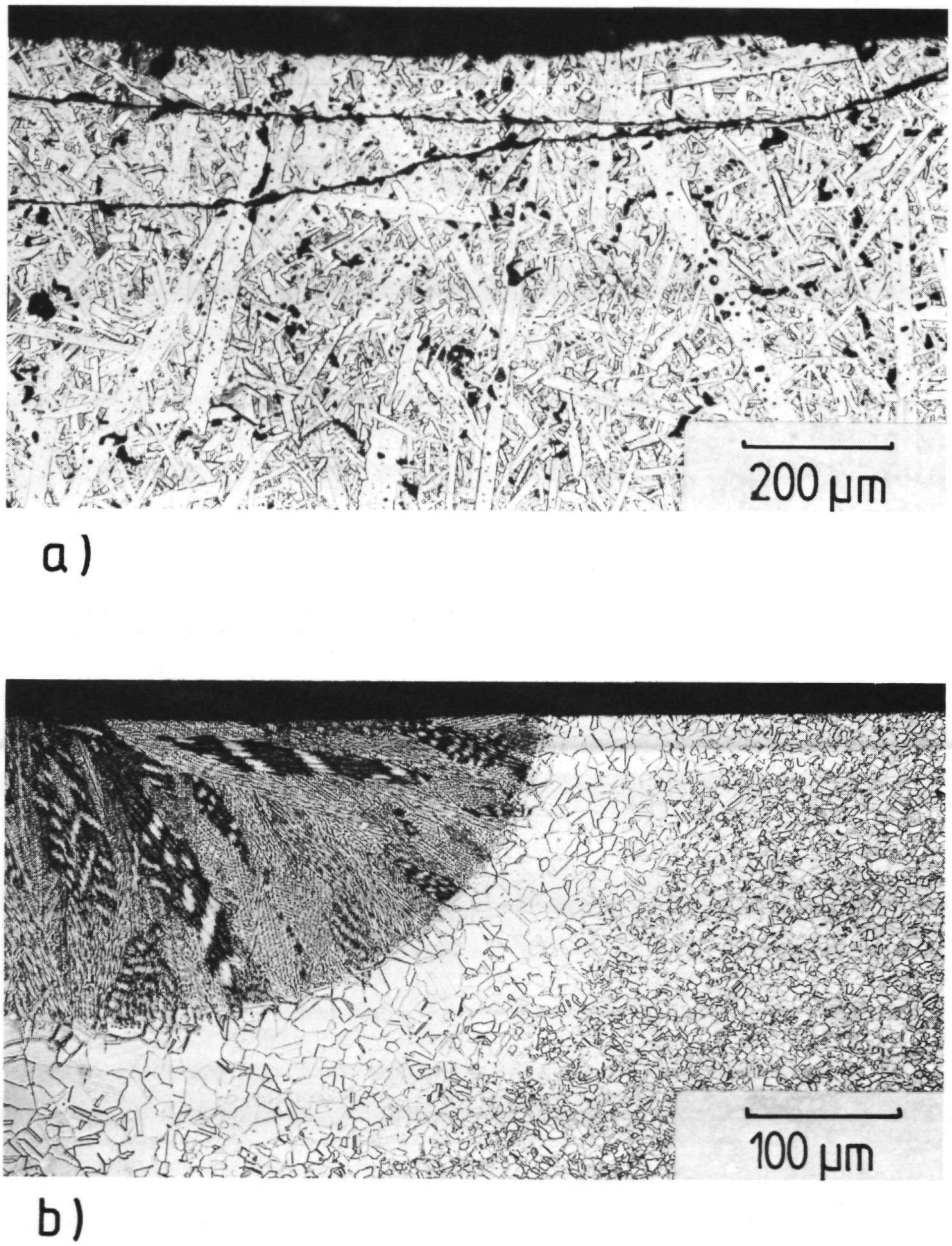


Fig. 25:
Metallographic sections of different materials after thermal shock experiments:
a) silicon carbide with severe cracking parallel sample surface
b) INCONEL 600, molten and recrystallized zone

	Materials	T melt (K)	behaviour: thermal-shock resistance	behaviour: arcing
bulk	alloys like INCONEL 600	1.500	– (melting and evaporation)	– (melting and cracking)
	Graphites, diff. qualities	3.800	+ + (evaporation)	O (little erosion)
	SiC + 2% AlN SiC + 0.1% Al SiC + 3% Al $SiSiC$	2.900	O O – – – (cracking and evaporation)	+ + O +
	AlN Si_3N_4 BN	2.500 – 2.600	– cracking + + (evaporation)	– – +
thin coating	TiC on C Cr_2C_3 on C	3.100 1.895	+ + (melting and evaporation)	O O (little erosion)

Tab. 1:
Investigated materials and first qualification from out-of-pile electron beam thermal shock test and in-pile TEXTOR test. Valuation reaches from very good (++) to very bad (--)

If the values of the power density and pulse duration of the electron beam are systematically varied in the electron beam test then - especially for materials with unfavourable thermal shock behaviour - a critical heat load can be determined. Below this material-specific value, a material does not suffer any appreciable damage during a brief power pulse, Fig. 26. SiC + 2 % AlN displays the highest critical heat load of the four SiC qualities illustrated.

The electron beam test is also suitable for testing the thermal shock resistance and adhesiveness of thin coatings applied externally to a material under the influence of extreme loads. An example of this is an INCONEL-625 specimen coated with a TiN layer 10...15 µm in thickness. In the thermal shock test the coating is completely destroyed by a beam pulse of 100 MWm^{-2} and

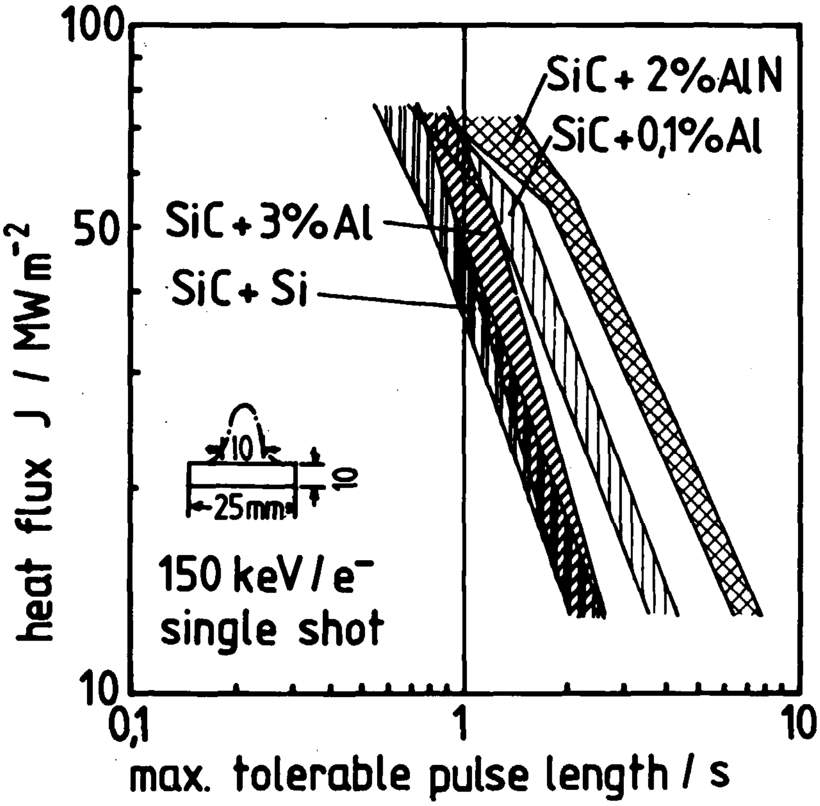


Fig. 26:
Critical heat loads which cause sample surface fracture for different qualities of SiC; electron beam thermal shock tests (one shot experiments)

0.1 s in duration. The underlying metal is melted and parts of the chipped-off layer are trapped in the solidified melt, Fig. 27.

The results of in-pile TEXTOR tests with the sandwich limiter currently available only comprise material loads during normal operation of this TOKAMAK. The most striking damage thus caused results from unipolar arcing, Fig. 28. It is striking that the electric insulators - SiSiC, BN, AlN, Si_3N_4 - do not display any or only very little arcing. At some locations unipolar arcing at the boundary of the conductor/nonconductor apparently seemed to "stand still for a brief period" and eroded deep craters in the metal, Fig. 29. Liquid metal is sputtered over relatively

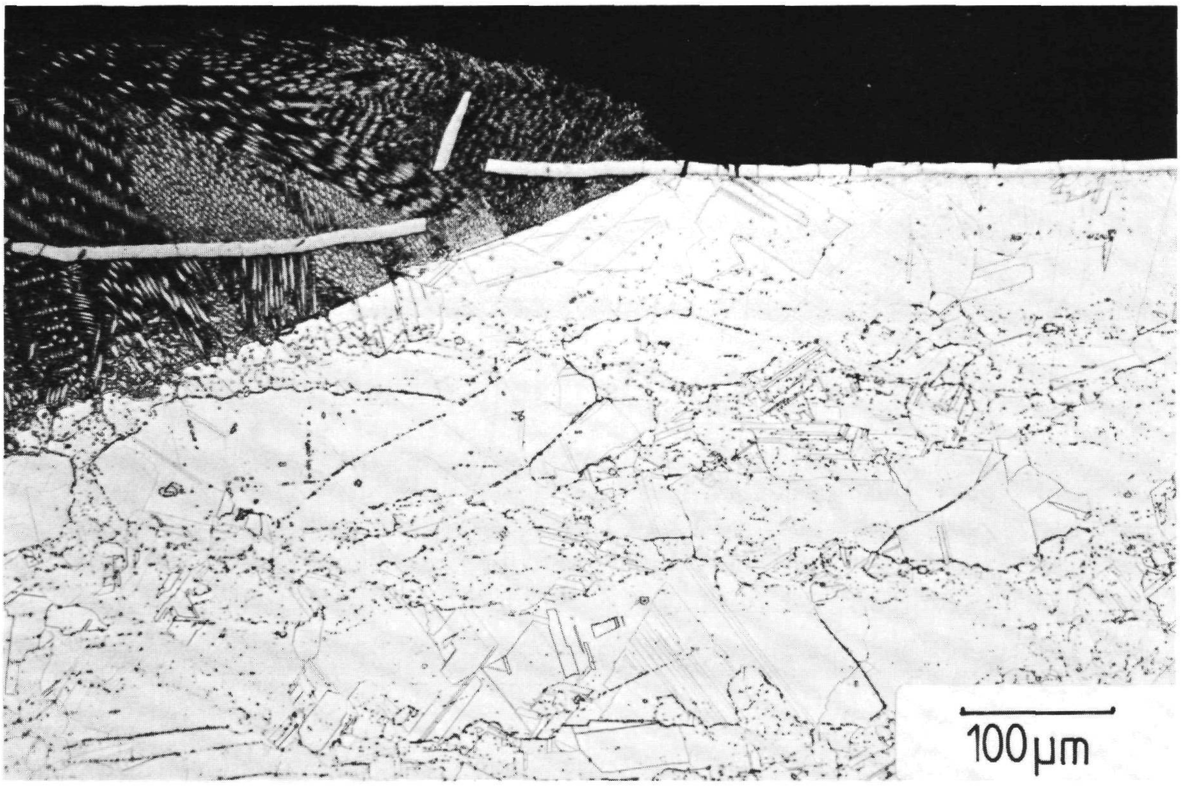


Fig. 27:
Electron beam thermal shock test (one shot experiment, 100 MW m^{-2}, 0.1 s) with a TiN-coated INCONEL 625-sample

large areas. In contrast, the adjacent ceramic shows severe chipping at the surface. Fig. 28 shows these phenomena for the material composition INCONEL 600-AlN-INCONEL 600 from the second loading of the sandwich limiter, Fig. 27.

Droplet formation, Fig. 30 a), and impregnation of the regions of material close to the surface, Fig. 30 b), can also be established after in-pile tests in TEXTOR.

Results to date from material studies enable the following conclusions to be made:

- Apart from SiC + 2 % AlN, the SiC qualities, AlN and Si_3N_4, are only suitable for thermally highly stressed components of the First Wall, e.g. limiters, to a certain extent because of their poor thermal shock behaviour.

Fig. 28:
Sandwich-limiter (second experimental version) after in-pile-test in TEXTOR, about 80 plasma shots

- In order to protect the vacuum vessel or liner from erosion by the hot plasma the whole vessel can be lined with tiles of a low-Z material with a low erosion yield. This also prevents medium- or high-Z material from the First Wall entering the plasma and being uncontrollably redeposited. SiC is suitable for this purpose due to the comparatively low thermal load.

- Alloying components with high steam pressure are preferentially eroded or evaporated (Cr from Fe- and Ni-base alloys) from the surface of the First Wall and redeposited in the vacuum vessel or on parts of it.

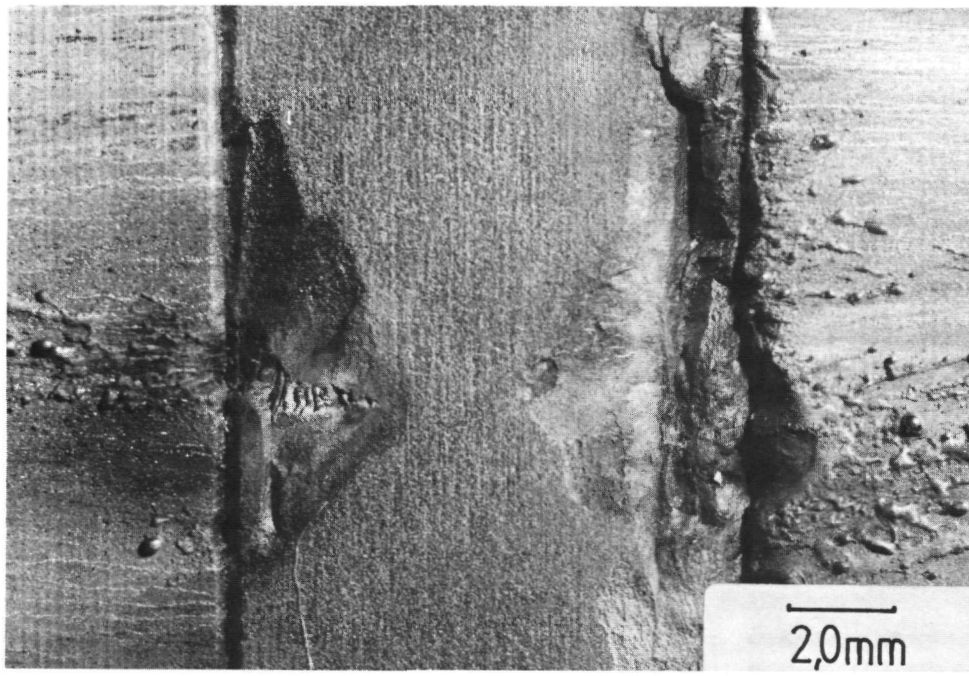
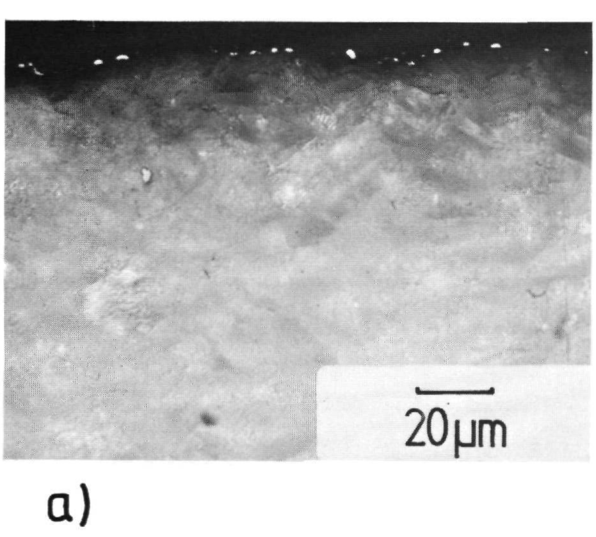
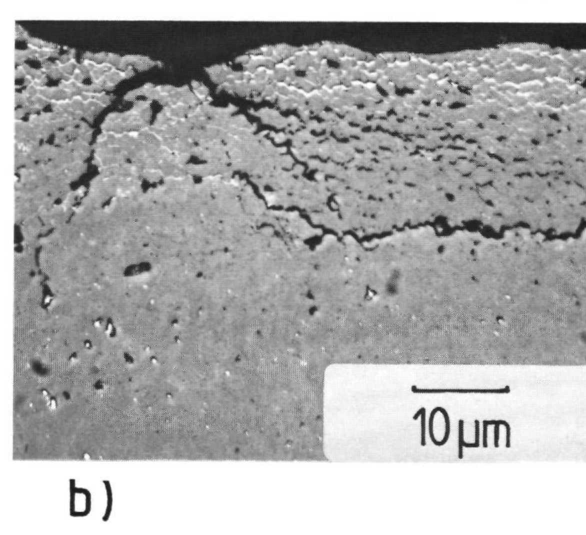


Fig. 29:
Detail of sandwich-limiter after TEXTOR test, deep crater at the end of arcing trace at the boundary metal-ceramic on the metal side and severe chipping on the ceramic side



a)



b)

Fig. 30:
Cross sections through sandwich-samples after TEXTOR test:
a) droplets on the surface of a BN-sample
b) impregnation and cracks in a SiC + 2 % AlN-sample

- The formation of droplets by redeposited material on the surface of highly stressed components of the First Wall can cause enhanced erosion or arcing.

- Redeposited material can impregnate regions of the First Wall components close to the surface and thus change their properties (erosion behaviour, thermal and electrical conductivity).

- Materials with low values for electrical conductivity do not show any, or only slight, erosion by arcing.

- Thin protective coatings applied externally (TiC on graphite, TiN on INCONEL) are probably not suitable for highly stressed components. They are destroyed too rapidly by possibly increased local erosion or by thermal shock loading.

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