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STRUCTURAL MATERIALS FOR HIGH-HEAT FLUX APPLICATIONS*

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Abstract

The structural materials for the ITER, (International Thermonuclear Experimental Reactor) divertor must perform reliably under complex and diverse operating requirements. Only a limited number of materials offer a potential for meeting these requirements for the wide temperature range of interest.

The candidate materials considered in the ITER design activity include copper, molybdenum, and niobium alloys. Molybdenum alloys being considered include dilute alloys of the TZM type and the Mo-Re system. Niobium alloys under consideration include Nb-V-Zr and Nb-Zr systems. Copper alloys being considered include precipitation strengthened alloys of the Glidcop and MAGT type, alloys of Cu-Mo system and dispersion hardened bronzes. The projected operating conditions for the ITER divertor and the criteria for evaluating the candidate materials are reviewed. This paper summarizes the data base and presents recent experimental results on these candidate divertor structural alloys.

1. Introduction

Structural materials for the divertor of a fusion reactor such as the International Experimental Power Reactor (ITER) must withstand severe and diverse operating conditions [1,2]. The divertor must accommodate high heat loads, be compatible with the coolant and the hydrogen plasma, be readily fabricable, and have adequate resistance to radiation damage. In addition, these materials must maintain mechanical integrity under a variety of loading conditions, be reliably bonded to the candidate plasma facing materials, and be resistant to various radiation damage mechanisms such as radiation embrittlement and swelling. Desirable properties that must be considered in the selection to the candidate divertor structure for ITER include:

- High thermal conductivity
- Low thermal expansion coefficient
- High yield strength
- High ductility/fracture toughness
- Resistance to hydrogen embrittlement
- Corrosion resistance in high velocity water

Only a limited number of materials offer a potential for meeting these requirements. The candidate materials considered in the ITER design activity include molybdenum-, niobium-, and copper alloys [2]. Copper alloys being considered include precipitation strengthened alloys of the Glidcop and MAGT type, alloys of Cu-Mo system, and dispersion hardened bronzes. Molybdenum alloys being considered include dilute TZM type and alloys of the Mo-Re system. Niobium alloys under consideration include Nb-V-Zr and Nb-Zr systems.

The criteria for selection of prime candidate divertor structural materials, identification of critical issues for each alloy system, and an assessment of the relevant data base for the candidate alloys are discussed in the following sections.

2. Principles and criteria for selection of divertor structure

This assessment of candidate divertor structural materials is based on the operating requirements specified in the ITER conceptual design [2]. The divertor structure must accommodate peak surface heat fluxes of 10 MW/m2 or higher. For the ITER design low temperature (50-80°C), low pressure (~1-3 MPa) water at ~10 m/s is proposed as the coolant. The main initial criterion is to accommodate these high heat fluxes with acceptable temperatures and stresses. Consequently, a high thermal conductivity and/or a low thermal expansion coefficient are necessary to minimize thermal stresses. A high yield stress and a low elastic modulus are also highly beneficial. The thermal stress factor, which incorporates these parameters, provides a preliminary basis for the comparison of candidate materials.

$$M = 2\,(1-\nu)\,(\lambda/\alpha)\,(\sigma_y/E) \tag{1}$$

where ν, λ, α, σ_y and E are Poisson's ratio, thermal conductivity, thermal expansion coefficient, yield stress, and elastic modulus, respectively. A higher value of M should provide a higher head load capability. For the case of ITER, which will operate in a cyclic mode, fatigue is also an important factor. In addition to the heat load capability, other factors that must be evaluated include:

- Fabrication/joining characteristics

- Effects of radiation on properties, particularly embrittlement
- Thermal expansion match with plasma facing materials
- Hydrogen interactions; embrittlement and tritium inventory
- Aqueous corrosion at high velocity
- Electromagnetic interactions
- Safety related issues; activation/afterheat

The main advantages and critical issues for each of the alloy systems are evaluated from available data.

3. Evaluation of candidate alloy classes

Selected copper, molybdenum and niobium alloys appear to offer potential as a divertor structure for ITER [2,3]. The specific types of alloys considered include:

- Copper alloys

  Solution strengthened: CuBe

  Precipitation strengthened: CuCrZr, CuMo

  Dispersion strengthened: $Cu\text{-}Al_2O_3$

- Molybdenum alloys

  Low alloyed: MoZrC, MoZrTi

  Mo-Re alloys: (1 to 47%) Re

- Niobium alloys

  Low alloyed: NbVZr, Nb-1Zr

Nominal compositions of these alloys are given in Table 1.

The main advantages of the copper alloys relate to their high thermal conductivities which tend to reduce the temperature gradient in the wall and the plasma side surface temperature. The main issues for copper alloys relate to their high thermal expansion coefficient and low melting temperature.

The main advantages of the molybdenum alloys are their high melting temperature, which provides greater margin in the event of over-heating caused by loss of flow or tile failure, and relatively low thermal expansion coefficient. The relatively good thermal expansion match with carbon and tungsten armor materials provide advantages associated with lower interfacial stresses. The main issues for the molybdenum alloys relate to their sensitivity to for radiation embrittlement and difficult fabrication/welding.

The niobium alloys exhibit similar advantages as the molybdenum alloys but are more readily weldable and are less susceptible to radiation embrittlement. The main issues relate to hydrogen interactions that could lead to hydrogen embrittlement and excessive tritium inventory or permeation.

The thermal stress factor M provides a preliminary basis for comparison of the heat load capability for the candidate alloys. The thermal stress factors calculated from baseline property data for selected alloys are given in Figure 1 for both the coolant side and plasma side of an idealized 4-mm-thick structure with a heat flux of 10 MW/m^2 and a coolant side temperature of 150°C. The figures indicate which types of alloys meet a prescribed set of criteria for M and the ductility δ at 150°C on the coolant side and for the calculated interface temperature. Additional consideration must be given for the effects of radiation and chemical environment on the properties. For the case of ITER, which will operate in a cyclic mode, fatigue is also an important factor. The calculated heat flux limit for an idealized wall of selected candidate materials is given in Table 2 for a fatigue life of 10^4 cycles. The calculated heat load limits for the selected copper, molybdenum, and niobium alloys are similar for this case [4]. Copper has high thermal conductivity but also high thermal expansion coefficient. Molybdenum has the lowest thermal expansion coefficient. Niobium has a lower thermal conductivity and higher thermal expansion coefficient than molybdenum; however, a lower elastic modulus and better apparent fatigue properties make up for the conductivity and expansion differences.

The critical new data base for the candidate alloys is reviewed and evaluated below.

3.1 Copper alloys

Based on the calculated thermal stress factor and baseline ductility several of the copper alloys appear to meet the preliminary criteria. However, when the effects of interfacial stresses are taken into account for tungsten and carbon armor, the M factors are significantly reduced because of the rather large thermal expansion miss-match

The projected operating temperature range for copper alloys is 50° to 300°C, which corresponds to a homologous temperature T/Tm of 0.2-0.4. Since a pronounced effect of neutron irradiation on strength and plasticity of metals is typical for homologous temperatures of 0.3-0.4 [5-10], neutron irradiation effects are a concern at the higher interface temperatures.

Figures 2 and 3 shows the effects of low fluence neutron irradiation on the yield strength and ductility of candidate copper alloys irradiated at 100° and 400°C [11,12]. The yield strengths of the CuBe and CuCrZrMg, alloys are significantly decreased by irradiation at 400°C. The dispersion strengthened alloy MAGT-0.2 is only moderately affected by irradiation at both temperatures. More detailed information on effects of irradiation on copper alloys including swelling, creep and corrosion under irradiation are given in Refs. 13 and 14. The best materials of this group for the divertor applications appear to be the MAGT and GLIDCOP alloys and possibly the CuBe alloys. Softening under irradiation at 300°-400°C temperature range is a serious concern.

Corrosion/erosion of copper alloys by high velocity water is also a concern. Modest corrosion of GLIDCOP Al-15 (40 μm after ~600 h) was observed at 12 m/s low pressure water [15]. Severe corrosion of OFHC copper was observed (1 mm after 140 h) at 33 m/s water under high heat flux conditions (40 - 60 MW/m^2) [16].

3.2 Molybdenum alloys

Based on the calculated thermal stress factors and baseline ductility several of the molybdenum alloys appear to meet the preliminary criteria. Because of the better thermal expansion match of molybdenum with tungsten and carbon, the interfacial stresses are much lower than those for the copper alloys. For the reference heat fluxes of 10 MW/m^2, the maximum molybdenum alloy temperatures are less than 500°C, which corresponds to homologous temperatures of 0.1-0.3. The major concern at these low temperatures is low ductility and fracture toughness. Since the Mo-Re alloys were believed to be less sensitive to embrittlement [2,13], they have been suggested as leading candidates. Figure 4 shows a reduction in the DBTT at higher Re concentrations in the Mo-Re alloys while little change is observed in the yield strength [13]. The therma conductivity, thermal expansion coefficient and heat capacity of MoRe alloys as a function of rhenium content are given in Figure 5 [13]. The thermal conductivity decreases rapidly with an increase in

Re while the thermal expansion shows a modest increase. In order to minimize these changes and still benefit from the decrease in DBTT, a composition of 3-5% Re appears optimal.

The effects of low fluence (1 to 5×10^{21} cm^{-2}) irradiation at ~100°C in SM-2 and WWR reactors on the yield strength and ductility of selected molybdenum alloys are presented as a function of test temperature in Figures 6 and 7 [17]. Pronounced radiation embrittlement and hardening is observed for all alloys tested. Additional results are presented in reference 17. Both the Mo and the MoZrC exhibit severe loss of ductility when tested below 500°C. The Mo-5 Re alloy retains significant ductility at 500°C but exhibits severe embrittlement at 300°C after a fluence of only 10^{21} cm^{-2}. It appears that the DBTT of molybdenum alloys increases by ~500°C after fluences of 10^{21} cm^{-2} which corresponds lifetimes of only 2-3 weeks of equivalent operation of the ITER first wall. Therefore, radiation-induced embrittlement remains a feasibility issue for the molybdenum alloys.

3.3 Niobium alloys

Recently, low-alloyed niobium alloys were proposed as a candidate divertor structure for ITER [2,4]. Although data are limited, selected niobium alloys appear to be much less prone to irradiation embrittlement than the molybdenum alloys [18-21]. For example, the total elongation of Nb-1 Zr is ~10% after irradiation at 25 and 400°C to fluences of nearly 4×10^{22} cm^{-2}. Although the most extensive data base exists for Nb-1 Zr, a Nb-5V-1.25Zr alloy (similar to Cb 753) exhibits superior base properties. For example the yield and ultimate strengths of Cb 753 at 600°C are 640 and [illegible] MPa, respectively, compared to corresponding values of 210 and 140 MPa for Nb-1Zr [22]. The main issues for Nb alloys relate to hydrogen interactions from the plasma or from water corrosion. Figure 8 indicates that stable oxide films are formed on a Nb-2.5 V alloy exposed to 300°C water and that the corrosion rate is similar to that of zircaloy [23]. Results shown in Table 3 indicate that the hydrogen pickup and tendency for embrittlement strongly varies with alloy composition. Additional data on niobium alloys are given in references 23 and 24. Based on this information, the comparison of properties with Nb-1Zr, and the calculated heat flux limits for Nb-1Zr, the Nb-5V-1.25Zr alloy or a similar type of alloy appears to be a good candidate for the divertor structure. Additional data on hydrogen interactions, aqueous corrosion, and radiation embrittlement are required.

4.0 Summary of divertor structure issues

The critical factors for the divertor structure in addition to the heat flux limits are summarized as follows.

4.1 Fabrication/joining

Selected copper and niobium alloys have a significant advantage with respect to welding/joining. Niobium is readily weldable in an inert atmosphere. Molybdenum is very difficult to weld. The dispersion strengthened copper alloys cannot be welded without substantial loss of mechanical properties.

4.2 Radiation damage resistance

Molybdenum alloys are generally sensitive to low temperature radiation embrittlement. Molybdenum alloys with rhenium were thought to be less sensitive; however, as discussed, Mo-Re alloys also appear to be sensitive to low fluence irradiation and rhenium creates additional safety issues as discussed below. If larger amounts of rhenium are necessary, the thermal conductivity is substantially reduced and cost is significantly increased. Niobium and copper appear to offer significant advantages with respect to embrittlement at higher fluence irradiation conditions.

4.3 Safety related issues

The higher melting temperatures of refractory metals provide significant advantages compared to copper in the event of a LOCA. Since rhenium presents significant safety concerns associated with volatile activation products, niobium provides safety advantages compared to the Mo-Re alloys. Also, niobium and copper provide advantages with respect to lower short term afterheat compared to molybdenum.

4.4 Thermal expansion match with plasma facing materials

Both molybdenum and niobium have relatively low thermal expansion coefficients that provide a better match and lower interfacial stresses with carbon and tungsten plasma facing materials. The low modulus of elasticity characteristic of niobium is an advantage for minimizing interfacial stresses. Copper has a better thermal expansion match with beryllium; both being relatively high.

4.5 Low activation/afterheat considerations

All of the three materials produce long-lived activation products and are similar with respect to waste management considerations. Therefore, this criterion does not provide a distinguishing characteristic. Niobium and copper exhibit lower short-term afterheat compared to molybdenum.

4.6 Aqueous corrosion

All three materials appear to be compatible with water cooling at the projected temperatures. Minor alloying additions to niobium and molybdenum provide significant benefits for corrosion resistance. Since copper is more susceptible to erosion in high velocity water, the refractory metals have some advantage with respect to erosion in high-velocity water.

4.7 Hydrogen interactions

Hydrogen permeabilities in molybdenum and copper are much lower than in niobium. However, appropriate alloying of niobium provides effective oxide barriers when exposed to water. The hydrogen-related issues are critical to the use of niobium alloys. Existing data indicate that selected alloys behave much differently than pure niobium with respect to hydrogen interactions.

4.8 Electromagnetic interactions

Because of the high electrical conductivity of copper, additional design constraints for accommodating disruption loads are required compared to the refractory metals.

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Table Headings

1. Nominal Compositions of Candidate Alloys.
2. Calculated Surface Heat Flux Limits for Divertor Structure.
3. Hydrogen Concentrations and Brittleness Index in Corrosion Tested Niobium Alloys Exposed for 30 Days to 300°C Water.

Table 1. Nominal Compositions of Candidate Alloys (w/o)

<u>Copper Alloys</u>	
CuBe	Cu-2Be-0.4Ni
CuCrZr	Cu-0.5Cr-0.1Zr
CuCrZrMg	Cu-0.5Cr-0.2Zr-0.06Mg
CuMo	Cu-5Mo-0.1Y
MAGT-0.2	Cu-0.3Al-0.1Hf-0.08Ti-0.3Al_2O_3
MAGT-0.05	Cu-0.1Al-0.1Al_2O_3
GLIDCOP-AL15	Cu-0.15Al_2O_3
<u>Molybdenum Alloys</u>	
Mo-1Re	Mo-1Re
Mo-5Re	Mo-5Re
Mo-9Re	Mo-9Re
<u>Niobium Alloys</u>	
NbZr	Nb-1Zr
NbVZr (Cb753)	Nb-5V-1.25Zr

Table 2. Calculated Surface Heat Flux Limits for Divertor Structure

Material	Heat Flux Limit* Expand but not Bend
Nb-1Zr	17-18 MW/m^2
Dispersion Strengthened Copper	~14 MW/m^2
TZM	~20 MW/m^2

* Nominal 4 mm wall, 10 MW/m^2 surface heat flux, 50°C water coolant, 10^4 cycles

Table 3. Hydrogen Concentrations and Brittleness Index in Corrosion Tested Niobium Alloys Exposed for 30 Days to 300°C Water

Alloy	Hydrogen Concentration, ppm	Percent H Captured	Brittleness[b] Index
Pure Nb	730[a]	16	5
Nb-2.5 Zr	85	7	1
Nb-2.5 V	269	35	5
Nb-2.5 Hf	120	8	2
Nb-2.5 Ta-2.5 Ti	63	5	2
Nb-2.5 Mo	207	16	5

[a]Solubility limit at 25°C-366 ppm

[b]Brittleness Index: 5 - Fracture on bending
1 - Neither fracture nor surface cracking of corrosion layer

Figure Captions

1. Calculated thermal stress factor versus ductility for candidate structural alloys = (a) copper alloys and (b) molybdenum and niobium alloys.

2. Tensile yield strength and elongation at 100°C for unirradiated and irradiated copper alloys.

3. Tensile yield strength and elongation at 400°C for unirradiated and irradiated copper alloys.

4. Yield strength and ductility as a function of Re concentration for binary Mo-Re alloys.

5. Physical properties of Mo-Re alloys as a function of Re concentrations.

6. Yield strength and tensile ductility as a function of test temperature for Mo and Mo-5Re alloy after irradiation to 10^{21} cm^{-2} at 100°C in SM-2 reactor.

7. Yield strength and tensile ductility as a function of test temperature for Mo and MoZrC after irradiation to 5 x 10^{21} cm^{-2} at 90°C in WWR reactor.

8. Corrosion of Nb, Nb-2.5Ta and Nb-2.5V as a function of time in 300°C water.

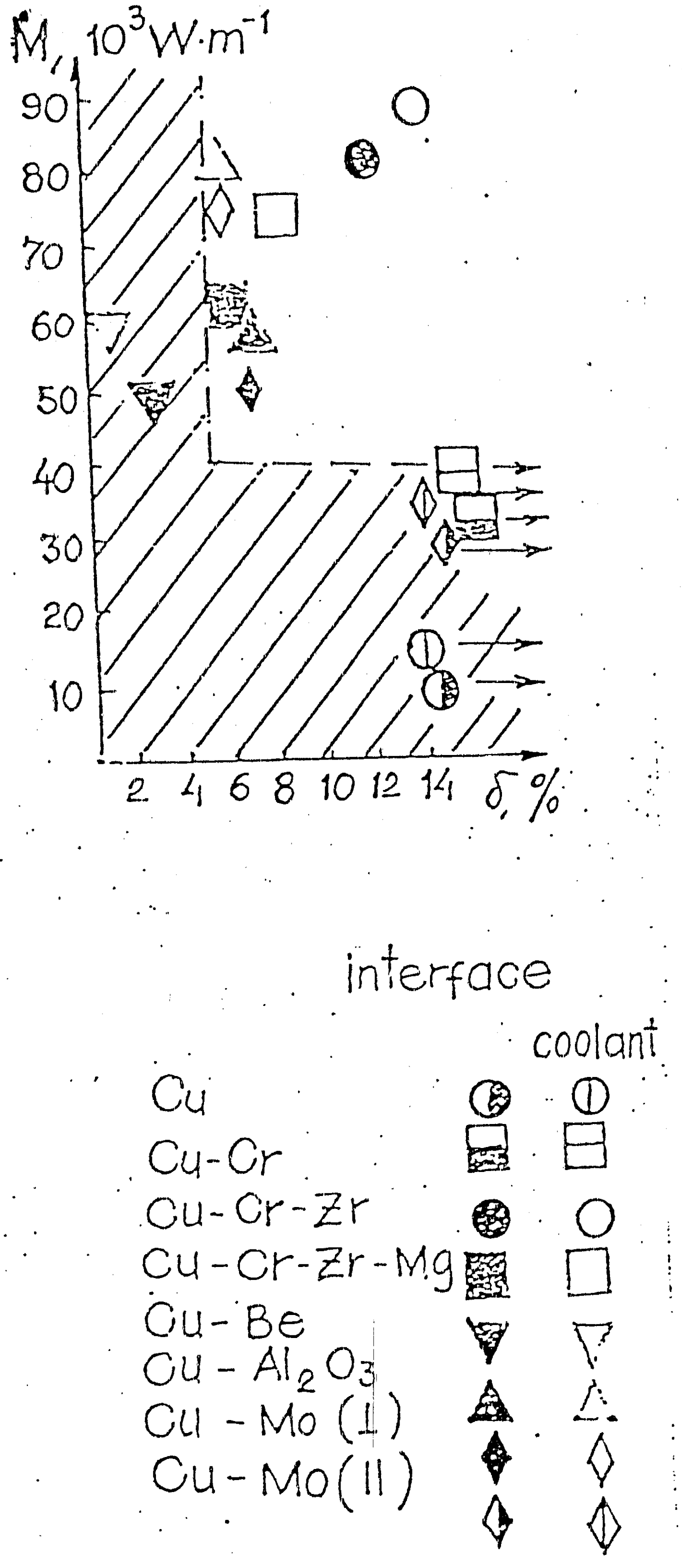


Figure 1-a

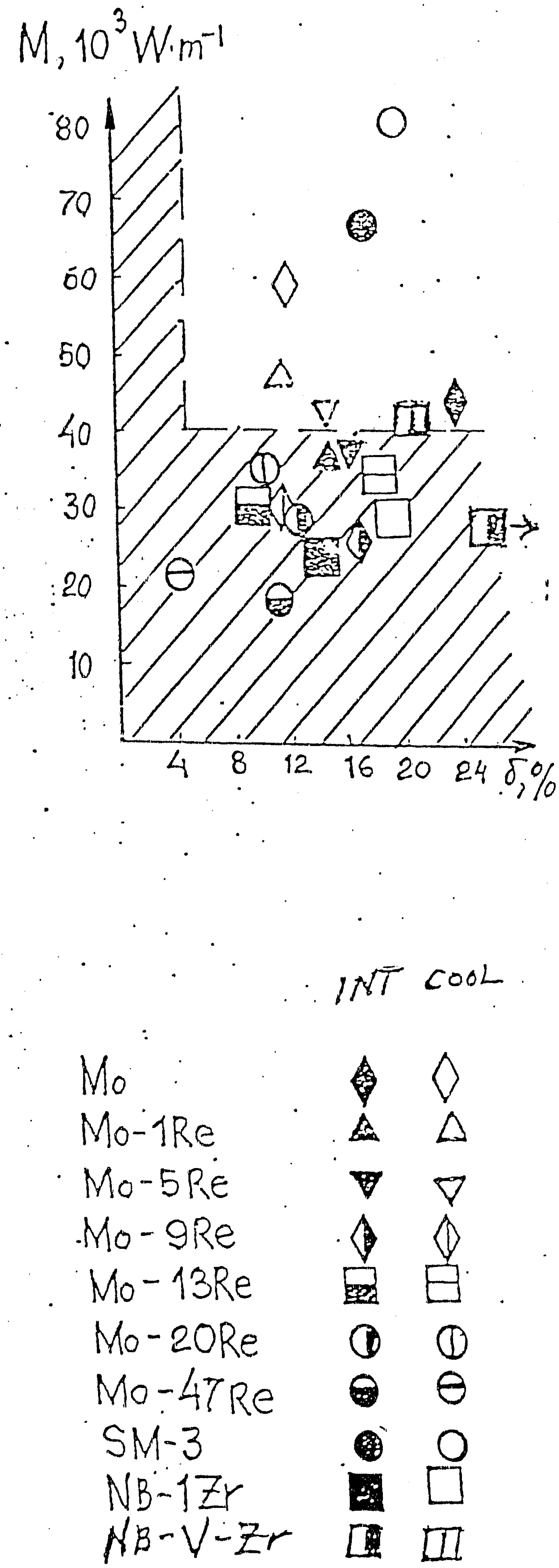


Figure 1-b

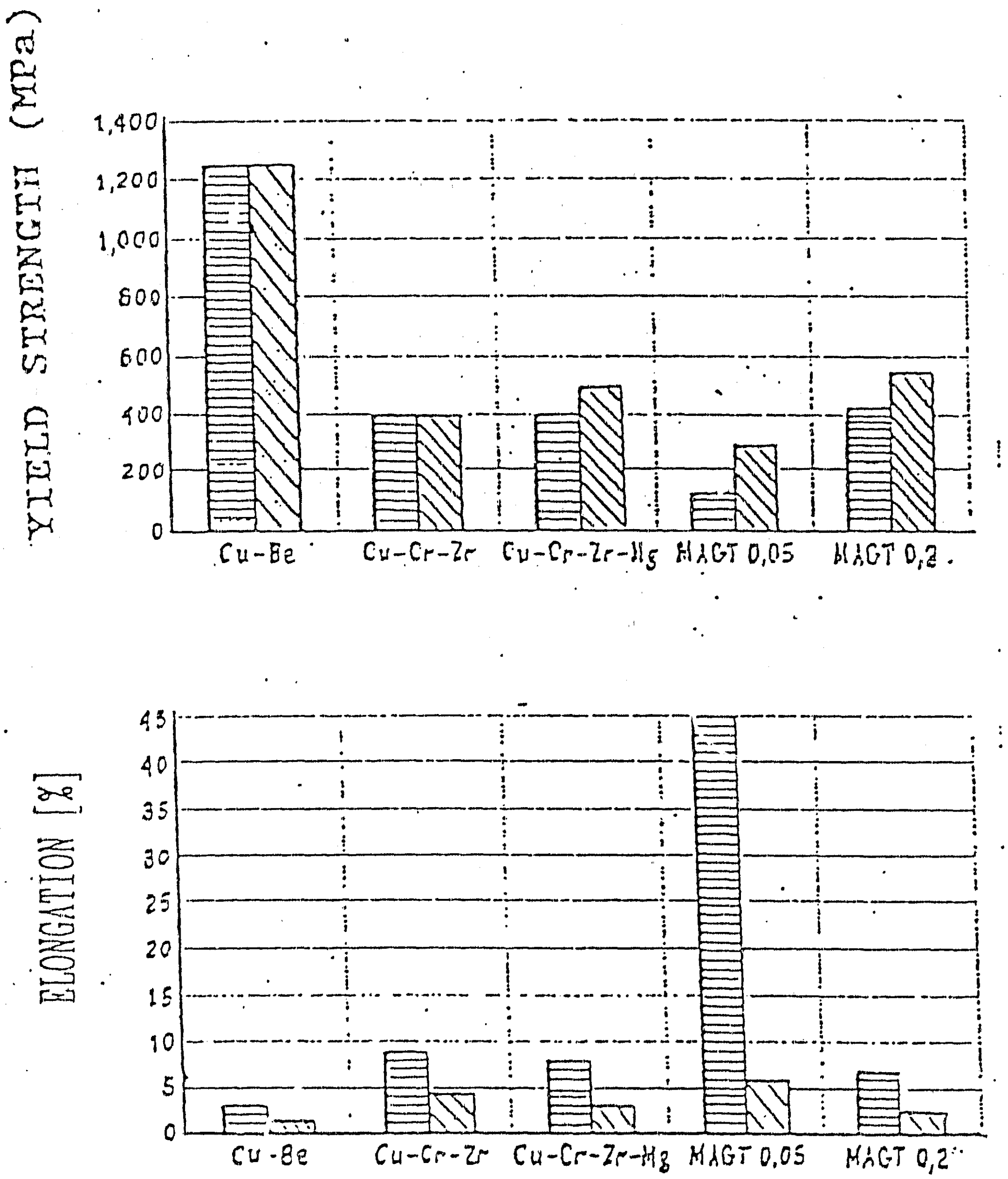


Fig.1 Tensile yield strength and elongation, measured at $T_{test}=100^{o}C$, for unirradiated and irradiated copper base alloys.

▤ - unirradiated;

▧ - $Fl \sim 10^{21}$ n/cm^2, $T_{irr} \sim 100^{o}C$, SM-2.

Fig 2

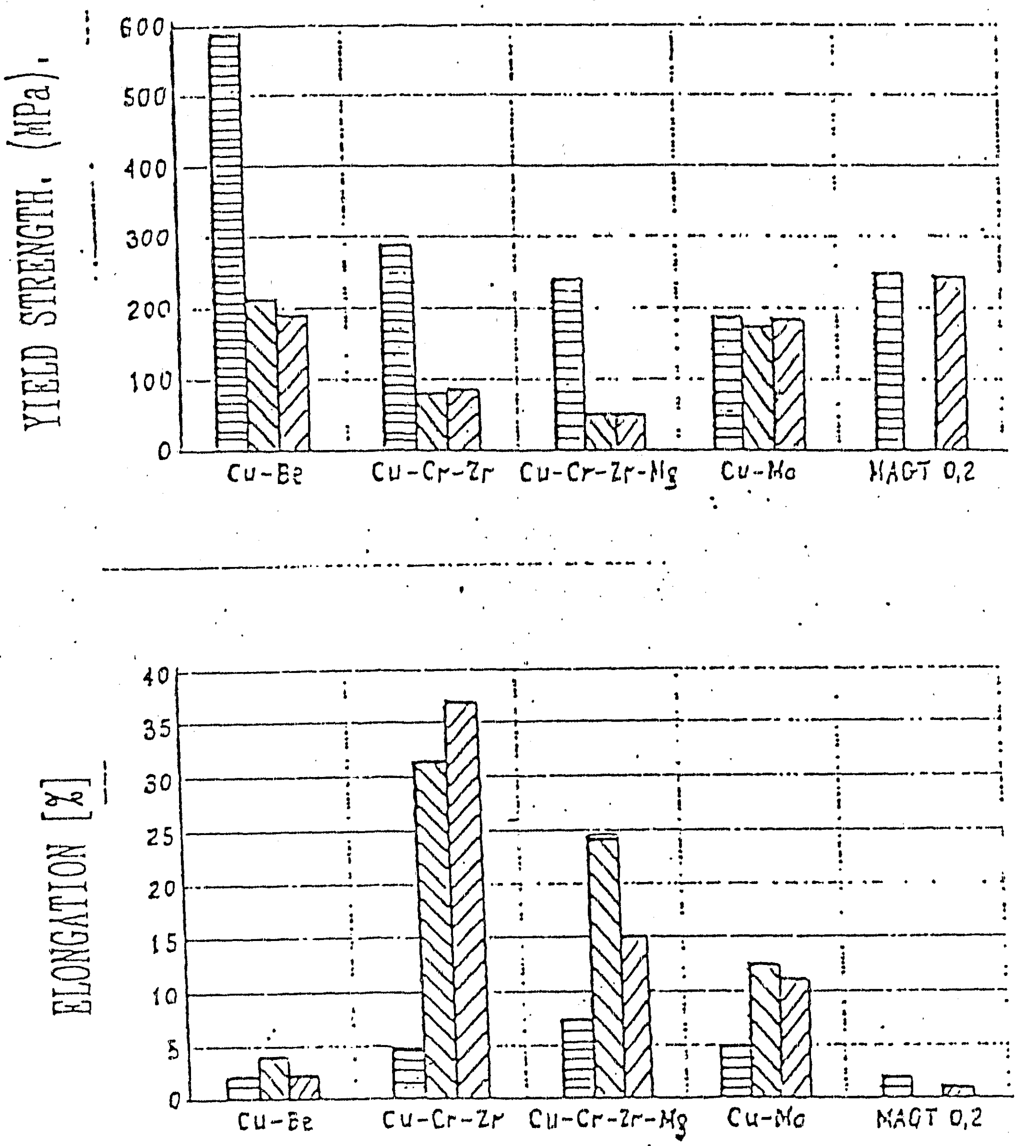


Fig.2 Tensile yield strength and elongation, measured at T_{test}=400°C, for unirradiated and irradiated copper base alloys.

▤ - unirradiated;

▧ - FL~10^{21} n/cm^2, T_{irr}~400..450°C, SM-2;

▨ - FL~10^{22} n/cm^2, T_{irr}~400..450°C, BOR-60.

Fig 3

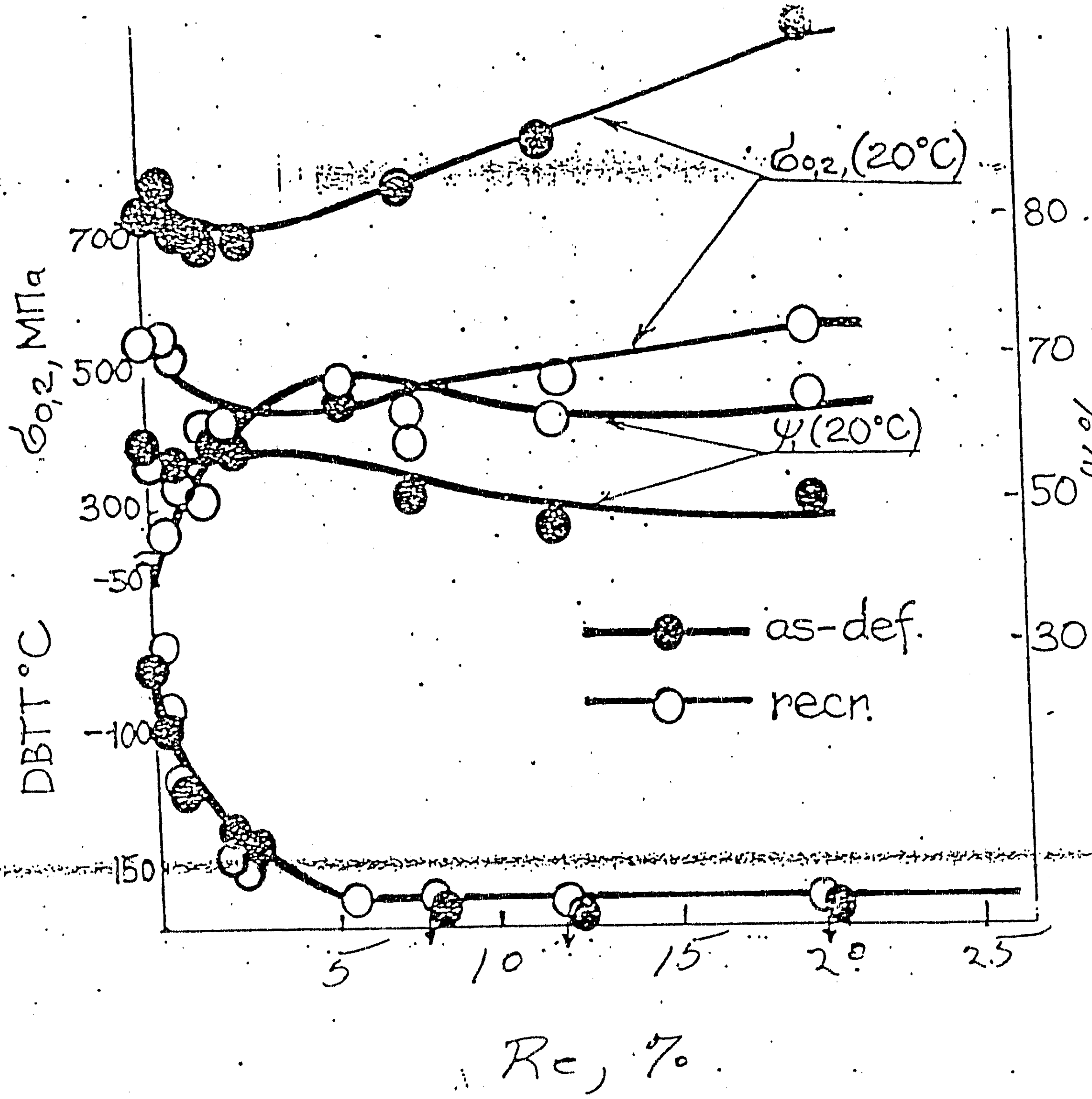
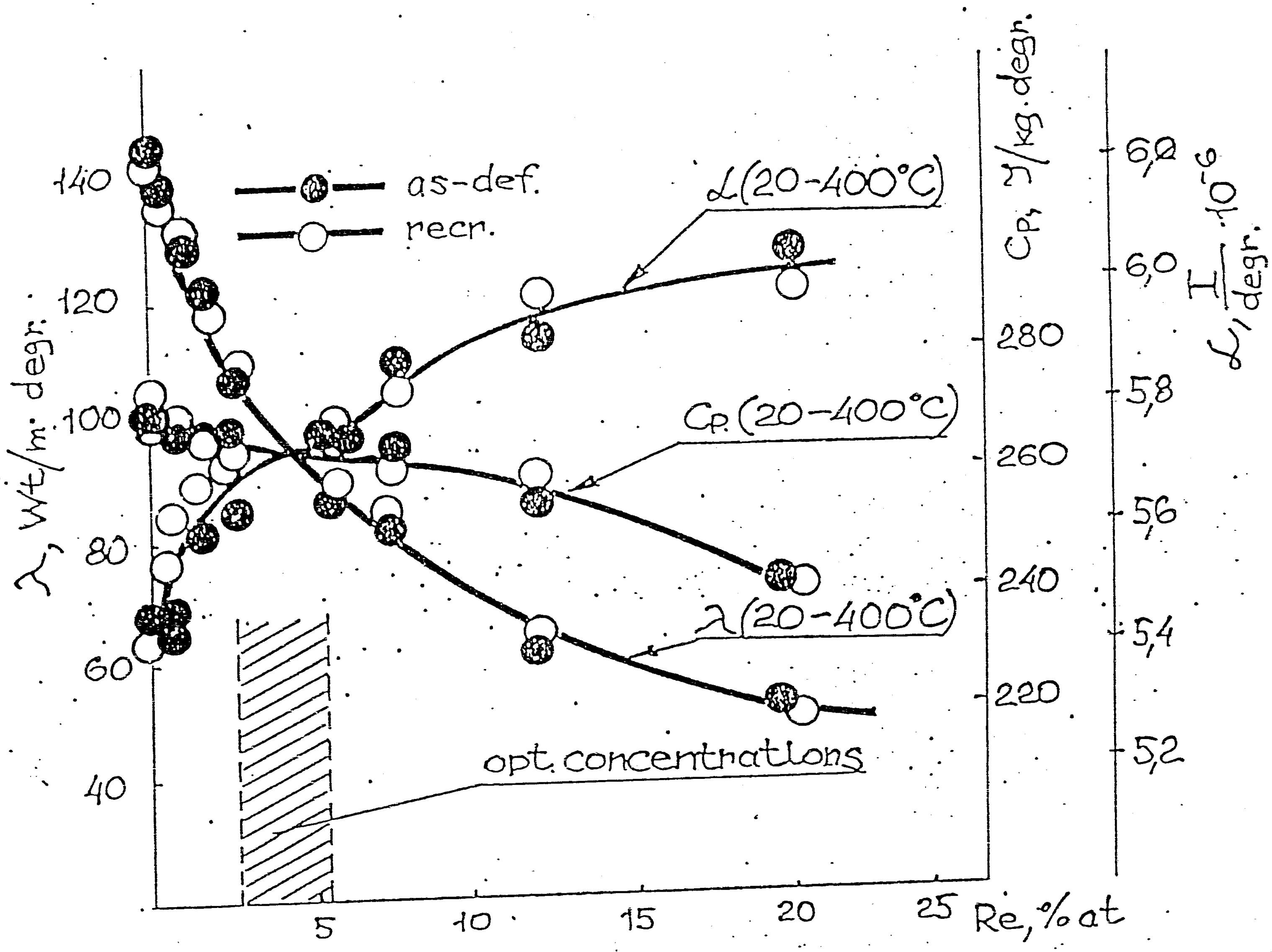


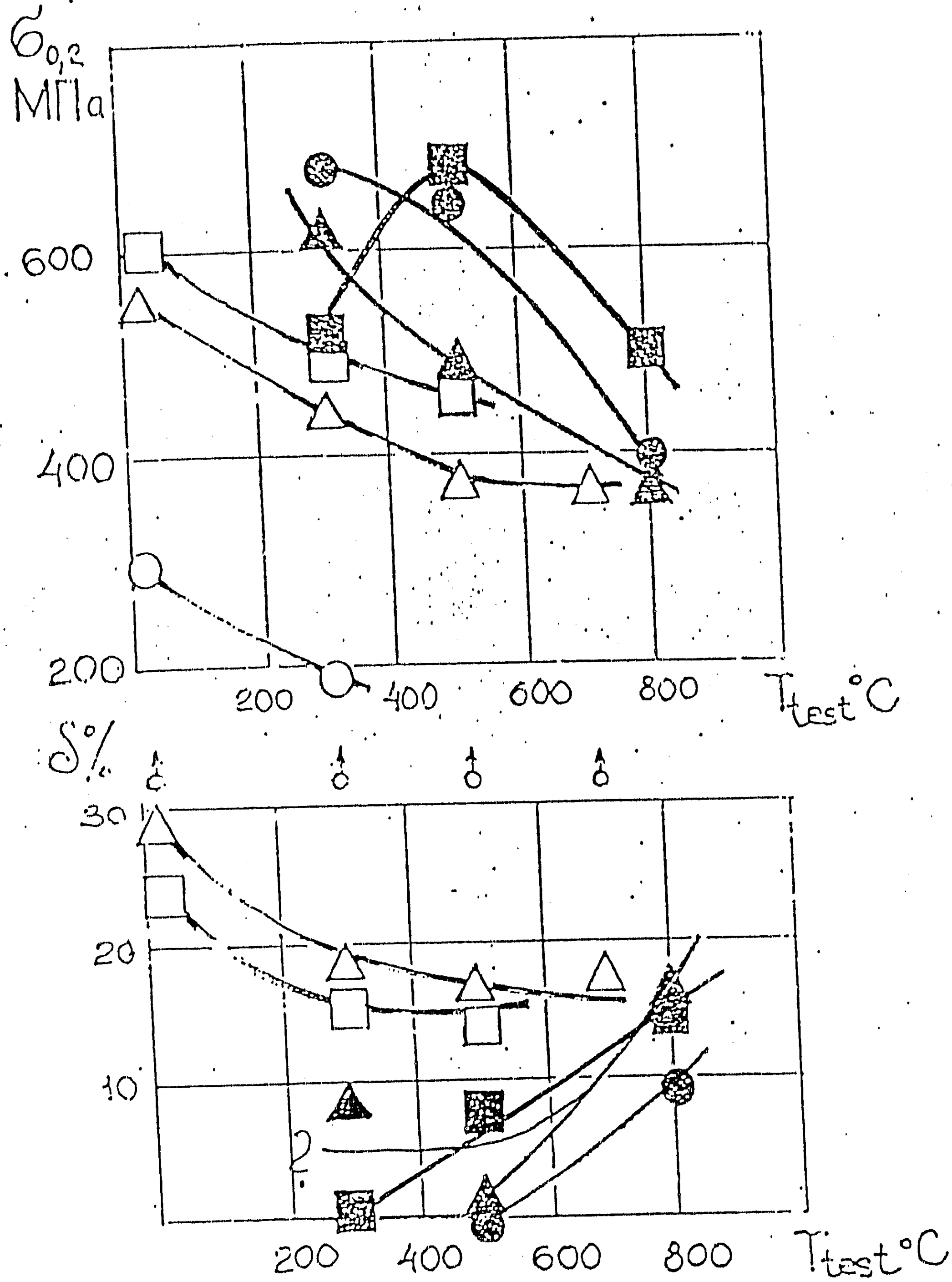
Fig 4 Effect of Re concentration on the yield strength and DBTT of Mo Re alloys

#7



The properties of the Binary
Mo-Re alloys vs. rhenium content

Fig 5



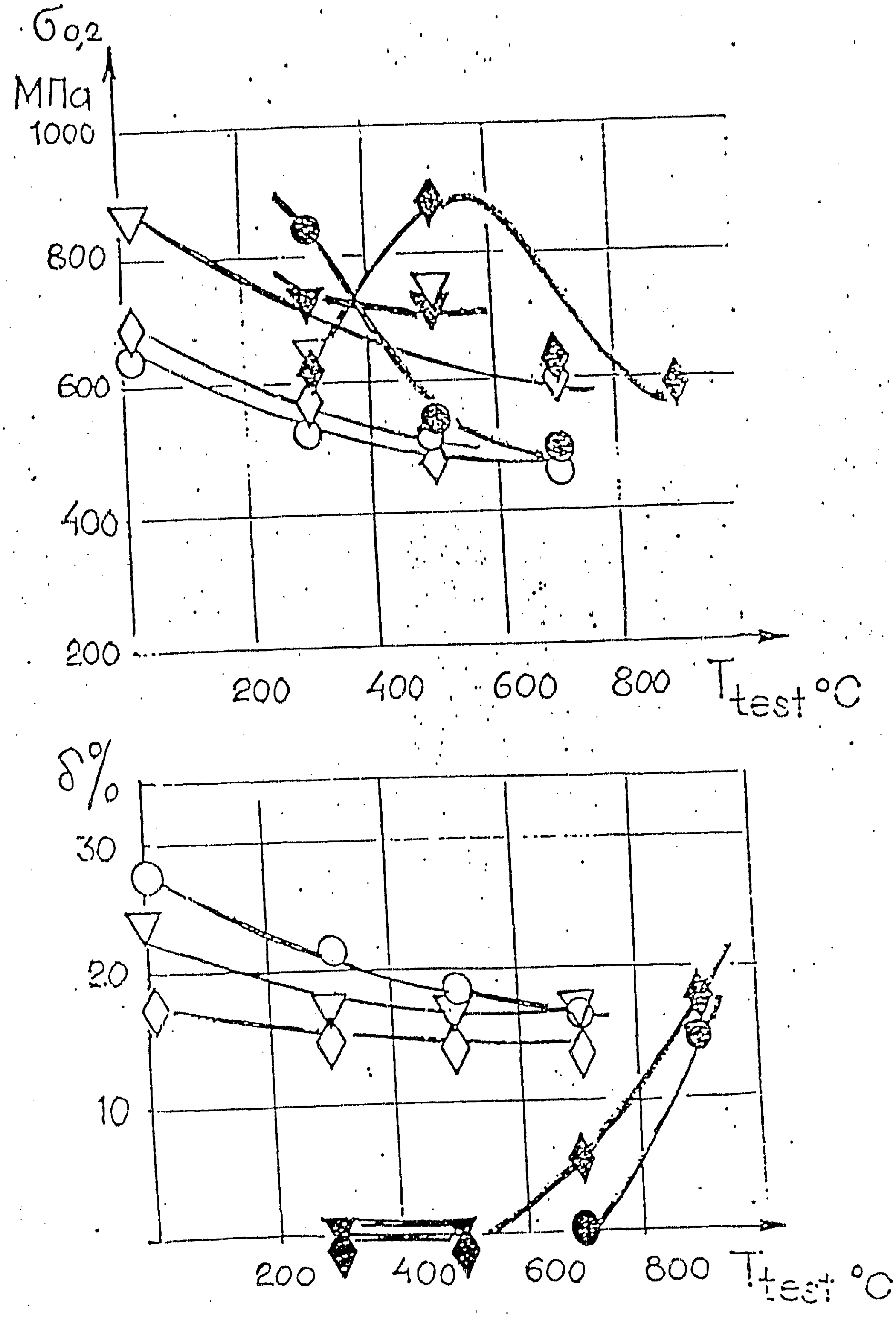
material initial state Irrad SM-2

Mo def △ ▲ Tirr

Mo recr ○ ●

Mo5Re def □ ■ $\Phi = 10^{25}$ H/M²

Fig 86



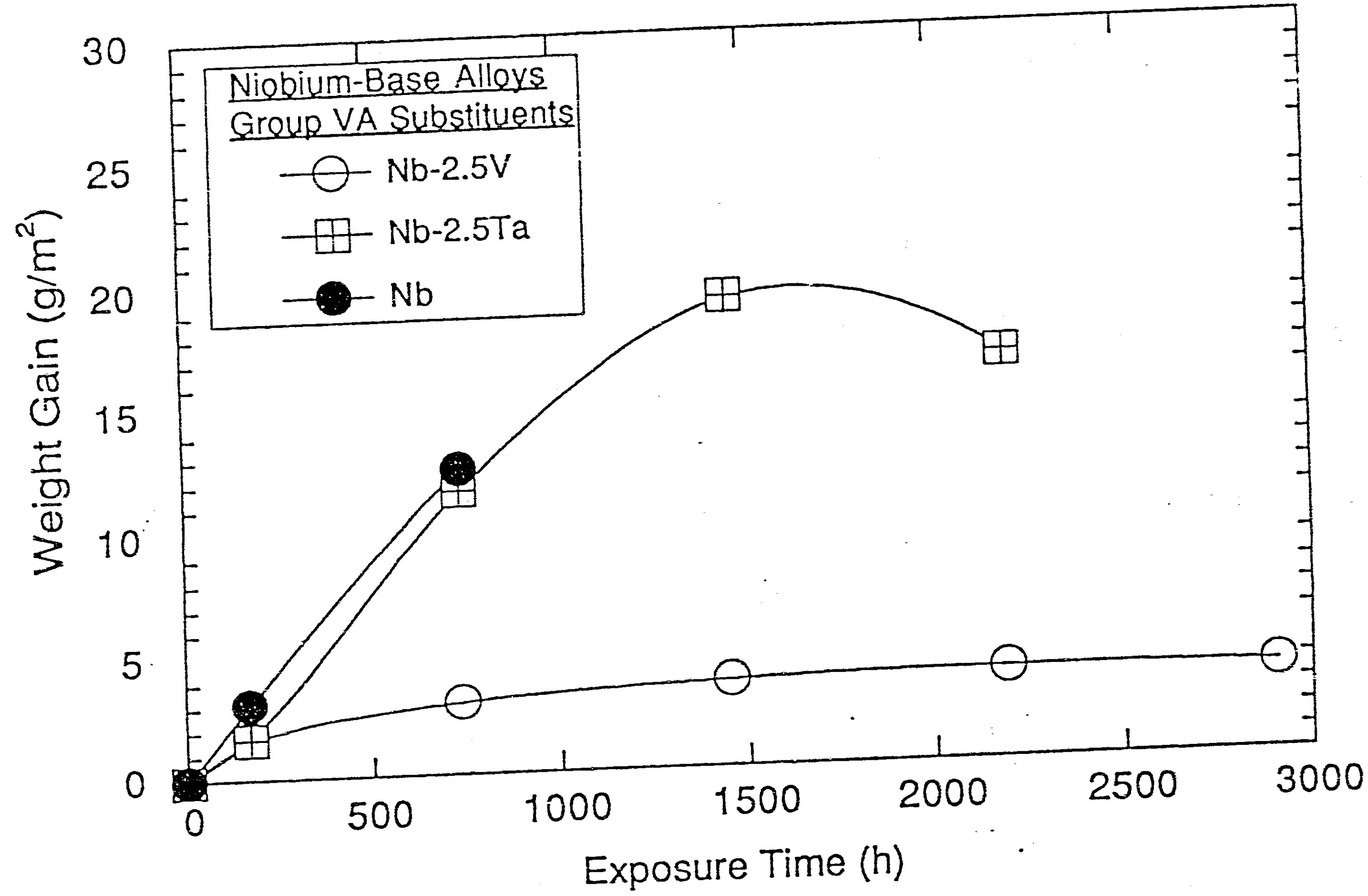
material initial state irrad. WWR

Mo Zr C def ▽ ▼ T_{irr} = 90°C

Mo Zr C recr ○ ● $F = 5 \cdot 10^{23}$ n/m

Mo ReC ann ◇ ◆

Fig 7



Corrosion of Nb, Nb-2.5Ta, Nb-2.5V in 300°C Water

(corrosion rate of Nb-2.5V is similar to that of zircalloy)

Fig. 8

END

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