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NOTICE OF ENTITLEMENT

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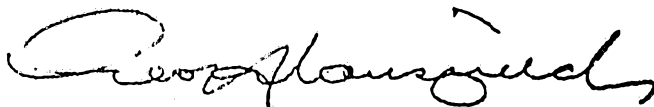
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being the applicants in respect of an application for a patent for an invention entitled
CASTING OF METAL (Application No. 45703/96), state the following:

1. The nominated persons have, for the following reasons, gained entitlement
from the actual inventor since on grant of the patent for the invention, the
nominated persons would be entitled to have a patent assigned to them.

2. The nominated persons are the applicants on the provisional application listed
on the Patent Request.

DATE: 14 August 1998

ISHIKAWAJIMA-HARIMA HEAVY INDUSTRIES COMPANY LIMITED
BHP STEEL (JLA) PTY LTD

GRIFFITH HACK
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Patent Attorney for and
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AUSTRALIA
Patents Act 1990

PATENT REQUEST : STANDARD PATENT

We, being the persons identified below as the Applicants, request the grant of a Standard Patent to the persons identified below as the Nominated Persons, for an invention described in the accompanying complete specification.

Applicants and
Nominated Persons: ISHIKAWAJIMA-HARIMA HEAVY INDUSTRIES COMPANY LIMITED

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Invention Title: CASTING OF METAL

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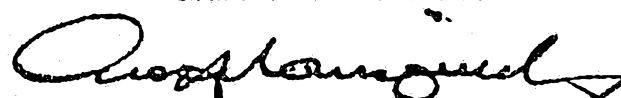MELBOURNE VIC 3004

Attorney Code: HA

BASIC CONVENTION APPLICATION DETAILS

Application No:	Country:	Application Date:
PN1764	AU	March 15 1995

Drawing number recommended to accompany the abstract: 26

DATED: February 21 1996

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(12) PATENT ABRIDGMENT   (11) Document No. AU-B-45703/96
(19) AUSTRALIAN PATENT OFFICE   (10) Acceptance No. 697384

(54) Title
CONTINUOUS CASTING OF FERROUS METAL STRIP

International Patent Classification(s)
(51)[6] B22D 011/06   B22D 011/14   B22D 011/18   C22C 038/00
C22C 038/02   C22C 038/06

(21) Application No. : 45703/96   (22) Application Date : 22.02.96

(30) Priority Data

(31) Number   (32) Date   (33) Country
PN1764   15.03.95   AU AUSTRALIA

(43) Publication Date : 26.09.96

(44) Publication Date of Accepted Application : 01.10.98

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(56) Prior Art Documents
AU 17896/95 A1
AU 54594/94 A1

(57) Claim

1.   A method of casting steel strip comprising:

introducing molten steel into a nip between a pair of parallel chilled casting rolls to form a casting pool of the molten steel supported on casting surfaces of the rolls above the nip, said casting surfaces having an Arithmetic Mean Roughness Value (R_a) of less than 5 microns;

rotating the rolls to produce a solidified steel strip delivered downwardly from the nip;

forming on each of the casting surfaces of the rolls during metal solidification a layer of oxide material, a major proportion of which layer is liquid at the commencement of steel solidification on the casting surfaces, said molten steel having a composition selected so as to form said oxide material from the molten steel, said oxide material being deposited on the

casting surfaces by the rotation of the rolls in
contact with the molten steel to form said layer,
said oxide material forming liquid oxide phases
at the casting temperature to produce said major
proportion of liquid in the layer.

2.   A method as claimed in claim 1, wherein the
liquid of said layer has a wetting angle of less than 40°
on said casting surface.

3.   A method as claimed in claim 1, wherein said
layer is less than 5 microns thick.

4.   A method as claimed in claim 3, wherein said
layer is no more than 1 micron thick.

5.   A method as claimed in claim 1, wherein the
liquid fraction of said layer is at least 0.75.

6.   A method as claimed in claim 1, wherein the
molten steel is a manganese/silicon killed steel and said
layer is a slag containing a mixture of iron, manganese and
silicon oxides and wherein the proportions of manganese and
silicon oxides in the slag is such that a major part of
those oxides is in the form of liquid phases.

7.   A method as claimed in claim 6, wherein the slag
contains MnO and SiO_2 in proportions of about 75% MnO and
25% SiO_2.

8.   A method as claimed in claim 6, further
comprising controlling the free oxygen to the casting pool
to enhance formation of iron oxide and of MnO and SiO_2 in
the slag.

9.   A method as claimed in claim 6, wherein the steel
melt is generally of the following composition:

                                                          .../3

Carbon	0.06% by weight
Manganese	0.6% by weight
Silicon	0.28% by weight
Aluminium	≤0.002% by weight

10.   A method as claimed in claim 1, wherein the molten steel is an aluminum killed steel such that said layer is a slag containing a mixture of iron, silicon and aluminum oxides and comprising the step of adding calcium to the molten steel such that the proportion of calcium to aluminium in the melt is in the range of 0.2 to 0.3 by weight.

11.   A method as claimed in claim 10, wherein the

molten steel is an aluminum killed steel comprising about 0.06% by weight of carbon, about 0.25% by weight of manganese, about 0.15% by weight of silicon, about 0.05% by weight of aluminum and a purposeful addition of calcium such that the proportion of calcium to aluminum in the melt is in the range 0.2 to 0.3 by weight.

COMPLETE SPECIFICATION

STANDARD PATENT

Applicants:	ISHIKAWAJIMA-HARIMA HEAVY INDUSTRIES COMPANY LIMITED
	BHP STEEL (JLA) PTY LTD A.C.N. 000 011 058
Invention Title:	CASTING OF METAL

The following statement is a full description of this invention, including the best method of performing it known to me/us:

CASTING OF METAL

This invention relates to the casting of metal. It has particular but not exclusive application to the casting of ferrous metal strip.

5   It is known to cast metal strip by continuous casting in a twin roll caster. In this technique molten metal is introduced between a pair of contra-rotated horizontal casting rolls which are cooled so that metal shells solidify on the moving roll surfaces and are brought together at the nip between them to produce a solidified strip product delivered downwardly from the nip between the rolls. The term "nip" is used herein to refer to the general region at which the rolls are closest together. The molten metal may be poured from a ladle into a smaller vessel from which it flows through a metal delivery nozzle located above the nip so as to direct it into the nip between the rolls, so forming a casting pool of molten metal supported on the casting surfaces of the rolls immediately above the nip and extending along the length of the nip. This casting pool is usually confined between side plates or dams held in sliding engagement with end surfaces of the rolls so as to dam the two ends of the casting pool against outflow, although alternative means such as electromagnetic barriers have also been proposed.

25   Although twin roll casting has been applied with some success to non-ferrous metals which solidify rapidly on cooling, there have been problems in applying the technique to the casting of ferrous metals. One particular problem has been the achievement of sufficiently rapid and even cooling of metal over the casting surfaces of the rolls.

Our International Patent Application PCT/AU93/00593 describes a development by which the cooling of metal at the casting surface of the rolls can be dramatically improved by taking steps to ensure that the roll surfaces have certain smoothness characteristics in conjunction with the application of relative vibratory

movement between the molten metal of the casting pool and the casting surfaces of the rolls. Specifically that application discloses that the application of vibratory movements of selected frequency and amplitude make it

5   possible to achieve a totally new effect in the metal solidification process which dramatically improves the heat transfer from the solidifying molten metal, the improvement being such that the thickness of the metal being cast at a particular casting speed can be very significantly

10   increased or alternatively the speed of casting can be substantially increased for a particular strip thickness. The improved heat transfer is associated with a very significant refinement of the surface structure of the cast metal.

15   Our Australian Patent Application 17896/95 describes a further development whereby effective relative vibration between the molten metal of the casting pool and the casting surface can be induced by the application of sound waves to the molten metal of the casting pool whereby

20   increased heat transfer and solidification structure refinement can be achieved by the application of sound waves in the sonic range at quite low power levels.

         We have now carried out extensive research on the heat transfer mechanism occurring at the interface between

25   the casting surface and the molten metal of the casting pool and have determined that the heat flux on solidification can be controlled and enhanced by ensuring that the casting surfaces are each covered by a layer of a material which is at least partially liquid at the

30   solidification temperature of the metal. It is thus possible in accordance with the invention to achieve improved heat transfer and this may be achieved without necessarily generating relative vibration between the casting pool and the rolls. If the enhanced heat transfer

35   is produced in accordance with the invention on a smooth casting surface it is possible also to achieve refined surface structure of the cast metal.

In the ensuing description it will be necessary
to refer to a quantitative measure of the smoothness of
casting surfaces. One specific measure used in our
experimental work and helpful in defining the scope of the
5   present invention is the standard measure known as the
Arithmetic Mean Roughness Value which is generally
indicated by the symbol R_a. This value is defined as the
arithmetical average value of all absolute distances of the
roughness profile from the centre line of the profile
10   within the measuring length l_m. The centre line of the
profile is the line about which roughness is measured and
is a line parallel to the general direction of the profile
within the limits of the roughness-width cut-off such that
sums of the areas contained between it and those parts of
15   the profile which lie on either side of it are equal. The
Arithmetic Mean Roughness Value may be defined as

$$R_a = \frac{1}{l_m} \int_{x=0}^{x=l_m} |\ y\ |\ dx$$

20

A method of casting steel strip comprising:

25   introducing molten steel into a nip between a
pair of parallel chilled casting rolls to form a
casting pool of the molten steel supported on
casting surfaces of the rolls above the nip, said
casting surfaces having an Arithmetic Mean
30   Roughness Value (R_a) of less than 5 microns;

rotating the rolls to produce a solidified steel
strip delivered downwardly from the nip;

35   forming on each of the casting surfaces of the
rolls during metal solidification a layer of
oxide material, a major proportion of which layer

is liquid at the commencement of steel
solidification on the casting surfaces, said
molten steel having a composition selected so as
to form said oxide material from the molten

5   steel, said oxide material being deposited on the
casting surfaces by the rotation of the rolls in
contact with the molten steel to form said layer,
said oxide material forming liquid oxide phases
at the casting temperature to produce said major

10   proportion of liquid in the layer.

Preferably, said layer is less than 5 microns
thick and the liquid of said layer has a wetting angle of
less than 40° on said casting surface.

15

It is preferred that the liquid fraction of said
layer is at least 0.75.

The metal may be steel, in which case the pool

20   may contain slag comprising iron, manganese and silicon
oxides and said layer may comprise iron, manganese and
silicon oxides deposited on the casting roll from the slag.

The slag may also comprise aluminium oxide and

25   said material may accordingly comprise a mixture of iron,
manganese, silicon and aluminium oxides.

In order that the invention may be more fully
explained the results of experimental work carried out to

30   date will be described with reference to the accompanying
drawings in which:

Figure 1 illustrates experimental apparatus for
determining metal solidification rates under conditions

35   simulating those of a twin roll caster;

Figure 2 illustrates an immersion paddle

incorporated in the experimental apparatus of Figure 1;

Figure 3 illustrates thermal resistance values obtained during solidification of a typical steel sample in the experimental apparatus;

5

Figure 4 illustrates the relationship between wettability of an interface layer and measured heat flux and interface resistance;

10

Figures 5, 5A and 6 illustrate variations in heat flux obtained by the additions of tellurium to stainless steel melts;

15 Figure 7 illustrates typical heat flux values obtained on solidification of e⁻ ⌐rolytic iron with and without oxygen addition;

Figures 8 and 9 illustrates the results of tests 20 in which oxide film was allowed to build up gradually during successive oxide immersions;

Figure 10 is a phase diagram for Mn-SiO mixtures;

25 Figure 11 shows wetting angle measurements for various manganese and silicon oxide mixtures;

Figure 12 is a three-component phase diagram for manganese, silicon and aluminium oxide mixtures;

Figures 13 and 14 illustrate the effect of varying aluminium content on solidification from a steel

5   melt;

Figure 15 illustrates the effect of free oxygen on the slag liquidus temperature of steel melts;

Figure 16 illustrates the manner in which total heat flux achieved in the solidification of steel specimens

10   was related to the liquidus temperature of the steel deoxidation products;

Figure 17 illustrates an important relationship between the total heat flux obtained on solidification of steel specimens and the proportions of the steel

15   deoxidation products which became liquid during the solidification process;

Figure 18 is a phase diagram for $CaO-Al_2O_3$ mixtures;

Figures 19 and 20 show the results of calcium

20   additions on solidification of specimens from AO6 steel melts;

Figure 21 illustrates the results of model calculations on the effect of the thickness of the surface layer;

25   Figure 22 is a plan view of a continuous strip caster which is operable in accordance with the invention;

Figure 23 is a side elevation of the strip caster shown in Figure 22;

Figure 24 is a vertical cross-section on the line

30   24-24 in Figure 22;

Figure 25 is a vertical cross-section on the line 25-25 in Figure 22;

Figure 26 is a vertical cross-section on the line 26-26 in Figure 22; and

35   Figure 27 illustrates the oxide phases present in a melt of manganese/silicon killed steel melt.

Figures 1 and 2 illustrate a metal solidification

test rig in which a 40 mm x 40 mm chilled block is advanced into a bath of molten steel at such a speed as to closely simulate the conditions the casting surfaces of a twin roll caster. Steel solidifies onto the chilled block as it

5   moves through the molten bath to produce a layer of solidified steel on the surface of the block. The thickness of this layer can be measured at points throughout its area to map variations in the solidification rate and therefore the effective rate of heat transfer at

10   the various locations. It is thus possible to produce an overall solidification rate as well as total heat flux measurements. It is also possible to examine the microstructure of the strip surface to correlate changes in the solidification microstructure with the changes in

15   observed solidification rates and heat transfer values.

The experimental rig illustrated in Figures 1 and 2 comprises an induction furnace 1 containing a melt of molten metal 2 in an inert atmosphere of argon gas. An immersion paddle denoted generally as 3 is mounted on a

20   slider 4 which can be advanced into the melt 2 at a chosen speed and subsequently retracted by the operation of computer controlled motors 5.

Immersion paddle 3 comprises a steel body 6 which contains a substrate 7 in the form of a chrome plated

25   copper disc of 46 mm diameter and 18 mm thickness. It is instrumented with thermo-couples to monitor the temperature rise in the substrate which provides a measure of the heat flux.

Tests carried out on the experimental rig

30   illustrated in Figures 1 and 2 have demonstrated that the observed solidification rates and heat flux values as well as the microstructure of the solidified shell are greatly affected by the conditions at the shell/substrate interface during solidification and that significantly increased heat

35   flux and solidification rates can be achieved by ensuring that the substrate is covered by a partially liquid layer during the solidification process so that the layer is

interposed between the substrate and the solidifying shell. The tests have shown that high heat flux and solidification rates can be achieved with smooth substrate surfaces having an Arithmetical Mean Roughness Value (R_a) of less than 5
5   microns and that this results in a refinement of the grain structure of the solidified metal.

         During solidification the total resistance to heat flow from the melt to the substrate (heat sink) is governed by the thermal resistances of the solidifying
10   shell and the shell/substrate interface. Under the conditions of conventional continuously cast sections (slabs, blooms or billets), where solidification is completed in around 30 minutes, the heat transfer resistance is dominated by the solidifying shell
15   resistance. However, our experimental work has demonstrated that under thin strip casting conditions, where solidification is completed in less than a second, the heat transfer resistance is dominated by the interface thermal resistance at the surface of the substrate.

20   The heat transfer resistance is defined as

$$R_{(t)} = \frac{\Delta T_{(t)}}{Q_{(t)}}$$

where Q, ΔT and t are heat flux, temperature difference
25   between melt and substrate and time, respectively.

         Figure 3 illustrates thermal resistance values obtained during solidification of a typical MO6 steel sample in the test rig. This shows that the shell thermal resistance contributes only a small proportion of the total
30   thermal resistance which is dominated by the interface thermal resistance. The interface resistance is initially determined by the melt/substrate interface resistance and later by the shell/substrate interface thermal resistance. Furthermore, it can be seen that the interface thermal
35   resistance does not significantly change in time which indicates that it will be governed by the melt/substrate

thermal resistance at the initial melt/substrate contact.

For a two-component system (melt and substrate), the melt/substrate interface resistance and heat flux are determined by the wettability of the melt on a particular substrate. This is illustrated in Figure 4 which shows how interface resistance increases and heat flux decreases with increasing wetting angle which corresponds with reducing wettability.

The importance of wetting of the substrate by melt was demonstrated by the developmental work described in our aforesaid International Patent Application PCT/AU93/00593 which discloses application of vibratory movements. The application of vibratory movements was for the purpose of promoting wetting of the substrate and increasing the nucleation density for the melt solidification. The mathematical model described at page 10 of that case proceeded on the basis that full wetting was required and considered the vibrational energy required to achieve this. In the experimental work which verified this analysis it was shown that significant improvement in heat flux could nót be obtained unless the substrate was smooth. More specifically, it is necessary for the substrate to have an Arithmetic Mean Roughness Value (R_a) of less than 5 microns in order to obtain adequate wetting of the substrate, even with the application of vibration energy. The same results apply to the application of the present invention, and is therefore necessary to have a smooth casting surface having an Arithmetic Mean Roughness Value (R_a) of less than 5 microns.

The importance of the wettability of the melt on the substrate and the need for a smooth substrate is confirmed by results obtained on solidification from melts containing additions of tellurium which is known to reduce the surface tension of iron. Figure 5 illustrates maximum heat flux measurements obtained on solidification of stainless steel onto smooth chromium substrates from melts containing tellurium additions. It will be seen that the

heat flux was strongly affected by the tellurium additions
and was in fact almost doubled by tellurium additions of
0.04% of more.

Figure 6 plots maximum heat flux measurements
against varying surface tension of the melt produced by the
tellurium additions and it will seen that the heat flux
increased substantially linearly with corresponding
reductions in surface tension.

Figure 5A illustrates maximum heat flux
measurements obtained on solidification of stainless steel
with tellurium additions onto chromium substrates with
textured surface. The lower line shows the results for a
textured surface having flat top pyramids at 150 microns
pitch and the upper line shows the results for a surface
textured by regular ridges at 100 microns pitch. It will
be seen that in both cases the heat flux was unaffected by
the tellurium additions. With a textured surface the
nucleation density is established by the texture and heat
flux cannot be dramatically improved by enhanced
wettability of the melt whereas a significant improvement
can be obtained on a smooth substrate.

The significance of wettability of the melt on
the substrate has been further demonstrated by examining
the effect of oxygen additions on the resulting heat flux.
Oxygen is surface active and is known to reduce the surface
tension of iron, although not to the same degree as
tellurium. Figure 7 illustrates typical heat flux values
obtained on solidification of electrolytic iron with and
without oxygen addition. It will be seen that the heat
flux is dramatically increased by the oxygen addition,
particularly in the early stages of the solidification
process.

The test results described thus far were obtained
from strictly controlled two component melt and substrate
systems. Usually a third component is present at the
melt/substrate interface in the form of oxides. These
oxides are most likely originated at the melt surface and

subsequently deposited on the substrate surface as a thin
film. When casting steel in a strip caster such oxides
will generally be present as slag floating on the upper
surface of the casting pool and are deposited on the
5   casting surface as it enters the pool. It is generally
been considered necessary when casting steel in a twin roll
caster to brush or otherwise clean the casting rolls to
avoid the build up of oxides which have been recognised as
contributing to thermal resistance and causing significant
10   reduction in heat flux and solidification rates.

        In order to examine the effect of oxide build up
on the substrate, oxide film was allowed to build up
gradually during successive substrate immersions in a
stainless steel melt and heat flux measurements were taken
15   on solidification during each immersion. Figure 8
illustrates results obtained from these experiments.
Initially the build up of oxides produced a progressive
reduction in measured heat flux. However, when the oxide
layer exceeded approximately 8 microns in thickness, a very
20   large initial increase in heat flux was observed followed
by a sharp reduction. Examination of the oxide surface
revealed signs of melting and coalescence into coarser
oxide grains. The oxide layer was found to be mainly
composed of manganese and silicon oxides.
25   The Mn-SiO$_2$ phase diagram presented in Figure 10
(Glasser [1958]) shows that for a full range of
compositions, some liquid is present above 1315°C and that
in the eutectic region melting can start from 1251°C.
Mathematical analysis of the results obtained on
30   solidification of the stainless steel on a substrate with a
heavy oxide deposit as represented in Figure 8 showed that
at the early stages of melt/substrate contact the surface
of the oxide layer reached high enough temperatures to melt
and remain molten for a period of 7 to 8 milliseconds as
35   illustrated in Figure 9. This period corresponded to the
period of increased heat flux indicated in Figure 8 and
demonstrates that the increased heat flux was due to

presence of a partially liquid layer at the substrate/melt
interface at this period.

   In view of the demonstrated importance of
wettability at the melt/substrate interface it was
5 concluded that the melting of the manganese and silicon
oxides produced improved wettability so as to increase the
heat flux at the relevant time. This conclusion was tested
by measuring the wettability of various manganese and
silicon oxide mixtures on a Cr substrate. The results of
10 these measurements are illustrated in Figure 11 which shows
that at typical temperatures between 1250 and 1400°C
mixtures of MnO and SiO_2 of varying proportions all exhibit
good wetting angle measurements. A mixture of the
proportions 75% MnO and 25% SiO_2 exhibits particularly good
15 wettability on a Cr substrate. This result is consistent
with the proposition that if a mixture of MnO and SiO_2 is
present at temperatures at which this mixture melts, this
particular molten mixture will enhance wettability at the
substrate interface with consequent dramatic improvement in
20 total heat flux.

   It should be observed that all of the melting
angle measurements exhibited in Figure 11 represent very
good wetting indeed. The highest melting angle observed
was slightly less than 40° and the majority were much less
25 than this. These results show that by appropriately
choosing the proportions of silicon and manganese it is
possible to produce a dramatic transition from very poor
wettability to extremely good wettability with melting
angles of less than 40°.

30 When casting steels the melt will usually contain
aluminium as well as manganese and silicon and accordingly
there will be a three phase oxide system comprising MnO,
SiO_2 and Al_2O_3. In order to determine the melting
temperature of the oxides it is therefore necessary to
35 consider the three-component phase diagram as illustrated
in Figure 12.

   Our experimental work has shown that total heat

flux obtained on solidification reduces with increasing
aluminium content of the melt as illustrated by Figure 13.
The reduction in heat flux is caused by the formation of
Al_2O_3 during solidification as illustrated in Figure 14.

5   From the above results it appears that increased
heat flux can be obtained if a partially liquid oxide layer
is present on the substrate, particularly a layer of MnO
and SiO_2 and if the formation of Al_2O_3 can be minimised.

        In order to test this, the effect of oxygen
10   blowing on a typical MO6 melt was investigated since the
presence of oxygen is such as to affect the slag liquidus
temperature. Oxygen has a very strong affinity for iron
and the transient effect of increasing the availability of
free oxygen is to produce much more iron oxide than would
15   be achieved under equilibrium conditions. This has the
effect of lowering the melting temperature of the oxide
layer with the result that the oxide layer is more likely
to be liquid during casting conditions. The presence of
free oxygen also increases the production of MnO and SiO_2
20   in proportions closer to a eutectic composition which will
also enhance the formation of a liquid oxide layer at
typical casting temperatures.

        The effect of free oxygen in the melt on the slag
liquidus temperature of typical MO6 steels of varying
25   manganese content at a temperature of 1650°C is illustrated
in Figure 15. These results show that the liquidus
temperature of the slag can be minimised by controlling the
availability of free oxygen at a relevant casting
temperature. Examination of the surface microstructure of
30   samples solidified under these varying conditions showed
that there was enhanced formation of MnO and SiO_2.

        Figure 16 illustrates the manner in which total
heat flux was related to the deoxidation product liquidus
temperature. It will be seen that the total heat flux
35   increases substantially linearly with decreasing liquidus
temperatures of the deoxidation products. In steel melts
the deoxidation products comprise FeO, MnO, SiO_2 and Al_2O_3

which throughout the casting temperature range will at best
be a liquid/solid mixture. We have determined that there
is a very important correlation between the liquid fraction
of oxides and the total heat flux during the solidification

5 process. Figure 17 presents total heat flux measurements
obtained on solidification of steel specimens plotted
against the proportion of the deoxidation products which
was liquid during the solidification process. In these
tests the melt temperature was 1620°C. It will be seen

10 that for this temperature there is a quite precise
relationship between the measured heat flux and the
fraction of the deoxidation products which was liquid at
that temperature. The correlation holds for other
temperatures within the normal working range of melt

15 temperatures extending from 1900°C to 1400°C.

The experimental results described thus far
establish that heat flux on solidification can be
significantly increased by ensuring that there is
interposed between the melt and the solidification

20 substrate a layer of material which is at least partly
liquid, which initially improves wettability of the melt on
the substrate and which subsequently improves wettability
between the substrate and solidified shell interface. When
casting steel, the interface layer may be formed from steel

25 deoxidation products in the form of a mixture of oxides
which will at least partially melt. The proportion of the
deoxidation products such as FeO, MnO, SiO_2 and Al_2O_3 can
be adjusted to ensure that the liquidus temperature of the
mixture is reduced to such a degree that there will be

30 substantial melting of the mixture at the casting
temperature and there is an important relationship between
the fraction of the mixture which is liquid during
solidification and the total heat flux obtained on
solidification. The proportions of the oxides in the

35 mixture and the liquidus temperature of the mixture can be
affected by supply of oxygen to the melt during
solidification and in particular the liquidus temperature

may be reduced so as to enhance the heat flux obtained. This may be of particular advantage in the casting of manganese-silicon killed steels such as M06 grades of steel.

5   Aluminium killed steel such as A06 steel present particular problems in continuous strip casting operations, especially in twin roll casters. The aluminium in the steel produces significant quantities of Al_2O_3 in the deoxidation products. This oxide is formed as solid

10   particles which can clog the fine passages in the distribution nozzle of a twin roll caster. It is also present in the oxide layer which builds up on the casting surfaces and causes poor heat transfer and low total heat flux on solidification. We have determined that these

15   problems can be alleviated by addition of calcium to the melt so as to produce CaO which in conjunction with Al_2O_3 can produce liquid phases so as to reduce the precipitation of solid Al_2O_3. This not only reduces clogging of the nozzles but improves wettability of the substrate in

20   accordance with the present invention so as to enable higher heat flux to be achieved during the solidification process.

       Figure 18 shows the phase diagram of CaO-Al_2O_3 mixtures and it will be seen that the eutectic composition

25   of 50.65% CaO has a liquidus temperature of 1350°C. Accordingly if the addition of calcium is adjusted to produce a CaO-Al_2O_3 mixture of around this eutectic composition, this will significantly increase the liquid fraction of the oxide layer so as to enhance total heat

30   flux.

       We have carried out solidification tests on a large number of A06 steel specimens with varying calcium additions on a smooth substrate at a melt temperature of 1595°C. Results of these tests are shown in Figures 19 and

35   20. Figure 19 plots the measured heat flux values over the period of solidification for varying calcium additions. Specifically five separate curves are shown for increasing

Ca/Al compositions in the direction indicated by the arrow. Figure 19 plots the maximum heat flux obtained in each solidification test against the Ca/Al content.

5   The results displayed in Figures 19 and 20 show that significant increases of heat flux can be obtained by increasing the Ca/Al content so that the $CaO-Al_2O_3$ mixture is close to its eutectic.

     Our experimental work has shown that the substantially liquid oxide layer which covers the substrate
10 under strip cooling conditions is very thin and in most cases is of the order of 1 micron thick or less. In the tests carried out the experimental apparatus illustrated in Figures 1 and 2, examination of the substrate and cast specimen surfaces after casting have revealed that both the
15 substrate and cast surface have particles of manganese and silicon compositions which must have solidified from the liquid layer. On each surface these particles have been at sub-micron levels indicating that the thickness of the liquid layer is of the order of 1 micron or less.

20   Model calculations demonstrate that the thickness of the layer should not be more than about 5 microns, otherwise the potential improvement in heat flux due to the enhanced wettability of the layer is completely offset by the increased resistance to heat flux due to the thickness
25 of the layer. Figure 21 plots the results of model calculations assuming perfect wettability. This supports the experimental observations and further indicates that the oxide layer should be less than 5 microns thick and preferably of the order of 1 micron thick or less.

30   Figures 22 to 26 illustrate a twin roll continuous strip caster which has been operated in accordance with the present invention. This caster comprises a main machine frame 11 which stands up from the factory floor 12. Frame 11 supports a casting roll
35 carriage 13 which is horizontally movable between an assembly station 14 and a casting station 15. Carriage 13 carries a pair of parallel casting rolls 16 to which molten

metal is supplied during a casting operation from a ladle
17 via a tundish 18 and delivery nozzle 19 to create a
casting pool 30. Casting rolls 16 are water cooled so that
shells solidify on the moving roll surfaces 16A and are
5   brought together at the nip between them to produce a
solidified strip product 20 at the roll outlet. This
product is fed to a standard coiler 21 and may subsequently
be transferred to a second coiler 22. A receptacle 23 is
mounted on the machine frame adjacent the casting station
10   and molten metal can be diverted into this receptacle via
an overflow spout 24 on the tundish or by withdrawal of an
emergency plug 25 at one side of the tundish if there is a
severe malformation of product or other severe malfunction
during a casting operation.
15   Roll carriage 13 comprises a carriage frame 31
mounted by wheels 32 on rails 33 extending along part of
the main machine frame 11 whereby roll carriage 13 as a
whole is mounted for movement along the rails 33. Carriage
frame 31 carries a pair of roll cradles 34 in which the
20   rolls 16 are rotatably mounted. Roll cradles 34 are
mounted on the carriage frame 31 by interengaging
complementary slide members 35, 36 to allow the cradles to
be moved on the carriage under the influence of hydraulic
cylinder units 37, 38 to adjust the nip between the casting
25   rolls 16 and to enable the rolls to be rapidly moved apart
for a short time interval when it is required to form a
transverse line of weakness across the strip as will be
explained in more detail below. The carriage is movable as
a whole along the rails 33 by actuation of a double acting
30   hydraulic piston and cylinder unit 39, connected between a
drive bracket 40 on the roll carriage and the main machine
frame so as to be actuable to move the roll carriage
between the assembly station 14 and casting station 15 and
vice versa.
35   Casting rolls 16 are contra rotated through drive
shafts 41 from an electric motor and transmission mounted
on carriage frame 31. Rolls 16 have copper peripheral

walls formed with a series of longitudinally extending and circumferentially spaced water cooling passages supplied with cooling water through the roll ends from water supply ducts in the roll drive shafts 41 which are connected to

5 water supply hoses 42 through rotary glands 43. The roll may typically be about 500 mm diameter and up to 2000 mm long in order to produce 2000 mm · ide strip product.

Ladle 17 is of entirely conventional construction and is supported via a yoke 45 on an overhead crane whence

10 it can be brought into position from a hot metal receiving station. The ladle is fitted with a stopper rod 46 actuable by a servo cylinder to allow molten metal to flow from the ladle through an outlet nozzle 47 and refractory shroud 48 into tundish 18.

15 Tundish 18 is also of conventional construction. It is formed as a wide dish made of a refractory material such as magnesium oxide (MgO). One side of the tundish receives molten metal from the ladle and is provided with the aforesaid overflow 24 and emergency plug 25. The other

20 side of the tundish is provided with a series of longitudinally spaced metal outlet openings 52. The lower part of the tundish carries mounting brackets 53 for mounting the tundish onto the roll carriage frame 31 and provided with apertures to receive indexing pegs 54 on the

25 carriage frame so as to accurately locate the tundish.

Delivery nozzle 19 is formed as an elongate body made of a refractory material such as alumina graphite. Its lower part is tapered so as to converge inwardly and downwardly so that it can project into the nip between

30 casting rolls 16. It is provided with a mounting bracket 60 whereby to support it on the roll carriage frame and its upper part is formed with outwardly projecting side flanges 55 which locate on the mounting bracket.

Nozzle 19 may have a series of horizontally

35 spaced generally vertically extending flow passages to produce a suitably low velocity discharge of metal throughout the width of the rolls and to deliver the molten

- 20 -

metal into the nip between the rolls without direct
impingement on the roll surfaces at which initial
solidification occurs. Alternatively, the nozzle may have
a single continuous slot outlet to deliver a low velocity

5   curtain of molten metal directly into the nip between the
rolls and/or it may be immersed in the molten metal pool.

The pool is confined at the ends of the rolls by
a pair of side closure plates 56 which are held against
stepped ends 57 of the rolls when the roll carriage is at

10   the casting station. Side closure plates 56 are made of a
strong refractory material, for example boron nitride, and
have scalloped side edges 81 to match the curvature of the
stepped ends 57 of the rolls. The side plates can be
mounted in plate holders 82 which are movable at the

15   casting station by actuation of a pair of hydraulic
cylinder units 83 to bring the side plates into engagement
with the stepped ends of the casting rolls to form end
closures for the molten pool of metal formed on 1e casting
rolls during a casting operation.

20   During a casting operation the ladle stopper rod
46 is actuated to allow molten metal to pour from the ladle
to the tundish through the metal delivery nozzle whence it
flows to the casting rolls. The clean head end of the
strip product 20 is guided by actuation of an apron table

25   96 to the jaws of the coiler 21. Apron table 96 hangs from
pivot mountings 97 on the main frame and can be swung
toward the coiler by actuation of an hydraulic cylinder
unit 98 after the clean head end has been formed. Table 96
may operate against an upper strip guide flap 99 actuated

30   by a piston and a cylinder unit 101 and the strip product
20 may be confined between a pair of vertical side rollers
102. After the head end has been guided in to the jaws of
the coiler, the coiler is rotated to coil the strip product
20 and the apron table is allowed to swing back to its

35   inoperative position where it simply hangs from the machine
frame clear of the product which is taken directly onto the
coiler 21. The resulting strip product 20 may be

subsequently transferred to coiler 22 to produce a final
coil for transport away from the caster.

Full particulars of a twin roll caster of the
kind illustrated in Figures 22 to 26 are more fully
5   described in our United States Patents 5,184,668 and
5,277,243 and International Patent Application
PCT/AU93/00593. In accordance with the present invention
steel has been cast in such apparatus with steel melt
compositions chosen such that the deoxidation products
10   produce an oxide coating on the casting rolls which has a
major liquid fraction at the casting temperature. As a
result, it has been confirmed that a preferred MO6 steel
composition to achieve optimum results is as follows:

Carbon   0.06% by weight
15   Manganese   0.6% by weight
Silicon   0.28% by weight
Aluminium $\leq$ 0.002% by weight
Melt free oxygen   60-100 parts per million.

It has also been determined that with
20   manganese/silicon killed steels the melt free oxygen level
is important. Figure 27 illustrates the oxide phases
present in a MO6 steel of the preferred composition over a
range of melt temperatures at differing free oxygen levels.
It is preferred to maintain conditions which produce MnO +
25   SiO_2 and to avoid the conditions which produce either Al_2O_3
or solid SiO_2 oxides. It is therefore preferred to have a
melt free oxygen level in the range 60 to 100 parts per
million from melt temperatures below 1675°C.

It has further been determined that a suitable
30   AO6 composition to achieve optimum results with appropriate
calcium addition is as follows:

Carbon   0.06% by weight
Manganese   0.25% by weight
Silicon   0.015% by weight
35   Aluminium   0.05% by weight

The coating on the roll may be produced entirely
by build up of oxides from the casting pool. In this case

it may be necessary for an initial quantity of strip to be
produced before there is sufficient build up to produce a
partially liquid layer to the extent to achieve the desired
heat flux consistent with the speed of strip production.
5   There may thus be an initial start up period which will
produce scrap product before stable high heat flux
conditions are achieved.

Rather than rely on the build up of oxides on the
roll it is feasible within the scope of the present
10   invention to apply an appropriate oxide composition to the
roll surfaces immediately in advance of their entry into
the pool or to provide the rolls with a permanent coating
of oxides which partially melt on contact with the casting
pool. Suitable low melting point coating material could be
15   rhodium oxide, potassium oxide and bismuth oxide.

The invention is not limited in its application
to twin roll casters and it may be applied in any
continuous strip casting operation such as casting carried
out on a single roll caster or a belt caster. It may also
20   find application in other casting processes in which metal
must be rapidly solidified by contact with a chilled
casting surface.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1.   A method of casting steel strip comprising:

introducing molten steel into a nip between a
pair of parallel chilled casting rolls to form a
casting pool of the molten steel supported on
casting surfaces of the rolls above the nip, said
casting surfaces having an Arithmetic Mean
Roughness Value (R_a) of less than 5 microns;

rotating the rolls to produce a solidified steel
strip delivered downwardly from the nip;

forming on each of the casting surfaces of the
rolls during metal solidification a layer of
oxide material, a major proportion of which layer
is liquid at the commencement of steel
solidification on the casting surfaces, said
molten steel having a composition selected so as
to form said oxide material from the molten
steel, said oxide material being deposited on the
casting surfaces by the rotation of the rolls in
contact with the molten steel to form said layer,
said oxide material forming liquid oxide phases
at the casting temperature to produce said major
proportion of liquid in the layer.

2.   A method as claimed in claim 1, wherein the
liquid of said layer has a wetting angle of less than 40°
on said casting surface.

3.   A method as claimed in claim 1, wherein said
layer is less than 5 microns thick.

4.   A method as claimed in claim 3, wherein said
layer is no more than 1 micron thick.

5.   A method as claimed in claim 1, wherein the liquid fraction of said layer is at least 0.75.

6.   A method as claimed in claim 1, wherein the molten steel is a manganese/silicon killed steel and said layer is a slag containing a mixture of iron, manganese and silicon oxides and wherein the proportions of manganese and silicon oxides in the slag is such that a major part of th\, je oxides is in the form of liquid phases.

7.   A method as claimed in claim 6, wherein the slag contains MnO and SiO_2 in proportions of about 75% MnO and 25% SiO_2.

8.   A method as claimed in claim 6, further comprising controlling the free oxygen to the casting pool to enhance formation of iron oxide and of MnO and SiO_2 in the slag.

9.   A method as claimed in claim 6, wherein the steel melt is generally of the following composition:

Carbon	0.06% by weight
Manganese	0.6% by weight
Silicon	0.28% by weight
Aluminium	$\leq$0.002% by weight

10.   A method as claimed in claim 1, wherein the molten steel is an aluminum killed steel such that said layer is a slag containing a mixture of iron, silicon and aluminum oxides and comprising the step of adding calcium to the molten steel such that the proportion of calcium to aluminium in the melt is in the range of 0.2 to 0.3 by weight.

11.   A method as claimed in claim 10, wherein the

molten steel is an aluminum killed steel comprising about
0.06% by weight of carbon, about 0.25% by weight of
manganese, about 0.15% by weight of silicon, about 0.05% by
weight of aluminum and a purposeful addition of calcium
5   such that the proportion of calcium to aluminum in the melt
is in the range 0.2 to 0.3 by weight.

Dated this 14th day of August 1998
ISHIKAWAJIMA-HARIMA HEAVY INDUSTRIES COMPANY LIMITED
10   BHP STEEL (JLA) PTY LTD
By their Patent Attorneys
GRIFFITH HACK
Fellows Institute of Patent
Attorneys of Australia

ABSTRACT

Method for continuously casting metal strip of the kind in which molten metal is introduced into the nip between a pair of parallel casting rolls (16) via a metal delivery nozzle (19) disposed above the nip to create a casting pool (30) of molten metal supported on casting surfaces (16A) of the rolls immediately above the nip and the casting rolls (16) are rotated to deliver a solidified metal strip (20) downwardly from the nip.

The casting surfaces (16A) are smooth so as to have an Arithmetic Mean Roughness Value (R_a) of less than 5 microns and the casting pool contains material to form on each of the casting surfaces a thin layer interposed between the casting surface and the casting pool during metal solidification a major proportion of which layer is liquid during the metal solidification and the liquid of the layer has a wetting angle of less than 40° on the casting surface. This promotes wetting of the smooth casting surfaces and increases heat flux during metal solidification.

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FIG. 1.
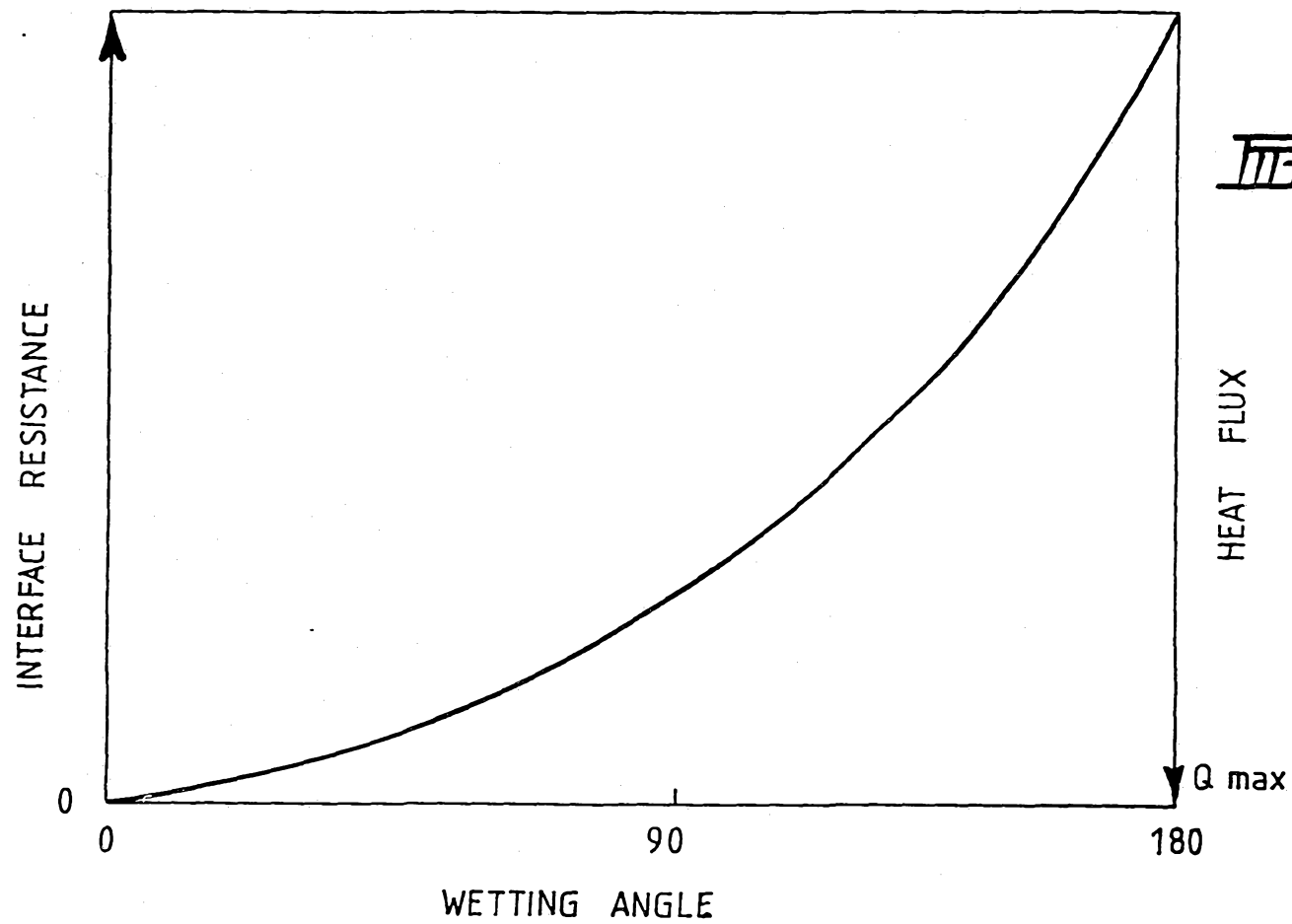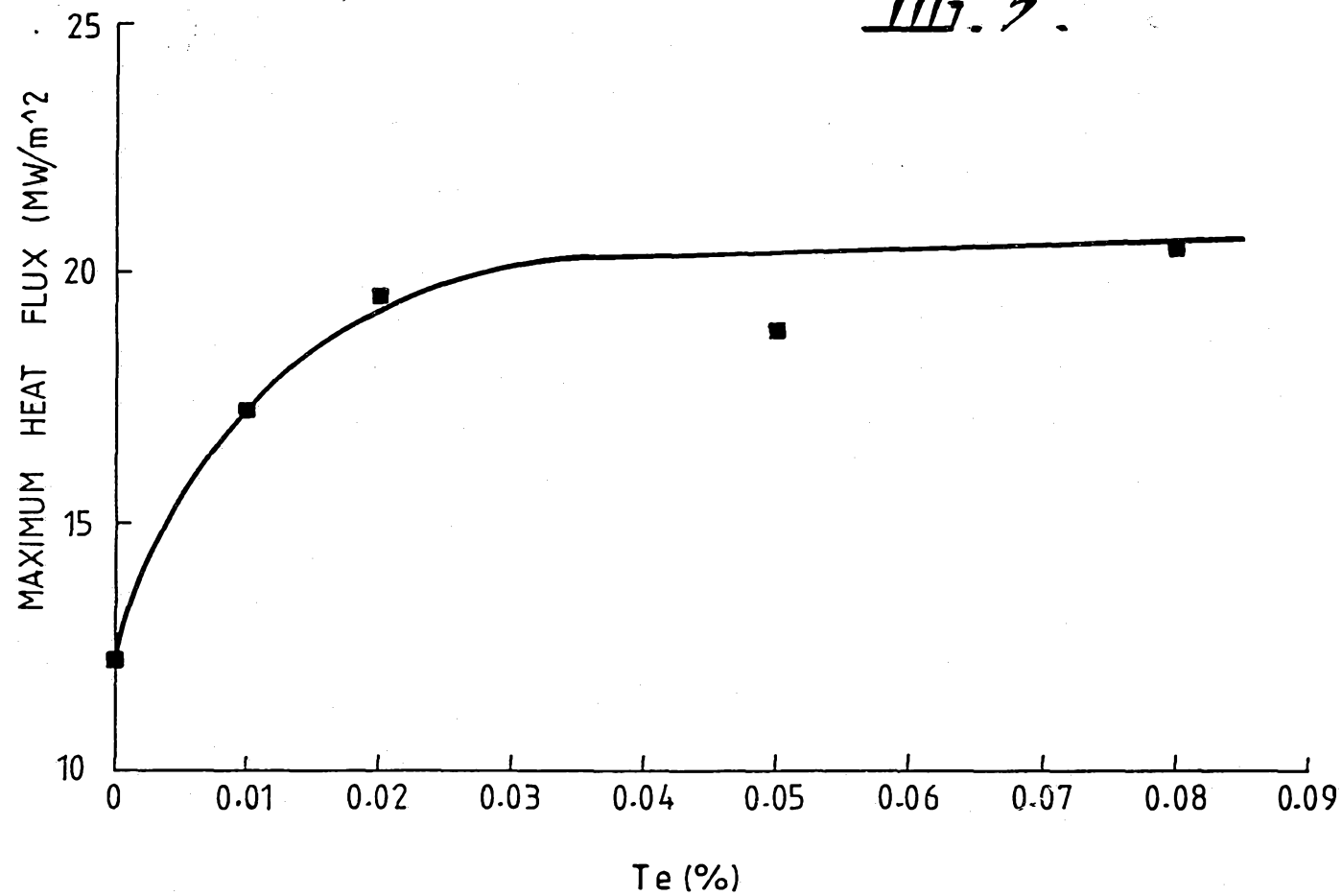
FIG. 2.

FIG. 3.

FIG.4.

INTERFACE RESISTANCE

HEAT FLUX

Q max

0

0   90   180

WETTING ANGLE

FIG. 5.

FIG.5A

FIG. 6.

FIG. 7.

FIG. 8.

FIG. 9

FIG. 10.

Phase diagram of the MnO–SiO$_2$ system. Temperature (°C) is plotted on the vertical axis from 1100 to 1900, and composition from MnO to SiO$_2$ (0 to 100) on the horizontal axis.

- 1850°
- TWO LIQUIDS
- 1723°
- 1705°
- LIQUID
- CRISTOBALITE & LIQUID
- MANGANOSITE & LIQUID
- Mn$_2$SiO$_4$ & LIQUID
- 1470°
- 1345°
- TRIDYMITE & LIQUID
- 1315°
- 1291°
- 1251°
- MnSiO$_3$ & LIQUID
- MANGANOSITE & TEPHROITE
- Mn$_2$SiO$_4$
- RHODONITE & TEPHROITE
- MnSiO$_3$
- RHODONITE & TRIDYMITE

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FIG. 11.

FIG. 12.

Ternary phase diagram of the system MnO–Al_2O_3–SiO_2 with axes labeled WEIGHT % MnO, WEIGHT % Al_2O_3, and WEIGHT % SiO_2. Phase fields shown include: TWO LIQUIDS, CHRISTOBALITE, MULLITE, TRIDYMITE, SPESSARTITE, RHODONITE, TEPHROITE, MANGANOSITE, GALAXITE, CORUNDUM. Compound points labeled MnO–SiO_2, $2MnO$–SiO_2, $2MnO$–$2Al_2O_3$–$5SiO_2$, $3MnO$–Al_2O_3–$3SiO_2$, MnO–Al_2O_3, $3Al_2O_3$–$2SiO_2$. Isotherms labeled 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000.

FIG. 13.

FIG. 14.

FIG. 15.

FIG. 16.

FIG. 17.

FIG. 18

FIG. 19.

FIG.20.

FIG. 21.

FIG. 22.

$\overline{I\!I\!I\!I}$. 23.

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$\overline{\text{Fig}}$. 24

55

19

81

81

56

14 37 34

16 60 16 38 15 23

13

31

32

43 42

32

33

24/21

101

40

97

39

99

96

11

FIG. 25.

25|27

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$\text{FIG. } 26$

17

46

47

48

18

24

52

25

53

31

60

19

30

16A

16A

16

16
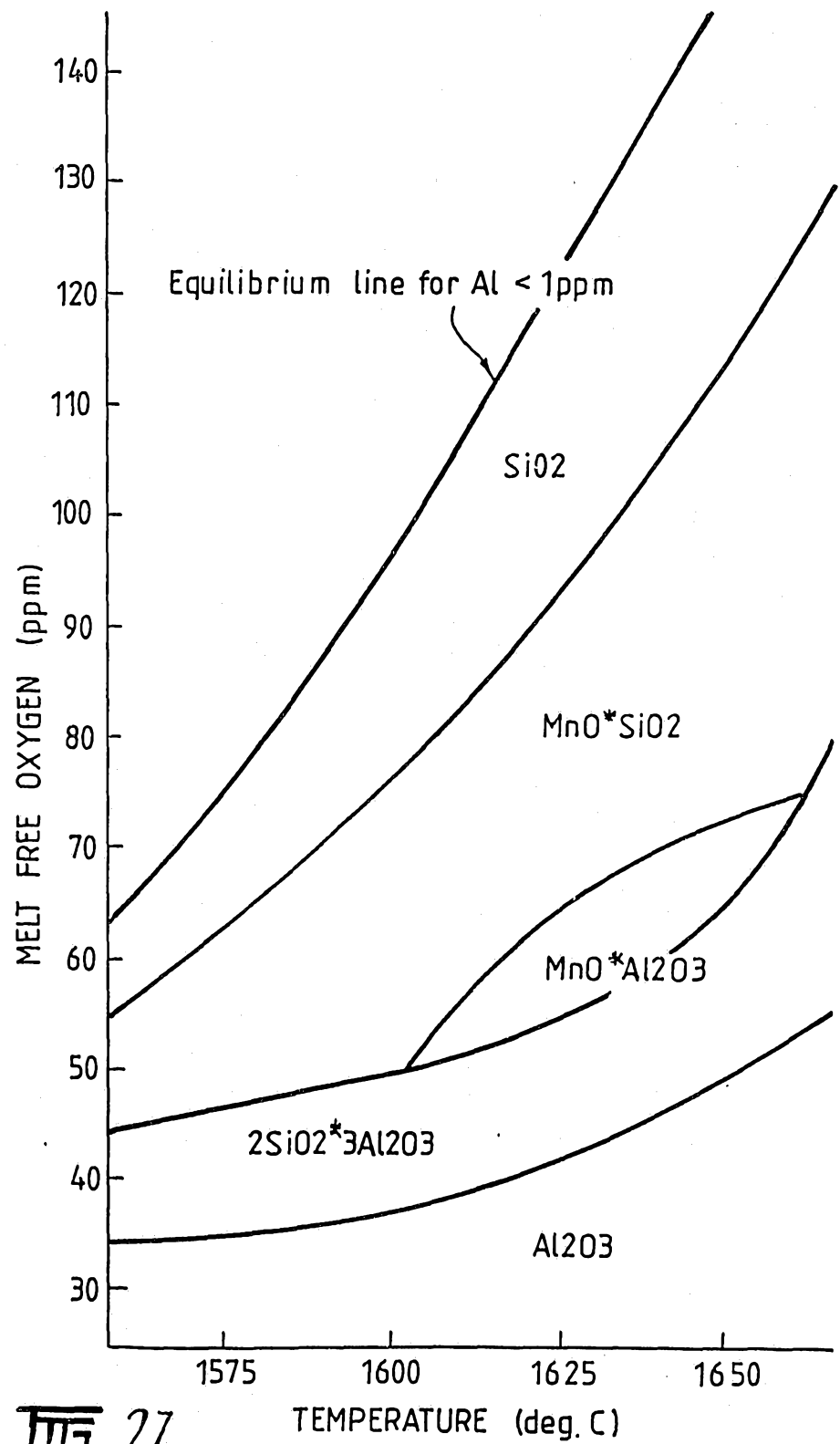
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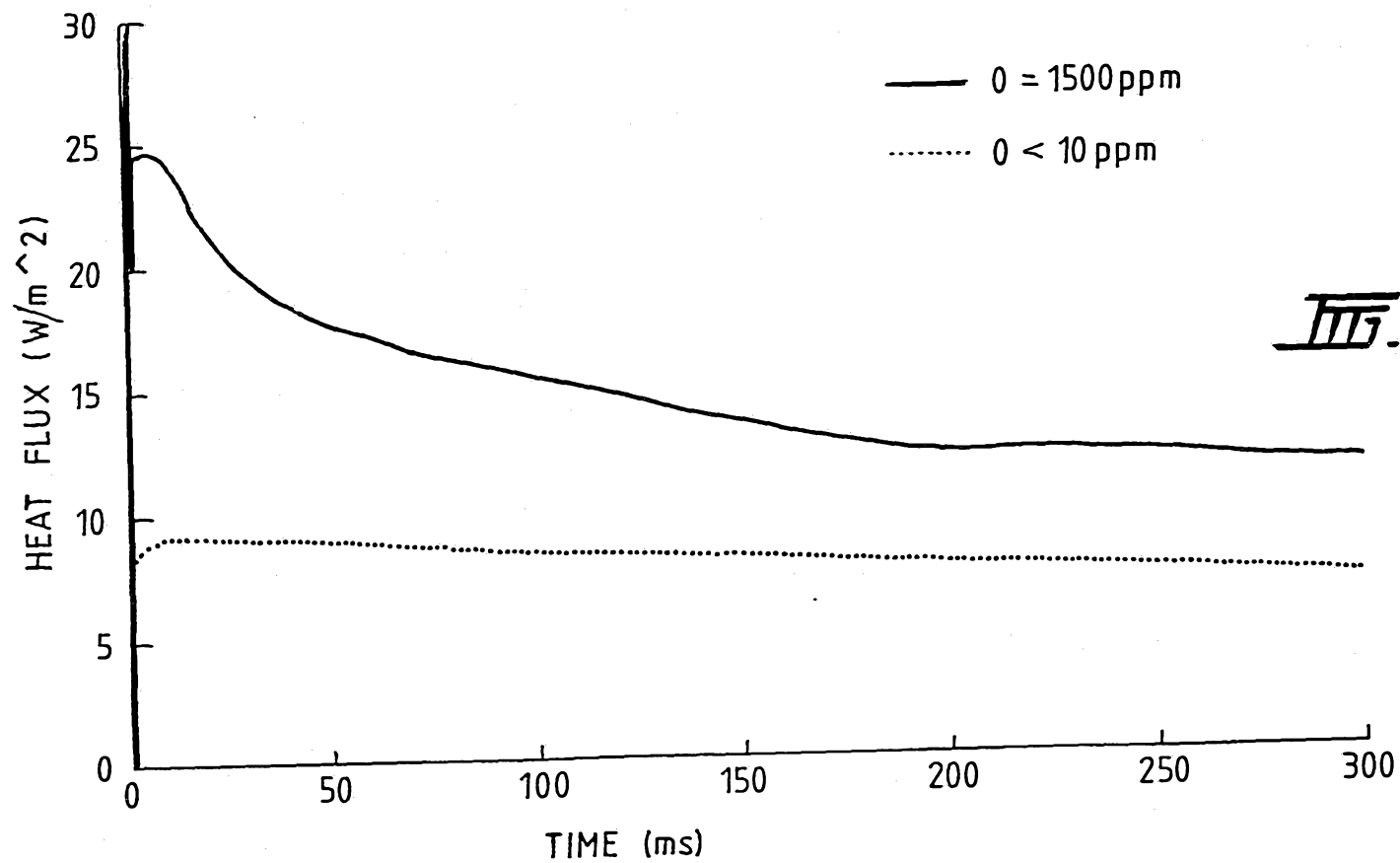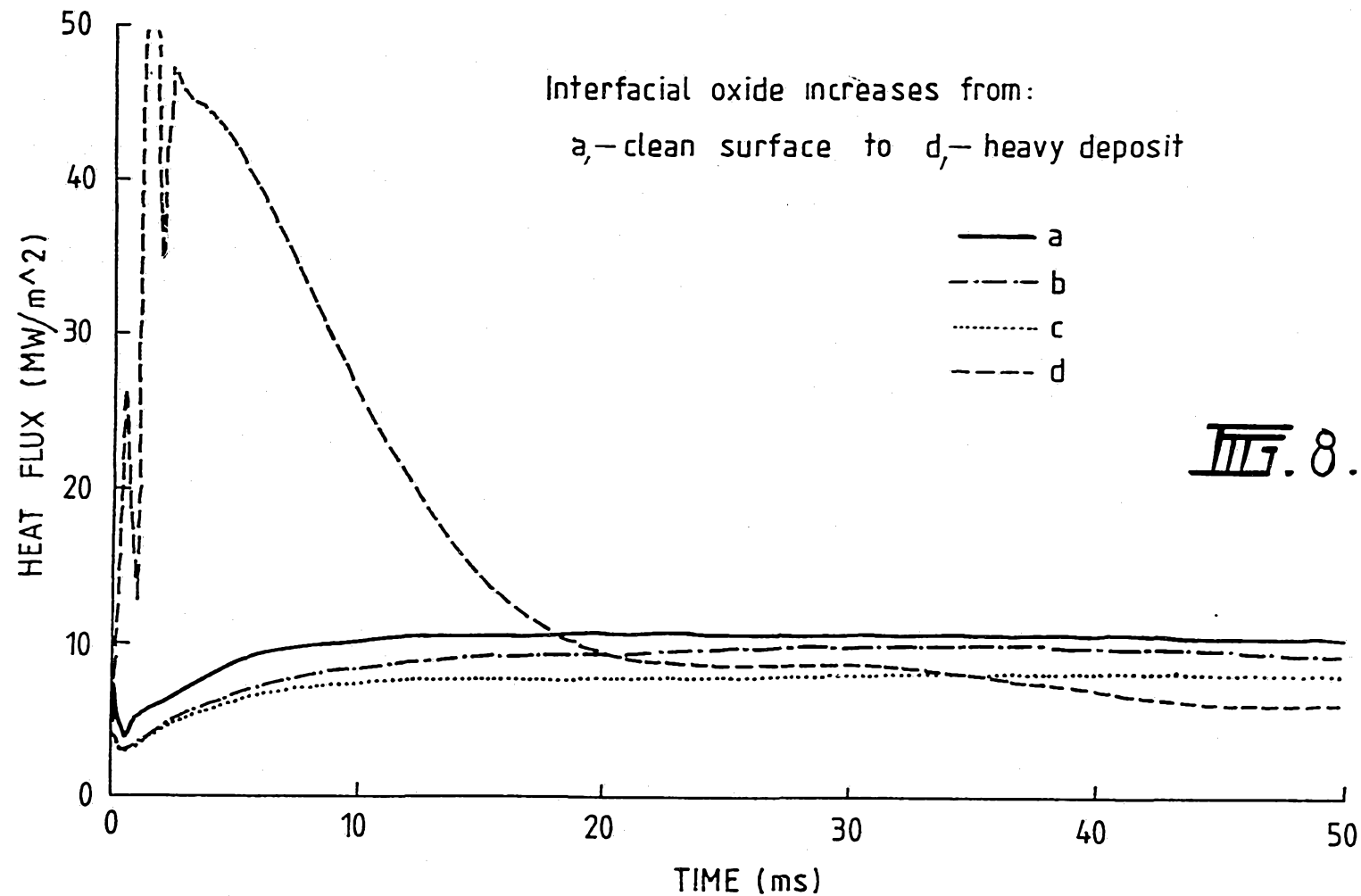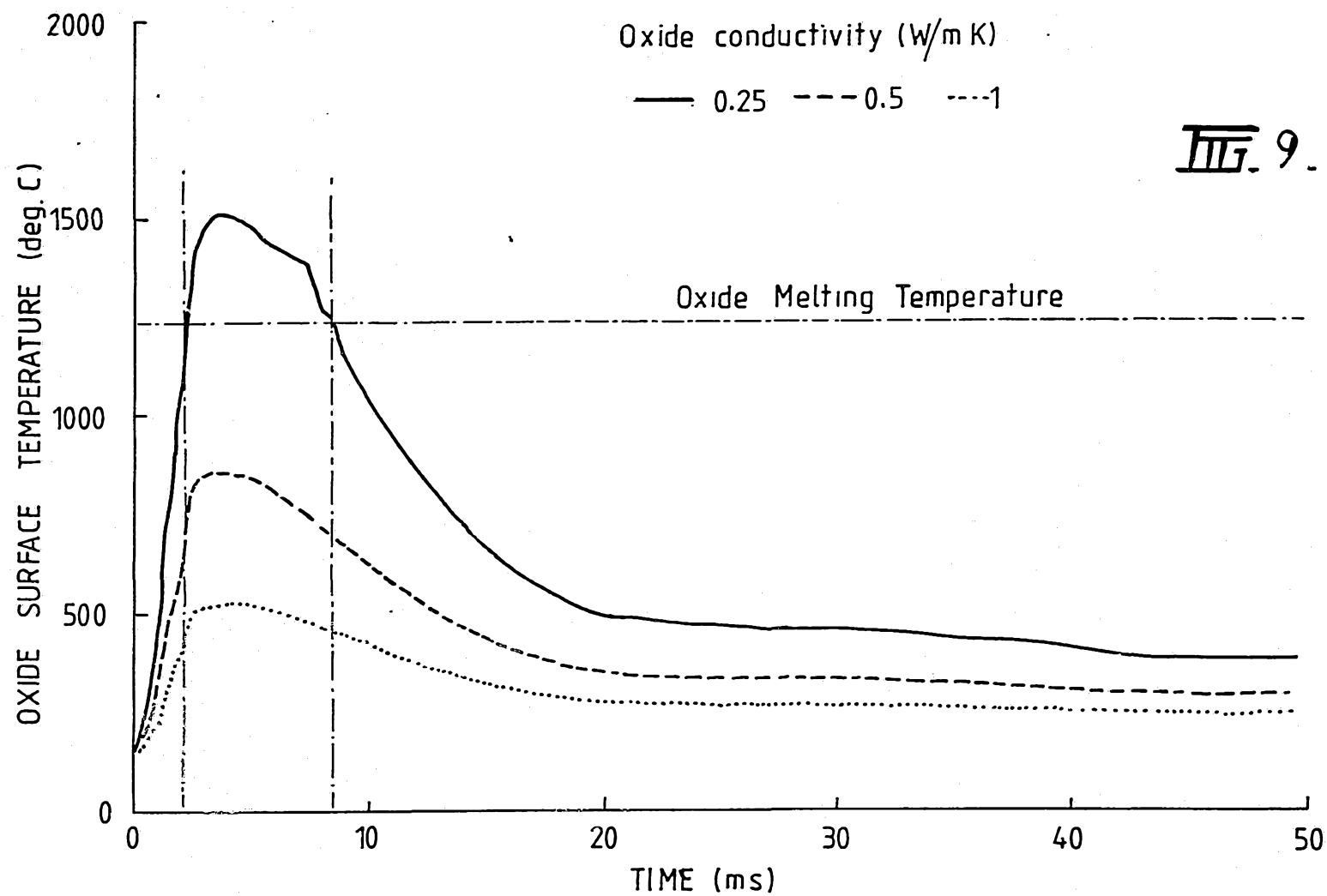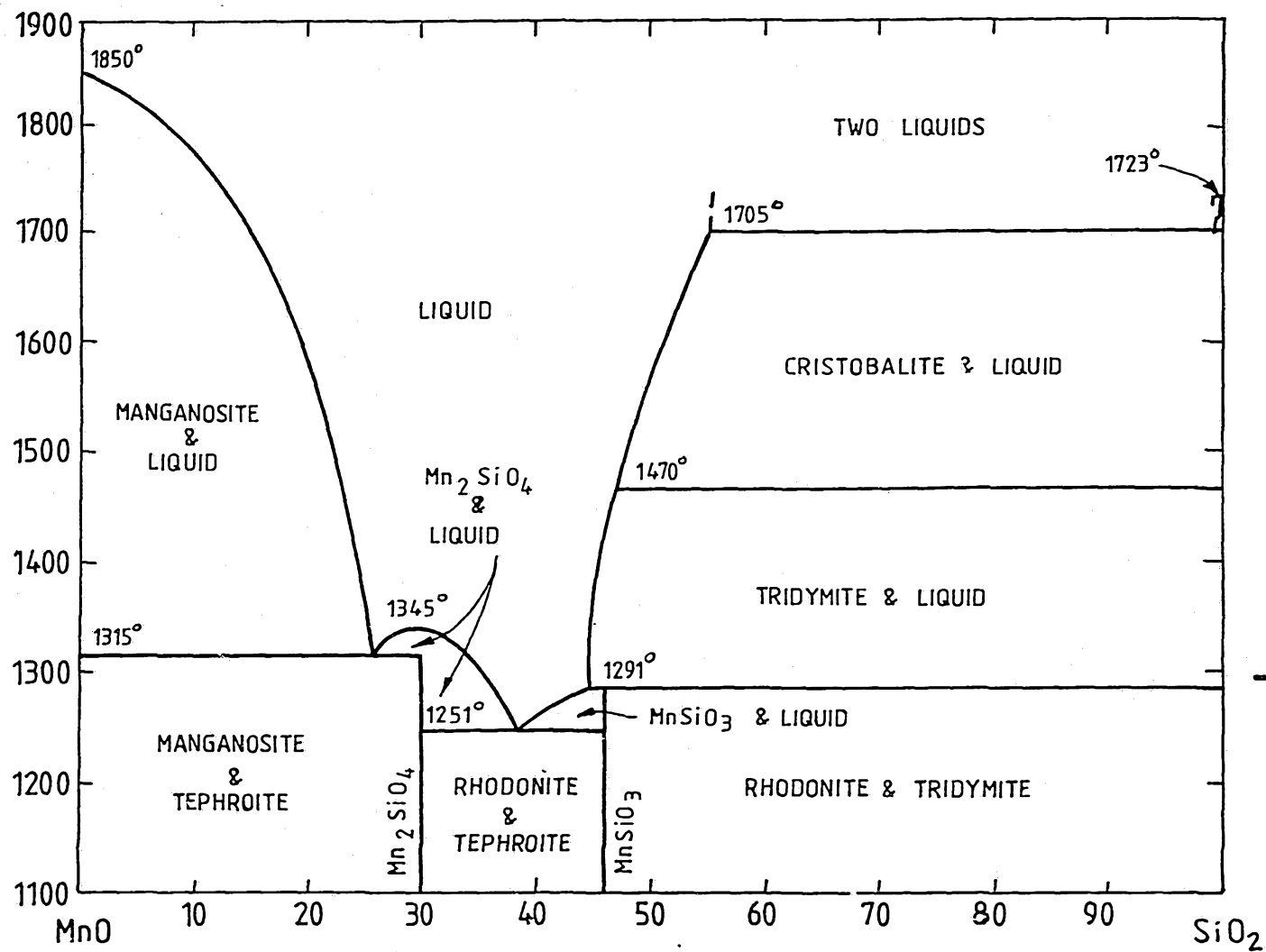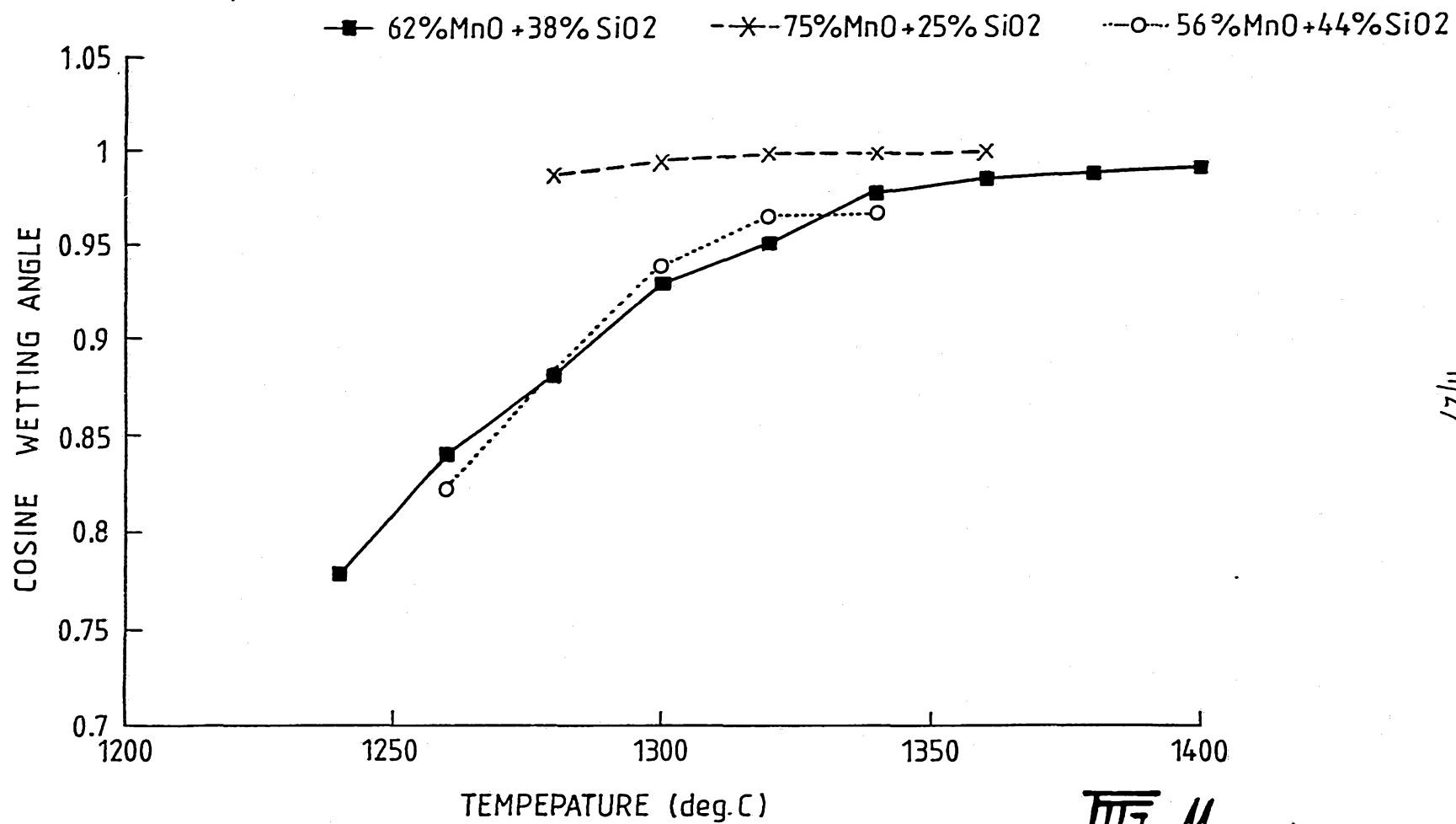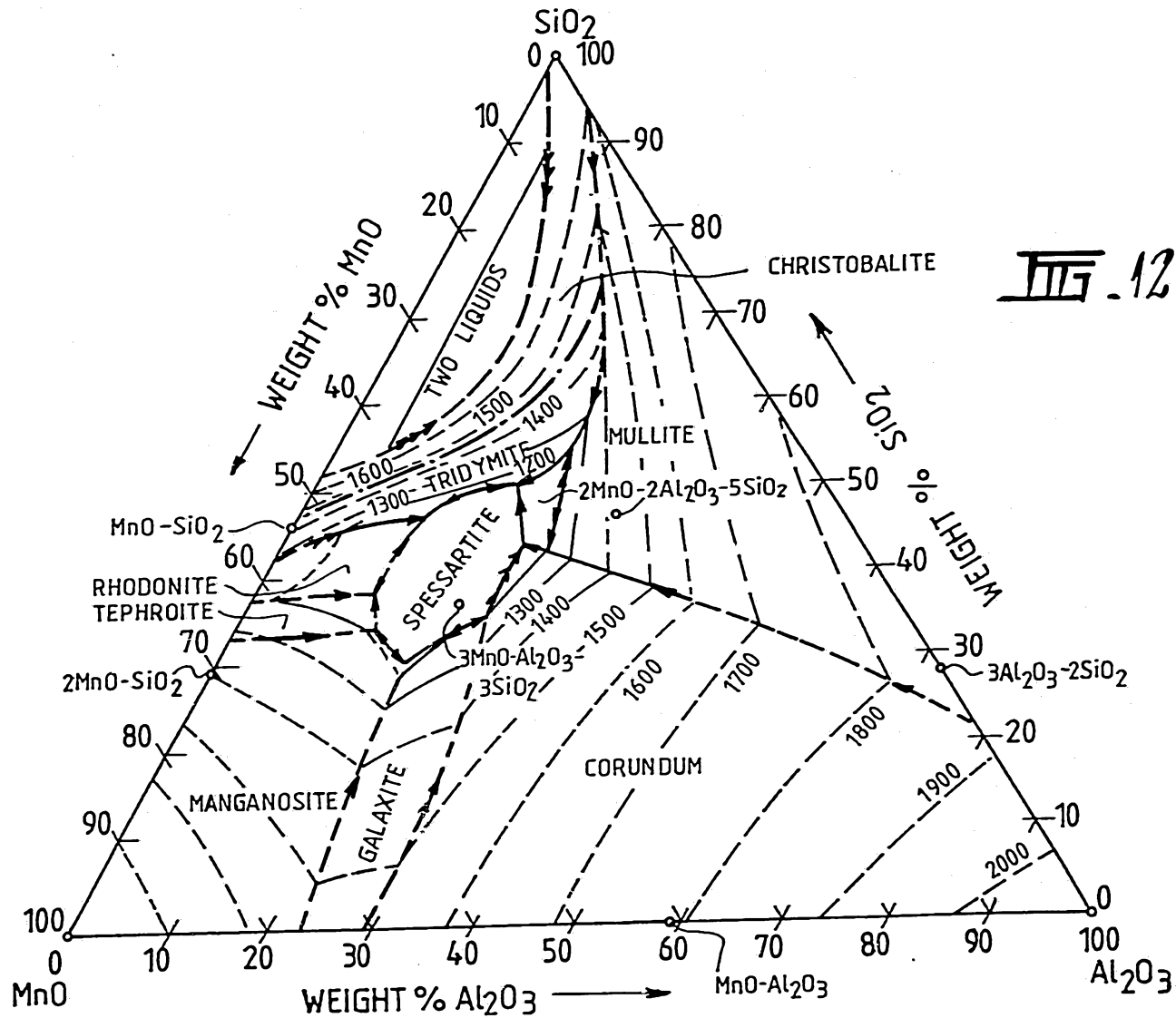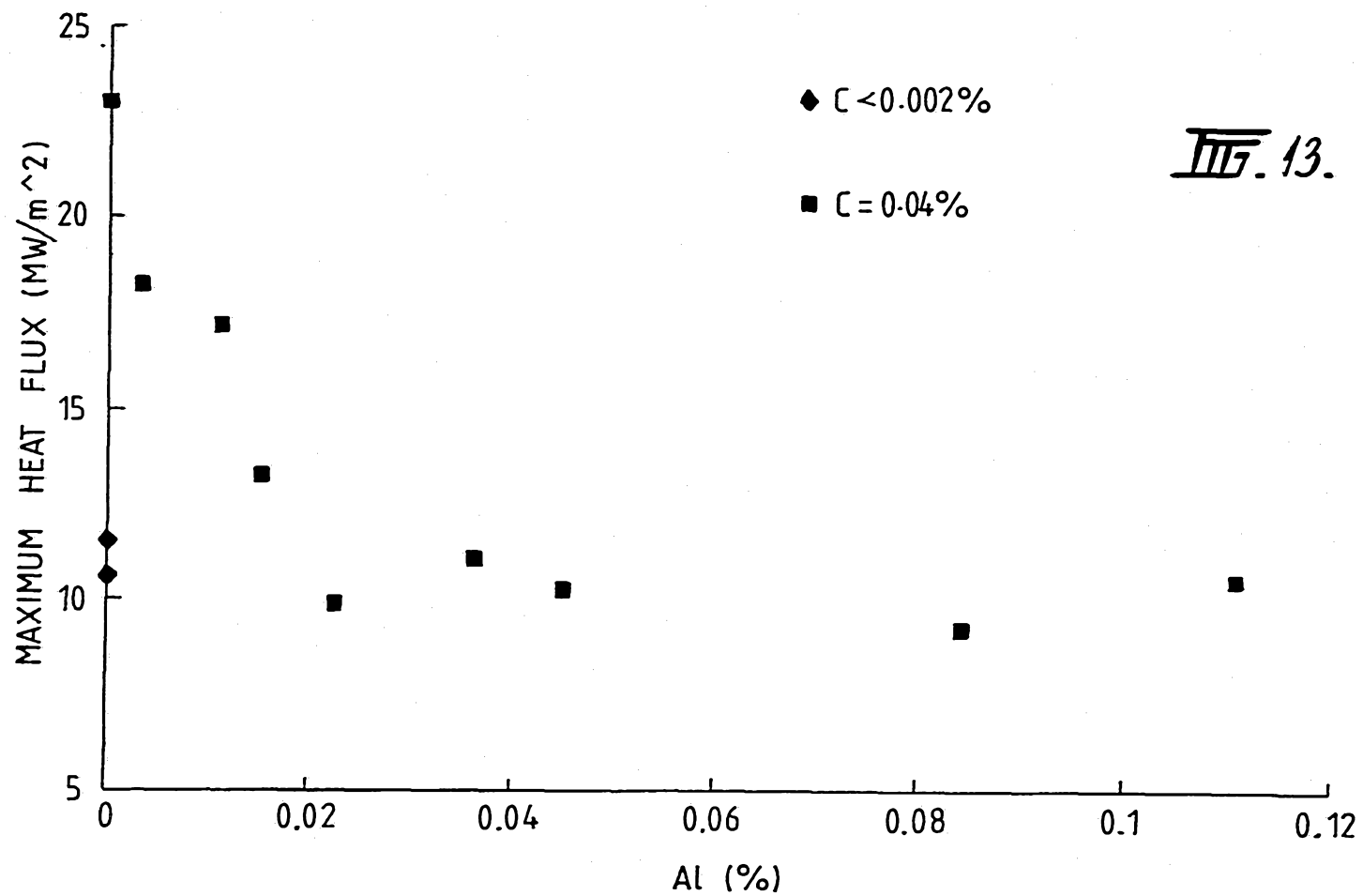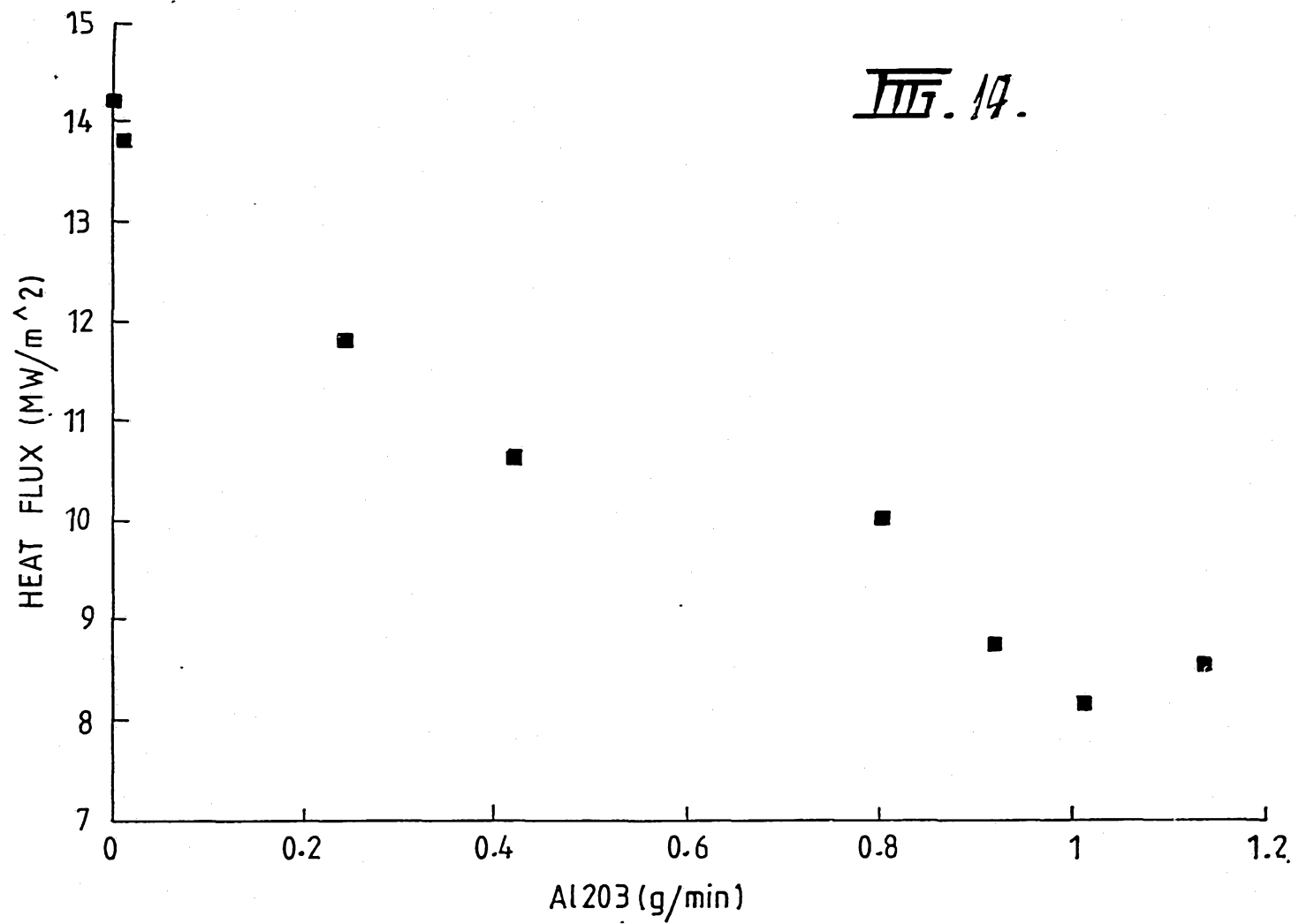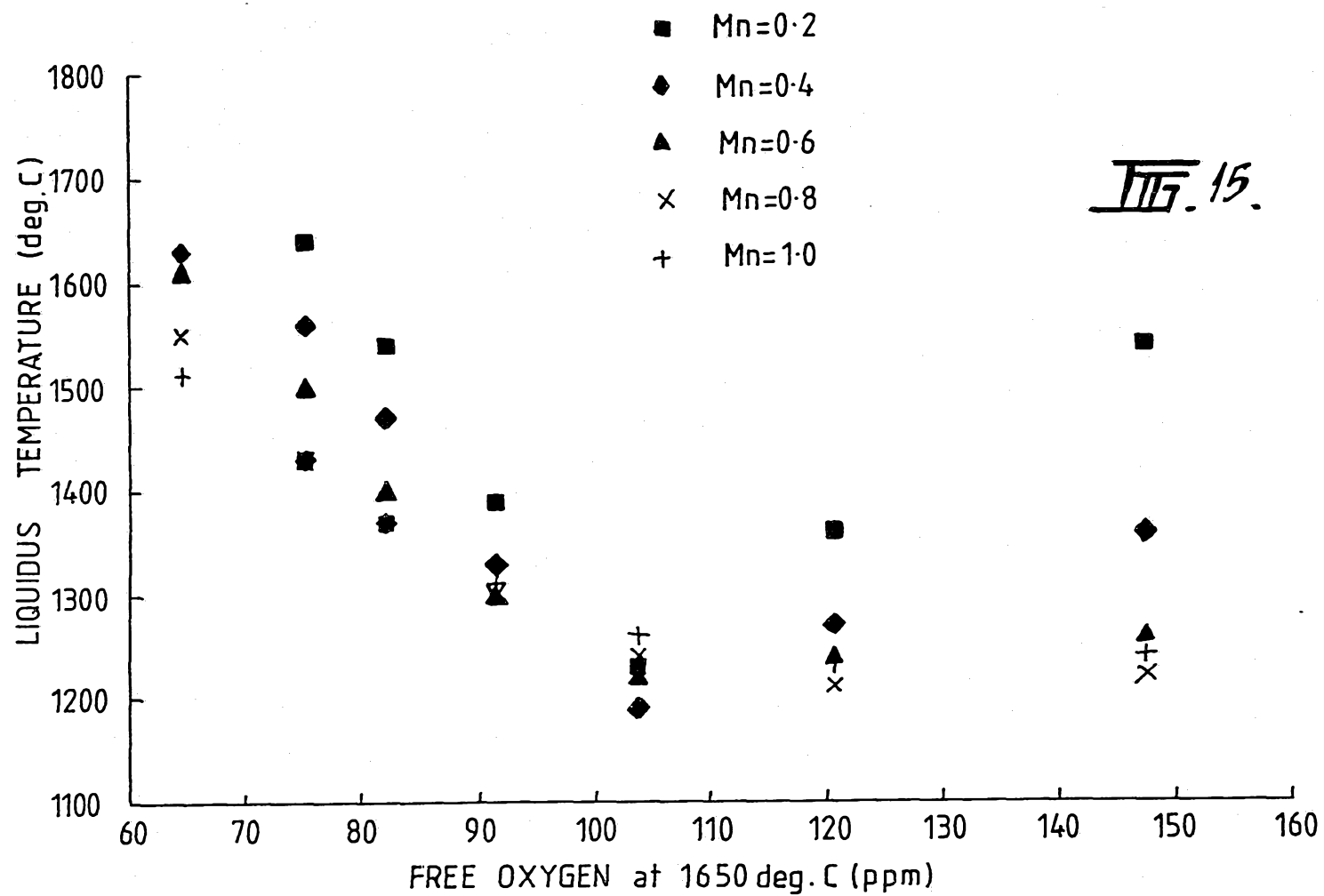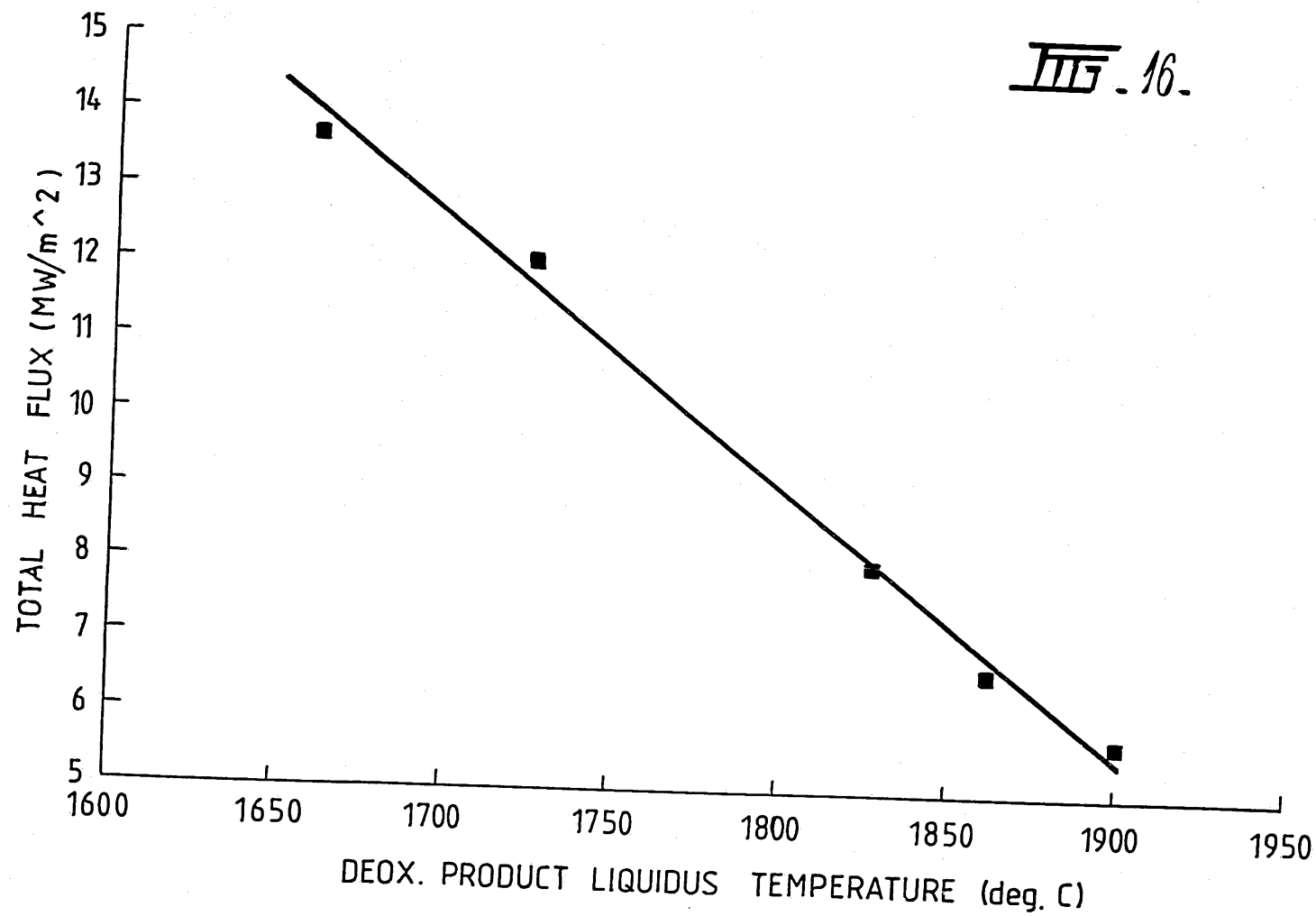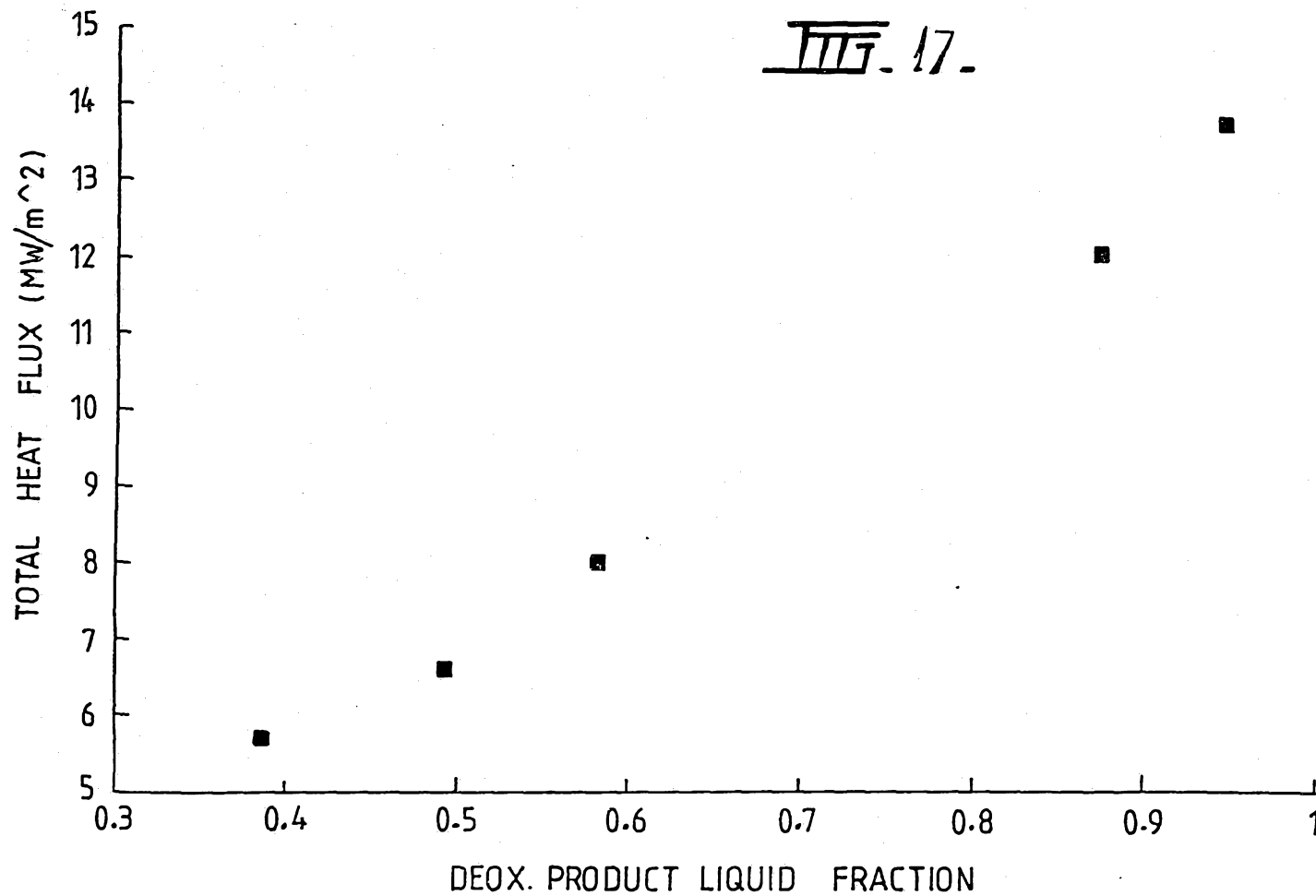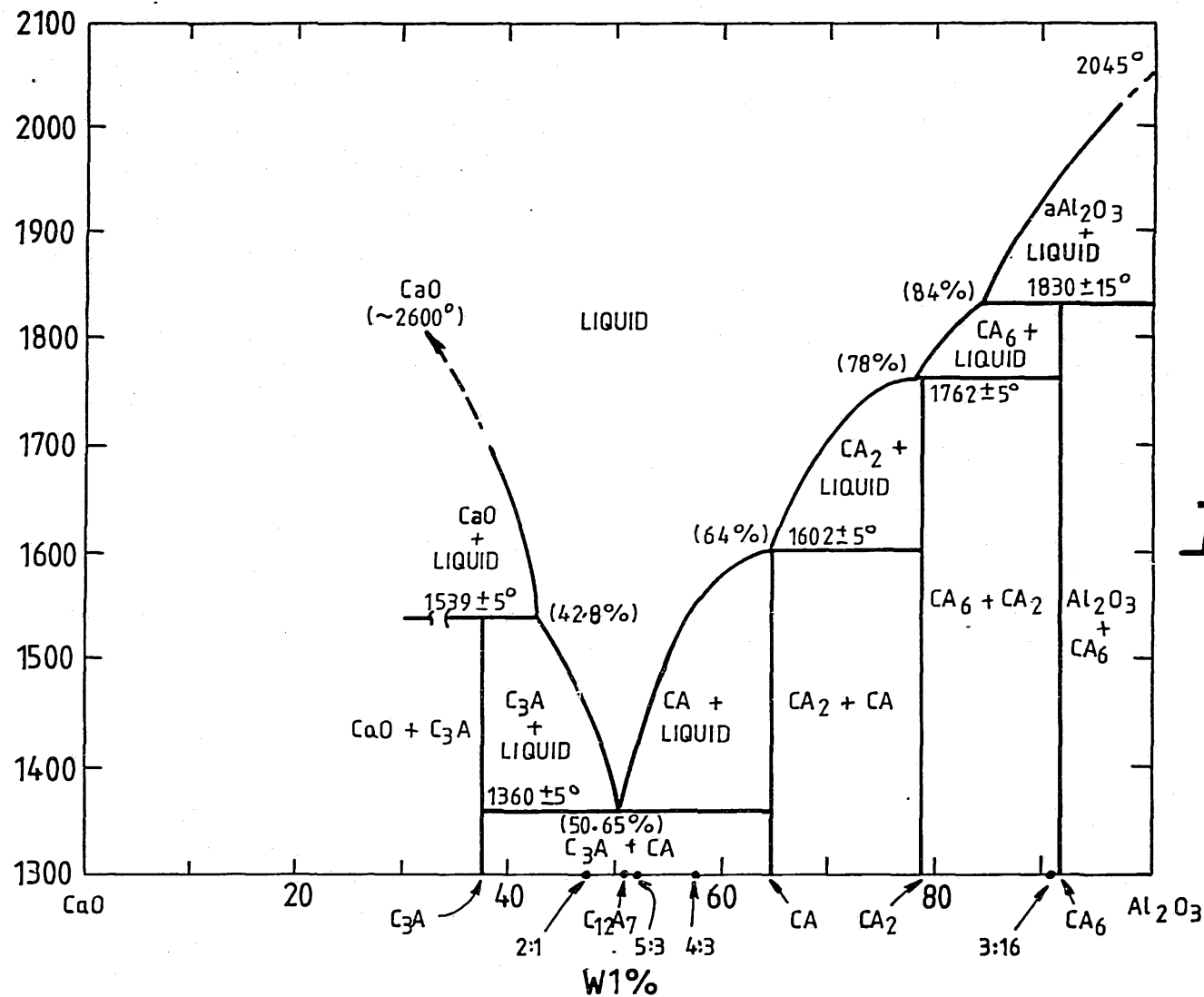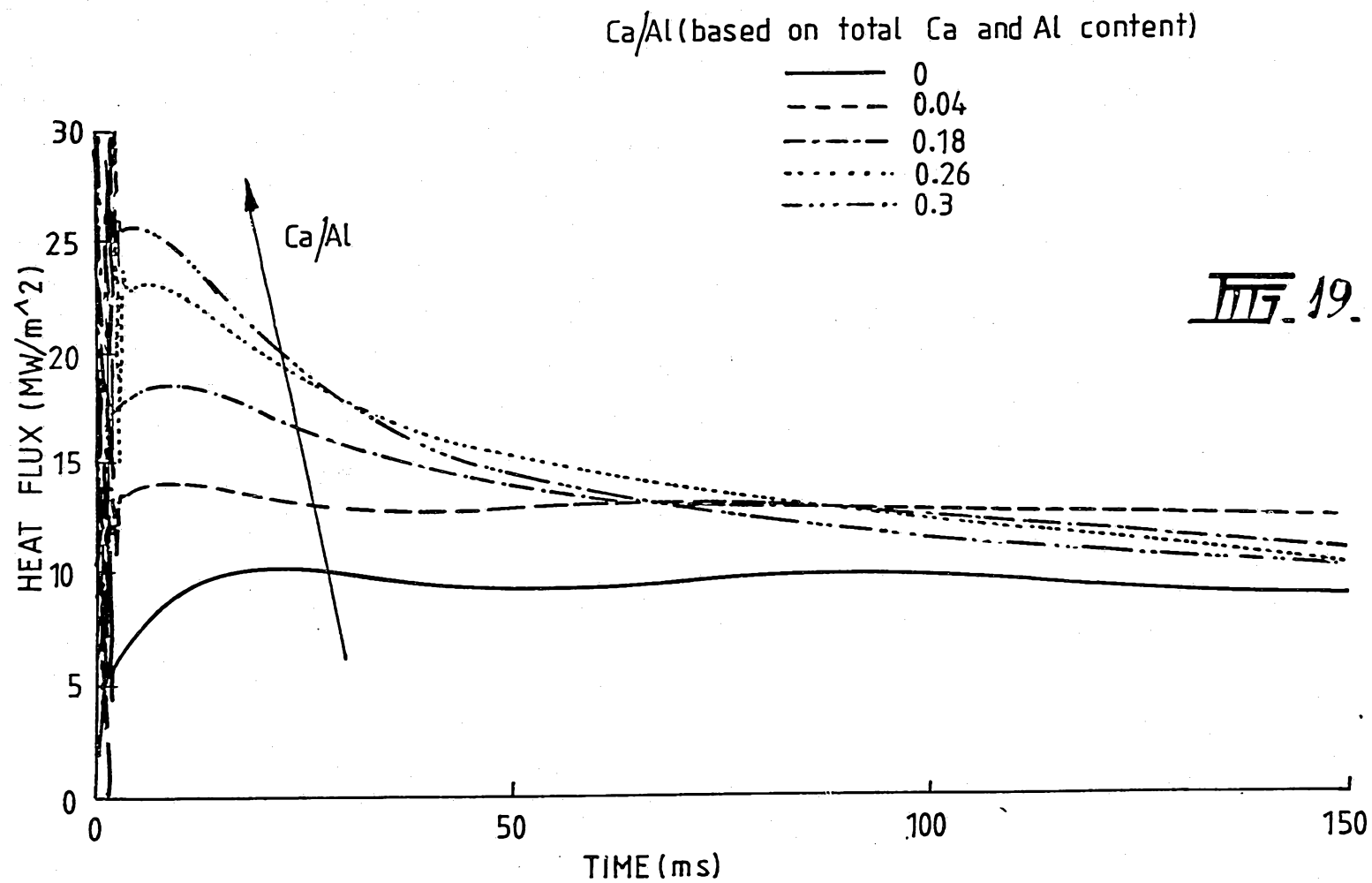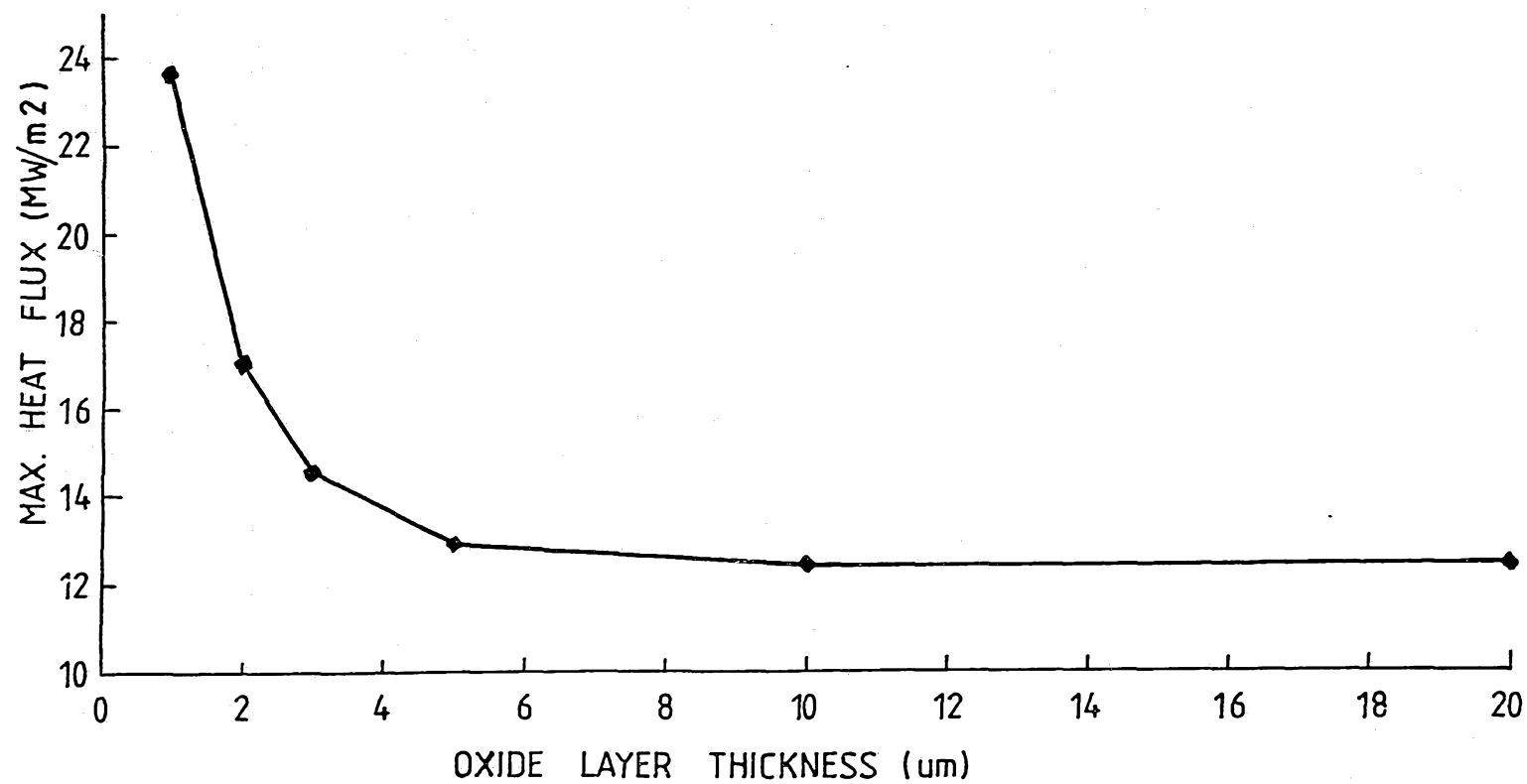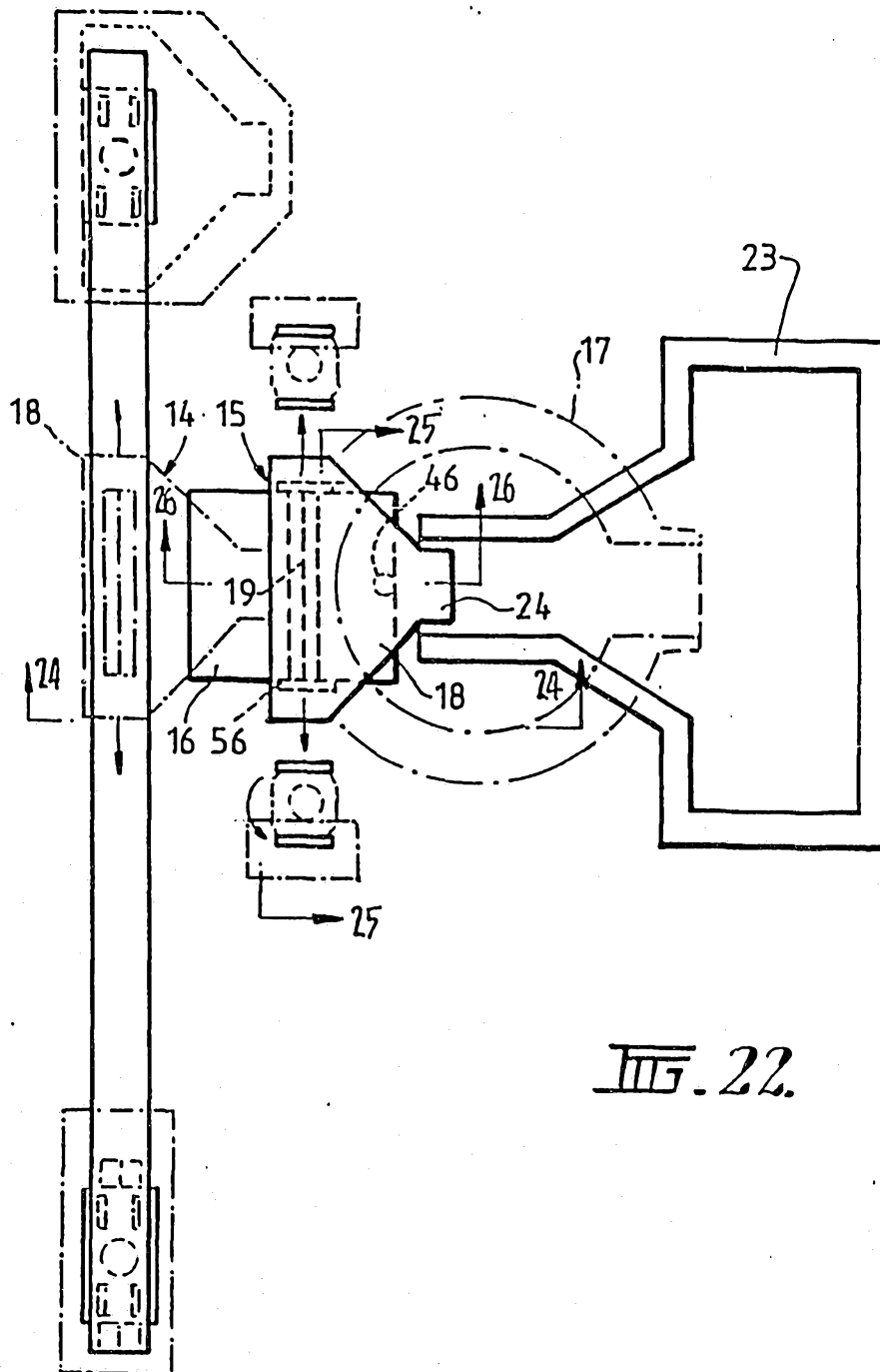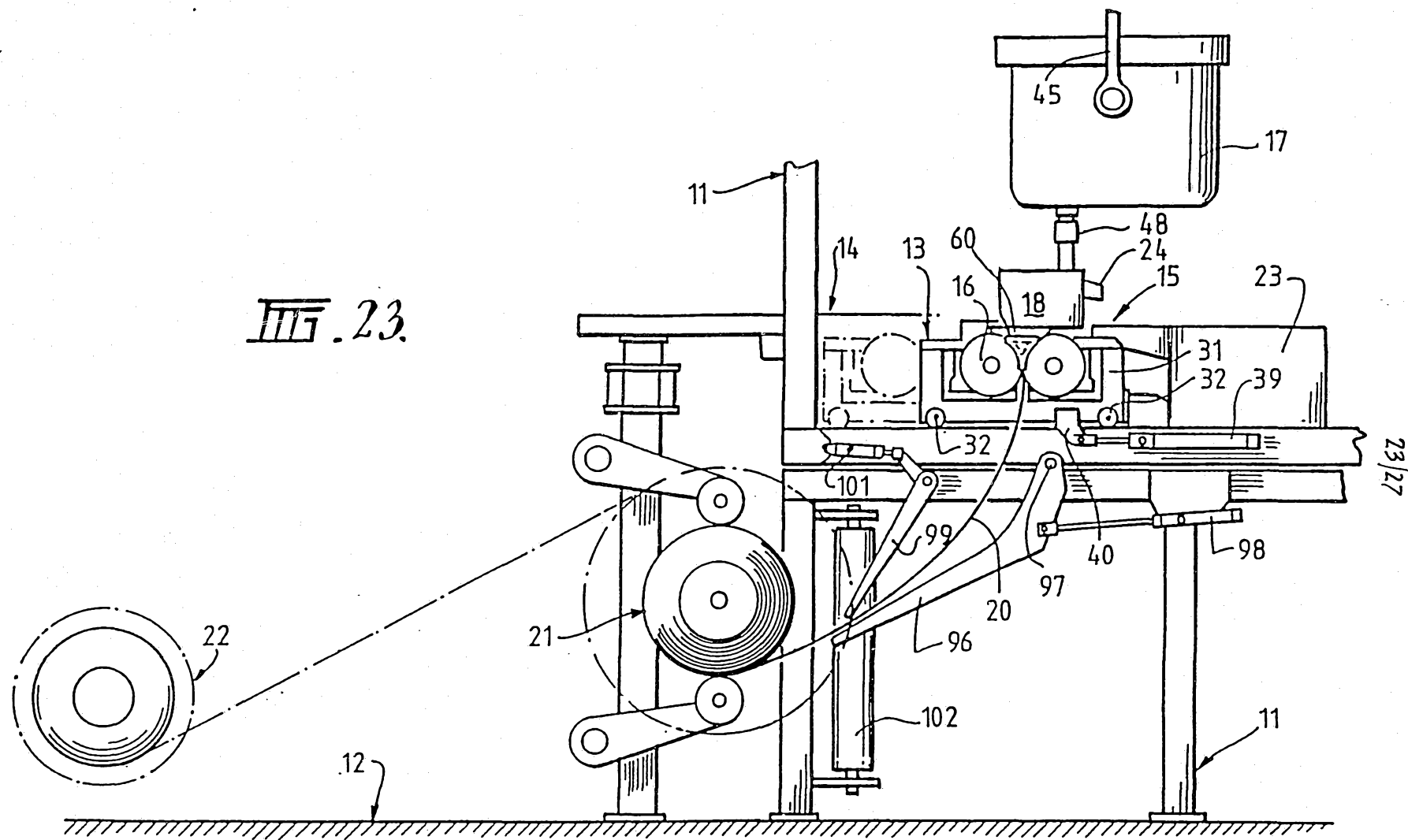
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TEMPERATURE - OXYGEN WINDOW
(C = 0.06 , Mn = 0.6 , Si = 0.28)

FIG.27.

Equilibrium line for Al < 1ppm

SiO_2

$MnO*SiO_2$

$MnO*Al_2O_3$

$2SiO_2*3Al_2O_3$

Al_2O_3

MELT FREE OXYGEN (ppm)

TEMPERATURE (deg. C)