



# **Deliverable D1.1**

# Current methodology for temperature measurements in industrial linings

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Primary Authors	Marc Huger, <u>marc.huger@unilim.fr</u> , UNILIM
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Project Coordinator	Marc Huger, marc.huger@unilim.fr, UNILIM
	Marc Huger, marc.huger@unilim.fr, UNILIM
<b>Document Contributors</b>	Diana Vitiello, diana.vitiello@unilim.fr, UNILIM
	Rafael Oliveira, rafael.oliveira@uc.pt, UMINHO

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### Table 1. Related Work Packages status

Work package		Status	Description		
WP 1: Improvement of measurement tools	Task 1.1: thermal instrumentation		Description of three main thermal instrumentation and applications in ATHOR project.		

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# **1.** Introduction

Task 1.1 "thermal instrumentation" is dedicated to the development of methodologies for temperature measurements up to 1500°C in steel ladle linings. It will be applied on laboratory scale tests (UMINHO, RHI-Magnesita and TATASTEEL) on masonry and for industrial applications like refractory linings in steel ladles (TATASTEEL).

In this report, the thermal equipment used in the ATHOR project and examples of their use are discussed. In Section 2 a description, including the working principle and the main advantages / disadvantages, of three thermal instruments is given. These devices are: thermocouples, infrared camera and laser scanner. In section 3, some examples of the use of this equipment within the ATHOR project are given, both in laboratory scale and in-situ measurements.

# 2. Thermal instrumentation

The lining of each steel ladle is composed of different materials with specific temperature dependent properties. In other words, the properties of the materials under service conditions are not the same as at room temperature. The acquisition of the temperature data at different points through the steel ladle lining and the effect of this on the properties of the materials used, commonly known as the temperature field, is therefore of paramount importance. Hence, the main goal of this task is to improve the methodologies used for temperature measurements in industrial applications. This ambitious purpose includes the development of laboratory scale equipment as well as industrial in-situ devices.

The thermal instrumentation that will be used and improved are:

- Thermocouples;
- Infrared (IR) camera;
- Laser scanner.

### 2.1. Thermocouples

A thermocouple is an electrical device for temperature measurement, which generates a voltage that changes with temperature[1]. It is comprised of at least two metals joined together to form two junctions: one is connected to the body which will have its temperature measured (this is the hot or measuring junction); the other is connected to a body of known temperature (this is the cold or reference junction). As the temperature changes from the junction to the ends of the wires, a voltage develops across the junction. Figure 1 shows a scheme of the thermocouple circuit.



Figure 1: Scheme of a thermocouple circuit.

If the temperature at the two junctions is the same, there is no flow of current through the thermocouple because equal and opposite electromotive forces (emf) are generated simultaneously. While if the two junctions are at different temperatures, the emf cannot be equal to zero and a net current flows through the circuit. The magnitude of this force depends on the materials used in the device. The amount of emf developed within the thermocouple circuit is very small, usually in millivolts, therefore highly sensitive instruments are required to carry out the measurement. Two commonly used devices are; the ordinary galvanometer and voltage balancing potentiometer.

The working principle is based on three effects, discovered by Seebeck, Peltier and Thomson:

- <u>Seebeck effect</u>: when a metal bar is heated at one end, a voltage (known as the Seebeck voltage) develops across
  the length of the bar. This voltage changes with the temperature and the type of metal used. By joining dissimilar
  metals that have different Seebeck voltages at a temperature-sensing junction, a thermocouple voltage (VTC) is
  generated.
- <u>Peltier effect</u>: it is the reverse phenomenon of the Seebeck effect; when a potential difference is applied across a thermocouple, it causes a temperature difference between the junctions of the different materials in the thermocouple. As a result of this effect, an electronic refrigerator can be made, which is known as the Peltier cooler.



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• <u>Thomson effect</u>: the evolution or absorption of heat when an electrical current passes through a circuit composed of a single material that has a temperature difference along its length. This transfer of heat is superimposed on the common production of heat associated with the electrical resistance to currents in conductors.

Combinations of different metals create a variety of voltage responses. This leads to different types of thermocouples used for different temperature ranges and accuracies (Table 1). The choice depends on: the temperature range required for the experiment, temperature accuracy, durability, conditions of use, expected service life, price etc.

Table 1: List of different available thermocouples. The most common and used is the type K.

Туре	Material	Temperature Range	Accuracy
Туре В	Platinum Rhodium - 30% / Platinum Rhodium - 6%	200°C to 1700°C	+/- 0.50%
Type S	Platinum Rhodium - 10% / Platinum	-50°C to 1480°C	+/- 1.5C or +/- 0.25%
Type R	Platinum Rhodium - 13% / Platinum	-50°C to 1480°C	+/- 1.5C or +/- 0.25%
Туре К	Nickel-Chromium / Nickel-Alumel	-270 °C to 1260 °C	+/- 2.2C or +/- 0.75%
Туре Е	Nickel-Chromium / Constantan	-270°C to 870°C	+/- 1.7C or +/- 0.50%
Type J	Iron / Constantan	-210°C to 760°C	+/- 2.2C or +/- 0.75%

The thermocouples can be classified into two different construction types: base metal thermocouples and noble metal thermocouples. The first are the most common thermocouples. The second are composed of precious metals such as platinum and rhodium. They are more expensive, and are used in higher temperature applications. The advantages and disadvantages of using thermocouples are summarized in Table 2.

Table 2: Summary of the main advantages and disadvantages of using thermocouples.

Advantages	Disadvantages
Most practical temperature ranges, from cryogenics to jet- engine exhaust, can be served using thermocouples. Depending on the metal wires used, a thermocouple is capable of measuring temperature in the range -200°C to +2500°C.	Substantial signal conditioning is necessary to convert the thermocouple voltage into a usable temperature reading. Traditionally, signal conditioning has required a large investment in design time to avoid introducing errors that degrade accuracy.
Thermocouples are rugged devices that are immune to shock and vibration and are suitable for use in hazardous environments.	In addition to the inherent inaccuracies in thermocouples due to their metallurgical properties, a thermocouple measurement is only as accurate as the reference junction temperature can be measured, traditionally within 1°C to 2°C.
Because they are small and have low thermal capacity, thermocouples respond rapidly to temperature changes, especially if the sensing junction is exposed. They can respond to rapidly changing temperatures within a few hundred milliseconds.	Because thermocouples consist of two dissimilar metals, in some environments, corrosion over time may result in deteriorating accuracy. Hence, they may need protection; and care. Maintenance are thus essential.
Because thermocouples require no excitation power, they are not prone to self heating and are intrinsically safe.	<ul> <li>When measuring microvolt-level signal changes, noise from stray electrical and magnetic fields can be a problem.</li> <li>Twisting the thermocouple wire pair can greatly reduce magnetic field pickup. Using a shielded cable or running wires in metal conduit and guarding can reduce electric field pickup. The measuring device should provide signal filtering, either in hardware or by software, with strong rejection of the line frequency (50 Hz/60 Hz) and its harmonics.</li> </ul>



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The thermocouples come in several different construction types, as shown in Figure 2. Thermocouples without a protective sheath are known as exposed thermocouples. These are used for small sensors, with direct heat transfer from the measured object. This type of thermocouple gives a fast sensor response. In a grounded thermocouple, the sensor is welded to the sheath. Often this sheath is composed of metal, which also allows for heat transfer, but adds an extra protection for harsh and difficult environments. However, because the thermocouple is welded to the metal sheath, there is an electrical contact. This makes the measurement susceptible to noise from ground loops. A sealed thermocouple is isolated from the sheath, adding a layer of insulation between the thermocouple and the measured object. This type of thermocouple has the slowest temperature response because of the insulating layer.



Figure 2: Thermocouple Construction Types.

# 2.2. Infrared (IR) camera

The infrared camera or thermal camera is an innovative tool that can measure the temperature distribution on the external surface of the steel ladle while the overhead crane transports it. This allows the continuous production of steel without contact between the camera and the analysed object. For covering the complete outer surface of the ladle including the bottom, generally 4 - 5 cameras are required. It should be noted that the IR camera cannot see through an obstacle, but instead reproduces the intrinsic temperature of a body or the heat flow caused by a heat source [2]. All the bodies with a temperature different from absolute zero emit a specific energy caused by the movement of the molecules. The intensity of this movement changes with the change of temperature of the body: the molecules move faster with high temperatures. This movement is also synonymous of a movement of electrical charges that generates electromagnetic radiation in the wavelengths of the infrared band (from 0.8 to 15  $\mu$ m). The infrared camera captures thus this energy and converts it into an electronic signal, which is processed by a software and transformed into a thermal image (**Erreur ! Source du renvoi introuvable**.). The image is used for temperature calculations and to evaluate the severity of the thermal problem, thanks to the possibility of quantifying the captured heat very precisely.



Figure 3: Example of an infrared image of four full steel ladles.



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For this type of experiment, a very important parameter is the emissivity  $\varepsilon$  of the analysed object, which is the ability of the body to emit infrared radiation, see Equ. 1. It is defined as the ratio between the power flow  $\varepsilon_{\lambda}$  emitted at a wavelength  $\lambda$  by a real body at a given temperature T and the power flow  $\varepsilon_{\lambda b}$  that would be emitted at the same wavelength  $\lambda$  by a black body brought to same temperature T. A black body is able to absorb any incident radiation regardless of its wavelength and to emit radiations at all wavelengths [3].

$$=rac{arepsilon_{\lambda}}{arepsilon_{\lambda h}}$$

Equ. 1

The  $\epsilon$  values of many of the most common materials can be easily found in the literature (Table 3 and Table 4).

ε

### Table 3: Emissivity of different materials – Part 1 of 2 – Metals – Source: Omegascope Company [5]

Material	Temp °F (°C)	د Emissivity	Material	Temp °F (°C)	ء Emissivity	Material	Temp °F (°C)	د Emissivity
Alloys			Polished	100 (38)	.03	Monel, Ni-Cu Oxid. at	1110 (599)	.46
20-Ni 24-CR 55-FE Oxid	392 (200)	90	Highly Polished	100 (38)	02	1110°F Nickel		
20-Ni, 24-CR, 55-FE, Oxid.	932 (500)	.97	Rolled	100 (38)	.64	Polished	100 (38)	.05
60-Ni , 12-CR, 28-FE, Oxid.	518 (270)	.89	Rough	100 (38)	.74	Oxidized	100-500 (38-260)	.3146
60-Ni , 12-CR, 28-FE, Oxid.	1040 (560)	.82	Molten	1000 (538)	.15	Unoxidized	77 (25)	.05
80-Ni, 20-CR, Oxidized	212 (100)	.87	Molten	1970 (1077)	.16	Unoxidized	212 (100)	.06
80-NI, 20-CR, Oxidized	1112 (000)	.87	Molten Niekel Plated	2230 (1221)	.13	Unoxidized	932 (000) 1922 (1000)	.12
Aluminum	2372 (1300)	-08	Dow Metal	0.4-600 (-18-316)	.15	Electrolytic	100 (38)	.04
Unoxidized	77 (25)	.02	Gold			Electrolytic	500 (260)	.06
Unoxidized	212 (100)	.03	Enamel	212 (100)	.37	Electrolytic	1000 (538)	.10
Unoxidized	932 (500)	.06	Plate (.0001)	000 750 (00 000)		Electrolytic	2000 (1093)	.16
Oxidized	390 (199)	.11	Plate on JUUUS Sliver	200-750 (83-388) 200-750 (83-388)	.1114	Ralladium Plate ( 00005	1000-2000 (038-1093)	.0880
Oxidized at 599°C (1110°F)	390 (199)	.11	Polished	100-500 (38-260)	.0708	on .0005 silver)	200-750 (93-399)	.1617
Oxidized at 599°C (1110°F)	1110 (599)	.19	Polished	1000-2000 (538-1093)	.03	Platinum	100 (38)	.05
Heavily Oxidized	200 (93)	.20	Haynes Alloy C,			Platinum	500 (260)	.05
Heavily Oxidized	940 (504)	.31	Oxidized	600-2000 (316-1093)	.9096	Platinum Platinum Plack	1000 (538)	.10
Roughly Polished	212 (100)	.09	Oxidized	600-2000 (316-1093)	86-89	Platinum, Black	500 (260)	.85
Commercial Sheet	212 (100)	.09	Havnes Alloy X.			Platinum, Black	2000 (1093)	.97
Highly Polished Plate	440 (227)	.04	Oxidized	600-2000 (316-1093)	.8588	" Oxidized at 1100°F	500 (260)	.07
Highly Polished Plate	1070 (577)	.06	Inconel Sheet	1000 (538)	.28	-	1000 (538)	.11
Bright Rolled Plate	338 (1/0)	.04	Inconel Sheet	1200 (649)	.42	Rhodium Flash (0.0002	200 700 (02 274)	10.10
Alloy A3003 Oxidized	600 (316)	.05	Inconel X. Polished	75 (24)	.00	Silver	200-700 (83-371)	.1010
Alloy A3003, Oxidized	900 (482)	.40	Inconel B, Polished	75 (24)	.21	Plate (0.0005 on Ni)	200-700 (93-371)	.0607
Alloy 1100-0	200-800 (93-427)	.05	Iron			Polished	100 (38)	.01
Alloy 24ST	75 (24)	.09	Oxidized	212 (100)	.74	Polished	500 (260)	.02
Alloy 24S1, Polished	75 (24) 75 (24)	.09	Oxidized	930 (499)	.84	Polished	1000 (538)	.03
Alloy 75ST Polished	75 (24)	08	Unoxidized	212 (100)	.05	Steel	2000 (1083)	.00
Bismuth, Bright	176 (80)	.34	Red Rust	77 (25)	.70	Cold Rolled	200 (93)	.7585
Bismuth, Unoxidized	77 (25)	.05	Rusted	77 (25)	.65	Ground Sheet	1720-2010 (938-1099)	.5561
Bismuth, Unoxidized	212 (100)	.06	Liquid	2760-3220 (1516-	.4245	Polished Sheet	100 (38)	.07
Brass			Cast Iron	1(/1)		Polished Sheet	500 (260)	10
73% Cu. 27% Zn. Polished	476 (247)	.03	Oxidized	390 (199)	.64	Polished Sheet	1000 (538)	.14
73% Cu, 27% Zn, Polished	674 (357)	.03	Oxidized	1110 (599)	.78	Mild Steel, Polished	75 (24)	.10
62% Cu, 37% Zn, Polished	494 (257)	.03	Unoxidized	212 (100)	.21	Mild Steel, Smooth	75 (24)	.12
62% Cu, 37% Zn, Polished	/10 (3/7)	.04	Strong Oxidation	40 (104)	.95	Mild Steel, Liquid	2910-3270 (1599-	.28
83% Cu, 17% Zn, Polished	530 (277)	.03	Strong Oxidation	482 (250)	.95	Steel, Unoxidized	212 (100)	.08
Matte	68 (20)	.07	Liquid	2795 (1535)	.29	Steel, Oxidized	77 (25)	.80
Burnished to Brown Color	68 (20)	.40	Wrought Iron	77 (00)		Steel Alloys	75 (0.0)	
Cu-Zn, Brass Oxidized	392 (200)	.01	Dull	77 (25) 880 (240)	.94	Type 301, Polished Type 201, Polished	/5 (24) 450 (222)	.2/
Cu-Zn, Brass Oxidized	1112 (600)	.61	Smooth	100 (38)	.35	Type 301, Polished	1740 (949)	.55
Unoxidized	77 (25)	.04	Polished	100 (38)	.28	Type 303, Oxidized	600-2000 (316-1093)	.7487
Unoxidized	212 (100)	.04	Lead			Type 310, Rolled	1500-2100 (816-1149)	.5681
Cadmium	77 (25)	.02	Polished	100-500 (38-260)	.0608	Type 316, Polished Type 316, Polished	/5 (24) 450 (222)	.28
Lamphlack	77 (25)	95	Oxidized	100 (38)	43	Type 316 Polished	1740 (949)	66
Unoxidized	77 (25)	.81	Oxidized at 1100°F	100 (38)	.63	Type 321	200-800 (93-427)	.2732
Unoxidized	212 (100)	.81	Gray Oxidized	100 (38)	.28	Type 321 Polished	300-1500 (149-815)	.1849
Unoxidized	932 (500)	.79	Magnesium Ouide	100-500 (38-260)	.0713	Type 321 w/BK Oxide	200-800 (93-427)	.6676
Gangle Soot	200 (121)	.80	magnesium Oxide	1880-3140 (1027- 1727)	.1020	Type 347, Oxidized	000-2000 (310-1093)	.8791
Filament	500 (260)	.95	Mercury	32 (0)	.09	Type 350	200-800 (93-427)	.1827
Graphitized	212 (100)	.76	Mercury	77 (25)	.10	Type 350 Polished	300-1800 (149-982)	.1135
Graphitized	572 (300)	.75	Mercury	100 (38)	.10	Type 446, Polished	300-1500 (149-815)	.1537
Chromium	932 (500)	./1	Molyhdenum	212 (100)	.12	Type 17-7 PH	200-600 (93-316)	.4451
Chromium	1000 (538)	.00	Molybdenum	500 (260)	.00	Polished	300-1500 (149-815)	.0916
Chromium, Polished	302 (150)	.06	Molybdenum	1000 (538)	.11	Type C1020, Oxidized	600-2000 (316-1093)	.8791
Cobalt, Unoxidized	932 (500)	.13	Molybdenum	2000 (1093)	.18	Type PH-15-7 MO	300-1200 (149-649)	.0719
Cobalt, Unoxidized	1832 (1000)	.23	<ul> <li>Oxidized at 1000°F</li> </ul>	600 (316)	.80	Stellite, Polished	68 (20)	.18
Columbium, Unoxidized	2000 (816)	.18	"Oxidized at 1000°F	700 (3/1) 800 (427)	.84	" " "	2000 (1002)	.14
Copper	2000 (1000)	-27	" Oxidized at 1000°F	900 (482)	.83	•	3600 (1982)	.26
Cuprous Oxide	100 (38)	.87	" Oxidized at 1000°F	1000 (538)	.82	•	5306 (2930)	.30
Cuprous Oxide	500 (260)	.83	Monel, Ni-Cu	392 (200)	.41	Tin, Unoxidized	77 (25)	.04
Black Ovidized	1000 (538)	.77	Monel, NI-Cu Monel, Ni-Cu	752 (400)	.44	Tinned Iron, Bright	212 (100)	.05
Etched	100 (38)	.09	Monel, Ni-Cu	68 (20)	.43	range non, ongin	212 (100)	.08
			Oxidized	()				
Matte Davethe Dalistant	100 (38)	.22						
Roughly Polished	100 (38)	.07						



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#### Table 4: Emissivity of different materials – Part 2 of 2 – Non-metals – Source: Omegascope Company [5]

Acts         6 (20)         00         Grant         10 (21)         42         Parts         10 (21)         43         Parts         10 (21)         43         Parts         10 (21)         44         Parts         10 (21)         44         Parts         10 (21)         44         Parts	Material	Temp °F (°C)	ء Emmissivity	Material	Temp °F (°C)	ء Emmissivity	Material	Temp °F (°C)	e Emmissivity
Absents         Oracle         Gravel         (10, 18)         23         Af actor         200 (10) $p_{24}$ Center, finite         2302 (12)         64         Sin, Rappin         3210 (12)         64         3210 (12)         64         55         Sin, Rappin         3210 (12)         64         55         Sin, Rappin         550 (12)	Adobe	68 (20)	.90	Granite	70 (21)	.45	Paints, Oil		
Back Context, Ref.         33.00 (1) (1) (2) (2) (2) (2) (2) (2) (2) (2) (2) (2	Asbestos			Gravel	100 (38)	.28	All colors	200 (93)	.9296
Cheme Robit         2550 (1971)         457         Linning         2.(1)         45         Company (1971)         45         Company (1971)         45           Content, White         106 (0.1)         0.0	Board	100 (38)	.96	Ice, Smooth	32 (0)	.97	Black Black	200 (93)	.92
Chemic Mone         2020 (1371)         36         Bask         200 (03)         64         Pression         16 (27)         35           Paper         (100 700 (03)         30         Case, on Bright Cu         200 (03)         66         Pression         70 (12)         55           State         66 (20)         37         Case, on Bright Cu         200 (03)         64         Lamp Back         220 (16)         67           Applat, proper         66 (20)         37         Case, on Firld (2         100 (08)         57         With end A Firld (2         100 (08)         57         With end A Firld (2         100 (08)         57         70         Gass, 1 firm         540 (22)         .00           Back         67 (21)         30         Long Karl (10)         100 (08)         57 (70)         Gass, 1 firm         540 (22)         .00           Gast         77 (21)         30         Long Karl (10) (00) (08)         57 (70)         Gass, 1 firm         540 (22)         .00           Gast         770 (21)         70         Long Karl (10) (00) (08)         55 (20) (20) (20) (20) (20) (20) (20) (20)	Cement Red	32-382 (0-200)	.90	loe, Rough	32 (0)	.80	Campullage Groop	10 (21)	.90
Chen         The birth         The	Coment, Red	2500 (1371)	.07	Black	200 (93)	08	Elat Black	80 (27)	CO. 88
Paper         100.750 (185         Xa         Classe mA H Far (2         200 (18)         BE (20)         Classe mA H Far (2         200 (18)         BE (20)         Classe mA H Far (2         200 (18)         Advalue mathem         TO (11)         Set           Asphalt, tar paper         40 (20)         40         Classe mA H Far (2         100 (13)         61 (74)         Ared         200 (18)         64         Large Black         200 (18)         44         100 (18)         57 (10)         63         65         Classe Large Black         200 (18)         100         100 (18)         75 (10)         100 (18)         100 (18)         75 (18)         100 (18)         100 (18)         100 (18)         100 (18)         100 (18)         100 (18)         100 (18)         <	Cloth	199 (93)	.00	Blue on Al Foil	100 (38)	78	Flat White	80 (27)	91
Auge         Dirac         Dira         Dirac         Dirac         D	Paper	100-700 (38-	93	Clear on Al Foil (2	200 (93)	08(09)	Grav-Green	70 (21)	95
State Applicit parmet         68 (20) (20)         97 (20)         Clear (20)         200 (8) (8)         64 (20)         Clear (20)         100 (20)         20 (20)         100 (20)	, aper	371)		coats)	200 (00)		only oreen	10(21)	
Applat, tar paper         100 (8)         60         Check on Tarlinged         200 (8)         64         Lang Black         200 (8)         64           Asphat, tar paper         66 (20)         Case         100 (3)         51 (74)         Ref         200 (8)         64           Bink         66 (20)         Case         100 (3)         51 (74)         Ref         200 (8)         64           Bink         66 (20)         Case         100 (3)         57 (7)         Gass, 18 mm         100 (22)         60           Gault Cream         (277)-700         24-30         Case         100 (3)         57 (7)         Gass, 18 mm         140 (22)         67           Umb Cay         200 (131)         7.5         Umsetme         100 (3)         56         68 mm         57 (20)         68           Umb Cay         200 (103)         7.5         "Felded Star         100 (3)         76         0assate         77 (20)         68           Start, Legand         1132 (100)         7.5         "Felded Star         100 (3)         75         0assate         100 (3)         76         0assate         100 (3)         68         0assate         100 (3)         85         0astad         66 (2)         77	Slate	68 (20)	.97	Clear, on Bright Cu	200 (93)	.66	Green	200 (93)	.95
Appakt tar paper         68 (20)         0.0         Descent of Apparent of	Asphalt, pavement	100 (38)	.93	Clear, on Tamished	200 (93)	.64	Lamp Black	209 (98)	.96
Aphabit praper         68 (C)         77         Wester, nA Fei (2         100 (3)         61 (74)         Med         200 (63)         64           Bick         77         Wester, on A Fei (2         100 (3)         50 (40)         Witter, Rengh, Fused         70 (21)         50           Bick, rough         70 (21)         63         AFe (2         100 (33)         57 (76)         Giass, 18 mm         540 (22)         90           Bick, rough         1200 (50)         2.5         Lime Mora         100 (30)         60         Giass, 18 mm         1420 (32)         44           Lipht Lift         1200 (50)         2.5         Lime Mora         100 (30)         60         Giass, 68 mm         1420 (32)         47           Lipht Lift         1200 (137)         7         Linestone         100 (33)         75         Giass, 68 mm         1420 (35)         47           Magresh, Refractory         1332 (100)         7.5         Mada         100 (33)         75         Ref Lasid         121 (100)         66 (20)         76           Static Ungitzer         200 (102)         .6         Cods         72 (22)         27         25         Sanditare         66 (20)         76           Static Ungitzer         200				Cu					
Bask         69 (2)         72         Wints Wints (mash)         200 (3)         65         Wints (mash)         Wints (mash)         Wints (mash)         200 (3)         65         Wints (mash)         Wints (mash)         94           Red, rough         70 (21)         03         Marting (mash)         100 (33)         65         Gast         Gast         100 (33)         65         Gast         Gast         100 (33)         64         Gast         100 (33)         64         Gast         100 (33)         64         Gast         100 (33)         64         Gast         63 mm         140 (35)         44           Light fair         100 (33)         75         Gast         Gast         63 mm         140 (35)         47           Type Sock         100 (33)         75         Gast         Gast         83 mm         140 (35)         47           Since, Glass         2000 (100)         75         75         Finder         72 (22)         77         Finder, Sock Gras         160 (30)         76           Gast         Glass         600 fin         72 (22)         77         Finder, Sock Gras         160 (30)         76         76           Gast         Glass         000 200 (427)         64	Asphalt, tar paper	68 (20)	.93	Red, on Al Foil (2	100 (38)	.61 (.74)	Red	200 (93)	.95
Bins         Ot (x)         Part of (x)         Part	Bacalt	80 (20)	70	coats)	200 (02)	05	White	200 (02)	04
Catal         Cost         Chronic Cost         Chroic Cost <thchroic cost<="" th="">         C</thchroic>	Brick	00 (20)	.12	White on Al Foil /2	100 (38)	60 ( 88)	Quartz Rough Eused	200 (83)	03
Red. rough         TO (1)         43         Velow, on Al Fol (2 bank Ordan         100-500 (38)         57 (70)         Glass, 1.8 mm         464 (28)         490           Gault Cream         2500-500         26-53         Lime Mortar         100-500 (38-20)         60-50         Glass, 1.8 mm         1540 (638)         41           Fee Cay         2500 (1311)	Dilok			coats)	100 (00)	.00(.00)	Guardz, Rough, Fuseu	10(21)	.00
Gashi Cram         2005/000         22-53         Lime Motar         100-200 (38-30)         60-52         Gass. 1.88 mm         156 (38)         41           Line Coy         2000 (137)         75         Immetione         100 (38)         86         Gass. 6.88 mm         560 (282)         93           Line Coy         2000 (137)         75         Immetione         100 (38)         86         Gass. 6.88 mm         560 (282)         42           Magests, Fractory         132 (1000)         75         Foldes         222 (100)         64         66 </td <td>Red, rough</td> <td>70 (21)</td> <td>.93</td> <td>Yellow, on Al Foil (2</td> <td>100 (38)</td> <td>.57 (.79)</td> <td>Glass, 1.98 mm</td> <td>540 (282)</td> <td>.90</td>	Red, rough	70 (21)	.93	Yellow, on Al Foil (2	100 (38)	.57 (.79)	Glass, 1.98 mm	540 (282)	.90
Gauli Cream         200-500         28-50         lime Mortar         100-500 (88-30)         60-62         60ass. 1.88 mm         1540 (83)         41           Light Buff         2000 (137)         40         100-103         56         60ass. 6.89 mm         1540 (83)         47           Light Buff         2000 (137)         45         100-103         56         60ass. 6.89 mm         1540 (83)         47           Free Bord         1823 (100)         7.5         100-103         57         60ass. 1.89 mm         1540 (83)         47           Stack, Bufgazed         2000 (103)         46         000 171         77 (21)         48         58         60ass. 1.91 (21)         58         58         58 <td< td=""><td></td><td></td><td></td><td>coats)</td><td></td><td></td><td>-</td><td></td><td></td></td<>				coats)			-		
Free City         (137)-7290 (137)-7290         Transtore         00 (38)         95         Issue, 58 mm         540 (253)         92           Line City         2000 (137)         44         *Snoch, White         100 (38)         95         Opagae         1570 (269)         92           Free fack         1532 (1000)         38         Magnesis, effractory         103 (38)         75         Opagae         1570 (269)         92           Kaske, Glaze         2000 (103)         38         0.002 *         72 (22)         75         Sandstore, Sort, Gray         76 (24)         88           Sinds, Glazed         2000 (103)         80         0.002 *         72 (22)         72         Sandstore, Red         100 (38)         66 (20)         76           Carbornucham         1950 (1010)         92         Thick *         72 (22)         82         Sandstore, Red         100 (38)         66 (20)         78           Alumia on Inconel         800-200 (427)         66-44         On Al Fol, Locata         220 (121)         50         Sandstore, Red         100 (38)         68         66 (20)         78           Carbornucham         1020 (1010)         92         On Al Fol, Locata         220 (121)         50         Sandstore         8	Gault Cream	2500-5000	.2630	Lime Mortar	100-500 (38-260)	.9092	Glass, 1.98 mm	1540 (838)	.41
Pre Lay         200 [127]         1.0         Linkelsce         100 [38]         58 mm         490 [22]         94           Linke Cay         200 [127]         4.5         "Sonce, Wate         100 [38]         50         Opage         154 (133)         68         69         Opage         154 (133)         68         69         Opage         154 (133)         68         69         Opage         154 (133)         68         Opage         74 (23)         94         68         100 (13)         68         Opage         74 (23)         74         63         77         72 (23)         72         Sandstone         100 (13)         66         77         72 (23)         72         Sandstone         100 (13)         66         76         Sandstone         100 (13)         77         Sandstone         100 (13)         66         77         72 (23)         72         Sandstone         100 (13)         76         Sandstone <td< td=""><td></td><td>(1371-2760)</td><td></td><td></td><td>100 (00)</td><td></td><td>~ ~ ~</td><td>540 (000)</td><td></td></td<>		(1371-2760)			100 (00)		~ ~ ~	540 (000)	
Light Edit, 100 (32) 42 Weare, 11(Weare, 100 (33) 42 Partials mm, 120 (33) 43 Partials mm, 120 (33) 44 Partials mm, 120 (34) 44 Partials mm, 120 (	Fire Clay	2500 (1371)	./5	Limestone	100 (38)	.95	Glass, 6.88 mm	540 (282)	.93
Time Brid         152 (100)         175 (30)         *Politable Gray         100 (30)         275         Opagie         140 (853)         455           Gray Brick         2012 (1100)         75         00         Nick         00         77         78         140 (853)         85         01 on Nickel         74         74 (33)         44           Stack, Okard         2000 (1003)         86         000 fm         72 (22)         24         Rubber, Soft, Gray         74 (33)         44           Stack, Okard         2000 (1003)         86         000 f*         72 (22)         24         Stadber, Soft, Gray         74 (33)         44           Carbornuchum         1850 (1010)         62         100 (1100)         72         172         372         Sandstone         100 (38)         66 (20)         56           Carbornuchum         1850 (1010)         64         100 (1100)         100 (1100)         100 (1100)         100 (1100)         58         Sandstone         100 (138)         68 (20)         56           Carbornuchum         1800 (200) (427         00-4         100 (38)         45         Sinc Carbornuchum         100 (38)         22         Sinc Carbornuchum         100 (38)         53         Sinc Carbornuchum	Light Buff	2500 (1271)	.80	"Smooth White	100 (38)	.90	Glass, 0.88 mm	1040 (838)	.4/
Magnesis, Refractory         1832 (100)         1.02 33         Moa         mon         100 (38)         75         Ref Land         1272 (100)         303           Sinz, Glazed         2000 (1003)         8         0.001 Film         72 (2)         46         Sandime         74 (23)         94           Sinz, Marked         2000 (1003)         8         0.002 -         72 (22)         46         Sandime         100 (88)         67           Carboundum         1680 (1010)         2         Tink -         72 (22)         42         Sandstone, Field         100 (88)         68 (20)         75           Carboundum         1680 (1010)         42         Tink -         72 (22)         42         Sandstone, Field         100 (88)         60.08           Carboundum         1680 (1010)         42         Tink -         70 (21)         00         64         6A / Fol, uncotated         250 (121)         56         Sinca, Ungazed         2012 (1100)         85           Eartherware, Marke         70 (21)         30         6A / Fol, zootts         250 (121)         51         Sinca, Ungazed         2012 (1100)         85           Coating No. C20A         200-750 (36)         73-67         Folin         Fol, Zootta         300-1	Eine Brick	1932 (1000)	75,90	" Polisbod Gray	100 (38)	.50	Opaque	1540 (238)	.82
Cirry Biol.         Di 2 (110)         T         Oli on Nickel         Tal. (k)         Pabber, Hard         T 4 (23)         Bub           Silas, Glazed         2000 (1093)         80         0.002 *         72 (22)         27         Sandstone         100 (8)         80           Silas, Glazed         2000 (1093)         80         0.002 *         72 (22)         72         Sandstone         100 (8)         66 (20)         76           Carbornutum         1890 (1010)         42         Tick *         72 (22)         32         Sandstone         100 (8)         68 (20)         76           Carbornutum         1990 (1010)         42         Tick *         72 (22)         32         Sandstone, Red         100 (8)         68 (20)         76           Alumia on Inconel         600 -2000 (427.         69 -69         For (1010)         100 (8)         42         Sinca (Lingat 168 (20)         68           Cartension, S210-20         200.770 (73         68 -62         For (1010)         100 (8)         45         Sinca (Lingat 168 (20)         78           Forension, S210-20         200 (69)         73 - 77         For Polished Iron, 001         100 (3)         45         Sinca (Lingat 168 (20)         78           Coraing No. C20A <td>Magnesite Refractory</td> <td>1832 (1000)</td> <td>.7000</td> <td>Mica</td> <td>100 (38)</td> <td>75</td> <td>Red Lead</td> <td>212 (100)</td> <td>.00</td>	Magnesite Refractory	1832 (1000)	.7000	Mica	100 (38)	75	Red Lead	212 (100)	.00
Sind, Glassed         2000 (103)         36         0.001 Film         72 (22)         44         Ruber, Soft, Gray         77 (24)         86           Sandime         2003 (101)         40         0.002 *         72 (22)         44         Sand store         100 (08)         66 (20)         76           Cataconolum         1060 (1010)         42         0.005 *         72 (22)         44         Sandstore. Red         100 (08)         60.005         76           Alumina on locorel         800-2000 (427, -         64-45         0.01 Film         72 (22)         44         Sandstore. Red         100 (08)         68 (20)         69           Eartherware, Glassed         10 (21)         60         0.01 Fold, 1 coat         220 (121)         56         Sinca, Glassed         1832 (1000)         85         86         200 (21 (100)         85         Sinca, Glassed         1832 (1000)         85         Sinca, Glassed         1832 (1000)         85         Sinca, Glassed         1832 (1000)         85         Sinca, Glassed         182 (1000)         86	Grav Brick	2012 (1100)	.75	Oil on Nickel			Rubber, Hard	74 (23)	.94
Siles, Updazed sandime         2000, (109) (127), 2700)	Silica, Glazed	2000 (1093)	.88	0.001 Film	72 (22)	.27	Rubber, Soft, Gray	76 (24)	.86
Sandime         2400-5000         49-63         0.005 *         72 (22)         72         Sandstore         100 (8)         .67           Cataronnium         1690 (1010)         .02         Thick *         72 (22)         .82         Sandstore Red         100 (8)         68 (20)         69         75           Alumina on Inconel         800-2000 (427, 103)         .00         Alumina on Inconel         100 (10)         .00         Alumina on Inconel         800-2000 (427, 103)         .00         Alumina on Inconel         100 (10)         .00         .00 (10) (30)         .22         Since Catala         .00 (10) (30)         .23         Since Catala         .00 (30)         .00         .00 (30)         .25         Since Catala         .00 (30)         .27.85         .20 (10) (40)         .78         .20 (10) (40)         .78         .20 (10) (40)         .78         .20 (10) (40)         .20 (10) (40)         .20 (10)	Silica, Unglazed	2000 (1093)	.80	0.002 *	72 (22)	.46	Sand	68 (20)	.76
Cathorndum         (1371-2780) Ceramic         Thick         Total         72 (22)         82 standard         Sandatore         Red         100 (36) (100 (36)         06-85 (120)           Aumma on Incorel         800-2000 (427- 100 (36)         69-45         Oil Linesed         250 (121)         00         Silica, Glazed         1832 (100)         66           Eartherware, Glazed         70 (21)         80         On A Foi L coats         250 (121)         56         Silica, Glazed         1832 (100)         77           Greens, No. 52 (10-2C         200-750 (83- 309)         73-87         On Poilshed Iron, 001         100 (38)         45         Silica, Glazed         100 (38)         201 (110)         76           Coating No. 620A         200-750 (83- 309)         73-87         On Poilshed Iron, 004         100 (38)         45         Silica, Clazed         100 (38)         66 (20)         78           Porcelain         72 (22)         92         On Poilshed Iron, 004         100 (38)         85         Sone, Fine Particles         20 (-7)         82           Ziroonia on Incorel         800-2000 (427- 57         62-46         Partis         Sond         Sone, Granular         18 (-8)         86           Clay         61 (20)         30         75 (24) <t< td=""><td>Sandlime</td><td>2500-5000</td><td>.5963</td><td>0.005 *</td><td>72 (22)</td><td>.72</td><td>Sandstone</td><td>100 (38)</td><td>.67</td></t<>	Sandlime	2500-5000	.5963	0.005 *	72 (22)	.72	Sandstone	100 (38)	.67
Carbondum         1850 (1010)         192         Tinck         72 (22)         28         Sandstöre, Hed         100 (38)         60-83         75           Alumina on Inconel         800-2000 (477.         69-46         On A Foi, 1 coat         250 (121)         50         Sandstöre, Hed         58 (120)         75           Earthenware, Matte         70 (21)         90         On A Foi, 1 coat         250 (121)         56         Silica, Unglased         2012 (1100)         75           Forens No. 510-2         200-750 (38.         89-82         For Polished Iron, 002         100 (38)         45         Silica, Unglased         2012 (1100)         75           Coating No. C20A         200-750 (38.         73-67         On Polished Iron, 002         100 (38)         85         Silac         100 (38)         66 (20)         78           Porcelain         72 (22)         92         For Polished Iron, 004         100 (38)         83         Sonow, Fine Particles         20 (-7)         82           Ziroonia on Inconel         800-2000 (427.         62-45         Fairs         Sonow, Granular         18 (-8)         88           Clay         68 (20)         38         Black, Cu2O3         75 (24)         94         Soit         Soit         100 (3		(1371-2760)							
Ortenting         B00-2000 (427- 1063)         On A Foil, Incoated 1063)         Control 250 (121)         Op Silica, Glazed         Solication (121)         Solicatio	Carborundum	1850 (1010)	.92	Thick " Oil Lincord	72 (22)	.82	Sandstone, Red	100 (38)	.6083
Calina of income         Concerved (no.)         Concerved	Alumina on Inconel	900-2000 (427-	80.45	On Al Foil upcosted	250 (121)	00	Shale	68 (20)	.75
Eartherware, Glazed         T0 (21)         90         On Al Fol. 1 coat         250 (121)         56         Slica, Glazed         1832 (1000)         85           Greens No. 5210-2C         200 750 (83- 989)         88-82         On Al Fol. 1 coats         250 (121)         56         Slica, Glazed         2012 (1100)         75           Coating No. C20A         200 750 (83- 989)         75- 70         On Ploited Iron, .002         100 (38)         .45         Sit Clefh         68 (20)         .76           Porcelain         72 (22)         .92         Controlished Iron, .004         100 (38)         .65         State         100 (38)         .67 × 80           Zironia on Inconel         800-2000 (427- 1083)         .62 × 75         .76 × 75 (24)         .98         Sold         .78 × 75 (24)         .78 × 75	Aldmina on inconer	1093)	.0840	on Arroli, uncoaled	200 (121)	.00	onale	00 (20)	.00
Earthenware, Matter 70 (21) 93 On Al Fol, 2 coats 250 (121) 51 Silica, Unglaxed 2012 (1100) 76 Greens No. 5210-2C 20750 (93 77.6 7 Greens No. 5210 (140-649) 83.496 Film 12 (22) 9.2 On Polished Iron, 002 100 (18) 45 Silate 100 (18) d5 Silate 100 (18)	Earthenware, Glazed	70 (21)	.90	On Al Foil, 1 coat	250 (121)	.56	Silica.Glazed	1832 (1000)	.85
Greens No. 5210-2C         200-750 (83- 399)         38-8.2 (81)         On Polished Iron, .001         100 (38)         22         Silicon Carbide         300-1200 (140-049)         .83-80           Coasing No. C20A         200-750 (83- 3390)         73-67         On Polished Iron, .002         100 (38)         .45         Silk Cloth         66 (20)         .77           Porcelain         72 (22)         92         On Polished Iron, .004         100 (38)         .65         Slate         100 (38)         .6780           White AL203         200 (43)         90         Porlished Iron, .004         100 (38)         .83         Snow, Fine Particles         20 (-7)         .82           Zironia on Inconel         800-2000 (427- .02,45         .62         .76         .44         .50         .77         .82           Clay         6 8(20)         .39         Blue, CuO3         75 (24)         .94         Surface         .100 (38)         .88           * Fired         158 (70)         .91         Black Loc3         .75 (24)         .94         Sort         .77           * Tiles, Light Red         (20)600         .78         White, A2O3         .75 (24)         .90         Acetylene         .75 (24)         .97           Conorete	Earthenware, Matte	70 (21)	.93	On Al Foil, 2 coats	250 (121)	.51	Silica, Unglazed	2012 (1100)	.75
389 Doating No. C20A         399 389 389 Second Porcelain         Film 0n Polished Iron, 002 Second 389 On Polished Iron, 004         100 (38) (38)         45 Second 880         Sik Cloth         68 (20)         75 Second 880           White Al2O3         200 (83)         40         On Polished Iron, 004         100 (38)         65         State         100 (38)         .67 - 80           Zirconia on Incorel         800-2000 (427 - 57 et al)         .62 - 45         Paints         Snow, Fine Particles         20 (-7)         .82           Zirconia on Incorel         800-2000 (427 - 68 (20)         .62 - 45         Paints         Snow, Granular         18 (-8)         .89           Clay         68 (20)         .39         Black, CuO         75 (24)         .44         Soil         "Fired         18 (-8)         .89           Clay         68 (20)         .32         .88         .64 (20)         .38         Green, Cu2O3         .75 (24)         .81         Soot         .81           "Tiles, Light Red         (1371 - 2700)         .82         Red, Fa2O3         .75 (24)         .80         Camplor         .75 (24)         .97           Concret         (1371 - 2700)         .78         White, MgCO3         .75 (24)         .90         Coale         .68 (20)         .8	Greens No. 5210-2C	200-750 (93-	.8982	On Polished Iron, .001	100 (38)	.22	Silicon Carbide	300-1200 (149-649)	.8396
Coating No. C20A         200-56 (82- 396)         .73-67         On Polished Iron, .002         100 (38)         .45         Site Cloth         68 (20)         .78           Porcelain         72 (22)         .92         On Polished Iron, .004         100 (38)         .65         State         100 (38)         .67-80           White A2O3         200 (83)         .00         On Polished Iron, .004         100 (38)         .83         Snow, Fine Particles         20 (-7)         .82           Zirconia on Inconel         800-200 (427.         .62-45         Paints         Soil         Snow, Granular         18 (-8)         .89           "Fred         158 (70)         .01         Black CuO         75 (24)         .94         Soil         Soil         Snow, Granular         18 (-8)         .89           "Fied         158 (70)         .01         Black CuO         75 (24)         .94         Soil		399)		Film					
Descelain         399         Prim           0rr Poished Iron, .004         100 (38)         .65         State         100 (38)         .6780           White Al2O3         200 (83)         .00         .6245         Fains         Snow, Fine Particles         20 (-7)         .82           Zirconia on Inconel         800-2000 (427         .6245         Pains         Snow, Granular         18 (-8)         .89           Clay         68 (20)         .39         Blue, Cu2O3         75 (24)         .94         Sol         Sol         Surface         100 (38)         .38           * Fired         18 (70)         .32         .44         Red, Fe2O3         75 (24)         .94         Sol         .38           * Tiles, Light Red         2500-500         .78         White, AIO3         75 (24)         .94         Soot         .38           * Tiles, Dark Purple         2500-500         .78         White, 270         75 (24)         .94         Soot         .36           Rough         32-2000 (0-         .94         White, 2702         .75 (24)         .90         Candie         250 (121)         .95           Tiles, Natural         2500-5000         .8783         White, TO2         .75 (24)	Coating No. C20A	200-750 (93-	.7367	On Polished Iron, .002	100 (38)	.45	Silk Cloth	68 (20)	.78
Proteenin         Table (22)         Back         This information (n, dot*)         Totol (36)         3.01         State         Totol (36)         3.01           White AZO3         200 (63)         90         0	Percelain	388) 72 (22)	02	Co Reliched Ison 004	100 (29)	85	Clata	100 (28)	87.00
White AI2O3         200 (83)         00         On Polished Iron, Tick Film         100 (38)         .83         Snow, Fine Particles         20 (-7)         .82           Zirconia on Inconel         800-2000 (427- 1083)         .62-46         Paints         Snow, Granular         18 (-8)         .89           Clay         68 (20)         .39         Blue, Cu203         75 (24)         .44         Soil         -         -         -         -         -         .89           Clay         68 (20)         .30         .66         .67 (24)         .44         Soil         -         -         .81 (20)         .66 (20)         .66         .68 (20)         .68 (20)         .68         .68 (20)         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .68 (20)         .68         .69         .68 (20)         .68         .69         .68 (20)         .68         .69         .68 (20)         .68         .69         .69         .68 (20)         .68         .69         .69         .69	Forcelain	12 (22)	.82	Film	100 (30)	.05	Siate	100 (38)	.0700
Thick Film         Thick Film         Thick Film         Thick Film         Source of the second	White Al2O3	200 (93)	.90	On Polished Iron.	100 (38)	.83	Snow, Fine Particles	20 (-7)	.82
Zirconia on Inconell         800-2000 (427- 108) (130)         62-45         Paints         Snow, Granular         18 (-8)         .89           Clay         68 (20)         .39         Blue, Cu2O3         75 (24)         .94         Soil         *           "Fired         158 (70)         .91         Black, CuO         75 (24)         .92         Surface         100 (33)         .38           "Shale         68 (20)         .68         Green, Cu2O3         75 (24)         .92         Black Loam         68 (20)         .68           "Tiles, Red         2500-5000         .40-51         White, AI2O3         75 (24)         .94         Soot         *           "Tiles, Dark Purple         2500-5000         .78         White, Y2O3         75 (24)         .94         Soot         *         .97           Concrete         *         White, Y2O3         .75 (24)         .94         Soot         .96 (20)         .95           "Brown         2500-5000         .63-62         White, MgCO3         .75 (24)         .91         Canle         250 (21)         .95           "Brown         2500-5000         .87-83         White, ThO2         .75 (24)         .90         Sonework         100 (38)         .67				Thick Film			-		
1093         1093         Blue, Cu203         75 (24)         94         Soil           - Fired         158 (70)         91         Black, CuO         75 (24)         96         Surface         100 (38)         .38           - Shale         68 (20)         .69         Green, Cu203         75 (24)         .92         Black, Loam         68 (20)         .68           - Tiles, Light Red         .2500-5000         .32 .34         Red, Fe2O3         .75 (24)         .91         Plowed Field         .68 (20)         .38           - Tiles, Red         .2500-5000         .40 .51         White, Al2O3         .75 (24)         .94         Soot	Zirconia on Inconel	800-2000 (427-	.6245	Paints			Snow, Granular	18 (-8)	.89
Clay         68 (20)         .39         Blue, Cu203         75 (24)         .94         Soil           * Fried         158 (70)         .91         Black, Cu0         75 (24)         .92         Black Loam         68 (20)         .66           * Thes, Light Red         2500-5000         .32-34         Red, Fe2O3         75 (24)         .91         Plowed Field         68 (20)         .86           * Tiles, Light Red         2500-5000         .40-55         White, AI2O3         75 (24)         .94         Soot           * Tiles, Dark Purple         2500-5000         .78         White, Y2O3         75 (24)         .90         Acetylene         75 (24)         .91           Concrete         (1371-2760)         White, M2O3         75 (24)         .91         Camphor         75 (24)         .94           Rough         32-2000 (0.         .63-62         White, M2O3         75 (24)         .91         Cambhor         75 (24)         .91           Tiles, Natural         2500-5000         .63-62         White, M2O2         75 (24)         .91         Cambhor         100 (38)         .93           * Brown         (1371-2760)         White, M2O2         75 (24)         .90         Stonework         100 (38)		1093)							
Price         18 (10)          Black, CuU         75 (24)          Black, Loam         (10) (35)	Clay	68 (20)	.39	Blue, Cu2O3	75 (24)	.94	Soil	100 (20)	
* Tiles, Light Red         2500-5000         .32.34         Red, Fe2O3         75 (24)         .91         Data Learnin         05 (20)         .33           * Tiles, Red         2500-5000         .40-51         White, Al2O3         75 (24)         .91         Plowed Field         68 (20)         .38           * Tiles, Red         2500-5000         .40-51         White, Al2O3         75 (24)         .94         Soot	- Shale	108 (70)	.91	Green Cu2O3	75 (24)	.90	Surface Black Learn	100 (38)	.35
Tiles, Red         2500-5000         .40-51         White, Al2O3         75 (24)         .94         Soot           "Tiles, Dark Purple         2500-5000         .40-51         White, Al2O3         75 (24)         .94         Soot           "Tiles, Dark Purple         2500-5000         .78         White, Y2O3         75 (24)         .90         Acetylene         75 (24)         .97           Concrete         (1371-2760)         White, ZnO         75 (24)         .95         Camphor         75 (24)         .94           Rough         32-2000 (0-         .94         White, MgCO3         75 (24)         .95         Calle         250 (121)         .95           Tiles, Natural         2500-5000         .6362         White, ZrO2         75 (24)         .90         Stonework         100 (38)         .93           "Black         2500-5000         .8783         White, MgO         75 (24)         .90         Stonework         100 (38)         .67           Conto Cloth         68 (20)         .77         White, PbCO3         75 (24)         .90         Water         100 (38)         .67           Gass         Corrundum         176 (80)         .80         26% Al         100 (38)         .27         Oak, Plane	* Tiles Light Red	2500-5000	32, 34	Red Fe2O3	75 (24)	01	Plowed Field	68 (20)	38
* Tiles, Red       2500-5000       .40-51       White, Al2O3       75 (24)       .94       Soot         * Tiles, Dark Purple       2500-5000       .78       White, Y2O3       75 (24)       .90       Acetylene       75 (24)       .97         Concrete       (1371-2780)       White, X2O3       75 (24)       .90       Acetylene       75 (24)       .94         Rough       32-2000 (0-       .94       White, MgCO3       75 (24)       .91       Candle       250 (121)       .95         Tiles, Natural       2500-5000       .8362       White, TrO2       .75 (24)       .90       Stonework       100 (38)       .93         * Brown       2500-5000       .8783       White, MgO       .75 (24)       .90       Stonework       100 (38)       .93         * Black       2500-5000       .9491       White, MgO       .75 (24)       .91       Waterglass       .86 (20)       .96         Controloth       .68 (20)       .77       White, MgO       .75 (24)       .93       Waterglass       .86 (20)       .96         Dolomite Lime       .68 (20)       .71       Yellow, PbCrO3       .75 (24)       .93       Waterglass       .86 (20)       .96         Convex D	nies, Eight Neo	(1371-2760)	.02.004	1100,10200	10 (24)		r lowed field	00 (20)	
"Tiles, Dark Purple       2500-5000       .78       White, Y2O3       75 (24)       .90       Acetylene       75 (24)       .97         Concrete       "Mite, ZnO       75 (24)       .95       Camphor       75 (24)       .94         Rough       32-2000 (0-       .94       White, MgCO3       75 (24)       .91       Canele       250 (121)       .95         Tiles, Natural       2500-5000       .63-62       White, ZrO2       75 (24)       .91       Coale       68 (20)       .95         "Brown       2500-5000       .87-83       White, MgCO3       75 (24)       .90       Stonework       100 (38)       .93         "Black       2500-5000       .87-83       White, PbCO3       75 (24)       .90       Water       100 (38)       .67         Conto Cloth       68 (20)       .77       White, PbCO3       75 (24)       .90       Water       100 (38)       .67         Conto Cloth       68 (20)       .71       White, PbCO3       75 (24)       .90       Water       .90       .90         Emery Corundum       176 (80)       .86       Yellow, PbC rO4       .75 (24)       .93       Waterglass       68 (20)       .94         Gaiss       "Paints, Alum	" Tiles, Red	2500-5000	.4051	White, Al2O3	75 (24)	.94	Soot		
* Tiles, Dark Purple         2500-5000         .78         White, Y203         76 (24)         .90         Acetylene         75 (24)         .97           Concrete         White, ZnO         75 (24)         .95         Camphor         75 (24)         .94           Rough         32-2000 (0- 1093)         .94         White, MgCO3         75 (24)         .91         Camphor         75 (24)         .94           Tiles, Natural         2500-5000         .63-62         White, ZrO2         75 (24)         .95         Coal         Coal         88 (20)         .95           * Brown         2500-5000         .8783         White, ThO2         75 (24)         .90         Stonework         100 (38)         .93           * Black         2500-5000         .9491         White, MgO         75 (24)         .90         Water         100 (38)         .67           Cotton Cloth         68 (20)         .77         White, PbCO3         75 (24)         .90         Water         100 (38)         .67           Convex D         812 (010)         .80         Yellow, PbCO4         75 (24)         .90         Water         100 (38)         .67           Convex D         610 (316)         .80         20* Al         100	-	(1371-2760)							
Concrete Rough         (1371-2780)         White, ZnO         75 (24)         .95         Camphor         75 (24)         .94           Rough         32-2000 (0- 1093)         .94         White, MgCO3         75 (24)         .91         Candle         2500 (121)         .95           Tiles, Natural         2500-5000         .6362         White, ZrO2         75 (24)         .95         Coal         68 (20)         .85           * Brown         2500-5000         .8783         White, ThO2         75 (24)         .90         Stonework         100 (38)         .83           (1371-2760)         (1371-2760)         White, MgO         75 (24)         .91         Water         100 (38)         .67           (1371-2760)         (1371-2760)         White, MgO         75 (24)         .91         Water         100 (38)         .67           (1371-2760)         White, PbCO3         75 (24)         .90         Wood         Low .806-80           Cotton Cloth         68 (20)         .77         White, PbCO3         75 (24)         .90         Wood         Low .806-80           Emery Corundum         176 (80)         .88         Yellow, PbCO4         75 (24)         .90         Wood         Low .806-80	* Tiles, Dark Purple	2500-5000	.78	White, Y2O3	75 (24)	.90	Acetylene	75 (24)	.97
Concrete         White, ZhO         75 (24)         .96         Campnor         75 (24)         .94           Rough         32-2000 (0-         .94         White, MgCO3         75 (24)         .91         Campnor         250 (121)         .95           Tiles, Natural         2500-5000         .6362         White, ZrO2         75 (24)         .95         Coal         68 (20)         .95           "Brown         2500-5000         .8783         White, ThO2         75 (24)         .90         Stonework         100 (38)         .93           "Black         2500-5000         .9491         White, MgO         75 (24)         .90         Water         100 (38)         .67           Conto Cloth         68 (20)         .41         White, MgO         75 (24)         .90         Water descents         .68 (20)         .66           Dolomite Lime         68 (20)         .41         Yellow, PbO         75 (24)         .90         Waterglass         68 (20)         .66           Conto Cloth         68 (20)         .41         Yellow, PbCrO4         .75 (24)         .90         Waterglass         .68 (20)         .66           Convex D         212 (100)         .80         28' Al         .100 (38) <t< td=""><td>Connector</td><td>(1371-2760)</td><td></td><td>What 7-0</td><td>75 (04)</td><td></td><td>Complexe</td><td>75 (04)</td><td></td></t<>	Connector	(1371-2760)		What 7-0	75 (04)		Complexe	75 (04)	
Rough         32-200 (10- 1083)         arr         Write, MgCOS         15 (24)         arr         Calible         250 (121)         arr           Tiles, Natural         2500-5000         .63-62         White, TO2         75 (24)         .95         Coal         68 (20)         .85           "Brown         2500-5000         .87-83         White, ThO2         75 (24)         .90         Stonework         100 (38)         .93           "Black         2500-5000         .94-91         White, MgO         75 (24)         .90         Water         100 (38)         .67           Cotton Cloth         68 (20)         .77         White, PbCO3         75 (24)         .91         Water         100 (38)         .67           Dolomite Lime         68 (20)         .71         White, PbCO3         75 (24)         .90         Water         100 (38)         .67           Glass	Concrete	22,2000,0	04	White, ZhO	70 (24)	.90	Campnor	75 (24)	.94
Tiles, Natural         2500-5000         .6362         White, ZrO2         75 (24)         .95         Coal         68 (20)         .95           * Brown         2500-5000         .8783         White, ThO2         75 (24)         .90         Stonework         100 (38)         .93           * Black         2500-5000         .9491         White, MgO         75 (24)         .91         Water         100 (38)         .67           (1371-2760)         (1371-2760)         White, MgO         75 (24)         .91         Water         100 (38)         .67           (1371-2760)         (1371-2760)         White, MgO         75 (24)         .91         Water         100 (38)         .67           Cotton Cloth         68 (20)         .41         Yellow, PbO 75 (24)         .93         Waterglass         68 (20)         .96           Emery Corundum         176 (80)         .88         Yellow, PbC 74         .75 (24)         .90         Wood         Low 38090         .94           Glass         10% Al         100 (38)         .2767         Oak, Planed         158 (70)         .94           Convex D         202 (500)         .78         Dow XP-310         200 (93)         .22         Spruce, Sanded	Rough	32-2000 (0-	.84	white, MgCO3	75 (24)	.91	Candle	200 (121)	.80
(1371-2780)         International (138)         International (138) <thinternational (138)<="" th="">         International</thinternational>	Tiles, Natural	2500-5000	.6362	White, ZrO2	75 (24)	.95	Coal	68 (20)	.95
* Brown         2260-5000         .8783         White, ThO2         75 (24)         .90         Stonework         100 (38)         .93           * Black         2500-5000         .9491         White, MgO         75 (24)         .91         Water         100 (38)         .67           Cotton Cloth         68 (20)         .77         White, PbCO3         75 (24)         .91         Water         100 (38)         .67           Dolomite Lime         68 (20)         .77         White, PbCO3         75 (24)         .90         Water         100 (38)         .67           Cotton Cloth         68 (20)         .41         Yellow, PbCrO4         75 (24)         .90         Wood         Low         .8090           Emery Corundum         176 (80)         .86         Yellow, PbCrO4         75 (24)         .93         Beech Planed         158 (70)         .94           Convex D         212 (100)         .80         Paints, Aluminium         100 (38)         .27-87         Oak, Planed         100 (38)         .91           Convex D         932 (500)         .76         Dow XP-310         200 (93)         .22         Nonex         000 (316)         .82         Gum Varish (3 coats)         70 (21)         .53      <		(1371-2760)			()				
(1371-2780)         White, MgO         75 (24)         .91         Water         100 (38)         .67           Cotton Cloth         68 (20)         .77         White, MgO         75 (24)         .93         Water         100 (38)         .67           Dolomite Lime         68 (20)         .41         Yellow, PbO         75 (24)         .93         Waterglass         68 (20)         .96           Emery Corundum         176 (80)         .86         Yellow, PbO 75 (24)         .93         Beech Planed         158 (70)         .94           Convex D         212 (100)         .80         10% AI         100 (38)         .27-67         Oak, Planed         100 (38)         .91           Convex D         803 (500)         .76         Dow XP-310         200 (93)         .22         Spruce, Sanded         100 (38)         .89           Convex D         932 (500)         .78         Gum Varnish (2 coats)         70 (21)         .53           Nonex         932 (500)         .78         Gum Varnish (3 coats)         70 (21)         .34           Nonex         932 (500)         .78         Gum Varnish (3 coats)         70 (21)         .34           Nonex         932 (500)         .78         Gum Varnish (3 coats) <td>" Brown</td> <td>2500-5000</td> <td>.8783</td> <td>White, ThO2</td> <td>75 (24)</td> <td>.90</td> <td>Stonework</td> <td>100 (38)</td> <td>.93</td>	" Brown	2500-5000	.8783	White, ThO2	75 (24)	.90	Stonework	100 (38)	.93
* Black         2500-5000 (1371-2760)         9491         White, MgO         75 (24)         .91         Water         100 (38)         .67           Cotton Cloth         68 (20)         .77         White, PbCO3         75 (24)         .93         Water         100 (38)         .67           Dolomite Lime         68 (20)         .41         Yellow, PbC O         75 (24)         .90         Wood         Low         .8090           Emery Corundum         176 (80)         .86         Yellow, PbC C04         75 (24)         .90         Wood         Low         .8090           Glass         0         Yellow, PbC C04         75 (24)         .93         Beech Planed         158 (70)         .94           Glass         0         100 (38)         .2767         Oak, Planed         100 (38)         .91           Convex D         600 (316)         .80         26% AI         100 (38)         .52         Spruce, Sanded         100 (38)         .89           Convex D         932 (500)         .76         Dow XP-310         200 (93)         .22         Nonex         212 (100)         .82         Paints, Bronze         Low         .3480         Nonex         .932 (500)         .78         Gum Varnish (2 coats)		(1371-2760)							
Cotton Cloth         68 (20)         77         White, PbCO3         75 (24)         93         Waterglass         68 (20)         .66           Dolomite Lime         68 (20)         .41         Yellow, PbC         75 (24)         .90         Wood         Low         .8090           Emery Corundum         176 (80)         .86         Yellow, PbCrO4         75 (24)         .93         Beech Planed         158 (70)         .94           Convex D         212 (100)         .80         100 (38)         .2767         Oak, Planed         100 (38)         .91           Convex D         600 (316)         .80         28% Al         100 (38)         .52         Spruce, Sanded         100 (38)         .89           Convex D         932 (500)         .76         Dow XP-310         200 (93)         .22          Nonex         212 (100)         .82         Gum Varnish (2 coats)         70 (21)         .53          Smooth         .32-200 (0-93)         .9294         Cellulose Binder (2         70 (21)         .34          Cellulose Binder (2         .04         .44         .44         .44         .44         .44         .44         .44         .44         .44         .44         .44         .44	" Black	2500-5000	.9491	White, MgO	75 (24)	.91	Water	100 (38)	.67
Controlloin         08 (20)         .17         Write, PBCOS         75 (24)         .85         Waterglass         06 (20)         .80	Catter Clath	(13/1-2/00)	77	White Phoop	75 (24)	02	Waterelace	89 (20)	08
Docume Line         Total (2)         Tri (allor, 10 / 10 / 10 / 10 / 10 / 10 / 10 / 10	Dolomite Lime	68 (20)	41	Vellow PbO	75 (24)	.83	Wood	00 (20)	80-90
Glass         Definition         100 (38)         .2767         Oak, Planed         100 (38)         .91           Convex D         212 (100)         .80         105 Al         100 (38)         .52         Spruce, Sanded         100 (38)         .89           Convex D         600 (316)         .80         26% Al         100 (38)         .30         .00         .89         .89           Convex D         932 (500)         .76         Dow XP-310         200 (93)         .22         .80         .89           Nonex         212 (100)         .82         Paints, Bronze         Low         .3480         .40         .80         .89           Nonex         600 (316)         .82         Gum Varnish (2 coats)         .70 (21)         .53         .53         .53         .53         .53         .53         .53         .53         .53         .54         .55         .53         .53         .54         .55         .55         .53         .55         .53         .54         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .55         .5	Emery Corundum	176 (80)	.86	Yellow, PbCrO4	75 (24)	.93	Beech Planed	158 (70)	.00 .00
Convex D         212 (100)         .80         10% AI         100 (38)         .52         Spruce, Sanded         100 (38)         .89           Convex D         600 (316)         .80         26% AI         100 (38)         .30         .30           Convex D         932 (500)         .76         Dow XP-310         200 (93)         .22	Glass			Paints, Aluminium	100 (38)	.2767	Oak, Planed	100 (38)	.91
Convex D         600 (316)         .80         26% AI         100 (38)         .30           Convex D         932 (500)         .76         Dow XP-310         200 (93)         .22           Nonex         212 (100)         .82         Paints, Bronze         Low         .3480           Nonex         600 (316)         .82         Gum Varnish (2 coats)         70 (21)         .53           Nonex         932 (500)         .78         Gum Varnish (3 coats)         70 (21)         .50           Smooth         32-200 (0-93)         .9294         Cellulose Binder (2         70 (21)         .34	Convex D	212 (100)	.80	10% AI	100 (38)	.52	Spruce, Sanded	100 (38)	.89
Convex D         932 (500)         .76         Dow XP-310         200 (93)         .22           Nonex         212 (100)         .82         Paints, Bronze         Low         .3480           Nonex         600 (316)         .82         Gum Varnish (2 coats)         70 (21)         .53           Nonex         932 (500)         .78         Gum Varnish (2 coats)         70 (21)         .50           Smooth         32-200 (0-93)         .9294         Cellulose Binder (2         70 (21)         .34	Convex D	600 (316)	.80	26% AI	100 (38)	.30			
Nonex         212 (100)         .82         Paints, Bronze         Low         .3480           Nonex         600 (316)         .82         Gum Varnish (2 coats)         70 (21)         .53           Nonex         932 (500)         .78         Gum Varnish (3 coats)         70 (21)         .50           Smooth         32-200 (0-93)         .9294         Cellulose Binder (2         .70 (21)         .34	Convex D	932 (500)	.76	Dow XP-310	200 (93)	.22			
Nonex         932 (500)         .78         Gun Varnish (2 coals)         70 (21)         .53           Smooth         32-200 (0-93)         .9294         Cellulos Einder (2 70 (21))         .34	Nonex	212 (100)	.82	Paints, Bronze	Low 70 (24)	.3480			
Smooth         32-200 (0-93)         .9294         Cellulose Binder (2 coats)         70 (21)         .34	Nonex	000 (310)	.62	Gum Varnish (2 coats)	70 (21)	.03			
coats)	Smooth	32-200 (0-93)	.9294	Cellulose Binder (2	70 (21)	.34			
				coats)					

However, these values are not always useful when dealing with an IR system for two main reasons:

- The table does not contain any information about the direction and the wavelength that the emissivity refers to.
- State of the viewed surface: tables presented in literature include terms like polished, cast, rolled, oxidized, heavily oxidized etc., and emissivity values range inside very large intervals; such values cannot thus be used to get accurate temperature measurements.

A better way is to directly measure the emissivity with the same IR camera. The procedure involves simply in comparing the radiation emitted by the sample material and that emitted by a blackbody at the same temperature. Almost every IR thermographic system is equipped with software for emissivity calculations.

When considering the calibration of numerical models, the infrared cameras present some advantages compared to the use of thermocouples. This equipment, in fact, provides full field measurement of the temperatures, while thermocouples provide punctual measurements. If the problem involves a significant gradient of temperatures (an example is described in the Paragraph 3.1.1), a large number of thermocouples would be necessary to evaluate the system, whereas only one IR camera would be









required to provide all the necessary measurements. A drawback is the limitation of measuring temperatures inside the linings and between the layers, so in such cases, thermocouples are more suitable.

A second parameter to consider when using the IR camera is the environment or more specifically the specific transmissivity of the path made by the radiation. The atmosphere, for example, has three transmission windows in the infrared (near, medium, far) and it is in these wavelength bands that the detectors are optimized. It must also be considered that certain components of the atmosphere, such as water vapour and carbon dioxide, absorb infrared radiation at a certain wavelength and cause transmission losses.

### 2.3. Laser scanner

The laser scanner technique does not allow the direct measurement of temperature, this is evaluated using a pyrometric channel. This channel measures the heat radiation of the material at different hot spots. The laser scanner equipment was invented to measure the distance between the laser source and the "target" by sending an infrared laser pulse from outside the ladle to the wall and the bottom (Figure 4) [4]. Knowing the original dimensions, the shape and any deformations of the ladle, it is then possible to evaluate the reduction of the thickness. This control is really important in order to avoid breakouts which can have serious consequences in terms of production (economical aspect) and general safety of personnel (human aspect). In fact, the refractory bricks are continuously subjected to corrosive attacks by hot liquid steel and slag that cause a reduction in thickness of the lining.



Figure 4: Laser scanner measures on the internal surface of the ladle from the outside the steel ladle.

Two problems can be detected:

- the accuracy of the measurements depends on the angle of incidence of the laser beam;
- the shadowed area under the mouth is not accessible for the laser beam.

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The second disadvantage has an impact on the measurability of the slag zone, a very important area in ladle lining relating to the risk of a breakthrough. To overcome the above problem, a laser head system has been developed [4].

The entire measurement takes less than 3 minutes and it can be divided in three steps (Figure 5):

- a) the laser head is positioned such that the laser scanner sees the outer contour and a part of the mouth of the ladle in order to find the exact position of the ladle by using a "3D structure finding" software;
- b) the second scan is carried out in front of the mouth to measure the area of the bottom of the ladle;
- c) the laser head moves completely through the mouth inside the hot ladle and it measures the ladle wall lining with a 360° rotating laser scanner; each scan takes only 20 seconds.

Once the measurement is finished, the head returns at the position zero. The data are collected (generally 3.9 million points with accuracy better than 5 mm) and processed.









Figure 5: Measurement procedure.



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# 3. Application in ATHOR project

The devices presented is this document are being used to perform the thermal instrumentation of laboratory tests and in-situ measurements in industrial scale. Some cases are detailed in the next sections.

### 3.1. Laboratory experiments

### 3.1.1. ATHORNA Device

The ATHORNA Device (Advanced measurements for in-situ THermo-mechanical monitoring of large sample uNder thermal gradient) is being developing inside the scope of ATHOR Project. The objective of the equipment is to study the thermo-mechanical behaviour of refractory materials under thermal gradient and consequently evaluate their resistance to thermal shocks.

A cylindrical sample with a diameter of ø100 mm and thickness of 10mm to 20mm is subjected to CO<sub>2</sub> laser pulses. The power discharged by the laser can vary from 50W up to 2000W, which leads to an increase in sample temperature, the exposed face may reach temperatures as high as the temperatures in service conditions of refractory materials. The strain fields at the bottom face are evaluated using a stereoscopic optical system with two cameras. The temperatures at the bottom face are measured using one infrared camera. Acoustic emission sensors will be installed in the future to evaluate the acoustic activity of the sample and to track the cracks. The experimental setup of the ATHORNA device is presented in Figure 6.



Figure 6: Experimental setup – ATHORNA Device

The laser pulses increase the temperature at the centre of the sample, which leads to two different temperature gradients:

- i) **Diametral temperature gradient:** the higher temperatures at the centre of the sample result in a restrained thermal expansion. This leads to compression stresses at the centre of the sample and tangential tensile stresses at the borders of the sample. The tangential tensile stresses lead to crack initiation and propagation.
- ii) **Temperature gradient across the thickness of the sample:** the higher temperatures at the top face (exposed-face) leads to a thermal bowing of the sample.







The measurement of temperatures by the IR camera at the bottom face is presented in Figure 7. Figure 7 (a) and (c) represent the thermal image and the diametral temperature at the beginning of the test, respectively. Figure 7 (b) and (d) present the measurements during laser application.





(a)



(c)

(b)





(d)

# Figure 7: Temperature measurements using IR Cameras on ATHORNA device: (a) IR Camera image – Beginning of the test; (b) IR Camera image – During laser application; (c) Diametral temperature – Beginning of the test; (d) Diametral temperature – During laser application

The Digital Image Correlations (DIC) technique allows the measurement of the total strain in the sample ( $\epsilon_{total}$ ). However, in order to best analyse the problem it is necessary to decouple the strains components in mechanical strains ( $\epsilon_{mec}$ ) and thermal strains ( $\epsilon_{thermal}$ ), as described in Equ. 2:

$$\varepsilon_{total} = \varepsilon_{mec} + \varepsilon_{thermal}$$

The thermal strains can be predicted based on the temperature fields and the thermal expansion coefficient of the material. Therefore, the thermal instrumentation is important for the accuracy of the study. The procedure used to determine the mechanical strain fields is presented at Figure 8.



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Moreover, numerical models are being used to predict the behaviour of the material in the regions where the instrumentation (thermal and mechanical) is not applicable, such as in the hot face and inside the sample. The calibration of the numerical models are important to increase the agreement between the experimental and numerical results. The IR camera is used to validate the numerical heat transfer analysis.

Figure 9 (a) presents the temperature at the centre of the bottom face, the experimental measured and numerical predicted values are presented in blue and green, respectively. Figure 9 (b) presents the diametral temperature at the beginning and by the end of cycle C15. The measured temperatures at the bottom face are presented by the dashed blue line, the predicted temperatures at the bottom and top face are presented by the continuous line in blue and red, respectively.



Figure 9: Temperatures measurements – Experimental and Numerical values: (a) Temperature at the centre of the sample versus time; (b) diametral temperature at cycle C15.



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### 3.1.2. Compressive test in masonry wallets

Two sets of compressive tests in masonry wallets are foreseen inside the scope of ATHOR Project:

- i) Uniaxial compressive tests: The compressive load will be applied in one direction. These tests will take place at the ISISE laboratory of the University of Coimbra, in Coimbra Portugal.
- ii) Biaxial compressive tests: The compressive load will be applied in two orthogonal directions. These tests will take place the Research Centre of RHI-Magnesita, in Leoben Austria.

The experimental setup of these tests are presented in Figure 10 and Figure 11. The thermal instrumentation to be used in the experimental layout is presented.



Figure 10: Experimental setup: Uniaxial compressive test: (a) Front view (b) Cut (2017) [6]





### 3.1.2.1. Thermal instrumentation of the uniaxial compressive test

The uniaxial compressive tests will last for four hours and the temperature of the furnace is limited to 1200 °C. An electrical furnace will be used to heat the one face of the wall(hot face), the other face (cold face) will be used for the thermal instrumentation. In order to design the experimental layout and to determine the thermal instrumentation, some predictive models were used. The predicted temperatures at the hot face (HF) and at the cold face (CF) are presented in Figure 12 (a). Figure 12 (b) presents the distribution of temperatures at by the end of the test.









#### Figure 12: Uniaxial compressive test: Prediction of temperatures: (a) Temperature vs time, (b) Temperature distribution.

Based on the temperatures fields by the end of the test, the thermal instrumentation was defined. Type K thermocouples will be used. This type of thermocouples (Nickel-Chromium / Nickel-Alumel) can operate in temperatures up to 1260°C and present good accuracy (+/- 2.2C or +/- 0.75%). Moreover, this equipment is relatively cheap and easy to weld and install. The thermocouples will be installed in different positions of the wall and in both faces (hot face and cold face), in order to evaluate the temperatures and thermal gradients across the thickness of the wall, as presented in Figure 13.





#### 3.1.2.2. Thermal instrumentation of the biaxial compressive test

The biaxial compressive tests aims to represent the service conditions of masonry linings. The heating rate of 25°C/h will be used, representing the heating rate usually used in industrial linings. The samples will be tested in different temperatures: *i*) Room temperature, *ii*) 600°C, *iii*) 1.000 °C and *iv*) 1.500 °C.







The thermal instrumentation was defined based on the temperatures of the test. Type K thermocouples will be used for the tests at 600°C and 1000°C. However, the tests at 1500 °C exceed the working temperature of these thermocouples (1260 °C): Therefore it will be necessary the use of another type of thermocouple, as presented in Table 1.

The thermocouples will be installed in different positions of the wall and in both faces (hot face and cold face), in order to evaluate the temperatures and thermal gradients across the thickness of the wall (Figure 14).



Figure 14: Biaxial compressive test: Thermal instrumentation

### 3.2. In-situ measurements

A 3D pilot scale model will be constructed inside the scope of ATHOR Project. It consists of a cylindrical steel shell with a welded plane bottom. The refractory lining will be arranged in concentric layers at the side of the steel ladle and stacked layers at the bottom. The schematic drawing of the pilot ladle is presented in Figure 15.



Figure 15: Pilot Steel Ladle.

To perform the numerical calibration and the validation of the developed models, it will be necessary to measure the temperature distribution and the temperature fluxes. Some predictive models are being used to design the pilot ladle and to determine the thermal instrumentation of the system, as presented in Figure 16.



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Figure 16: Prediction of temperatures (°C)

Based on the predicted temperatures, the thermal instrumentation comprises:

- Type K thermocouples: the thermocouples will be installed in the steel shell and between the refractory layers aiming to measure the temperature gradient across the thickness of the ladle.
- IR Cameras: these devices will be used to measure the temperature fields at the wear layer and also at the steel shell.

More information about the pilot steel ladle is presented in Deliverable D1.5 and D1.6.

# 4. Conclusions

This document summarizes the current methodology used for thermal instrumentation on industrial vessels, including suitable acquisition equipment and techniques. This deliverable is the output of the "Task 1.1 – Thermal Instrumentation" as a task of "WP1 - Improvements of measurements tools".

Section 2 described the techniques used for thermal instrumentation currently used in industrial measurements and in academic researches. Some techniques, such as thermocouples, infrared cameras and laser scanning, were presented. Section 3 described how these techniques are being used inside the scope of ATHOR Project.

As presented in this document, there are many techniques available for the evaluation of temperatures in industrial devices. However, the elevated temperatures in which refractory ceramics work may require some improvements, as these techniques may not be fully suitable. These improvements are being developed within the scope of WP1.

In conclusion, the improvement of measurement tools performed within WP1, including the "Tasks 1.1 - Thermal instrumentation", "Task 1.2 - Strain Instrumentation", "Task 1.3 – Devices for thermo-physical properties characterization" and "Task 1.4 - Devices for thermomechanical characterization" are increasing the current knowledge and will be used in "WP1 - Improvements of measurements tools", "WP2 - Advanced characterization of materials, refractories and joints" and "WP4 -Advanced measurements for numerical validation"

# **5.** References

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