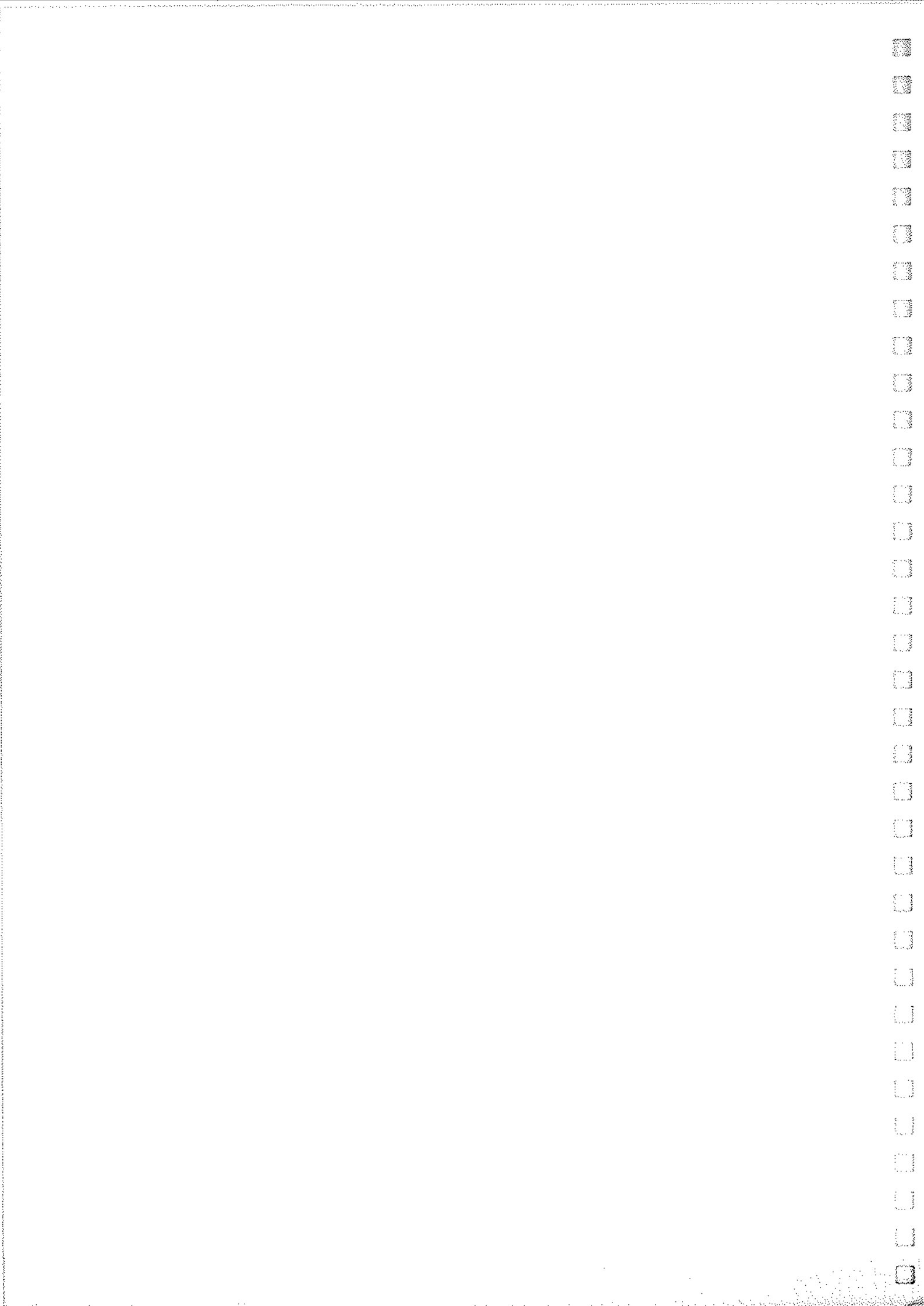


REPORT

Reviews of the Requirements for Thermal Conductivity of Mould Materials

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and J Shaw[†]

April 1998



Reviews of the Requirements for Thermal Conductivity of Mould Materials (Project MMP05)

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- (i) Refractory mould materials conductivity data requirements and process route factors which influence thermal properties.
- (ii) Heat transfer in Investment-, Sand- and Die-Casting.
- (iii) Review of thermal property data for sand- and investment-casting.
- (iv) Review of methods for the measurement of thermal conductivities of sand-, investment- and die-mould materials.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Centre for Materials Measurement and Technology

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EXECUTIVE SUMMARY

In this investigation, two major activities have been carried out, viz

- (i) a survey of the needs of British foundries for thermophysical property data for mould materials used in sand-, investment- and gravity die-casting (carried out by the Casting Development Centre).
- (ii) a survey of the heat absorbing properties of materials involved in investment-, sand- and die-casting (carried out by NPL).

About 250 questionnaires were sent out and a total of 42 returns were received. These returns provided valuable information on

- (a) how the foundries would use thermophysical property data
- (b) their perception of the need for more data
- (c) how such data could be most usefully presented
- (d) the types of mould materials being used
- (e) the mixing ratios of the various materials.

In addition, several companies were audited to ascertain the effects of process route factors on the thermal properties of the mould (and subsequently on the cast product). It was found that the various companies used the same materials but material mixing ratios were very different which will lead to large differences in the thermal properties. This highlights the problems encountered when end-users transfer pattern equipment to a different foundry.

The survey of the heat absorbing properties of mould materials used in sand-, investment- and gravity die-casting includes three separate reports detailing:

- (i) a review of published thermophysical property data for mould materials
- (ii) a review of experimental methods which could be used to obtain the required property data
- (iii) analyses of the heat transfer mechanisms in the three processes and a recommendation on how to obtain the required data.

The heat transfer mechanisms in sand- and investment casting is exceedingly complex. It is dependent upon a variety of factors such as porosity, grain size etc. Consequently, it is proposed that a measurement programme should be established in which measurements on well-characterised samples should be carried out to determine the effects of the different variables (eg porosity, grain size etc) which will allow the required data to be calculated. It is concluded that the best techniques for measuring the thermal conductivity (or diffusivity) of

- (i) investment moulds (< 4 mm thick) is the laser pulse method (> 4 mm thick) is the guarded hot plate
- (ii) sand moulds is the hot wire method and
- (iii) gravity-die mould is the laser pulse method.





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Report to National Physical Laboratory

Refractory Mould Material Conductivity Data Requirements
and Process Route Factors Which Influence Thermal Properties

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Contents

- 1 Executive summary
- 2 Survey on refractory mould material conductivity data requirements
- 3 Sand casting process
- 4 Process route factors which influence thermal properties
- 5 Investment casting process
- 6 Process route factors which influence thermal properties
- 7 Die casting process
- 8 Process route factors which influence thermal properties
- 9 Foundry review comparison

Appendix 1 Questionnaires circulated to foundries

Appendix 2 Returned questionnaires for the sand casting process

Appendix 3 Returned questionnaires for the investment casting process

Appendix 4 Returned questionnaires for the gravity die casting process



1 Executive Summary

A survey has been carried out on three methods of producing moulds for metal castings:

- i) Sand moulds
- ii) Investment cast ceramic moulds
- iii) Gravity die cast moulds

Two hundred and fifty companies have been circulated with a questionnaire to collect details of the production methods used to produce moulds in their company.

Data has been collected on:

- i) Use of conductivity data
- ii) Percieved need for more data
- iii) Method of presentation of suitable data
- iv) Types of moulding materials used
- v) Mixing ratio for various mould materials

Several companies have been audited to determine the effects of process route factors which will influence the thermal properties of moulds. These companies have all been found to be producing moulds using the same base materials, but in significantly varying degrees of material mixing ratio. This will have the effect of producing moulds which will have significantly varying thermal properties.

This difference in the production of moulds highlights one of the difficulties faced by users of castings when transferring pattern equipment between different foundries. A pattern and production method which will successfully produce sound castings in one foundry can often be found to produce shrinkage defects in a different foundry using the same type of mould system.

2 Survey On Refractory Mould Materials in use and Conductivity Data Requirements

The following is the results of a survey of UK based foundries to assess needs for conductivity data, factors which contribute to differing effects of conductivity and the potential outlet if further data is generated. A questionnaire has been sent to two hundred and fifty companies, and copies of the replies are included in the appendix. Fourty replies have been recieved which corresponds to sixteen percent of the circulation.

Of the fourty replies,

- i) Thirty seven feel there is a need for more conductivity data, and would make more use of it if it was readily available.
- ii) Many would like the data to be published in a broadsheet, and be in a suitable format for input into simulation modelling software.
- iii) Three companies feel that there is no need for further information.
- iv) Current sources of data are text books, published papers and software data bases.

All companies were asked which mould materials they would wished to be measured. These are detailed below for sand, investment and gravity die casting.

2.1 Sand Moulding Process

Sand Type	Binder Type	Binder Ratio %
Silica	Clay	8.0
Silica	Clay	7.0
Silica	Aluminium Pep-Set 5000	1.3
Silica	Alphaset Alkaline Phenolic	1.4 -1.6
Silica	Isocure 901/902 + Novaset 725	1.0-1.5
Silica	Novaset 725	1.4-1.6
Silica	Bentonite	6.0-8.0
Silica	Ashland Furacol 1000	0.7
Silica	Furan Resin	0.7-1.0
Silica	Alkaline Phenolic	1.0
Silica	Novathane	1.0
Silica	Sodium + Calcium Bentonite	6.0-80
Furan	Ashland Superset 63	0.9
Furan	Borden CS5000/TCS200	1.0-1.4
Chromite	Ashland 730	1.4-1.5
Chromite	Ashland 730 Alkaline Phenolic	0.9 -1.5
Resin Shell	Hepworth M&C 3AKPR	4.0



2.2 Investment Casting Ceramic Shell Process

Mould Type	Primary Coat	Slurry Type
Molochite 16/30	Zircon	Water based
Molochite 30/80	Zircon	Water based

2.3 Gravity Die Casting Process

Mould Type

Grey Iron
H13 Tool Steel

3 Sand Casting Process

The process falls into four main categories of:

- i) Hot Curing
- ii) Cold Curing
- iii) Clay Bonded
- iv) Gas Curing

Of these there are also numerous variations due to the type of binder and resin system used, and the differing amounts of each which are added to the sand. The list following details the main sand process types and variations.

3.1 Sand Types

The main types of sands used in the foundry industry are silica, chromite, zircon, and resin shell. The characteristics of these sand types are as follows:

- i) Silica - cheap and versatile, this is the predominant sand product used by the industry.
- ii) Chromite - more refractory than silica, thermally stable, greater chilling power, and provides a better surface finish on large castings; mainly used for production of large castings, and in areas of the mould where chilling is required;
- iii) Zircon - similar to chromite, but used in a finer grade, so produces better finish;
- iv) Resin shell - actually refers to a binder system, but the product as sold, consists of either silica or zircon sand pre-coated with the resin; commonly used for production of moulds and cores to a high dimensional accuracy, is easily removed from internal cavities, and produces a good surface finish.

3.2 Binder System Usage

Foundries today have an unprecedented range of binder systems to choose from with new products being launched at regular intervals. At last count, there were over 400 different products available. Many of these can be assigned to one of the following generic groups:

- i) Alkaline Phenolic - an alkaline phenol formaldehyde resin, available in self-set or gassed variations-
- ii) Furane - a resin of urea formaldehyde and/or phenol formaldehyde and furfuryl alcohol, which is self-set with acids;
- iii) Phenolic Urethane - a phenol formaldehyde and isocyanate resin, available in self-set or gassed variations;
- iv) Resin Shell - normally packaged as a sand pre-coated with a phenol formaldehyde novalak resin, and set by heating;
- vi) Silicate - an inorganic system, self-set using esters or gassed with CO₂.
The setting methods available with the different systems are summarised

3.3 Sand Reclamation

Sand reclamation also plays a large part in the conductivity effects of the mould as almost all foundries are reclaiming sand. This is either by thermal or cold reclamation to break down the resin coating on the sand to aid its reuse. This has differing effects dependant upon the efficiency of the system used and the temperatures sand is reclaimed at. After reclamation the sand is passed through a cooler classifier to reduce the temperature to a suitable working temperature for the addition of resin and binder and to sieve the particle to an acceptable grain size.

Reclaim sand is then mixed with additions of new sand in the amounts detailed below.

Percentage Reclaim / New sand

100% new
90 / 10
80 / 20
70 / 30
60 / 40
50 / 50
25 / 75
100% reclaim

3.4 Sand Mould Coatings

Sand moulds are generally coated with a refractory mould paint to seal the granular surface and improve the as cast surface of the casting and reduce the occurrence of sand inclusion defects. Some companies are however adopting practices of using no mould coats by using a system which has a finer base sand to achieve an improved surface finish. The list below details the varying type of mould coats and number of coats applied. The number of mould coats applied will also have an influence as this will alter the permeability and heat extraction rate of the surface sand layer.

CoatingType	No. of Coats/Thickness
None	None
Holcote 110	300-500 microns
Rheotec 402DG	0.3 mm
Zircon	1 coat
Zircon	2 coats
Durans	Flood coat
Blacking	1 coat
Coal dust	5kg/mould

3.5 Mould Temperatures

Sand moulds are also exposed to a significantly varying temperature during the pouring of metal into the mould as detailed below. The temperatures listed are for non-ferrous, iron and steel castings in degrees C.

Non-ferrous	Iron	Steel
760	1200	1580
770	1350	1600
780	1400	1640
	1420	
	1450	
	1460	

4 Process Route Factors Which Influence The Thermal Properties of Sand Moulds

Several companies have been visited to review their manufacturing facilities and determine factors which will influence thermal properties.

- i) For sand casting one of the most important and varying factors is the sheer number of different sand systems, and binder content ratio. As can be seen from the survey results there is almost every combination of mixing of reclaim to new sand.
- ii) The resin/binder mixing ratio will determine the effective permeability and breakdown properties of the sand when in use. This numerous companies have found out to their cost when trying to make moulds from sand mixes of all reclaim sand. The sand in this condition is often a very poor conductor of heat and large areas of burnt on sand is often found adhering to the casting, despite applying a refractory mould coating to the sand surface.
- iii) The mould coating type, how it is applied and the coating thickness will also affect the mould permeability and its conductivity at the coating sand interface.
- iv) The temperature that the sand is mixed at will also have an effect on the properties of the sand during moulding and this will influence the bonding, permeability and breakdown properties.
- v) The local environmental temperatures will also influence the sand properties as resin and binder contents are often altered from summer to winter conditions. This is due to the ambient temperatures having an effect on their setting properties and therefore the useable bench life of the sand.
- vi) The method of producing sand mould will also have an influence on the thermal properties in that moulds produced by hand ramming will have a higher permeability due to lower packing density, but lower conductivity due to less intimate grain contact, than a mould produced on a vibration table, which will have a greater packing density, higher potential conductivity and lower permeability.
- vii) The pouring temperatures used will have the most significant influence on the properties of the sand layer closest to the metal surface, and the higher temperatures will have the most significant effect. In the pouring of high temperature steels the sand layers closest to the casting will be subjected to temperatures which will in effect thermally reclaim the sand due to the high local heat content. The sands thermal properties in this area will therefore be significantly altered in a short period of time.

- viii) The thermal effects of the sand moulding process therefore appears to be a system containing an almost infinite number of combinations of sand type, resin and binder content, reclaim methods and mixing ratio, mould production methods and mould coatings. All contributing to form a constantly changing thermal effect.
- ix) This is probably one of the main contributory factors in the reason why a production method which is successful in one foundry is not transferrable to another, without the production of defective castings.

5 Investment Casting Process

Investment casting generally requires that a pattern or facsimile of the component to be cast is first made in a wax material. The wax pattern is then coated by dipping with a face, or prime ceramic slurry of a controlled composition and rheology, which is either alcohol or more water based, the dipped pattern then receives a stucco coating of dry grains of a ceramic material.

The ceramic material commonly comprises one or more selected from the group which includes alumina silica, alumino-silicates, zirconium silicate, for example, and is of a controlled particle size range.

The dipped and stucco coated pattern is then dried and given a second slurry coating, again of a carefully controlled composition and rheology, which again also receives a second stucco coating of ceramic material. The desired mould is built-up in this fashion with several slurry and stucco repeat coatings until the desired mould thickness is achieved. The wax pattern is finally removed, usually in a steam autoclave, to leave a mould cavity having the desired shape.

The resulting "green" or unfired mould is then fired at between 800 to 1000C, for 30 to 45 minutes under a precisely controlled heating cycle to increase its strength and to burn off residual wax. The binder material in the slurry is often colloidal silica, in which case, the strength increase is achieved by creation of siloxane bonds within the ceramic matrix.

Such moulds possess a degree of inherent porosity due to their particulate makeup.

Molten metal is then poured into a preheated mould which is then allowed to cool by radiation of heat from the mould exterior. The metal solidifies by nucleation and growth at many sites throughout the casting to give an equiaxed grain structure. If solidification is too rapid, defects such as cold-shuts, misruns and shrinkage porosity frequently occur. Information collected from investment casting foundries details the following practices.

Number of shell coats	Thickness mm	Drying Temp C	Maximum Mould Temp C
6	10	20	1600
6	6	23	1000
8-14	14	20	1150
7-15	7-15	40	1200

6 Process Route Factors Which Influence The Thermal Properties of Investment Casting Moulds

The thermal properties of the resulting mould may be controlled through several factors.

- i) The type (alcohol/water based) and thickness of the primary slurry layer, which will be influenced by the method of application.
- ii) The size and type of particulate facing material.
- iii) The backup coat slurry is also often different from the primary coat slurry.
- iv) The backup stucco will have a larger particulate size, often increasing with further coatings.
- v) The number of coats applied will probably have a large effect.
- vi) The method of stucco application, with differences between raining and fluidised beds, and hand manipulation versus computer controlled robot systems.
- vii) The build up of each shell particulate layer and its method of application will have a significant effect on the inherent porosity of the shell and its conductivity.
- viii) Other factors such as drying times and temperatures between coats, and final firing times and temperatures will all contribute to produce a shell of considerably varying properties.
- ix) These factors will also be influenced by the actual shape of the component, as the shell formed will vary in thickness due to shell buildup and runoff at pockets and corners.
- x) These factors will also be influenced by the actual position of the pattern on the gating system.

7 Die Casting Process

The die casting process consists of two or more metal mould sections used to form the cast profile. In gravity and low pressure die casting the mould surface is coated with a refractory mould paint to aid filling of the die cavity and to control the solidification of the casting. With high pressure die casting a lubricant spray is used to coat the die surface.

The main materials used for die blocks are Grey Iron and H13 Tool Steel, these are used predominately for their good thermal properties and resistance to thermal fatigue and wear.

Several die casters were contacted during the survey but only one has supplied details of their process and data requirements.

8 Process Route Factors Which Influence The Thermal Properties of Gravity Dies

- i) The temperatures that the die is heated to and cycled at during production will be one of the main contributors to variations in the thermal properties of the die.
- ii) The die surface coating material and the number of coats applied will also have a significant influence on the thermal balance of the die.
- iii) A general rule is that the casting form will have a thin coating, with increasing thicknesses being applied to the gating system and feeder heads.
- iv) Cooling rates can be increased locally by removing all the coating so that the metal has a direct contact with the metal die.
- v) Dies are often damaged or wear during production and have repair sections set into the die.
- vi) The interface of the inserted piece will have a significant effect on the local thermal properties of the die, as the joint face will not conduct heat as readily as the parent die and local increases in die temperature will result.
- vii) Additional forced cooling using air or water in controlled channels is also used to increase the solidification rate in difficult to produce sections.
- viii) In positions where extreme cooling rates are required copper chills are used, also with water cooling.
- ix) Local heat extraction is also increased by cutting a fine grid into the die surface in some areas of the casting. This increases locally the surface area in contact with the casting and casts small raised areas which initiate increased solidification rates.
- x) Sand cores are a common addition to many dies and these will have a significant local insulating effect, due to the sands low thermal conductivity, when compared to the surrounding die.

9 Foundry Review Comparison

Twelve foundries have been visited to review the effects of process route factors which influence thermal properties, the results of which have been detailed previously. Detailed below are the results from four sand foundries producing iron castings of the same type. This highlights the vast differences between foundries and the possible reasons for variations in production quality when a pattern is transferred from one foundry to another.

Four Iron foundries have been visited who produce large iron castings from polystyrene patterns. The process variables which may contribute to variations in thermal properties are:

Pattern Density	Coating	Application	Thickness	No. Coats
18 g/cc	Holcote 702/fm	Brush	2-3mm	2 1st coat Graphite 2nd coat Zircon
18 g/cc	Holcote 702/fm	Spray	2-3mm	2 1st coat Graphite 2nd coat Zircon
22 g/cc	Huttens Albertas	Spray	10mm	1 Graphite/Zircon 50/50
22 g/cc	Ashland Ceramco	Brush	2-3mm	2 both Zircon

Mould Sand

Type	New/Reclaim	Temp	Compaction	Grain Size/AFS
Furan	100% reclaim	20	Hand ram	50
Furan	70/30	25	Hand ram	50
Furan	80/20	25	Hand ram	50
Furan	100% new	30	Hand ram plus Pneumatic hammer	50

None have vibration tables

Appendix 1 Questionnaires circulated to foundries



Mould material data requirement questionnaire.

1. Company name.
2. Your name.
3. Your position.
4. Do you use Thermal conductivity data at present?
5. If so from where was it obtained? (i.e. textbook, software database etc.)
6. Do you feel there is a need for more mould related thermophysical data?
7. If the data was more readily available would you make more use of it?
8. How would you like to see it presented?
9. What is your sand system type?
10. Which base refractory mould material would you most like to see data for?
11. With which binder?
12. At what ratio?
13. What is your ratio of new to reclaimed sand?
14. If you use a chemical/resin binder what is it's trade name or composition?
15. Do you use a mould coat/wash?
16. If yes what is it and how much do you apply per mould?
17. What is the highest temperature you expose your sand to?
18. As a follow up to this questionnaire a survey of process variables within mould manufacture which influence thermal properties would need to be conducted. Would your foundry be interested in participating?

Mould material data requirement questionnaire.

1. Company name.
2. Your name.
3. Your position.
4. Do you use Thermal conductivity data at present?
5. If so from where was it obtained? (i.e. textbook, software database etc.)
6. Do you feel there is a need for more mould related thermophysical data?
7. If the data was more readily available would you make more use of it?
8. How would you like to see it presented?
9. Which base refractory mould material would you most like to see data for?
10. What is your slurry type, alcohol/water based?
11. What type of primary coat do you apply?
12. How many back up coats do you apply?
13. What grade of ceramic do you use?
14. What is your average shell thickness?
15. How are your shells dried?
16. At what temperature do you dry your moulds?
17. What is the highest temperature you expose your moulds to during firing/pouring?
18. Do you use insulation wrap or forced cooling?
19. As a follow up to this questionnaire a survey of process variables within mould manufacture which influence thermal properties would need to be conducted. Would your foundry be interested in participating?

Mould material data requirement questionnaire.

1. Company name.
2. Your name.
3. Your position.
4. Do you use Thermal conductivity data at present?
5. If so from where was it obtained? (i.e. textbook, software database etc.)
6. Do you feel there is a need for more mould related thermophysical data?
7. If the data was more readily available would you make more use of it?
8. How would you like to see it presented?
9. What are your base die materials?
10. Which base material would you most like to see data for ?
11. Which diecoats do you use?
12. How much do you apply and to which areas of the die ?
13. What type of cooling do you run in your dies if any?
14. What is the highest temperature you expose your dies to?
15. As a follow up to this questionnaire a survey of process variables within mould manufacture which influence thermal properties would need to be conducted. Would your foundry be interested in participating?

HEAT TRANSFER IN INVESTMENT-, SAND- AND DIE CASTING: A REVIEW OF REQUIREMENTS FOR THERMOPHYSICAL PROPERTIES OF MOULD MATERIALS

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EXECUTIVE SUMMARY

The heat transfer processes in investment-, sand- and die-casting have been analysed. It is shown that the heat transfer process is exceedingly complex involving thermal conduction contributions from lattice ('phonon'), λ_c , radiation (λ_R) and convective conductivity (λ_{conv}). These various parameters are dependent upon thickness of the ceramic, porosity, grain size transition metal oxide concentration etc. Thus any measurements carried out on one specific system would apply only to that system and probably would not apply to other conditions, eg a thicker shell. Consequently, it is recommended that the best approach would be to determine the effect of porosity etc on each of λ_c , λ_R and λ_{conv} separately and use a model or expert system to derive the thermal property data for input into the model. This would avoid having to make measurements for the numerous different moulding systems in use in the British foundry industry.

It is apparent that a variety of measurements will have to be made and these will have to be carried out on:

- (i) well-characterised samples (eg porosity, grain size)
- (ii) samples which have been prepared in an identical manner to the investment shell or sand mould.

Thus great attention should be focused on sample preparation.

Methods will have to be developed for the measurement of optical properties (emissivity, absorption and extinction coefficients), thermal conductivities and the separation of λ_c , λ_R and λ_{conv} interfacial thermal resistances.

It is probably not necessary to measure specific heats since estimated values are probably accurately enough, however some checks should be made to show that this is so.

With regard to the measurement of thermal conductivities (or diffusivities) there is no one method which can be used:

- (i) for thin investment shells (2-4 mm thick) and die coatings the *laser pulse method* could be used providing the samples are representative of the shell or coating.
- (ii) for sand casting samples it is suggested that the *line source* method should be adopted.
- (iii) for investment shells between 4 and 10+ mm the choice of method is less clear cut and some development would be required whichever was selected.

The following are candidate methods:

steady state (radial heat flow, guarded hot plate) and transient (transient plane source) and it is proposed that the guarded hot plate be used to its current maximum temperature (ca 1000 °C) and carry out further development to extend this temperature range.

It is important that (i) the specimen be optically thick for the thickness selected and (ii) the contribution from radiation conductivity can be calculated. The direct radiation across the pores will have to be accounted for and data for the mean pore size and emissivity will be needed in these calculations.

With regard to the measurement of the interfacial thermal resistance this could be derived in simulation experiments where molten metal is poured into a mould fitted with thermocouples and the use of inverse temperature modelling. The possibility of using a direct measurement of the interfacial thermal resistance using the method under development at Sheffield Hallam University should be explored.

1 INTRODUCTION

The mathematical modelling is seen to be a powerful tool in the improvement of mould design and the reduction of casting defects. These models have improved to the point where one of the prime requirements is for reliable thermophysical property data for the materials involved. Recently, CDC carried out a sensitivity analysis in which experimental data for the liquid metal were used in the model to predict the locations prone to defects [1]. It was found that these predictions were much closer to those obtained in practice than the predictions based on estimated data contained in the model.

However in investment-, sand- and die-casting the heat transfer from the metal involves thermal transport across ceramic layers. The heat transfer across these ceramic layers is exceedingly complex. Furthermore, in investment- and sand-casting a variety of materials or combinations are used to produce the mould. The thickness of the mould, the porosity, the grain size of the ceramic, the type of chemical binder and the change in mould structure with time can all have an effect.

Although there are few thermophysical data for sand mould materials there are virtually no data for investment shell. The extant data have usually been obtained for one specific set of conditions, (material of a certain thickness, porosity, grain size) and are probably not applicable to another system. Thus when the various combinations of conditions are taken into account it would take numerous measurements to satisfy the varying systems used in British foundries. Furthermore, measurements are made by pouring metal into a shell or mould and then monitoring the temperatures produced at specific sites in the ceramic to derive a value for the interfacial resistance. Frequently the thermal conductivity value used in the subsequent heat transfer analysis was derived for a specimen of different thickness, which may have a much different effective thermal conductivity and leads to an erroneous value for the thermal resistance.

2 OBJECTIVES

The objectives of this investigation were to:

- (i) Review the various factors, (arising from the process route), which affect the thermal properties of the mould.
- (ii) Review the dependence of the heat transfer upon these factors (such as porosity, grain size, etc).
- (iii) Review methods which could be used to determine the thermal conductivity and recommend methods which should be used.

3 INVESTMENT CASTING

3.1 PROCESS

The process, outlined in Figure 1, consists of the following steps:

- (i) the production of a die into which molten wax is poured
- (ii) the wax pattern is then removed from the die and attached to a 'tree'

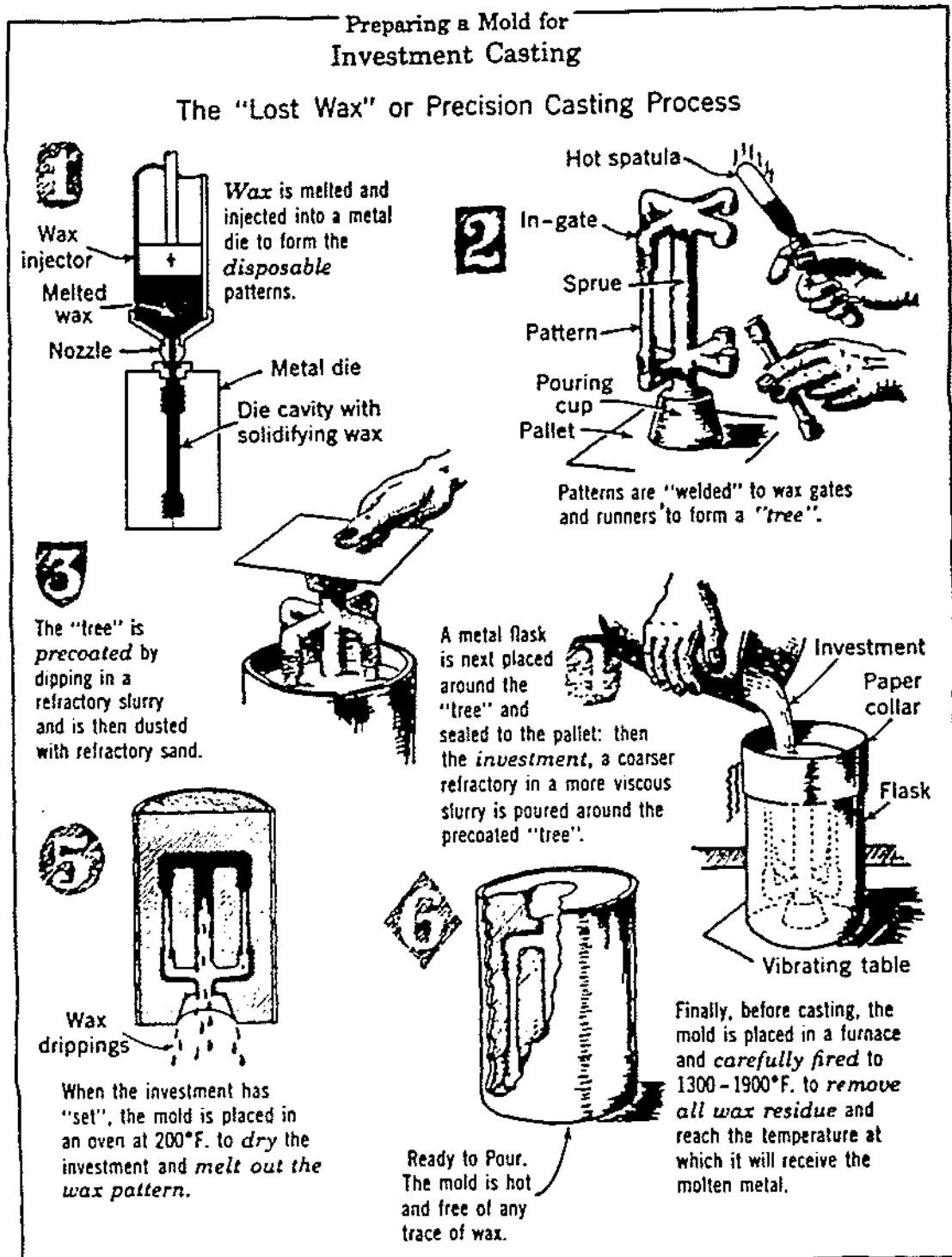


Figure 1 Schematic diagram showing the 'lost wax' investment process.

- (iii) the tree is coated with a *facing-coat* by dipping in a refractory slurry, allowed to drain, and then dusting with a refractory ('*stucco*')
- (iv) the coating is then increased by building up a series of coats by dipping in a more viscous slurry (typically 5-10 layers) and applying increasingly coarse stucco
- (v) the wax is then removed by autoclaving
- (vi) the *investment* is then fired at 750-1050 °C to receive the metal.

Shell moulds are typically 2 to 10 mm thick and make use of binders which are usually water or alcohol-based.

The following materials are used:

Face coats:	zircon sand, SiO_2 , Al_2O_3
Shell:	SiO_2 , Al_2O_3 , zircon sand ($\text{ZrO}_2 \cdot \text{SiO}_2$) alumino silicates including molochite ($\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$)
Cores:	usually SiO_2 or Al_2O_3
Binders:	colloidal SiO_2 or ethyl silicate, alumina sol, tetra-n-butyltitanate, sometimes phosphate and aluminates are used.

3.2 ANALYSIS OF HEAT TRANSFER

The aim is to optimise the heat loss from the investment casting. The heat transfer through the mould is very complex since there are several mechanisms involved in the heat loss and these can vary with time:

- (i) lattice thermal conduction through the ceramic
- (ii) radiation conduction through the ceramic and subsequent radiation from the shell surface
- (iii) convection from the passage of gases through the pores of the mould material which must be permeable since if the gases cannot escape they cause a pressure build-up and may lead to incomplete filling ('misrun').
- (iv) after a period of time, a thermal resistance at the metal/ceramic interface is produced as a result of thermal expansion differences in the two phases.

Thus, a change from radiant to conductive heat transfer may be anticipated as the shell temperature decreases and the colour (ie contamination) of shell changes.

The heat transfer can be considered in terms of thermal resistances (R) in series as shown in Figure 2.



Figure 2 Schematic diagram showing the different thermal resistances involved in the heat transfer.

$$R_{th} = R_{met/FC} + R_{FC/Inv} + \frac{d_{FC}}{\lambda_{FC}^e} + \frac{d_{Inv}}{\lambda_{Inv}^e} \quad (1)$$

where d is the thickness and λ^e the effective thermal conductivities of each layer and the subscripts C, R and conv represent the contribution from lattice conduction, radiation conduction and convection.

$$\lambda^e = \lambda_c + \lambda_R + \lambda_{conv} \quad (2)$$

Heat loss from the mould surface can occur by radiation, convection and conduction. In some cases the investment shell is wrapped in a refractory material, in this case two further terms, $R_{Inv/Wrap} + d_{wrap}/\lambda_{wrap}^e$ must be added to Equation 1.

3.2.1 Lattice conduction

The lattice conductivity, λ_c , is dependent upon:

- (i) the thermal conductivity of the investment material, eg SiO_2 , Al_2O_3 etc.
- (ii) the density of the mould material, ie porosity and the nature of the pores
- (iii) the grain size of the particles
- (iv) the nature of the binder which coats particles and affects particle/particle contact.

3.2.2 Radiation conductivity, (λ_R)

There are two radiation mechanisms involved in the heat transfer (i) direct radiation across the gas in the pore and (ii) radiation conductivity through the particles.

The radiation conductivity is dependent upon the following factors:

- (i) Thickness (d) of the investment

A sample is considered to be optically thick when $\alpha d > 3$ where α is the absorption coefficient, under these conditions λ can be calculated from the relation:

$$\lambda_R = \frac{16n^2\sigma T^3}{3\alpha} \quad (3)$$

where n = refractive index, σ = Stefan Boltzmann constant, T = thermodynamic temperature (K). Since radiation can be scattered as well as absorbed the scattering coefficient (S) should also be considered, the extinction coefficient (E), should be used instead of α .

$$E = \alpha + S \quad (4)$$

The radiation conductivity under these circumstances can be calculated [1,2] by

$$\lambda_R = \frac{8\sigma T_{\text{mean}}^3}{(\alpha + 2s)} \quad (5)$$

(ii) Transition metal oxide concentration

The absorption coefficient is affected by small concentrations of FeO, MnO, NiO, Cr₂O₃ etc and hence can reduce λ_R drastically (Eqn (5)).

(iii) Porosity affects radiation conductivity since increased pore diameter has been reported to increase both inter-granular and trans-granular radiation.

(iv) As particle size increases (i) the size of individual pores also increases and hence increases radiation conductivity and (ii) the contact points decrease and hence the ratio of (λ_e/λ_c) will increase.

(v) The nature of binder can affect λ_R since in some cases it fuses to make a glassy material at higher temperatures which will increase λ_R .

For the direct radiation mechanism across the pores, the associated conductivity $\lambda_R(p)$ is given by Equation 6 where ε = emissivity of the mould material, δ = pore size and f = pore size radiation shape factor.

$$\lambda_R(p) = 4f\sigma\varepsilon T^3 \delta \quad (6)$$

Thus $\lambda_R(p)$ increases with increasing pore size.

3.2.3 Convection heat transfer

This will obviously be influenced by the following factors:

- (i) permeability (ie porosity) of the investment
- (ii) whether gases are given off by the investment after contact with the hot metal.

3.2.4 Interfacial thermal resistances

After the metal has been poured into the investment mould the metal will tend to shrink and the mould to expand as it heats up. Ferrostatic pressure will tend to maintain good interfacial contact but after a time an interfacial resistance will be produced.

The interfacial resistance between the face coat and the remainder of the investment will probably be negligible.

3.3 METHODS OF MEASURING THE REQUIRED THERMAL PROPERTIES

Since radiation conductivity could be a prime mode of heat transfer in investment shells, it is essential that measurements of the absorption-, scattering-, and emissivity coefficients should be carried out on well-characterised, representative samples. The extinction coefficient could be measured by use of spectrophotometers to measure the transmissivity of polished discs. The emissivity could be measured by comparison of radiation emitted with that from a blackbody.

For thin investment shells (< 4 mm) the laser pulse would appear to be the best technique providing measurements are carried out on enough samples to guarantee that the specimens are representative of the shell.

For thicker investment shells the choice is less obvious and most of the techniques shown in Table 1 could be used. Further details are given in Section 6.

4 SAND CASTING

4.1 PROCESS

In sand casting, several sand mould segments are made and assembled to produce the final casting. Wood or metal patterns of the mould half are fabricated, placed in a box and packed with sand treated with a binder. The same sand as the mould or *face-coating* is usually applied to the surface of the pattern. The *core* is usually made from resin-bonded sand in order to (i) obtain greater strength and (ii) reduce the amount of volatile matter. The top segment of the mould is then aligned with the bottom segment and then metal is poured.

The following materials are used:

- Moulds and cores - silica, furan, chromite, alumina and zircon sands and mixtures of new and *reclaimed* sand (from previous castings) are used in mixtures of 0 to 100% reclaimed sand.
- Mould coats - refractories: graphite, talc, magnesite, olivine, alumina, zircon sand.
solvents: ethanol, methanol, IPA, water, chloroethane, carbon tetrachloride toluol
- Binders - fall into two categories:
 - Organic Thermosetting - shell, hot box, oil self setting - furan, phenolic, urethanes vapour cured (cold box) phenolic methane, phenolic peroxide, solvent evaporation.
 - Inorganic thermosetting - sodium silicate, ester hydraulic cured - cement, bentonite oxide cured - phosphate vapour-cured - sodium silicate + CO₂

The sand mould is preferably dry but some sand systems contain a small amount of water which will affect the thermal conductivity due to convection, λ_{conv} .

4.2 ANALYSIS OF HEAT TRANSFER

Heat transfer in sand moulds is complex (Figure 3). Using an Ohm's law analogy the total resistance, R_{th} , is given by Eqn 7.

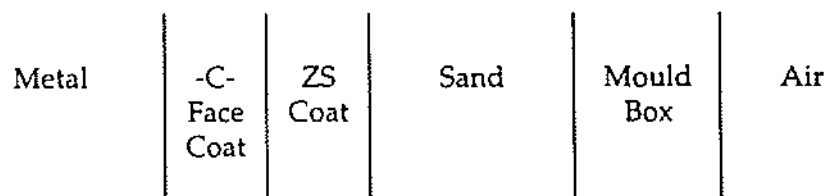


Figure 3 Schematic diagram showing the different thermal resistances involved in sand casting.

$$R_{th} = R_{Met/c} + R_{C/FC} + R_{FC/sand} + R_{sand/air} + \frac{d_c}{\lambda_c^e} + \frac{d_{ZS}}{\lambda_{ZS}^e} + \frac{d_{sand}}{\lambda_{sand}^e} \quad (7)$$

Since d_c is low and λ_c^e is relatively high we can probably neglect (d_c/λ_c^e) and possibly $R_{sand/air}$. The effective thermal conductivities (λ^e) probably contain contributions from radiation conductivity (λ_R except for the C layer) and convection (λ_{conv}) (see Section 3.2) and the magnitude of λ_R and λ_{conv} will probably vary with time. The radiation conductivity contribution can be expected to be dependent upon (i) the concentration of transition metal oxides, (ii) the magnitude of the pores (see Section 3.2), (iii) the binder which produces a glassy phase and (iv) the change in structure (of the sand) with time.

As the metal shell solidifies and thickens, it will contract away and produce an air-gap at the metal/face coat interface; the thermal resistance at this interface will vary with time. This will be dependent upon the differences in thermal shrinkage coefficients of the metal and the sand.

The lattice thermal conductivity will be a function of

- (i) nature of the sand and sand mix ratio
- (ii) the thickness of the sand layer
- (iii) the porosity of the mould material ie packing density
- (iv) the binder and binder contact and mixing ratio
- (v) the concentration of transition metal oxides and fines
- (vi) the water content of the sand
- (vii) the grain size and mixture of sieve sizes used
- (viii) the metal/sand reactions.

It is obvious that the heat transfer mechanism is very complex and that on the basis of the above factors there are thousands of different combinations available. There are two approaches

- (i) measure the heat fluxes for a specific system (composition, thickness, porosity etc)
- (ii) make measurements to quantify the individual contributions from λ_c^e , λ_R^e and λ_{conv}^e as functions of the relevant factors (eg thickness, porosity etc) develop a model or expert system. The model will then calculate the relevant thermophysical property data to be fed into the casting model. This approach would enable the heat flux to be calculated for all systems.

4.3 METHODS OF MEASURING THE REQUIRED THERMAL PROPERTIES

4.3.1 Sample preparation

It is obvious that it is essential that the specimens be (i) well-characterised and (ii) typical of normal sand casting systems. Thus great effort should be devoted to obtaining good

specimens. Furthermore, since sample thickness is important the specimens should be of the same size as those used in castings.

4.3.2 Measurement methods

Thermal conductivity

It is essential that the selected methods should be appropriate:

- (i) to allow the separation of the individual contributions of λ_c , λ_R and λ_{conv}
- (ii) for the required thickness
- (iii) for the thermal conductivity range (0.1 to $2 \text{ Wm}^{-1}\text{K}^{-1}$) of typical sand systems.

The various methods available for measuring thermal conductivity are outlined in Table 1. The thickness of the sand can vary and for this reason it is recommended that the line source method would be preferable, since it is a well-established method capable of giving reliable results. It is recommended that if possible the single wire approach [3] should be adopted if this is not possible the parallel wire system should be used.

A more detailed evaluation is given in Section 6.

5 DIE CASTING

5.1 PROCESS

In the die-casting process a SiO_2 -coating is applied to the die faces, these coatings have different thicknesses in different parts, eg a thin ($<0.5 \text{ mm}$) coat on casting, two coats on gating system and 3 coatings on feeder. The metal is poured and fills the mould. The casting is allowed to cool and the mould is then divided to allow the casting to be retrieved.

5.2 ANALYSIS OF HEAT TRANSFER

The heat transfer in this case can also be analysed using an Ohms Law analogy (Equation 8).

Metal	Coat	Mould (metal)	Cooling channel	Metal mould	Air
-------	------	------------------	--------------------	----------------	-----

$$\begin{aligned}
 R_{th} = & R_{\text{Met/coat}} + R_{\text{coat/mould}} + R_{\text{mould/cool}} + R_{\text{cool/mould}} + R_{\text{mould/air}} \\
 & + \frac{d_{\text{coat}}}{\lambda_{\text{coat}}^e} + \frac{d_{\text{mould}}}{\lambda_{\text{mould}}} + \frac{d_{\text{cool}}}{\lambda_{\text{cool}}} + \frac{d_{\text{mould}}}{\lambda_{\text{mould}}} + \frac{d_{\text{air}}}{\lambda_{\text{air}}}
 \end{aligned} \tag{8}$$

Figure 4 Schematic diagram showing various thermal resistances formed during die casting.

The heat transfer mechanism is as complex that for investment- and sand-casting. However, it is usually considered that the dominant resistance is $R_{\text{met/coat}}$ which results from the air gap formed by the shrinkage of the metal and the coating and will obviously be dependent upon the thermal contraction coefficients. The radiation conductivity term, λ_R , could make major contributions to the effective thermal conductivity of the mould, λ_R^e ; this parameter would be dependent upon (a) thickness of the coating and (b) the factors affecting the absorption and extinction coefficients viz porosity, grain size, concentration of transition metal oxide of the coating.

Measurements of the following properties would be required if the same approach recommended for sand and investment casting was adopted

- (i) thermal conductivity, λ^e , λ_C , λ_R for the coating, mould, cooling media
- (ii) extinction and absorption coefficients
- (iii) porosity
- (iv) grain size
- (v) thermal contraction coefficients of metal and coating.

5.3 METHODS

It may be difficult to measure the radiation conductivity contribution since there is a strong possibility that the coating will be optically thin. Probably the best approach is to place a coating on the metal (mould) sample and monitor the change in thermal conductivity by the laser pulse method.

6 GENERAL DISCUSSION ON METHOD SELECTION

The favoured approach to date has been to carry out simulation experiments in which metal is poured into a ceramic mould and monitoring the temperatures at specific locations in the mould. Then thermal conductivities were measured separately (frequently for a different thickness) and the interfacial thermal resistance derived from inverse temperature modelling. Such methods would only apply to one set of conditions, and as such thousands of measurements would be required to cover the different conditions used in British foundries, as can be seen from the questionnaire returns.

An alternative approach would be to determine the effects of different factors (eg composition, porosity, grain size) on λ_C , λ_R and λ_{conv} and to draw-up relations which could be used in a model or expert system which covered all conditions. This second approach is recommended here.

It is apparent that a series of different property measurements will be required if this approach was adopted, namely, thermal conductivity, optical constants (absorption, extinction and emissivity coefficients) and interfacial thermal resistances (R).

6.1 THERMAL CONDUCTION

6.1.1 Radiation conductivity, λ_R

It will be necessary to establish whether the specimen is *optically thick* (ie $\alpha d > 3$). Since radiation can also be scattered as well as absorbed it is necessary to use the extinction coefficient, E

$$E = \alpha + S$$

where S = scattering coefficient. For steady state methods operating under *optically-thick* conditions, Chen and Churchill [1] give

$$\lambda_R = \frac{8\sigma T_{\text{mean}}^3}{(\alpha + 2s)}$$

where σ = Stefan Boltzmann constant. However, for *optically-thin* conditions it would be difficult to calculate λ_R .

In order to ensure *optically-thick* conditions it will be necessary to adjust the thickness, d , of the specimen, which may not be compatible with the measurement requirements, such as those required for the radial heat flow method (Table 1). Transient methods have the advantage that λ_R is smaller than in steady state methods and several methods have been proposed to calculate λ_R for transient conditions. Ohta et al [4] have developed a method for separating λ_C and λ_R in semi-transparent slag melts which should be applicable to measurements on investment shells.

It will also be necessary to account for the direct radiation across the pore using Equn 6.

6.1.2 Convection thermal conductivity, λ_{conv}

The contribution to the overall thermal conductivity from convection contains contributions from (i) convection within a closed pore and (ii) gas flow through open pores. The latter can be determined by making measurements in vacuum and with different gases. The overall contribution can be determined in simulation experiments where the heat transfer in 'dry' and 'wet' conditions are compared.

Lattice conduction, λ_C

This can be derived by the subtraction of λ_R from the measured (effective) thermal conductivity. Most of the techniques listed in Table 1 would provide reliable values for λ_C providing the sample is optically thick. The *laser pulse method* is particularly suitable, providing the sample used is truly representative of the investment shell. However, it would be difficult to carry out measurements on samples with a thickness of 4 mm. The *line source method* has been widely used for measurements but requires a specimen at least twice the thickness of the investment shell (ie 20 mm). The *transient plane source method* is a similar technique and would seem to be particularly appropriate but the technique would need further development since the mica insulator would have to be replaced by another ceramic material for temperatures above 700 °C. The methods used to calculate λ_R in the *line source* and *transient plane source* methods would have to be verified.

The *steady state, radial heat flow* and *guarded hot plate* methods would need development to operate up to 1500 °C and would probably not be suitable for thin specimens since both methods require (a) elaborate equipment and (b) considerable operating time.

For thin investment shells (2-4 mm) and for the ceramic coatings used in die casting the laser pulse method would appear to be the most reliable technique.

For sand castings the *line source method* is probably the most appropriate technique providing a representative sample can be prepared. The method has been used for measurements up to 1500 °C and although there are discrepancies between the values obtained and those derived with the guarded hot plate (ca 10%) - this is probably the most suitable technique.

However, for the intermediate range of thickness (4-10 mm) for investment shells, the choice is less clear cut, the choice lying between using steady state methods and extrapolating transient results (line source, transient plane) source results to the thickness of the shell. Probably the best way is to use the guarded hot plate method to the maximum temperature available and seek to extend the temperature range to 1500 °C through further development.

The modulated beam method has the advantage that it has a relatively simple design.

Optical properties

The extinction coefficients can be measured by determination of the transmissivity of disc-shaped specimens. Initially these measurements could be carried out at room temperature using spectrophotometers operating in the infra-red wavelength range. Measurements of the emissivity can be made by comparing the emission from the shell with that from a blackbody.

Thermal resistance

The interfacial thermal resistances are usually derived by carrying out experiments simulating the casting process in which hot metal at a known temperature is poured into the mould and the temperature profiles are obtained using thermocouples in specified positions. The thermal resistance is then obtained by inverse temperature modelling. In general, inverse temperature modelling is not to be recommended since it can lead to unreliable values. Recently, Prof D Hills of Sheffield-Hallam University has been trying to develop a technique for the direct measurement of interfacial resistances, if this proves successful, this would be the recommended method for measurement.

Simulation experiments

Regardless of the method adopted for measuring the interfacial thermal resistance, it is recommended that experiments simulating the casting procedure should be carried out to provide results for a well-characterised system.

Heat capacity (C_p)

Heat capacity values can probably be estimated with sufficient accuracy for most materials from chemical composition. Binders and resins may have some effect on C_p and this would merit some exploratory studies using the high temperature DSC.

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TABLE 1
SUMMARY OF METHODS AVAILABLE TO MEASURE THERMAL CONDUCTIVITY

Method	Measure- ments	λ Range $\text{Wm}^{-1}\text{K}^{-1}$	d mm	Temp Range, $^{\circ}\text{C}$	Differentiate λ_R, λ_C	Gases	Advantages	Disadvantages	Application
Laser pulse	T	0.1-100	2-4	> 1500	Yes	Yes	Technique established for λ_C and λ_R	1) Difficult to ensure representative sample 2) Has been used for coatings	- Investment sand? - Die
Line source	λ	< 3	20	> 1500	with software	Yes		1) Sample must be optically thick 2) Reflection of thermal wave at long measurement times	- Sand
Transient plane source	λ, a	0.1-100	40	< 727	with software	Yes		- Insulator (mica) restricts temperature range - Needs development to higher temperature	- Sand - Possible die
Guarded hot plate	λ	suitable	> 5	< 1100	can calculate λ_R for optically thick if α known	Difficult	Can be used for stepwise cooling - T response yields a	- Needs to be optically thick - minimum thickness $d=3/\alpha$	- Investment - Sand
Radial heat flow	λ	suitable	> 2	1500		Yes		1) As above 2) Difficult to produce suitable sample	- Investment - Sand
Modulated beam (EB, laser or optical excitation)	a	suitable	< 2	1500	for optically thick	Yes		1) As above	- Investment - Sand
Rectangular heat pulse	T	suitable	disc - not given probably thin	1300		Yes		1) Radiation losses increase with increasing T and decreasing a 2) Must develop method of calculating λ_R	- Investment

T = transient, Q = quasi, SS = steady state methods, λ = thermal conductivity, a = thermal diffusivity

REVIEW OF THERMAL PROPERTY DATA FOR SAND- AND INVESTMENT-MOULDINGS

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ABSTRACT

Published thermophysical property data relevant to the heat transfer through the mould for sand- and investment-casting are correlated and reviewed. Thermal conductivity values for the mould materials are dependent upon a variety of factors, (i) temperature, (ii) porosity, (iii) grain size, (iv) amount and type of binder used, (v) moisture content. Radiation conductivity (k_R) becomes a major contributor to the heat transfer at high temperatures. It is suggested that estimates of the heat capacity (C_p) derived from the C_p -T relations for the parent oxides are probably sufficiently accurate for most purposes.

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SYMBOLS, ABBREVIATIONS, UNITS

C_p	Heat capacity, J. Kg ⁻¹ K ⁻¹
D	Diameter, m
k	Thermal conductivity Wm ⁻¹ K ⁻¹
k_c	Lattice thermal conductivity, Wm ⁻¹ K ⁻¹
k_{eff}	Effective thermal conductivity, Wm ⁻¹ K ⁻¹
k_g	Thermal conductivity derived from gas flow
k_R	Radiation conductivity, Wm ⁻¹ K ⁻¹
T	Temperature, °C or K
δ	Contact area, m ²
ϵ	Void fraction
ρ	Density, kg m ⁻³

1 INTRODUCTION

This report reviews the thermal property data affecting the heat transfer during casting in sand- and investment moulds.

Sand moulds usually are produced from (a) silica, (b) chromite, (c) zircon sands, (e) resin shell consisting of silica or zircon sand precoated with resin. The amount of *reclaimed* sand used may vary between 0 and 100% and can be achieved by *thermal* or *cold* reclamation to break down the resin coating on the sand grains. Reclaimed sand can have a lower thermal conductivity than new sand if reclamation is not properly carried out.

There are several different binders used to give the sand mould flexibility and strength, but these can also affect the thermal properties. Setting can be achieved by (a) self-setting, (b) heating and (c) passing CO₂. The types of binder can be classified as:

- (i) *alkaline phenolic* - available as self set or gas variations
- (ii) *furane* - a resin of urea formaldehyde and furfuryl alcohol, which is self-setting with acids
- (iii) *phenolic urethane* - produced by phenol formaldehyde and isocyanate resin which is available in self-setting and gas setting versions
- (iv) *resin shell sand* - which is sand precoated with phenol formaldehyde novalak resin and is set by heating
- (v) *silicate* - which is self-setting (using esters) or set by passing CO₂.

Mould coatings are sometimes applied to the surface of the mould to improve the as-cast surface. Various proprietary coatings are available and coats of zircon and paint are also used.

The pouring of hot metal (especially steel) will affect the sand in layers adjacent to the metal with a concomitant effect on the thermal properties.

Investment moulds are produced by dipping the wax pattern in a ceramic slurry followed by the addition of a *stucco* of a ceramic material applied by fluidised bed or raining methods. The investment is then built up to the required thickness by application of successive coats followed by stucco application. The '*green*' investment mould is then heated in an autoclave to remove the wax and is then fired at 800 to 1000 °C for 30 to 45 minutes. Insulating layers are sometimes wrapped around the investment to reduce the heat transfer rate since defects such as *cold-shuts*, *misruns* and *shrinkage porosity* can occur if the solidification rate is too rapid.

The principal materials used for the investments are alumina (Al₂O₃), silica, alumino-silicates (eg molochite) and zirconium silicate. Slurries can be water-based or alcohol-based but the latter are being phased out. The nature of the solvent may also have an effect on the thermal properties.

2 SAND-MOULDS

The thermal conductivity of the mould is dependent upon a variety of factors, (i) temperature, (ii) density and porosity, (iii) grain size, (iv) binder content, (v) water content, and (vi) the magnitude of the contribution from radiation conductivity which is affected by

sample thickness and the optical properties. The principle factors affecting thermal conductivity are the temperature and porosity at lower temperature.

Thermal conductivity data for sand moulds have been reported by several investigators [1-14]; details of these studies are given in Table 1.

Table 1
Details of thermal conductivity studies on sand mould materials

Investigator	System sand/binder/curing	Method (Sample thickness, mm)	Temp Range, °C	Measurements dependency upon
Atterton [1]	SiO ₂ /bentonite Olivine/bentonite Zircon sand/bentonite	Radial heat flow (10 mm)	20-1500	- chemical composition - grain size - porosity - binder and H ₂ O contents
Zeppelsauer Klimesch [2]	Silica/bentonite (6%) Silica/waterglass/CO ₂	Radial heat flow (50 mm diam)	20-1000	- density - binder
Nimoniya [3]	Silica sand/bentonite	Pouring	20-1600	- temperature
Berry [4,11]	Sand/6-7% bentonite		20-700	
Kubo [5]	SiO ₂ /6% bentonite 1.5% binder + catalyst Olivine Chromite Zircon sand	Pouring, Al Fe-C steel	20-1660 20-1150 20-1500	- composition - density (porosity) - radiation conductivity
Seshadri [6]		Pouring Al (80 mm diam)	20-660	
Beinik [7,5]		Pouring, Al Fe-C	20-660 20-1150	
Ruddle [8]	SiO ₂ /	Pouring (130 mm diam)		
Kannaiah [9]	Silica/8% bentonite Alumino-silicates/ 8% bentonite Al ₂ O ₃ /8% bentonite Zircon/8% bentonite	Pouring, Al	20-600	- chemical composites - grain size - grain size distribution - binder type
Song [10]	Chrome/8% bentonite Various sand/none/none Bentonite cement	Transient hot wire	20-60	- porosity - water content
Lucks [12]	Sand	Guarded hot plate	20-1250	

Wu et al [13] have reported a virtually constant value of k_{eff} of 1.0 Wm⁻¹K₁ for quartz sand with a sodium silicate binder by using the pouring method and using inverse temperature modelling to optimise the fit of temperatures. Luo et al [14] used a similar method and reported values of k_{eff} of 1.35 and 1.4 Wm⁻¹K⁻¹ silica sand with 8% bentonite and 6% sodium silicate respectively. The density in both studies is unspecified.

2.1 THERMAL CONDUCTIVITY QUARTZ or SILICA (SiO_2) SAND

2.1.1 Temperature dependence

The thermal conductivity values reported for various quartz sands with a density of around 1550 kg m^{-3} are shown in Figure 1. It can be seen that:

- (i) there is reasonable agreement between the results reported by the various investigations and the values obtained with the *pouring* method plotted using Al and assuming a mean temperature of ca 300°C are in reasonable agreement with those obtained by radial heat flow and line source methods
- (ii) the values reported by Song and Hahne [10] obtained with the line source method are lower than most of the other data which may have been due to the absence of bentonite (ie a binder) in their samples
- (iii) there is a minimum in the $400\text{--}600^\circ\text{C}$ range
- (iv) the k - T plots for the three sands reported by Atterton [1] diverge by 30–40%, particularly at higher temperatures
- (v) Atterton [1] attempted to determine the radiation conductivity (k_R) to the effective conductivity by plotting k_{eff} against T^3 where T is the thermodynamic temperature, K (Figure 2), it is significant that sand C had a much lower Fe content (0.2%) than sands A and B (0.7%) and showed a much k_R contribution at higher temperatures.

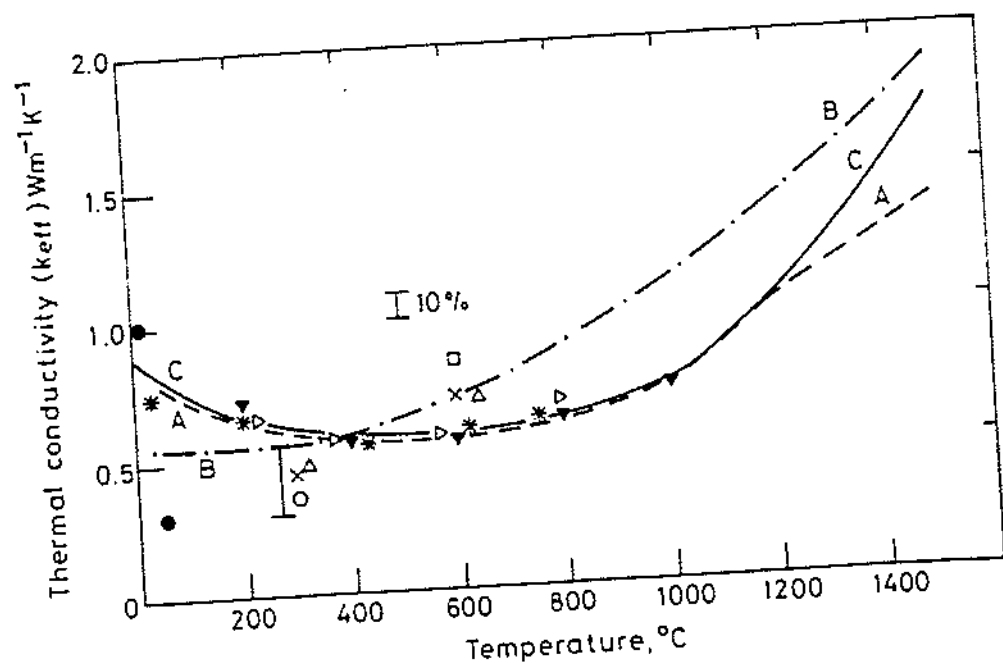


Figure 1

Thermal conductivities of quartz sands as a function of temperature for sands with a density close to 1550 kg m^{-3} , —, — —, — — —, sands A, B, C, Atterton [1] $\blacktriangledown$, Zeppelsauer [2] *, Ninomiya [3], $\triangleright$, Berry [4]; the following were obtained using the pouring methods and are plotted at mean temperatures relating to Al and (Fe or Cu) casting, 300 and 600°C , respectively; $\square$ Kubo, $\circ$ [5], Seshadri [6], Δ Beiruk [7]; $\times$ Ruddle [8] ($\rho = 1490 \text{ kg m}^{-3}$) and I, Kannaiah [9] limits depending upon binder used, $\bullet$, Song [10].

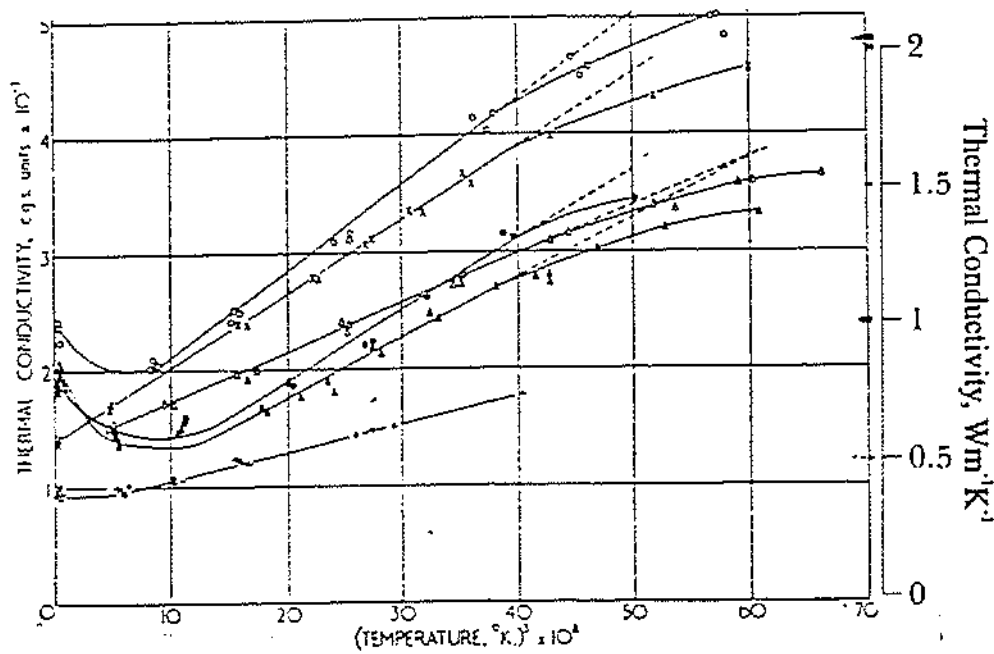


Figure 2 Thermal conductivity of quartz sands A and B as a function of T^3 where T is in K [1].

Kubo and Pehlke [5] proposed Equations 1 to 3 calculate the lattice thermal conductivity (k_c) for temperatures below 873 K (600 °C) for the following conditions:

(void fraction, ϵ) (porosity)	(0.385 - 0.494)	38.5 - 49.4%
binder fraction (w)	0.03 - 0.07	ie (%/100)
diameter of sand particles (D)	5.8 - 37.9	$\times 10^{-5}$ m

$$k_{eff} = \frac{1}{\frac{2}{3(1-\epsilon)k_{eff}} + \left(\frac{1}{\frac{3\delta k_s + (1-\epsilon-\delta)k_s}{\psi}} \right)} + k_g \quad (1)$$

where k_s , k_g (in $Wm^{-1}K^{-1}$) are thermal conductivity of the sand and the air ϵ = void fraction,

δ = contact area and $\psi = \left(\frac{\text{effective thickness of air film near contact point}}{\text{sand diameter } D} \right)$

$$\psi = 0.937 \epsilon^{1.32} \left(\frac{k_{eff}}{k_g} \right)^{0.284} \quad (2)$$

and δ is given by

$$\delta = 0.293 \epsilon^{-1.25} W^{-0.0106} \left(\frac{k_{eff}}{k_g^{-0.285}} \right) D^{0.234} \quad (3)$$

The radiation conductivity k_R (in $\text{Wm}^{-1} \text{K}^{-1}$) for dry silica sand and furan silica sands were given [5] by Equations 4 and 5, respectively.

$$k_R = 0.188 + 6.33 \times 10^{-4} T - 1.76 \times 10^{-6} T^2 + 1.46 \times 10^{-9} T^3 - 3.34 \times 10^{-13} T^4 \quad (4)$$

$$k_R = -0.0294 + 1.1 \times 10^{-3} T - 2.05 \times 10^{-6} T^2 + 1.54 \times 10^{-9} T^3 - 3.67 \times 10^{-13} T^4 \quad (5)$$

The values obtained by Kubo and Pehlke [5] are shown in Figure 3 and indicate that k_c decreases from 0.7 to 0.8 $\text{Wm}^{-1} \text{K}^{-1}$ at 25 °C to 0.5 to 0.6 at 1500 °C and k_R remains fairly constant at 0.25-0.20 $\text{Wm}^{-1} \text{K}^{-1}$ at 25 °C up to 700 °C and increases to 0.6 $\text{Wm}^{-1} \text{K}^{-1}$ at 1500 °C, with no apparent dependence on void fraction (porosity).

There are two radiation mechanisms associated with the thermal conduction process viz (1) direct radiation across the void space between the particles and (ii) radiation conduction through the particle.

In practice, k_R would depend upon (i) the optical properties and hence upon the iron oxide content, and would thus be expected to be dependent upon time, (ii) on the thickness of the sample and (iii) pore size, the direct radiation increasing as pore size increases.

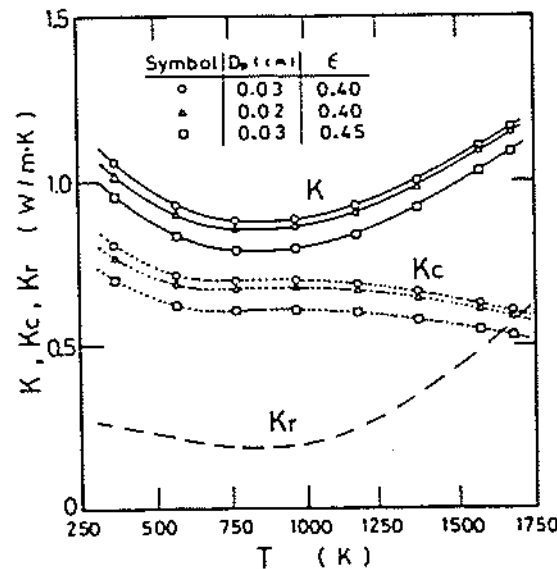


Figure 3 Effective thermal conductivity, k_{eff} , as a function of temperature showing the relative magnitudes of k_c and k_R as calculated by Kubo and Pehlke [5].

2.1.2 Density and Porosity

The dependence of thermal conductivity on density and porosity at room temperature has been studied by several investigators [1,10,12] and the results are shown in Figure 4. The effect of porosity on the thermal conductivities of quartz mould sands has also been studied by Geiger and Poirier [30] from the work carried out on packed beds.

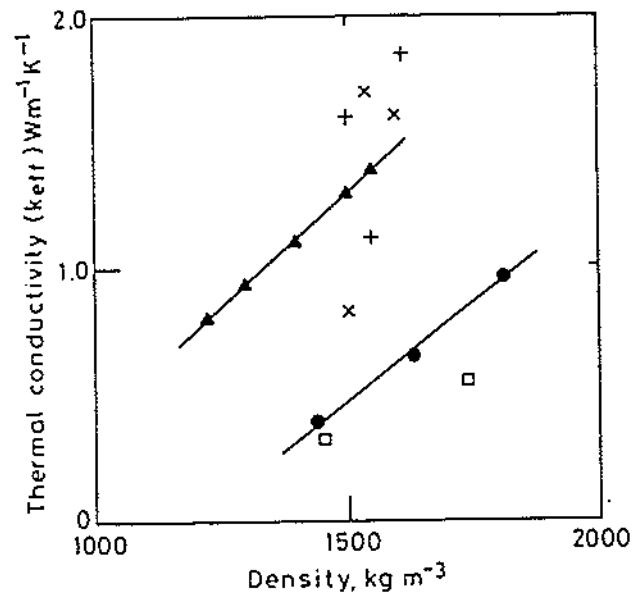


Figure 4 Effective conductivity of quartz sands + 4% bentonite at 25 °C as a function of density; $\square$, Lucks [12]; $\bullet$ Song [10]; $\times$, Atterton [1]; $\triangleright$, Zeppelsauer [2].

It can be seen that there is a high degree of scatter in the results although the slope of the k_{eff} - density plots reported by Zeppelsauer [2], Song [10] and Lucks [12] are similar, and the density range studied by Atterton was too narrow to determine a reasonable dependence between k_{eff} and density.

Song and Hahne [10] compared the measured thermal conductivity values at 20 °C with those predicted by the models due to Maxwell, Hamilton and de Vries as given by Woodside and Mesmmner [15] using a value of $k = 8.35 \text{ Wm}^{-1}\text{K}^{-1}$ for quartz of theoretical density; the de Vries model was found to give best agreement.

2.1.3 Dependence upon grain size

Song and Hahne [10] reported that the variations of thermal conductivities of samples with identical density but different grain size (0.1-2 mm diam) was 15%, k_{eff} increasing with increasing grain diameter. They report that Willhite et al [16] found a particle size effect of 20-25%.

These findings are in agreement with those reported by Kannaiah et al [9] who obtained the results in Figure 5 using the *pouring method* with molten Al and with those reported by Lucks [12], Atterton [1], Narayana et al [17], Saite et al [18] and Sanders et al [19].

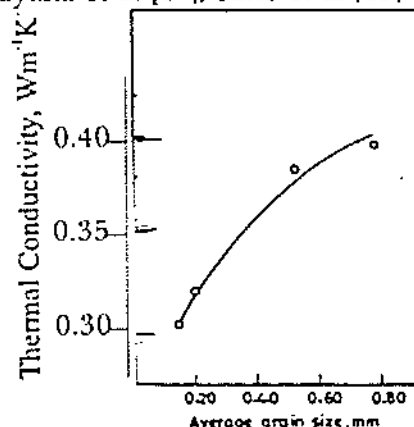


Figure 5 Effective thermal conductivity of quartz and sand + 8% bentonite as a function of grain size [9]

Kannaiah et al [9] report that the increase in k_{eff} with increasing grain diameter is due to:

- (i) an increase in thermal conductivity at the contact points (lower thermal resistance resulting from better contact)
- (ii) k_R increases as pore size increases (which has been established from work on packed beds [30] and
- (iii) k_R across the semi-transparent grain increases with increasing thickness.

Russell [20] concluded that k_R was dependent upon the pore size and that increased grain size would result sequentially in increasing pore size and higher k_R .

The contact points tend to interfere with the heat transfer by radiation conductivity in a grain.

2.1.4 Grain size distribution

Kannaiah et al [9] reported that the grain size distribution had little effect on the thermal conductivity, [Figure 6] as determined using the *pouring method*.

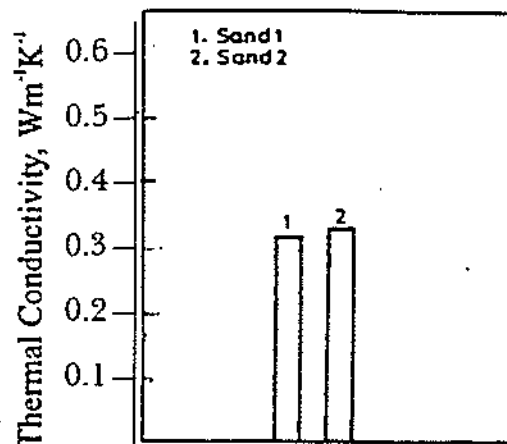


Figure 6 The effect of grain size distribution on the effective thermal conductivity [9]

2.1.5 Effect of different binders

The binder gives flexibility and strength to the sand compact. The binders tend to coat the grains and increase the contact area; thus an increase in the effective thermal conductivity with increasing binder content would be expected. The binder also helps to increase the density of the sand and this too would promote an increase in thermal conductivity.

Binders can be divided into the following types:

- (i) alkaline phenolic (self setting and gas setting)
- (ii) furane (self set)
- (iii) phenolic urethane (self set and gas setting)

- (iv) resin shell sand
- (v) silicate (self or gas setting).

Kannaiah et al [9] measured the thermal conductivities of silica sand bonded with different binders using the pouring method. The results are shown in Figure 7 and it can be seen that the thermal conductivities for quartz sand showed considerable variation with binders, ranging from $1.4 \text{ Wm}^{-1}\text{K}^{-1}$ for 6% sodium silicate to $0.7 \text{ Wm}^{-1}\text{K}^{-1}$ for 8% bentonite.

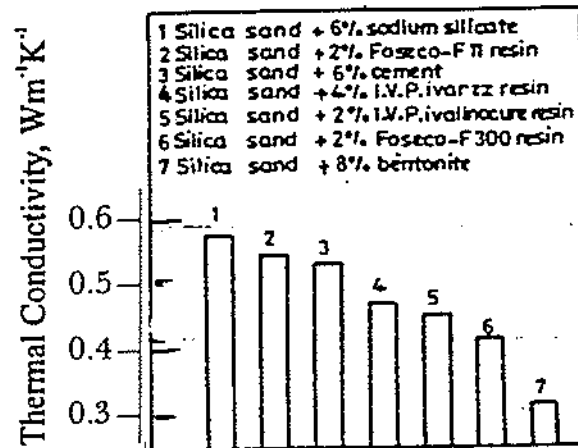


Figure 7 Thermal conductivities of quartz sand obtained with pouring melt and using Al as the metal showing the effect of different binders.

Zeppelsauer [2] also studied the effect of binders on the thermal conductivity of quartz sand. Roshan et al [21] measured the thermal conductivities using the line source method for quartz sand with different resin binders and showed that thermal conductivity was affected by the temperature and duration of the curing process and the temperature of the specimen. The thermal conductivity-temperature relation exhibited a minimum at $200\text{--}250^\circ\text{C}$ for both the specimen temperature and curing temperature.

2.1.6 Effect of moisture content

Water has a higher thermal conductivity than air and thus moisture in the pores of a refractory should lead to higher thermal conductivities. Song and Hahne [10] measured the thermal conductivity at 20°C using the line source method, the results shown in Figure 8 indicate an order of magnitude increase for increasing water contents from 0.4% to the saturation level ie for a specimen of 37.8% porosity.

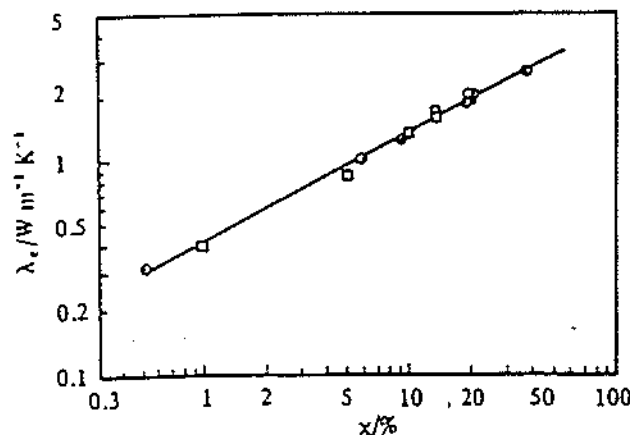


Figure 8 Thermal conductivity of unbonded quartz sand with a porosity of 37.8% as a function of moisture content.

Roshan et al [21] measured the apparent thermal conductivities of green sand and the dry sand (dried at 110 °C) and found that the green sand had the higher conductivity (Figure 9) which was attributed to the transportation of steam and the convection current produced. Other workers have also reported higher conductivities for the 'green' condition when compared with the dry condition.

However the transport of steam through the mould material is thought by other workers to make a significant contribution to the heat flux.

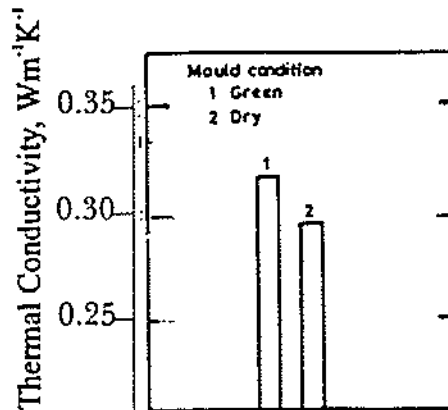


Figure 9 Thermal conductivities of green and dry sands

ZIRCON SAND (ZIRCONIUM SILICATE $\text{ZrO}_2 \cdot \text{SiO}_2$)

Thermal conductivities have been reported by Atterton [1] for zircon sand + 4% bentonite ($\rho_{\text{dry}} = 2960 \text{ kg m}^{-3}$) Ninomiya [3] with 3.8% bentonite and $\rho_{\text{dry}} = 2780 \text{ kg m}^{-3}$ and Kannaiah et al [9] with 8% bentonite and $\rho = 2320 \text{ kg m}^{-3}$. The results are shown in Figure 10 and indicate a minimum in the curve at around 600 °C

Roshan et al [21] reported that zircon sand had 60% higher conductivity than silica sand from measurements obtained with the pouring method. However, inspection of Figures 10 and 1, indicate that the thermal conductivities of zircon sand may be higher at temperatures below 600 °C but at higher temperature the conductivities are very similar to those for silica sands.

OLIVINE SANDS

Thermal conductivities for olivine sands have been reported by Atterton [1] and by Ninomiya et al [3] and are shown in Figure 11. On the basis of these results the apparent dependencies between effective thermal conductivity at 200 and 1000 °C and density are shown in Figure 11. There is a large amount of scatter in the results at lower temperatures.

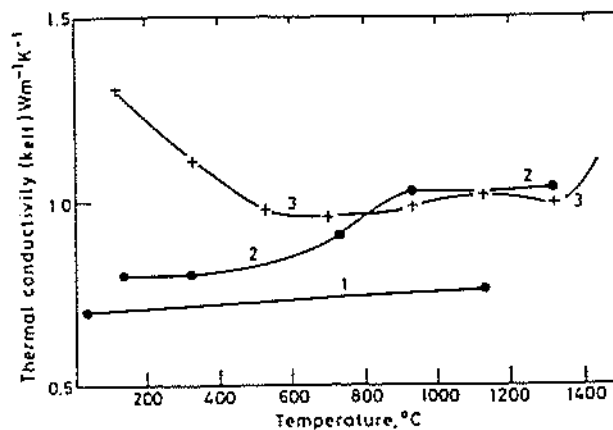


Figure 11 Thermal conductivity of olivine sands as a function of temperature; 1, Ninomiya [3] with $\rho = 1830 \text{ kg m}^{-3}$; 2,3 Atterton [1], $\rho = 2030$ and 2125 kg m^{-3} , respectively.

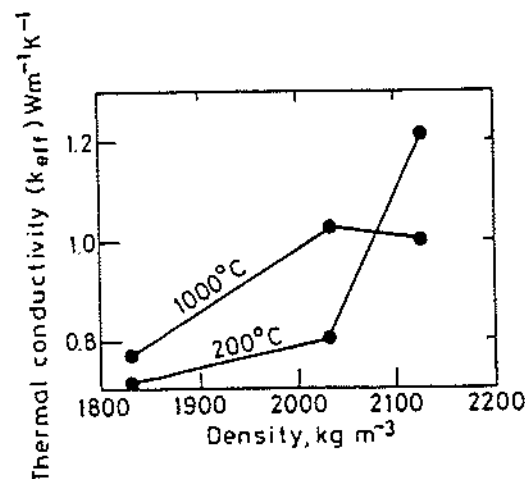


Figure 12 Thermal conductivities at 200 and 1000 °C as functions of densities at 20 °C

CHROMITE SANDS

Thermal conductivities have been reported for Ninomiya et al [3] for a sample with 3.9% binder and 2.2% H₂O and $\rho_{\text{dry}} = 2750 \text{ kgm}^{-3}$ and by Kannaiah et al [9] for a sample with 8% bentonite and a density of 1880 kgm^{-3} . The results are shown in Figure 13 and show reasonable agreement despite the differences in density.

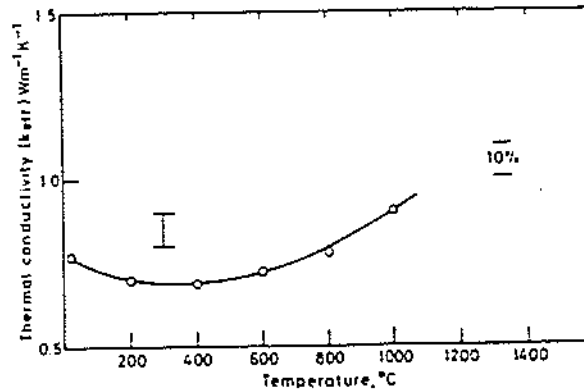


Figure 13 Thermal conductivity of chromite sands; —○—, Ninomiya [3] $\rho = 2750 \text{ kg m}^{-3}$; I, Kannaiah [9] $\rho = 1880 \text{ kgm}^{-3}$

ALUMINA (Al₂O₃)

Kannaiah et al [9] reported that alumina + 8% bentonite had the lowest thermal conductivity of all the mould materials tested (Figure 14) with a value of $0.18 \text{ Wm}^{-1}\text{K}^{-1}$

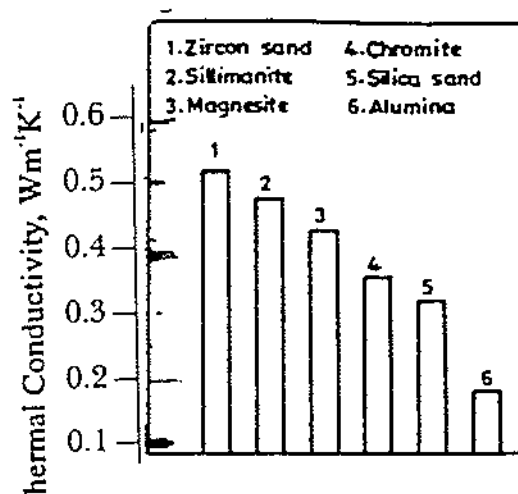


Figure 14 Thermal conductivities of various mould materials as determined by Kannaiah et al [9] using the pouring method with molten Al

MAGNESIA (MgO)

Kannaiah et al [9] used the pouring method with molten Al to derive a value of the effective thermal conductivity of magnesite + 8% bentonite of $0.43 \text{ Wm}^{-1}\text{K}^{-1}$ 20% higher than that of silica sand (Figure 14).

SILLIMANITE

Kannaiah et al [9] reported an effective thermal conductivity for sillimanite + 8% bentonite of $0.48 \text{ Wm}^{-1}\text{K}^{-1}$.

2.2 HEAT CAPACITY

Heat capacities (C_p) - temperature relations for quartz sand etc reported by Kubo and Pehlke [5] are given in Figure 15. It can be seen that there is little difference between the C_p values reported for quartz sand and those cited for pure silica.

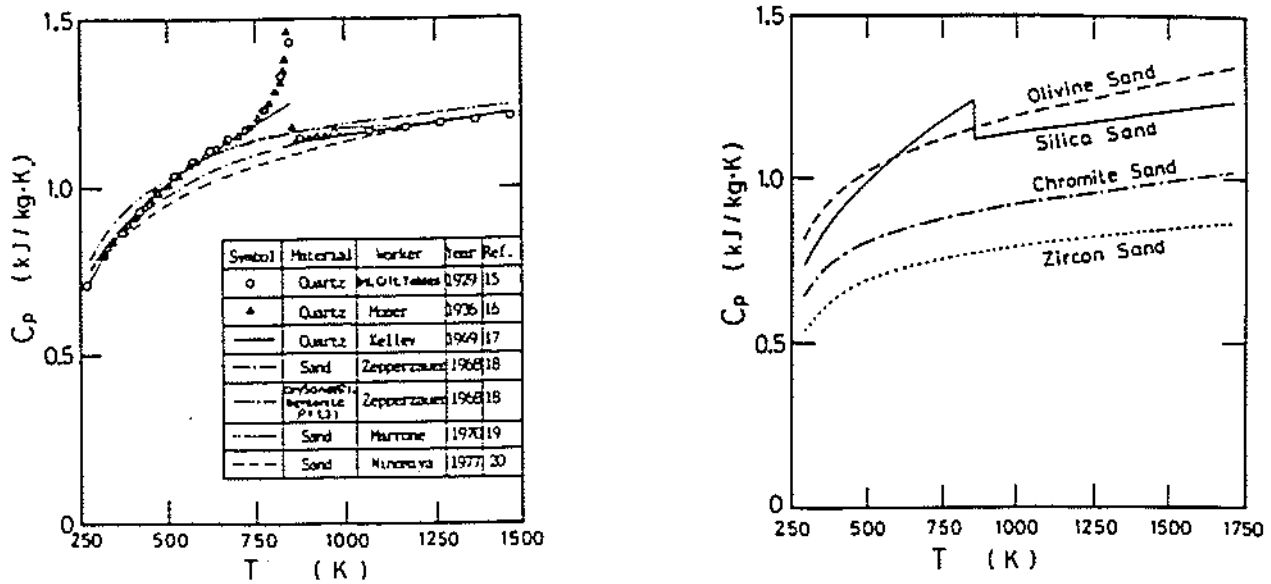


Figure 15 Heat capacity as a function of temperature for quartz sands and pure silica

Heat capacity-temperature relations can usually be expressed in the form

$$C_p = a + bT - cT^2 \quad (6)$$

where T is in K.

It is proposed that heat capacities of mould materials can be estimated to an accuracy of about $\pm 2\%$ using Equations 6 to 9 and the chemical composition of the mould material

$$a = \sum \left(\frac{w_1}{M_1} a_1 \right) + \left(\frac{w_2}{M_2} a_2 \right) + \left(\frac{w_3}{M_3} a_3 \right) + \dots \quad (7)$$

where w = mass % and M is the molecular weight (eg $M(\text{SiO}_2) = 60$) and the subscripts 1, 2, 3 denote different components in the mould material.

Similarly

$$b = \sum \left(\frac{w_1}{M_1} b_1 \right) + \left(\frac{w_2}{M_2} b_2 \right) + \left(\frac{w_3}{M_3} b_3 \right) + \dots \quad (8)$$

$$c = \sum \left(\frac{w_1}{M_1} c_1 \right) + \left(\frac{w_2}{M_2} c_2 \right) + \left(\frac{w_3}{M_3} c_3 \right) + \dots \quad (9)$$

Values for the principal oxides involved in mould materials are given in Table 2.

Table 2

Values of constants a, b and c for C_p ($J K^{-1}mol^{-1}$) =
 $a + 10^{-3} bT - c \times 10^{+5} T^{-2}$ for various oxides

Oxide	Molecular weight, g	Temperature range, K	a	b	c
SiO ₂	60	300 - 846 846 - 1800	47 60	34.3 8.1	11.3 -
Al ₂ O ₃	102	298-2000	115	11.8	25.0
ZrO ₂	123.2	298-2000	69.3	7.5	14.1
MgO	40.32	298-2100	42.6	7.3	6.2

Kubo and Pehlke proposed the use of an apparent specific heat which was not dependent upon the temperature of the cast but upon the interfacial temperature, T_i (Figure 16).

Kubo and Pehlke [11] give the following relations for 1 kg in Table 3.

Table 3

Apparent specific heat values for a' , b' and c' for C_p^{app} ($= J K^{-1}kg^{-1}$)
 $= a' + b' \times 10^{-4} T - c' \times 10^4 T^{-2}$ where T_i is in K
 and refers to the interface temperature

Mould material	Temperature Range (T) K	a'	b'	c'
Silica sand	$T_i < 846$ K $T_i > 846$ K	0.782 1.00	5.71 1.35	1.88 -
Olvine sand	298 - 1800	1.02	1.94	2.36
Zircon sand	298 - 1800	0.720	0.896	1.85
Chromite sand	298 - 1800	0.816	1.21	1.77

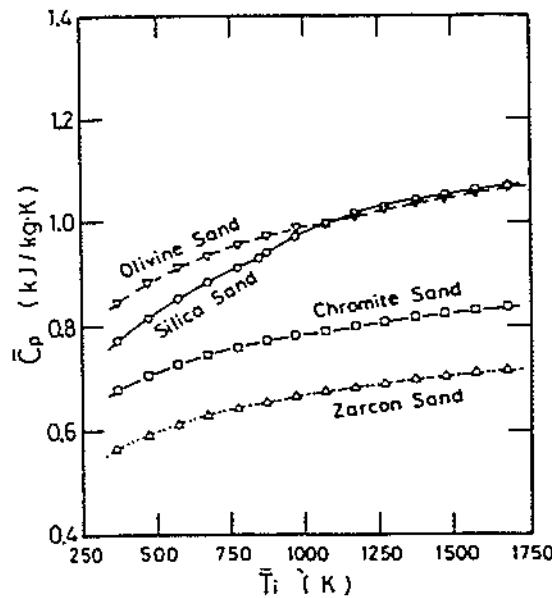


Figure 16 Apparent specific heat (C_p^{app}) as a function of the interface temperature (T_i)

2.3 DENSITY, THERMAL EXPANSION COEFFICIENTS

Kubo and Pehlke [5] reported the density of the sand mould varied according to the number of ramming strokes (Figure 17) and was also affected by the nature of the bonding system. They point out that silica has a relatively high thermal expansion coefficient. Some of the expansion is accommodated by movement into the pores, the remainder manifests itself as movement of the mould wall.

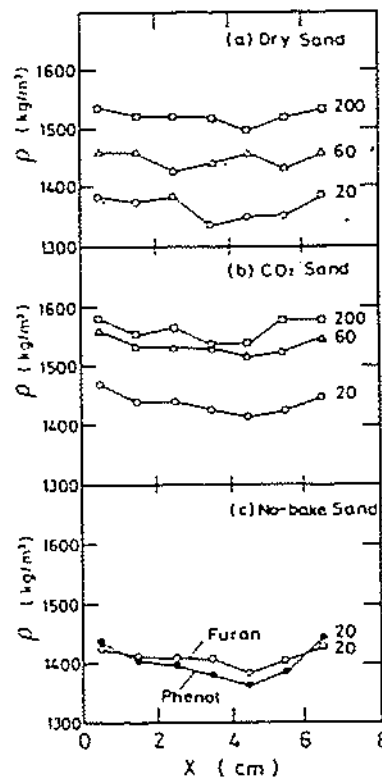


Figure 17 Density of (a) dry sand, (b) CO_2 -setting sand, (c) self-setting sand as a function of mould sand dimensions, (numbers refer to the number of ramming strokes)

Values for the various oxides with theoretical density are given [5] in Table 4.

Table 4

Density values for theoretically-dense materials at 25 °C

Oxide	SiO ₂	Al ₂ O ₃	Zircon sand	Olivine sand	Chromite sand
$\rho \text{ kgm}^{-3}$	2650	3970	4650 (4950) ^a	3150	4490 (4760) ^(a)

(a) values cited by ref [11]

Porosity varies but is generally around the 40-50% level.

2.4 INTERFACIAL THERMAL RESISTANCE

Reported values of the interfacial thermal resistance between the sand mould surface and the metal for the temperatures between the liquidus and solidus vary between 300 and 160 Wm⁻²K⁻¹, respectively, based on inverse temperature modelling studies.

3 INVESTMENT MOULDS

3.1 THERMAL CONDUCTIVITIES

The thermal conductivity measurements reported for investment mould materials are summarised in Table 5.

Table 5

Details of experiments used to measure the thermal conductivities of various investment moulds

Investigator	Method (Sample size)	Temperature Range °C	Materials Studied
Huang [22]	Hot wire method (not given)	20 - 750	Silica Alumino-silicates Silica-zircon
Hearnes [23]	Transient, line source method	20 - 1200	Alumino-silicates
Browne and Sayers [24,25]	Radial heat flow (30 mm diam x 200 mm)	200 - 900	Molochite with zircon face wall
Beffel [26]		500 - 1150	Mullite

ALUMINA

Huang et al [22] proposed Equation 10 for the effective thermal conductivity for temperatures below 1200 °C.

$$k_{\text{eff}}(\text{Wm}^{-1}\text{K}^{-1}) = 34.4 - 6.09 \times 10^{-3}T + 3.15 \times 10^{-5}T^2 \quad (10)$$

SILICA

Huang et al [22] proposed Equation 11 for k_{eff} for temperatures below 1000 °C, where T is in °C.

$$k_{\text{eff}}(\text{Wm}^{-1}\text{K}^{-1}) = 1.53 + 1.31 \times 10^{-1}T \quad (11)$$

ALUMINO-SILICATES

Thermal conductivities have been reported by Huang [20], Heames et al [31] and by Browne and Sayers [22,23] and Beffel [26] for aluminosilicates. The results are shown in Figure 18 and indicate a reasonable measure of agreement between the results of Browne and Sayers [24,25] with those reported by Huang [22] and with Heames [23] below 100 °C but the latter show a remarkable decrease at high temperatures.

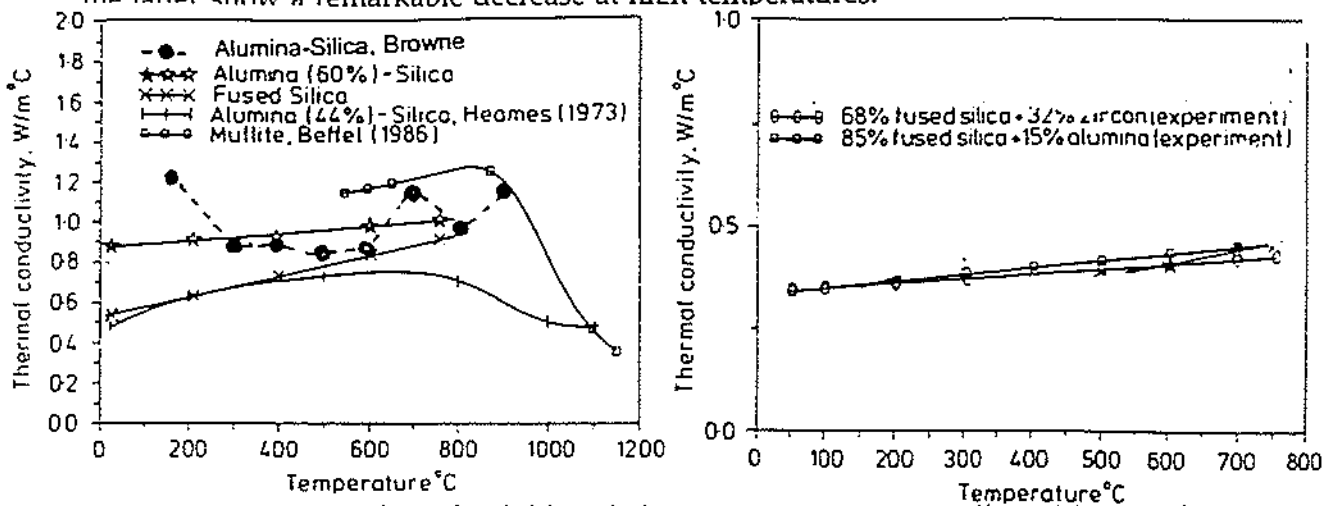


Figure 18 Thermal conductivities of aluminosilicates as a function of temperature

Huang et al [22] proposed Equation 12 for k_{eff} for temperatures below 1200 °C, where T is in °C.

$$k_{\text{eff}}(\text{Wm}^{-1}\text{K}^{-1}) = 6.51 - 5.15 \times 10^{-3}T + 2.5 \times 10^{-6}T^2 \quad (12)$$

ZIRCON ($\text{ZrO} \cdot \text{SiO}_2$)

Huang et al [22] proposed Equation 13 for k_{eff} for temperatures below 1200 °C, where T is in °C.

$$k_{\text{eff}}(\text{Wm}^{-1}\text{K}^{-1}) = 6.39 - 3.67 \times 10^{-3}T + 1.85 \times 10^{-6}T^2 \quad (13)$$

3.2 HEAT CAPACITY

The heat capacity of $\text{Al}_2\text{O}_3\text{-SiO}_2$ mixture, ZrO_2 can probably be estimated to an accuracy of $\pm 2\%$ using Equations 6 to 9 and the data given in Table 2. The heat capacity as function of the metal/investment interface temperature T_i can be estimated using Figure 16 or Table 3 but some caution should be used since these data refer to sand casting.

3.3 DENSITY, THERMAL EXPANSION COEFFICIENT

Chattejee and Roy [28] have reported thermal expansion results for zircon sand, alumina and alumino-silicates for temperatures up to 1300°C , the results are shown in Figure 19. The thermal expansion of silica sand was found to increase rapidly to 1.5% at 590°C , whereupon it underwent a phase transformation and consequently only increased slightly with temperature. The expansion-temperature relations for fused alumina and silica and "dead-burnt" magnesia are shown in Figure 20. The effect of calcination on the thermal expansion is shown in Figure 21. Calcination at 1600°C decreased the thermal expansion coefficients of zircon sands and kyanite.

Thermal expansion coefficients have been reported to be higher for fine grain size materials.

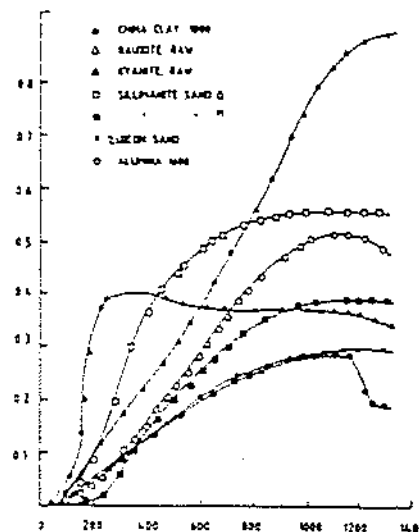


Figure 19 Thermal expansion as a function of temperature for alumina, zircon sand and alumino silicates.

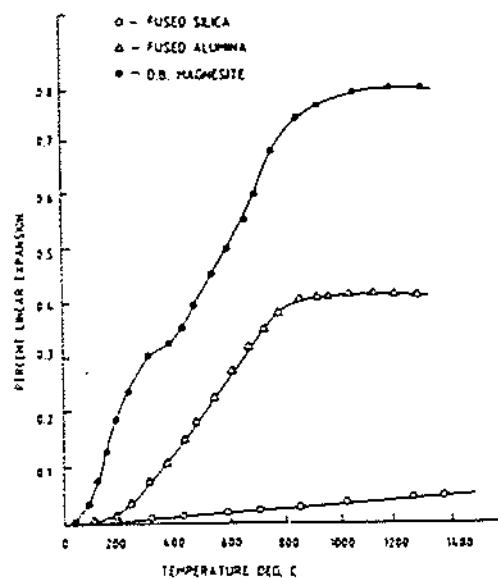


Figure 20 Thermal expansion as a function of temperature for fused alumina and silica and dead burnt magnesite.

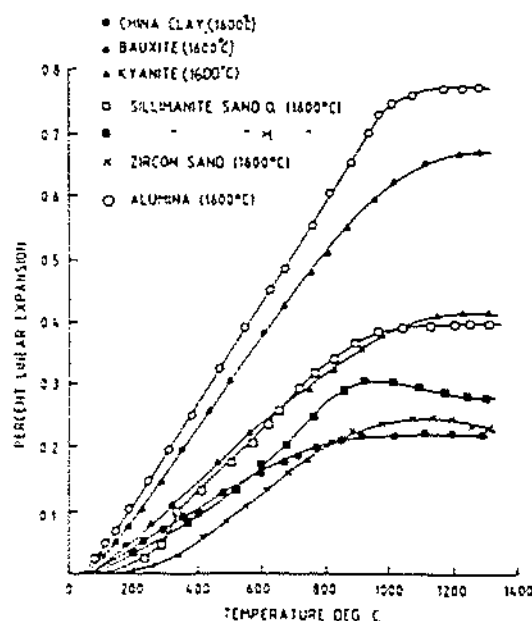


Figure 21 Thermal expansion as a function of temperature for calcined mould materials.

3.4 OPTICAL PROPERTIES

The total normal emissivity ϵ_{TN} of Al_2O_3 decreases from 0.75 at 300 K to 0.3 at 1850 K. Browne and Sayers [24] have reported an emissivity of $\epsilon = 0.615$ for molochite. A higher value has been reported in the literature [24].

For a grey body, $\epsilon = \alpha$ where α is the absorption coefficient, unfortunately Al_2O_3 does not approximate to a grey body. The emissivity of a rough surface, such as that of an investment casting, is higher than that of a polished surface.

3.5 INTERFACIAL HEAT TRANSFER COEFFICIENT

Hendriks and Engelhardt [27] carried out simulation experiments in which they monitored the rate of temperature loss (dT/dt) from which they calculated heat transfer coefficients (h) for systems involving a zircon primary coat followed by back up coats of silica and/or alumina. The units for h were given in $\text{cm}^{-1}\text{s}^{-1}$, instead of the usual $\text{Wm}^{-2}\text{K}^{-1}$.

Sahai and Overfelt [29] obtained the interfacial heat transfer coefficient using inverse temperature modelling for an axisymmetric casting of nickel alloy 718. The authors point out the sensitivity of the thermocouple responses to incorrect location of the thermocouples and to incorrect calibrations. They found that the contact conductances (or heat transfer coefficients) for systems where a face coat was applied were consistently smaller than those obtained without application of a face coat (standard) (possibly due (a) to larger air gaps being formed when using a face coat or (b) to a thermal resistance due to the face coat itself). These contact conductances were found to (i) decrease with time (Figure 22) to increase to (ii) to increase with metal temperature (Figure 23) and (iii) to be in good agreement with values derived from three different mathematical models (Figure 24).

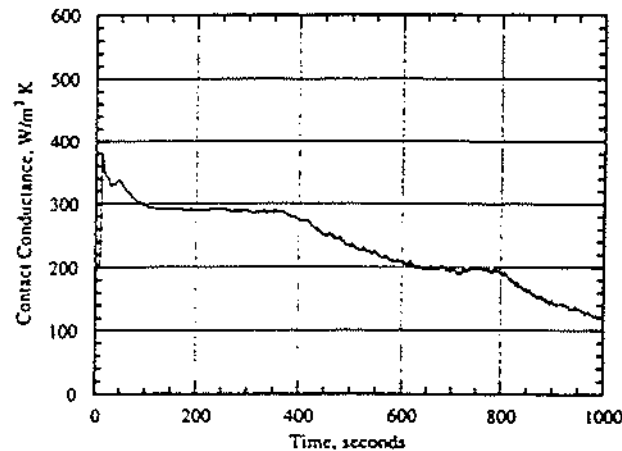


Figure 22 Contact conductance as a function of time

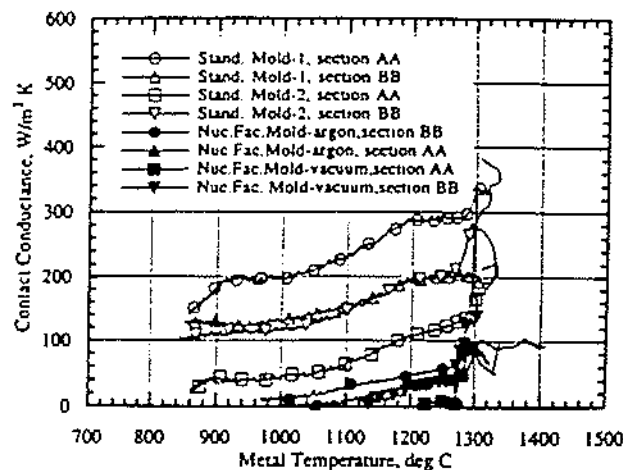


Figure 23 Contact conductance as a function of metal temperature

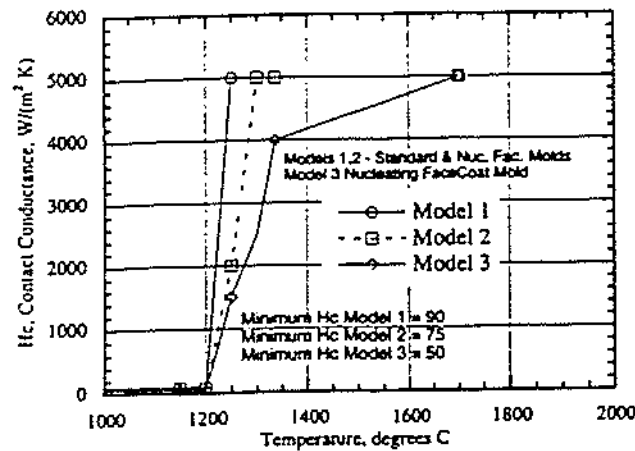


Figure 24 Contact resistance - temperature relations derived with different models

4 ACKNOWLEDGEMENTS

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REVIEW OF METHODS FOR THE MEASUREMENT OF THERMAL CONDUCTIVITIES OF SAND-, INVESTMENT- AND DIE-MOULD MATERIALS

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ABSTRACT

The methods used for the measurement of the thermal conductivity of mould materials can be classified into three groups (i) steady heat flow methods, (ii) transient methods and (iii) method simulating the heat transfer in the casting. The various methods are briefly described and their advantages and disadvantages for measurements of thermal conductivities of sand-, investment- and die-mould materials are summarised. The use of the following are recommended:

- (i) the laser pulse method for investment moulds (< 4 mm thick)
- (ii) the guarded hot plate or the radial heat flow method for investment moulds (> 4 mm)
- (iii) the hot wire (or line source) method for sand moulds
- (iv) the laser pulse method for die casting moulds.

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SYMBOLS, ABBREVIATIONS UNITS

a	thermal diffusivity (m^2s^{-1})
A	Area (m^2)
C _p	heat capacity ($\text{JK}^{-1} \text{kg}^{-1}$)
d	thickness of specimen (m)
f	pore radiation shape factor (m^{-1})
I	current
k	thermal conductivity ($\text{Wm}^{-1} \text{K}^{-1}$)
L	length of wire or specimen (m)
q	heat flux density (Wm^{-2})
Q	heat flux (W Js^{-1})
r	radius
s	scattering coefficient (m^{-1})
t	time (s)
T	temperature ($^{\circ}\text{C}$ or K)
α	absorption coefficient
δ	pore diameter (m)
ρ	density (kg m^{-3})
σ	Stefan Boltzanan coefficient = $5.87 \times 10 \text{ Wm}$

1 INTRODUCTION

Various methods have been used to measure thermal conductivities of the various mould materials used in sand-, investment- and die-casting. These can be divided into (a) conventional techniques and (b) methods which simulate the heat transfer in a casting. The conventional techniques can be divided into two classes, (i) *steady heat flow* methods in which the thermal conductivity, k , is derived from the measurement of a temperature gradient, and (ii) *transient* methods which usually give thermal diffusivity (α) values which are obtained from analysis of temperature-time relations.

There are several factors which complicate the measurement of thermal conductivities of mould materials, these are outlined below.

- (i) Porosity: Sand and investment-mould are porous which reduces the thermal conduction of heat from the casting (porosity is usually about 40%). Various models are available to estimate the effective thermal conductivity of mould (k_{eff}) from the thermal conductivity of the material with theoretical density (k_{TD}). The validity of these models has been discussed in various reviews [1-4]. However, it has been found that these models for industrial materials tend to overestimate k_{eff} by a factor of < 2 . This overestimation has been ascribed to the presence of microcracks in commercial samples [3]. Thus, it is essential that the specimen used should be representative of the mould material.

- (ii) Radiative heat transfer: Radiative heat transfer becomes increasingly important as the temperature increases. Radiation heat transfer can occur by two mechanisms:

- (i) *radiation across the pores* ($k_{R(p)}$) which is given [3] by Equation 1.

$$k_{R(p)} = 4f\sigma\epsilon T^3\delta \quad (1)$$

where ϵ = emissivity, σ = Stefan Boltzmann coefficient, δ = pore size, T is in K and f = is the pore radiation shape factor.

- (ii) *radiation conductivity* (k_R) which arises because materials like SiO_2 and Al_2O_3 are semi-transparent media. For optically thick conditions (ie when $\alpha d > 3$), this is given by Equation 2.

$$k_R = \frac{8\sigma T_{\text{mean}}^3}{(\alpha + 2s)} \quad (2)$$

where α = absorption coefficient, s = scattering coefficient, T_{mean} = mean temperature of material and T is in K. Thus the thickness of the specimen is important since it determines whether the specimen is 'optically thick' and hence whether k_R is calculable and the magnitude of k_R .

- (iii) Contact area of grains: This affects the magnitude of k_{eff} but is difficult to determine. It is affected by (a) the size of the grains, (b) the binder which coats the grains and thus increases the area of contact. Thus the nature of the binder can have a significant influence on the thermal conductivity.
- (iv) Gas convection: Gas convection through the pores and microcracks can contribute to the overall heat transfer. Since H_2 and He have much higher thermal conductivities than Ar , N_2 and air the use of different gases can help to determine the

magnitude of this form of heat transfer. Litovsky and Shipiro [3] have shown that the adjustment of the partial pressure of gas can give valuable information on the effect of microcracks on thermal conductivity and diffusivity of porous ceramics (Figure 1).

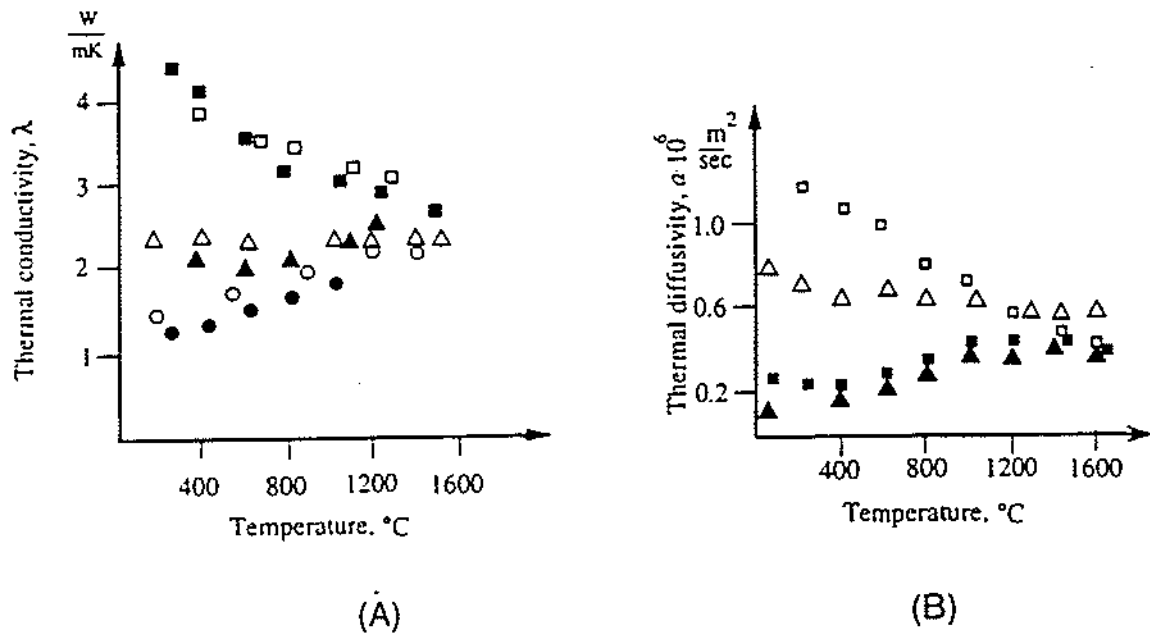


Figure 1 Thermal conductivities and thermal diffusivities of 2 types of chromemagnesite refractories with similar porosities and chemical compositions, (A) Ar; $\square$, $\blacksquare$, 10^5 Pa; Δ , $\blacktriangle$, 8×10^{-2} , 10^2 Pa; $\circ$, $\bullet$, 10^2 Pa; (B) N_2 ; $\blacksquare$, 10^2 Pa; $\square$, 10^5 Pa; $\blacktriangle$, 10^2 ; Δ , 10^5 Pa.

The various methods available for measuring thermal conductivities of mould materials are reviewed briefly below; for more detailed reviews the reader should consult references [6] and [7].

2 STEADY HEAT FLOW METHODS

2.1 GUARDED HOT PLATE METHOD

In this method the sample is in the form of a thin plate or disc and one-dimensional heat transfer is assumed (Equation 3). Heat losses are minimised by surrounding the sample with a guard plate with an identical temperature to that of the sample but separated from the sample to avoid conduction [6]. Thermocouples are embedded at known depths in the centre of the sample. A thermal gradient ($\Delta T/d$) is established by heating one side and the total heat flux Q is determined from either measurements of the voltage and current applied to the heater or by a water calorimeter (Figure 2). This method was adopted by Lucks [8] for measurements on sand moulds. The major problem is the loss of heat from the sides of the specimen. Consequently, it has been used as a relative technique in which the thermal gradient ($\Delta T/d$) of the specimen is compared with that of a reference material of known conductivity, which is usually adjacent to the specimen being studied

$$Q = kA \frac{\Delta T}{d} \quad (3)$$

where Q = heat flux, A = area of plate, and d is the distance separating the two thermocouples. The energy supplied to the heater can be used to measure Q if heat losses are negligible. Since heat losses increase with increasing temperature it becomes increasingly

difficult to keep a large apparatus at uniform temperature at high temperatures. Consequently, it is difficult to operate this apparatus at temperatures above 900 °C.

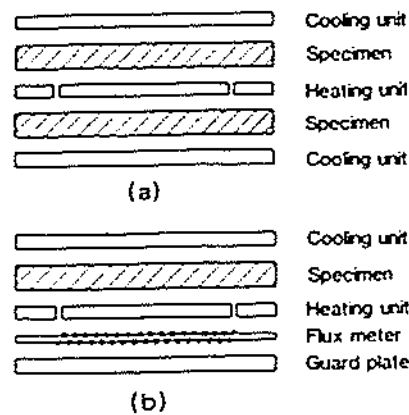


Figure 2 Schematic drawings of arrangements for (a) Guarded hot plate and (b) Bi-guarded hot plate.

2.2 AXIAL HEAT FLOW METHOD

The axial heat flow method uses bar-shaped specimens, but is similar to the guarded hot plate method. This is not a very convenient geometry for carrying out measurements on mould materials at high temperatures and consequently has not been widely used.

2.3 RADIAL HEAT FLOW METHOD

This method uses a specimen in the shape of a hollow cylinder. Atterton [9] used this method to measure the thermal conductivity of various mould sands. Thermocouples are embedded at known depths in the specimen around the centreline and the centre of the cylinder usually contains the heater (Figure 3). The furnace is heated to the required temperature and then a known amount of power is supplied to the heater and the temperatures (T_1 , T_2) of the two thermocouples recorded. The thermal conductivity is calculated from Equation 4

$$k = \left(\frac{P}{L} \right) \frac{\ln(r_2/r_1)}{2\pi(T_1 - T_2)} \quad (4)$$

where r is the radius, (P/L) is the power supplied per unit length of heat. It is important that the ratio of (specimen length, L / diameter D) is sufficiently large to ensure that heat transfer occurs solely in the radial direction.

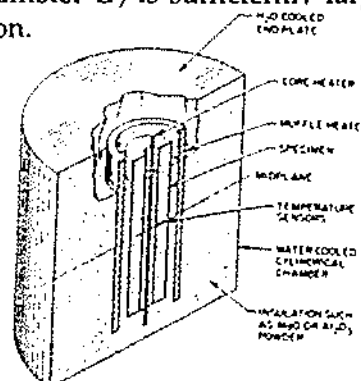


Figure 3 Schematic drawing showing the radial heat flow method.

The principal disadvantages of this method are the large specimen size and the difficulties associated with keeping the specimen isothermal in the vertical direction. The advantages are that it can be used up to high temperatures and can be applied to a large conductivity range.

2.4 MODULATED BEAM METHOD

In this method a periodic modulation signal (usually sinusoidal but square and triangular waves can be used) is applied to a surface. The modulated signal has a much smaller amplitude than that of the steady state signal, on which it is superimposed. This causes the temperature of the surface to be modulated too and a phase lag also develops. The modulated heat is then transferred through the disc-shaped specimen and both the amplitude and the phase lag of the back face are recorded. The phase shift and the decrease in amplitude are both related to the thermal diffusivity (a) which is related to the thermal conductivity (k) by Equation 5 where C_p and ρ are the heat capacity and density, respectively.

$$k = a \cdot C_p \cdot \rho \quad (5)$$

Electron beam and optical excitation techniques have both been applied to provide the periodic heating wave and both disc and hollow cylinder-shaped specimens have been used. The calculation procedures used for deriving thermal diffusivity are complex and the reader requiring further details is directed to reference [6].

3 TRANSIENT METHODS

3.1 LASER PULSE METHOD

In this method a laser pulse is directed onto the front face of a disc-shaped sample and the temperature of the back face is monitored continuously. Two methods are used to analyse the temperature transient of the back face to yield the thermal diffusivity of the specimen. In the first treatment the temperature transient of the back face (shown in Figure 4) is used to determine $t_{0.5}$, which is the time required to reach $0.5 \Delta T_{\max}$ where

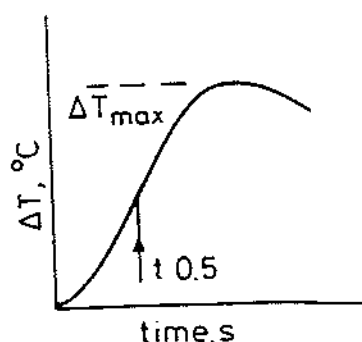


Figure 4 Schematic diagram representing the temperature transient recorded in laser pulse experiments.

$\Delta T_{\max}$ is the maximum temperature rise from which the thermal diffusivity ($\text{m}^2 \text{s}^{-1}$) can be calculated using Equation 6

$$a = \frac{0.1388 d^2}{t_{0.5}} \quad (6)$$

where d is the thickness of the disc. In fact, other fractions of $\Delta T_{\max}$ can be used to calculate k [6]. Corrections are made to account for radiative heat losses which is responsible for decrease in temperature after $\Delta T_{\max}$ shown in Figure 4. This treatment requires many measurements at short times. It is also necessary to ensure that the pulse is spread uniformly over the specimen [10].

The logarithmic method [10] is an alternative way of treating the temperature transients and requires many measurements for longer times. A review of data processing methods has shown that thermal diffusivity values obtained can differ significantly depending upon the method used, especially when heat losses (ie Biot Numbers) are high. The laser pulse has a wide range of application, is robust and can readily be operated up to high temperatures.

The principal disadvantages of the laser pulse method are:

- (i) that specimen thicknesses are restricted to around 2 mm due to the low conductivity of mould materials (4 mm may be considered to be the maximum)
- (ii) that it uses relatively small samples which consequently may not be truly representative of the mould
- (iii) the variation in thermal diffusivity values obtained as a result of the different methods of processing data especially where the conditions pertain to high Biot Numbers.

3.2 RECTANGULAR PULSE METHODS

This method is very similar to the laser pulse method in which an energy pulse from a xenon arc is focused onto the front face of a disc-specimen which has attained a steady temperature.

Kobayashi [7] has pointed out that radiative heat loss increases relatively with (i) high temperatures, (ii) low thermal diffusivities, (iii) low C_p . Thus, for measurements involving refractory materials at high temperatures it is important to have reliable values for the emissivity to improve the corrections for radiative losses.

This method will be restricted to relatively small specimens of about 2 mm thickness and may be prone to uncertainties arising from non-representative specimens.

3.3 HOT WIRE (OR LINE SOURCE) METHOD

This technique has been widely used for the measurement of refractories, gases and porous media such as soils etc [6,11,12]. The sample is usually in the form of a brick split longitudinally along its central axis (Figure 5) and two wires are embedded in grooves in the sample (either parallel or perpendicular to one another); one wire acts as a heating wire and the other is a thermocouple, the bead of which is in the centre of the sample. In some cases a single wire is used, which acts as both a heating element and a resistance thermometer. The sample is placed in the uniform temperature zone of a furnace and brought to a steady temperature and then a current is applied to heater and the temperature of the sample is monitored as a function of time. The thermal conductivity is given by Equation 7.

$$k = \frac{VI}{4\pi L} \frac{\ln(t_2/t_1)}{\Delta T} \quad (7)$$

where V and I are the applied voltage and current, L is the wire length, t_1 and t_2 are the times for which the temperature difference, ΔT , are plotted. The thermal conductivity is usually determined from the slope of a plot of ΔT against $\ln(t_2/t_1)$.

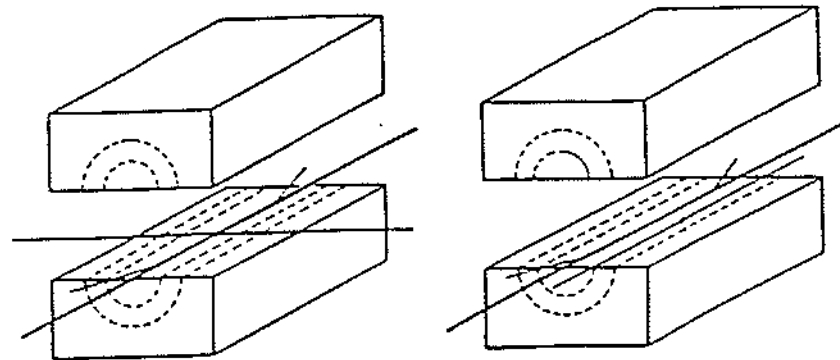


Figure 5 Schematic drawing showing typical arrangements for hot wire method.

The major problems with this method are:

- (i) The large size of the specimens and various attempts have been made to reduce the specimen dimensions [12] since it becomes progressively more difficult to obtain large uniform temperature zones at high temperatures.
- (ii) Poor contact between the wire and the sample and powder derived from the specimen can be added to the groove to improve thermal contact; the thermal contact is improved in the order, perpendicular < parallel < single wire.
- (iii) The reflection of the thermal wave (arising from the hot wire) which is an especial problem at long times and when using smaller samples.
- (iv) The range of application tends to be limited to materials with $k < 2 \text{ Wm}^{-1} \text{ K}^{-1}$ because of the thermal wave problem.

3.4 TRANSIENT PLANE SOURCE (TPS) METHOD

One development of the hot wire method is to replace the single wire with a thin metallic strip. Gustafsson and co-workers [13,14] maximised the length of the strip by forming it into a spiral (Figure 6) and this system is the basis of the Transient Plane Source (TPS) Method. The TPS elements are made from 10 μm thick Ni foils of width 0.40 mm. This is covered with an insulating layer eg mica for temperatures above 200 $^{\circ}\text{C}$ to minimise radial conduction.

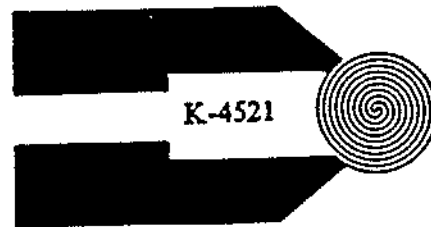


Figure 6 Schematic design of a hot disc TPS element.

The element/sensor is then placed between two cylinders of the sample material. The resistance of the disc is monitored to provide the temperature-time relation which is recorded (as in the hot wire method). The thermal conductivity (k) can be derived from Equation 8

$$\Delta T = \frac{P}{\pi^{3/2} r.k} D \quad (8)$$

where r = radius of sensor, P is the total power output and D is a theoretical expression for the time-dependent temperature increase for a disc sensor [11]. A thermal insulator is placed between coils of the spiral element to minimise conduction in the radial direction.

The technique is applicable to a wide-conductivity range ($0.05 - 150 \text{ Wm}^{-1} \text{ K}^{-1}$) but its application to mould materials with low conductivities is limited by:

- (i) the method has not been developed for operation above 700°C and an insulator would have to be found to replace mica
- (ii) the elimination of radial conduction becomes a more severe problem for low thermal-conductivity materials.

4 SIMULATION METHODS

These methods derive an apparent thermal conductivity when carrying out experiments which simulate the actual casting process. The values derived will reflect the changes in apparent conductivity when an interfacial thermal resistance is created at the metal/mould interface. Consequently, the reported values do not provide accurate thermal conductivity values for the mould material but do provide overall values relevant to the casting studied. It is not known how applicable the reported values would be to castings of different dimensions (both metal and mould).

4.1 POURING METHOD (or PLANE HEAT SOURCE METHOD)

This method has been widely-used for measurements on sand mould methods [15-17]. The apparatus is shown in Figure 7. The molten metal is poured into the mould which has a detachable panel (*specimen plug*). Then the specimen plug is removed after a set time and transferred quickly into a calorimeter which monitors the temperature rise of the calorimeter liquid and thus how much heat had been absorbed by the calorimeter. After the calorimeter has come to a steady temperature, the heat absorbed by the specimen plug, q , can be calculated by

$$q = m_l C_{p_l} (\Delta T) \quad (9)$$

from the temperature rise (ΔT) mass (m_l) and heat capacity (C_{p_l}) of the liquid. The heat absorbed, q , is derived for a series of contact times (from the time the metal was poured). A plot of q as a function of contact time (Figure 8) gives a linear relation. The heat flux density Q is derived from the slope of this plot divided by surface area of the specimen plug.

Measurements can be carried out with different molten metals eg Al, Cu, alloys, cast irons and steels.

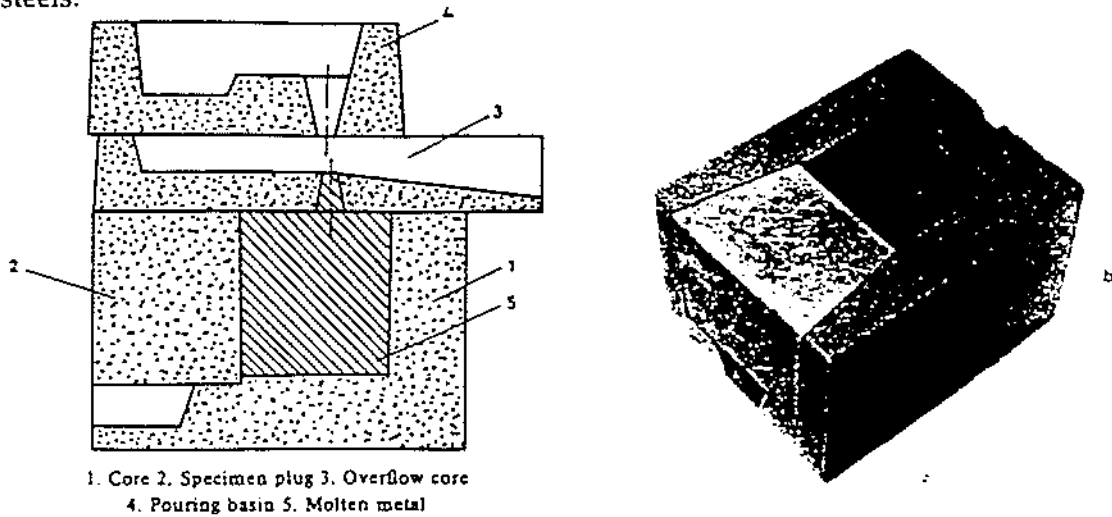


Figure 8 Schematic drawing showing the apparatus used in the pouring method.

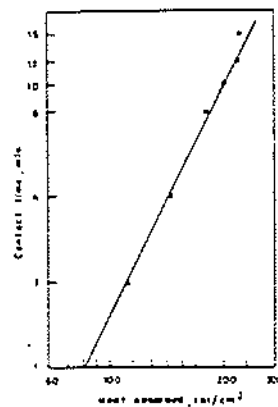


Figure 9 Typical plot of heat absorbed as a function of contact time in pouring method.

4.2 HEAT BALANCE METHOD

Luo et al [18] made a plate casting in a sand mould and monitored the temperatures of (i) the casting using a thermocouple placed centrally and (ii) the mould at 5 locations along the centreline in the sand casting as a function of time. The temperature profiles in the sand mould were assumed to have the form of

$$T = Ay^n + B \quad (10)$$

where y is the distance measured for the heat penetration and A , B and n are coefficients determined from the experimental data. The analysis of these time-temperature-position curves results in values for the apparent thermal conductivity.

Wu et al [19] also made a plate casting and monitored temperatures at various locations in the sand mould but used an optimisation process to provide "best-fit" values for the effective thermal conductivities and C_p values by carrying out inverse temperature modelling by assuming a polynomial relationship

$$k = x_1 + x_2 T + x_3 T^2 \dots x_n T^{n-1}$$

and Fouriers Second Law for a one-dimensional heat flow.

$$\rho_m C_{p_m} \frac{\partial T}{\partial t} = k_m \frac{\partial^2 T}{\partial z^2} + \frac{\partial k}{\partial T} \left(\frac{\partial T}{\partial z} \right) \quad (11)$$

5 DISCUSSION

Details of the various methods are summarised in Table 1.

The selection of the most appropriate method will be dependent upon certain criteria outlined at the end of Section 1 *viz*

- (i) that the method should be appropriate for the thermal conductivity range
- (ii) the specimen should have a similar thickness to that of the mould and the method should be suitable for handling this thickness of specimen
- (iii) the specimen should be '*optically thick*' to allow radiation conductivity to be calculated
- (iv) the method should be capable of to operating with different gases and gas pressures
- (v) the technique should use a sample of sufficient size to be representative of the mould.

It should also be noted that comparative inter-laboratory trials indicate that there are significant differences between the results obtained at higher temperatures, for instance those obtained using the guarded hot plate and hot wire methods. One possible reason for this discrepancy could be the magnitude of the radiation conductivity contribution; however there may be other sources of uncertainty in the two methods which could also be responsible for these differences.

5.1 INVESTMENT MOULDS

For thin investment moulds (< 4 mm) the laser pulse (or rectangular pulse method) would probably be the best method of determining the thermal conductivity. However, it is recommended that

- (i) results should be obtained on several specimens to ensure that the results are representative of the mould material
- (ii) results should be obtained with different gases and gas pressures to derive an idea of the magnitude of contributions from microcracks.

TABLE 1
SUMMARY OF METHODS AVAILABLE TO MEASURE THERMAL CONDUCTIVITY

Method [Reference]	Measure- ments	λ Range $Wm^{-1}K^{-1}$	d mm	Temp Range, $^{\circ}C$	Differentiate λ_R, λ_C	Gases	Advantages	Disadvantages	Application
Laser pulse [6,10]	T	a, C_p	0.1-100	2-4	> 1500	Yes	Technique established for λ_C and λ_R	1) Difficult to ensure representative sample 2) Has been used for coatings	- Investment sand? - Die
Line source [6,11,12]	T	λ	< 3	20	> 1500	Yes	with software	1) Sample must be optically thick 2) Reflection of thermal wave at long measurement times	- Sand
Transient plane source [13,14]	T	λ, a	0.1-100	< 727	40	Yes	with software	- Insulator (mica) restricts temperature range - Needs development to higher temperature	- Sand - Possible die
Guarded hot plate [6,8]	SS	λ	suitable	< 1100	> 5	Difficult	Can be used for stepwise cooling - T response yields a	- Needs to be optically thick - minimum thickness $d=3/\alpha$	- Investment - Sand
Radial heat flow [9]	SS	λ	suitable	1500	> 2	Yes		1) As above 2) Difficult to produce suitable sample	- Investment - Sand
Modulated beam [6] (EB, laser or optical excitation)	QSS	a	suitable	< 2	1500	Yes	for optically thick	1) As above	- Investment - Sand
Rectangular heat pulse [7]	T	a, C_p	suitable	disc - not given probably thin	1300	Yes		1) Radiation losses increase with increasing T and decreasing a 2) Must develop method of calculating λ_R	- Investment

T = transient, Q = quasi, SS = steady state methods, λ = thermal conductivity, a = thermal diffusivity

For thicker investment moulds (> 4 mm) the selection of the appropriate method is more difficult. The hot wire method does not seem appropriate for specimens of 2-12 mm, thus the guarded hot plate and radial heat flow methods would appear to be the prime candidates. The latter is capable of operating up to 1500°C but requires a stringent specimen geometry which might prove difficult to produce for investment-mould samples. The guarded hot plate uses a disc-shaped specimen of 5 to 10 mm which is convenient to produce as an investment mould sample but suffers from the fact that it has not been developed to operate above 1100°C .

The use of an interlaboratory comparison project involving both methods and using samples of mould materials produced under identical conditions would seem to be a profitable first step in obtaining thermal conductivities of thicker investment shells.

5.2 SAND MOULDS

The hot wire method (preferably using a single heater/sensor) would appear to be the most appropriate method since it is robust and has been used extensively to high temperatures at least in its two-wire form. However, given the discrepancy in the high temperature results obtained in inter-laboratory comparison programmes, involving this method and steady state techniques, a similar 'round robin' study for sand mould materials would appear to be particularly useful.

5.3 DIE MOULDS

The laser (or rectangular wave) pulse method would seem to be the most appropriate for measurement on die materials since the method has been successfully applied to thin films. However, the transient plane source (TPS) method has been used satisfactorily for measurements on thin layers of refractory materials up to 700°C and an intercomparison could prove beneficial.

5.4 CLASSICAL METHODS VERSUS CASTING SIMULATION METHODS

The simulation methods account for the interfacial thermal resistances ($R_{i/th}$) by incorporating this term into an overall thermal resistance (or conductivity). However, $R_{i/th}$ would be expected to be time-dependent. Thus if $R_{i/th}$ is a major contributor to the overall thermal resistance, (R_{eff}), it would be expected to result in a deviation from linearity for the heat flux density-contact time for longer times. In investment moulds $R_{i/th}$ would be expected to make a larger contribution to R_{eff} since the thermal resistance arising from the sample is much smaller in investment moulds than in sand moulds, since it is usually much thinner. Thus deviations from linearity might be anticipated if the method were applied to investment castings.

It is also possible that data obtained in these experiments can not be applied to the mathematical modelling of systems which are different to those studied ie where the thicknesses of the mould materials or the castings are different to those investigated. Experiments will have to be carried out to determine whether this is so.

In general, the use of data from casting simulation studies will be dependent upon whether (i) the model aims to follow the evolution of an interfacial thermal resistance during the solidification of the casting or (ii) the model merely incorporates the interface resistance into an effective thermal resistance (or conductivity). Thus actual thermal conductivities would be required in the first case and simulation trials would be of use in the second case. Thus, the selection of the method will also be affected by the approach taken by the model.

6 CONCLUSIONS AND RECOMMENDATIONS

- (i) The laser pulse method is the preferred method for obtaining thermal conductivity measurements on investment mould materials with thicknesses less than 4 mm but it is recommended that measurements should be obtained on several specimens to guarantee that the specimens are truly representative of the mould.
- (ii) For thicker investment moulds (4-10 mm), either the guarded hot plate or the radial heat flow method would appear to be the most appropriate technique.
- (iii) The line source method seems to be the most appropriate technique for measurements on sand moulds.
- (iv) The laser pulse method appears to be the most suitable technique for die moulds.
- (v) Inter-laboratory comparisons involving different techniques for various mould materials would be very useful in determining the most reliable thermal conductivity values at higher temperatures and the probable level of uncertainty.

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