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OPEN FIREPLACES AND INSERT SOLID FUEL STOVES - AN EXPERIMENTAL AND ANALYTICAL STUDY

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PREFACE

The Building Research Association of New Zealand (BRANZ) undertook the work reported here primarily in order to establish whether current New Zealand Standards which set requirements for construction of fireplaces and chimneys were adequate in terms of fire safety.

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This report is intended for researchers in fire safety science, Code writers, testing laboratories and as a background document to other BRANZ publications aimed at approving authorities, Fire Service personnel and members of the home heating industry.

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From Construction Industry Thesaurus, BRANZ edition: Analysis; Chimneys; Computer; Domestic; Fire; Fireplaces; Installing; Modelling; New Zealand; Solid Fuel heating; Statistical Data; Stoves.

ABSTRACT

The requirements of current new Standards for clearances between concrete and masonry fireplaces and chimneys and adjacent wall framing have been confirmed as adequate for both open fireplaces and insert heaters. A test rig has been developed for assessing the performance of an open fireplace and an insert heater. A mathematical model has been constructed to allow prediction of temperatures on materials around fireplaces. The model is of a general nature and will be usable in other fire situations.

Recommendations are made for further work towards improvements in the test rig and its operation, the modelling technique and fire incident data collection.

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INTRODUCTION

The work reported was undertaken following approaches to the Building Research Association of New Zealand (BRANZ) by the Fire Safety Division of the New Zealand Fire Service (NZFS) who were concerned for life safety following a spate of domestic fire incidents which occurred during the winter of 1986 in the Wairarapa region. These incidents were investigated by Fire Safety Officers and BRANZ staff and found to be related to incorrect construction and installation practices involving solid fuel burning insert appliances, i.e. heaters designed for installation into existing conventional open fireplaces.

BRANZ therefore began a research project aimed at identifying the causes and quantifying the extent of such fires.

Subsequent analysis of NZFS incident data revealed that similar fires were occurring throughout the country and for the same primary reasons, see Table 1:

Category	Reported Incidents		% of Reported Incidents		% of the "Population"	Incidents/10,000 installations	
	1987	1988	1987	1988		1987	1988
open fireplace	20	40	17	23	46	0.8	1.6
insert heater	31	53	26	30	18	3.1	5.3
freestanding heater	52	65	44	37	36	2.6	3.3
other	16	17	13	10	-	-	-
Total	119	175	100	100	100	-	-

Comment on Table 1

"Other" includes incidents where the heating source was not identified or where the means of installation could not be classified according to the above system, e.g., a coal range, or through-wall heater.

The "population" of a given heating source is defined as its estimated occurrence in New Zealand dwellings. The values used, based on the 1981 Census of Population and Dwellings and information from the NZ Home Heating Association, were:

Open Fireplaces	250,000
Insert Heaters	100,000
Freestanding Heaters	200,000
Population Total	550,000

Table 1: Analysis of Fire Incident Data from 1987 and 1988

This analysis, by Woodside (1988), includes reference to freestanding solid fuel burning heaters. They did not form part of the present research and data relating to them are reproduced for the sake of completeness. The data presented in Table 1 have been updated from those published by Woodside (1988).

It was recognised that the first step in the experimental phase of the research was to confirm the adequacy of construction and installation methods recommended by the existing New Zealand Standards: NZS 1900 Chapter 7: 1985 Small Chimneys and Appliance Installation; NZS 7421: 1985 Installation of Solid Fuel Burning Domestic Appliances; and NZS 7401: 1985 Solid Fuel Burning Domestic Appliances. In summary, these Standards require that clearances of framing timber to concrete or masonry fireplaces and chimneys be established at not less than 25 mm for a conventional open fireplace and 50 mm where an insert heater is installed. Since some of the requirements in these Standards are based on overseas experience it was not clear whether they were appropriate for several reasons:

- Building materials and techniques commonly used in New Zealand may not necessarily be accommodated.
- The experimental basis for the requirements is not known.
- Modern solid fuel heating appliances have developed to a point where the appliance may be expected to perform very differently, in terms of heat output and combustion efficiency, from earlier generations of appliance.
- The current New Zealand Standards do not include a test method for assessing whether insert heaters could be installed in conditions other than those prescribed, for example in terms of clearances.
- There is no test method described in the Standards for assessing the performance of conventional open fireplaces.

It was also the intent of the research to examine the feasibility of using a mathematical modelling technique as a tool for investigating the characteristics of heat flow around a fireplace with and without an insert heater installed. This had been attempted to some degree by Peacock (1987a).

DESCRIPTION OF THE MATHEMATICAL MODEL

Time and cost restraints make it impossible to attempt experimental runs covering every situation of interest. Nevertheless, information was required on a range of different fireplace designs and a range of clearances of the timber members from the fire surround. To acquire this knowledge it was decided to model the fireplaces mathematically, as a good mathematical model allows analysis in principle of any fireplace made of any materials with any clearances.

However, the accuracy of the model depends upon the degree of knowledge of the underlying physics of the situation. Fully reliable modelling would require detailed understanding and modelling of a number of components, including:

- The kinetics and heat transfer processes of the fire.
- The flow dynamics and heat transfer processes of the flue gases in the chimney.
- The heat transfer processes within the fire surround and structure.

Only a little is known of some of these processes. Furthermore any attempt to account for them all in detail would result in a very complex model. Fortunately, for the task at hand, namely to offer sound advice on what clearances are safe, it was unnecessary to achieve the degree of detail that a more complete model might achieve. It was judged that sufficient accuracy could be obtained by modelling the heat transfer processes within the fire surround and structure, taking into account the effect of the fire and hot gases by choice of appropriate boundary conditions (see below).

EXPERIMENTAL METHOD

Construction and Instrumentation of Test Rig

The test rig was developed by BRANZ in conjunction with the NZFS and the New Zealand Home Heating Association (NZHHA), and was used for test runs of both an open fire and an insert heater.

A fireplace and chimney were built to simulate a chimney on an external wall which complied with the minimum requirements of NZS 1900 Chapter 7. The "Standard Exterior" model of precast pumice concrete construction, built by Firth Industries of Waikanae, was chosen as being representative of many New Zealand constructions. The model as specified varied from the requirements of NZS 1900 Chapter 7 in the following ways:

1. The fireplace jambs were 85 mm thick at the front tapering to 100 mm at the rear and the breast was 95 mm thick at its thinnest part. NZS 1900 Chapter 7 requires that these dimensions be at least 100 mm.
2. The lintel was cast integrally with the breast block using pumice concrete whereas Chapter 7 specifies that the lintel should be a separate component of ordinary concrete.
3. The manufacturers of the precast units for the fireplace and chimney have advised that the mix proportions used were 245 kg of pumice to 61 kg of cement, a ratio of approximately 4 to 1, whereas Chapter 7 specifies 5 parts of pumice to one part of cement by volume.

It was considered that these variations would not lead to any reduction in temperatures measured on the surface of adjacent timber framing - a data sheet is attached as Figure 1.

For use of the rig as a conventional open fireplace, firebricks were installed according to trade practice. These were removed for installation of an insert heater.

The attached drawings (Figures 2 and 3), show the general arrangement of the fireplace, chimney, wall framing and other construction details.

The wall framing was constructed such that the trimming studs were in contact with the fireplace jambs, the lintel was in contact with the breast block, the centre jack stud contacted the breast block at its lower end, and the soffit framing, rafters and weatherboards contacted the chimney blocks.

The wall framing was dry ex 100 x 50 mm No.1 framing grade *Pinus radiata*.

Bevelback timber weatherboards over building paper were fixed to the outside of the wall framing.

The roof and soffit framing were clad with sheet material to minimise air circulation around the chimney at eaves level and the gaps between the sides of the chimney and the weatherboard profile were closed off by use of timber scribers cut to shape.

R 1.6 fibreglass batts (75 mm thick) were installed in one half of the wall (see Figure 4).

The wall lining was 9.5 mm thick paper-faced gypsum plaster board.

The fireplace surround was 70 mm thick "normal weight" (nominally 2400 kg m^{-3}) precast concrete fixed to the firebox and sealed with ceramic fibre rope. The fireplace opening thus created was 600 mm in height and 560 mm wide.

The above specification formed the basis for the test rig which was designed so that the clearances of framing timber to concrete could be varied from 0 to 25 to 50 mm. Figures 4-7 show details of the rig under construction. During the course of testing, and in order to more accurately simulate a room with a fireplace installed in it, the wall containing the fireplace was extended to 3.0 m in width, 1.8 m long side walls were built on and the ceiling appropriately extended. The ceiling was fully insulated while the side-walls were not.

A means of removing smoke from the chimney was designed so as not to result in forced extraction. This comprised a 2 m x 2 m x 600 mm deep metal hood suspended above the chimney top and fitted with ducting to allow discharge outside the laboratory. A 400 l s^{-1} capacity propeller fan with variable speed controller was situated in the ducting to allow for clearing of the system and the prevention of smoke-logging. The fan speed was set to ensure subjectively assessed, unforced extraction.

Figures 2, 3, 8 and 9 include schematic drawings of thermocouple placement within the test rig. In addition, thermocouples were placed within and on the inner surface of the chimney flue blocks and in the extraction flue at the position of the extract fan. The room ambient temperature was determined by locating a shielded thermocouple 1.2 m above the floor on the wall of the test enclosure, as recommended by NZS 7421 Clause A4.6. The ambient temperature throughout the experimental series lay within the 15-25 °C range recommended for testing of solid fuel heaters (NZS 7421 Clause A6.3).

Type K (chromel-alumel) thermocouples (±3 °C tolerance) were used and fixed to timber surfaces by embedding in a shallow groove drilled into the surface so that the thermocouple tip lay flush with it. Lead wires were stapled in place to ensure stability. Fixing to concrete surfaces was either by this means or by holding the thermocouple tip in place using a screw-fixed metal disc.

Fixing to metal surfaces was by means of a riveted metal strap holding the thermocouple tip flush with the surface, or by drilling into the surface and using a metal punch to keep the tip in place.

Thermocouples used to record temperatures within the metal flue and firebox of the insert appliance were radiation-shielded by running them axially within two concentric stainless steel tubes of length 120 mm and nominal outside diameter of 15 and 25 mm.

A pitot-static tube with output to a micromanometer was installed in the chimney and metal flue cavities to measure gas flow rates.

A water-cooled "Land" radiometer was placed on the floor 500 mm in front of the glass door of the insert heater during its operation in order to gain a measure of the level of radiated heat energy emitted by the heater. The radiometer output was read as a voltage and recorded, along with the micromanometer output, on a 2-pen chart recorder.

Data from all thermocouples were collected by a Hewlett Packard HP3497A datalogger of 80 channel capacity and processed by use of "Stovetemp", a purpose-built software package developed in-house to run on an HP87 computer.

Insert Heater

The model used was of a type common in New Zealand. It is of the"box-in-a-box" generic type and comprises a steel plate firebox within an aluminised mild steel cabinet. Clearances between the two "boxes" are approximately 65 mm at the sides, 90 mm at the top and 20 mm at the rear. When installed in the fireplace opening, after removal of the firebricks, the clearances from the outer cabinet to the fireplace walls were:

Side walls: 70 mm at the front tapering to 90 mm at the back

Rear wall: 50 mm

Lintel : 220 mm.

The heater is supplied with a metal fascia (containing upper and lower grilles) which was screwed to the concrete fireplace surround to seal the heater into the opening.

There are two combustion chambers in this model. Combustion air enters the heat exchanger via an air control slide above the door. It then passes downwards over the door glass and becomes pre-heated before entering the firebed and moving towards the rear of the firebox. Primary combustion occurs in this region and the hot gases then move towards the roof of the primary chamber, undergoing further partial combustion before entering the secondary chamber through a baffle.

In this model a damper was positioned in the flue stub as it emerged from the rear of the top surface of the heat exchanger. Its position could be altered to control gas flow into the flue system. During experimental runs the air inlet slide was fully open and the damper was fully closed, conditions which resulted in maximum continuous heat output.

A continuous, 150 mm diameter stainless steel flue (in two sections fixed together with screws) was fitted into the flue collar on the appliance and emerged through a metal flashing plate (mortared to the top chimney block) and outer flue shield (250 mm) to fit into the manufacturer's recommended cowl. Any build-up of hot gases in the chimney cavity could thus vent via the annular gap (approx. 3×10^4 mm ^{2}) between flue lining and shield at the top of the flue system.

The heater manufacturer provided estimates of maximum heat output of 14.7 kW and overall efficiency (combustion efficiency x heat transfer efficiency) of 65-70 per cent.

In summary, this heater model is typical in most respects of the range of insert solid fuel burning appliances available in New Zealand.

Fuelling

In general, fuel was used as per the recommendations of NZS 7421 Clause A5.1.3. Wood used in fuelling the rig, both as a conventional open fireplace and with an insert solid fuel burning heater installed, comprised 100 x 50 x 300 mm weighed blocks of kiln-dried untreated *Pinus radiata* timber. Roughsawn or dressed timber was used according to availability. The moisture content averaged 16-19 per cent as measured by a resistance type moisture meter of expected accuracy ±2 per cent.

The average density of the wood was 500 kg m^{-3}.

Coal, as used in several test runs in the open fireplace, was of a sub-bituminous variety with a gross calorific value (GCV) of ~20-25 MJ kg^{-1}.

The fuelling regime adopted for the open fireplace configuration involved adding the blocks of timber or weighed amounts of coal at regular intervals so as to maintain a constant fuelling rate as expressed in kg hr^{-1}.

In the case of the insert heater, the fuelling regime as described in NZS 7421 Clause A5.2 was followed. This aims to achieve maximum output operation through addition of fuel blocks (timber only was used in this test series) at regular intervals to build up the base fire to a level not greater than 75 per cent of the total firebox height. The "flash fire" as described in Clause A5.3 was not carried out.

Thermal stability of the test rig was defined as in UL 1482:1981 Room Heaters, Solid Fuel Type, i.e. all relevant thermocouple readings (in this case those on timber framing surfaces) should be static or in decline over a period of three successive half-hour intervals. For safety reasons and to extend the working life of the test rig, the maximum temperature of timber framing was not allowed to exceed 150 °C during any test run.

The following, Table 2, contains descriptions of experimental runs, in chronological order, upon which later Figures are based. Only those runs which led to results relevant to the reported conclusions are included here. All runs started with the timber framing of the test rig at ambient temperature unless otherwise stated.

RUN	TYPE	TIMBER TO CONCRETE CLEARANCE mm	FUEL	FUELLING RATE kg hr^{-1}	TIME TO STABILITY hr
A	Open Fire	25	Wood	5.4	34
B	"	25	Wood	10.2	26
C	"	25	Wood	10.2	15 (Warm Start)
D	"	25	Coal	4.8	10
E	"	25	Coal	2.4	21
F	"	0	Wood	5.5	38.5
G	Insert (Chimney Sealed)	0	Wood	3.9	29
H	Insert (Chimney Vented)	0	Wood	3.8	31

Table 2: Description of experimental runs

The Mathematical Model

The model used in this analysis was a finite difference nodal model based on a general purpose model described by Cunningham (1989) tracing heat and mass transfer in structures. The model used differs from Cunningham's in that heat transfer alone is accounted for.

The structure being modelled is divided into a number of nodes, the size, location and number of which are governed by the state of knowledge of the physics governing the behaviour of that component or the amount of detailed information required of that part of the system.

Energy is conserved at node i as follows:

Rate of gain of heat at node i = net rate of flow of heat into node i by conduction, convection and radiation

$$\rho_i c_i V_i \frac{T_i' - T_i}{\Delta t} = \sum_j U_{ij} A_{ij} (T_j - T_i) \qquad (1)$$

where c_i Specific heat of the material making up node i (J kg $^{-1}$ °C^{-1}).

A_{ij} Area of the interface between node i and node j (m^2).

T_i Temperature of node i (°C)

Δt Time step (s).

V_i Volume of node i (m^3)

ρ_i Density of the material in node i. (kg m^{-3})

U_{ij} here is an effective conductance whose value is temperature-dependent in the case of convection and radiation (and perhaps also for conduction). An expression for U_{ij} in the case of conduction follows from fundamental definitions, which give:

$$\frac{1}{U_{ij}} = \frac{X_{ij}}{k_i} + \frac{X_{ji}}{k_j} + R_{ij} \qquad (2)$$

where k_i is the conductivity of the material making up node i

X_{ij} is the distance in the direction of heat flux between node i and the boundary between node i and node j

R_{ij} is the contact resistance between node i and node j.

Equivalent expressions for the effective conductance U_{ij} in the case of convection and radiation can be found in Cunningham (1989).

To solve for the temperatures at each node, equation 1 is rearranged to give a set of simultaneous equations in T'_i. The equations are implicit and non-linear as the U_{ij} are temperature-dependent, so that at each time step new values of U_{ij} are calculated and the process continued iteratively until the temperatures calculated converge at that time step. For this work, the experimental runs continued until steady-state was reached.

This situation can be simulated either by allowing the model to run until such time as the temperatures at a given time step are insignificantly different from the temperatures at the previous time step, or by solving the equations with t set to ∞. (1/Δt set to zero.) Both methods were used with identical answers.

The chief (and time-consuming) issue facing the user of the model is to specify the geometry of the structure under consideration and to specify the type and details of thermal transfer between each node. The model has a number of input data structures for this task.

The program is coded in FORTRAN-77 and currently runs on a Microvax II computer.

The time to convergence for the model is approximately proportional to the square of the number of nodes specified. For the nodal arrangement used in this work (see Figure 10) the model run time was less than one minute.

A cross section was taken through the middle of the fireplace from the centreline vertically through the chimney to the interior of the living space, see Figure 10, and the component of heat flow from the fire box internal walls through the structure to the interior living space was modelled two-dimensionally. This figure also shows how the area was divided into nodes.

All important physical parameters are ascribed a wide range of values in the literature (ASHRAE (1985), Jonsson & Pettersson (1985), Harmathy (1970, 1983)).

Estimates used in this work for thermal conductivities and their temperature dependence (where accounted for) are shown in Table 3. All emissivities were taken as 0.8 and all contact resistances as 0.05 m^2 °C W^{-1}.

Material	Reference temperature °C	Conductivity $W\ m^{-1}\ °C^{-1}$	Temperature dependence of conductivity $W\ m^{-1}\ °C^{-2}$
Brick		1.2	
Wood	100	0.15	3×10^{-4}
Fibreglass	50	0.06	3×10^{-4}
Plasterboard		0.16	
Concrete		1.4	
Pumice Concrete	150	0.17	3×10^{-4}
Clay		1.0	

Table 3: Thermal conductivities and their temperature dependence

The node representing the interior living space was ascribed a temperature of 20 °C and the two nodes in the fire/chimney area and the node representing the airspace between the chimney and the external cladding (see Figure 10) had their temperatures determined by the calibration process described next.

The calibration process consisted of adjusting the temperature values at the boundary nodes until the temperatures predicted throughout the structure were as close as possible to those measured experimentally. Calibration was undertaken at two widely different conditions to ensure that the validity of the system modelled was as good as could be obtained. One condition was at a fire fuelling rate of 11.0 kg hr^{-1} and 50 mm clearances and the second was at a fire fuelling rate of 5.5 kg hr^{-1} with no clearances. As well as setting the effective temperature of the three nodes, the calibration process was used to make minor changes in thermal conductivity values within the accepted range reported in the literature to aid the process of obtaining best agreement between measured and predicted temperatures.

Early experimental work quickly established that temperatures at critical points were significantly higher in an insulated wall than in an uninsulated wall, so that modelling of insulated walls only was undertaken, confident in the knowledge that uninsulated walls would perform better in the sense of having lower temperatures at critical points.

The main approximation made is the assumption that fixed boundary conditions can be used as the geometry of the fireplace is changed. This is likely to be a reasonable approximation if the internal geometry only of the structure changes, i.e., clearances only are changed, but must be a poorer approximation if the overall fireplace design is changed. In the latter case better results would be obtained if it were possible to recalibrate the model using experimental data from the new fireplace.

The other main area of uncertainty is in the choice of thermal conductivities of the materials making up the fireplace and surrounds. Any values chosen from the literature could easily be quite different from those of the actual materials present in the structure being modelled. Some improvement in confidence in the values actually chosen is given because the calibration process used allowed some minor variations to be made to the thermal conductivities to give better agreement with the internal temperatures measured experimentally.

Taken together it is estimated that the temperatures predicted by the model would be within 10 °C of their actual values for a fireplace of the same design as that on which the model has been calibrated, and perhaps 15 °C for other designs.

RESULTS

Open Fireplace Data

In Figures 11-15 all temperatures quoted are maxima at stability. Thermocouple positions are as shown in Figures 2 and 3.

Figure 11 shows temperatures in the rig as a function of position for a typical run.

Figure 12 shows the relationship between timber surface temperature and timber to concrete clearance.

Figures 13 and 14 show the effect on timber surface temperatures of fuelling rate and fuel type.

Figure 15 shows the influence on timber surface temperatures and time to thermal stability as a function of temperatures within the rig at the start of an experimental run.

Figure 16 shows the model-predicted maximum temperature of the timber trimmer above the lintel for an insulated wall for various trimmer/lintel clearances at a fuelling rate of 5.5 kg hr^{-1}, established at steady-state i.e. after about 36 hours. Experimental results for comparison are 107 °C at zero clearance (model prediction 103 °C), and 75 °C at 25 mm clearance (model prediction 85 °C). Reasons for these differences are discussed below.

Figure 17 shows predicted maximum temperatures on the trimmer surface in brick and ordinary (normal weight) concrete fireplaces assuming a fuelling rate of 5.5 kg hr^{-1}.

The brick fireplaces modelled, illustrated in Figures 18 and 19, are a double brick design, and a single brick with clay liner design as detailed by the New Zealand Pottery and Ceramics Association (PACRA) (1981). The "ordinary concrete" fireplace is one of identical design to that used in the experimental rig except that the thermal conductivities of all concretes including that of the firebox were taken as 1.4 W m^{-1} $°C^{-1}$.

Insert Heater Data

All temperatures quoted in Figures 20 and 21 are maxima at stability. Thermocouple positions are as shown in Figures 2 and 3.

Figure 20 shows the typical temperatures within the rig and illustrates the hazard resulting from an incorrect installation technique in which the annular gap at the top of the flue system, between the metal flue and its flue shield, was packed with fibreglass batts. This technique is one used in the field to combat any tendency towards over-cooling of the flue leading to creosote build-up. Bulletin 259 of the Building Research Association of New Zealand (1988) advises against this practice, recommending that insulation only be used in the section of the flue system outside the building.

Figure 21 shows the typical temperatures within the rig where a recommended method of installation has been used, i.e., the annular gap referred to above was not packed and so the chimney cavity was freely vented.

Figure 22 shows typical maximum temperatures of the heater, flue and flue gases where a recommended method of installation has been used. The descriptors 'inner' and 'outer' refer to the heat exchanger and its outer cabinet respectively. The temperatures of both flue surface and flue gas are highest at the heater outlet and decrease progressively towards the top of the flue system.

DISCUSSION

Fire Incident Data

Comparison of fire incident data from New Zealand (see Table 1 and Woodside, 1988) with other, selected, countries is fraught with problems which are outlined below in more detail. There is also difficulty in comparing test data from this work with those derived from testing done elsewhere.

The incompleteness of data (from all countries) and the different terminology used in reports makes it unwise to infer too much with regard to New Zealand's fire safety record in the area of solid fuel heating. The small sample size reflected in New Zealand data also makes comparison of some parameters meaningless. For example, the US Consumer Product Safety Commission (1988) reports that the risk of death from fires in the USA involving "solid fuel equipment" was estimated as 0.2 death/100 incidents in 1985. In order to register a similar level of risk New Zealand would need to have 500 reported incidents before observing one "statistical death". Even given that current reporting procedures are inadequate, it is unlikely that this country will reach that annual level of incidence.

The US Consumer Product Safety Commission report also allows breakdown of data to provide a comparison in terms of numbers of fire incidents per 10,000 installations.

For solid fuel heating equipment, i.e., not including open fireplaces, a figure of 74 has been calculated for the USA in 1985 compared with about 8 for New Zealand in 1988 (Table 1).

Table 1 shows the detailed breakdown of reported fire incidents according to type and heating source, (open fireplaces and insert heaters being of interest to this analysis). Woodside (1988) further analysed the data to identify the primary causes of ignition of combustible materials which led to the fire incidents. For the conventional open fireplace these were:

- Construction defects:
  - inadequate clearance to combustibles.
  - a defective seal of the fireplace surround to the firebox.
- Inadequate maintenance:
  - cracks and mortar defects in the chimney.

Of the above, inadequate clearances were identified in about 40 per cent of fire incidents, with a similar percentage showing signs of inadequate maintenance. It is usually not possible to identify which of several "primary causes" contributed most to a fire incident. In some (perhaps many) cases a combination of factors will have led to an outbreak of fire.

In the case of insert heaters, primary causes of fire were identified as:

- Improper installation technique:
  - inadequate clearances
  - damage caused to lintel during installation
  - inadequate ventilation of the chimney cavity
  - misuse of insulating materials (usually associated with the flue system).
- Inadequate maintenance:
  - cracks and mortar defects in the chimney.
  - flue defects.

Of the above, inadequate clearances were present in almost 50 per cent of the incidents and about 20 per cent showed signs of cracks and mortar defects. These findings reinforce the need for good construction, installation and maintenance practices, as discussed in BRANZ Bulletin 259 (1988).

The Adequacy of New Zealand Standards

A major aim of this study was to assess whether current New Zealand Standards were adequate in terms of their provision for construction and installation practices for open fireplaces and solid fuel insert heaters. Peacock (1987b) has summarised similar work carried out over a number of years in the USA.

This aim has been achieved and is illustrated by Figure 12 where, in the case of an open fireplace, critical temperatures were measured on wall framing timber surfaces where there was contact (zero clearance) between timber and the (pumice) concrete of the fireplace and chimney.

NZS 1900 Chapter 7 requires that clearances of 25 mm be established in the construction of an open fireplace.

"Critical" refers to surface temperatures in excess of 90 °C, a figure based on the commonly accepted view that long-term exposure of wood to relatively low temperatures can result in ignition, see for example McGuire (1969). By contrast, timber ignites at higher temperatures if exposed for a shorter time -about 350 °C for piloted and 520 °C for non-piloted ignition.

90 °C is used in NZS 7421 as the acceptable limit for temperatures on "medium heat resistant materials" which include timber.

In the case of insert heaters it has been shown (Figure 21) that timber surface temperatures approaching 90 °C are reached, under the chosen fuelling regime, where there are zero clearances. Although no experimental runs were carried out at 50 mm clearances, experience with the modelling of the open fireplace leads to a reasonable expectation that the establishment of 50 mm clearances, as required by both NZS 1900 Chapter7 and NZS 7421, would result in test temperatures less than the 'critical' 90 °C.

It was also obvious that good installation technique is needed since the reduction of adequate ventilation of the chimney cavity results in timber surface temperatures well in excess of 90 °C. (see Figure 20). It is noteworthy that these experimental runs were carried out under laboratory conditions in a relatively sound rig. No attempt was made to simulate the likely deterioration with time of concrete and mortar as can happen in field installations. Such defects would be likely to compound the effects of inadequate clearances and/or faulty installation practice.

Correlation with Field Incidents and Faulty Installation Techniques

Measurement of timber surface temperatures has also enabled correlation of hazards identified experimentally with field-reported incidents. For example, the highest such temperatures recorded were invariably on the timber trimmer (see Figure 11) which confirms the observation that the majority of reported fire incidents are known to have originated in this area. This is the case for both open fireplace and insert heaters. However, it can be seen (Figure 21) that with an insert heater there is the added danger of critical temperatures higher up in the building structure, at rafter and soffit level. This is a reflection of the higher flue gas temperatures at these levels (of the order of three times more, in Celsius terms, than for an open fire). It further emphasises the need to ensure that the chimney structure is sound and that there is no insulating material around the flue in this region.

The Development of a Test Method

Current Standards (NZS 1900 Chapter 7 and NZS 7421) do not contain test methods to allow assessment of the performance of open fireplace design with and without an insert heater installed. There is thus no option for manufacturers of fireplaces and heaters but to construct and install according to the prescriptive requirements of current Standards. In the case of clearances this means 25 mm for open fireplaces and 50 mm for insert heaters.

The design and building of an experimental rig has allowed consideration of whether a test method could form part of a future, performance-oriented, Standard. In this regard, a great deal has been learned about the heat flow characteristics of the rig during operation. These relate to both the rig construction and the test method used.

The rig was built with standard fibreglass insulation in one half of the wall containing the fireplace. During operation it was found that temperatures on timber surfaces were, generally, lower in the uninsulated half of the structure. This was always true in the critical areas around the lintel but elsewhere the situation varied depending on a number of parameters such as the radiation view factors of the thermocouples, air flow patterns and the location of the hottest point in the fire itself. No attempt has been made to quantify these factors.

In terms of the test method there are a number of variables whose influence on temperatures at stability have been observed.

The type of fuel used and its rate of addition to the fire are obviously prime factors in determining both the final temperatures attained (on timber surfaces) and to a lesser extent the time to stability. Figures 13 and 14 show the detail of these observations. It is noteworthy that temperatures were much lower when coal was used in the open fireplace and it proved difficult to maintain a "continuous" fuelling rate (at 15 minute intervals) such that the fire did not become "choked". In retrospect it may have been more realistic to adopt an intermittent rather than a "continuous" fuelling regime.

Walker and Fletcher (1987) used coal in an insert heater in test runs which, after a 24 hour low burning period, had fuel added at 4 or 6 hour intervals. This method is the preferred approach to the test fuelling of coal-burning heaters.

Despite the difficulty experienced in the coal fuelling regime chosen for the present series it is clear that no hazard exists when coal is used for open fireplaces built according to NZS 1900 Chapter 7. A coal-burning insert heater was not assessed during this work, wood being the preferred solid fuel in New Zealand.

The temperature of the components of the rig (framing timber and fireplace concrete) at the beginning of a fuelling run influence, as expected, the time to reach thermal stability rather than the maximum temperatures. In fact as Figure 15 shows, these temperatures are within 2-3 °C at stability. In that regard, these two consecutive runs give an indication of the repeatability of the test method although they take no account of the influence of ageing of the rig components which is discussed below.

In relating the results of experimental behaviour to likely field conditions it is worth noting that when fuelling an already warm fireplace (as would happen the morning after a domestic fireplace had been "banked" for all-night low output), it takes a relatively short time (4 hours in the experimental run C, Table 2) for timber framing temperatures to pass the critical 90 °C mark.

Throughout the series of experimental runs the laboratory ambient temperature varied between 15-25 °C and did not significantly affect temperatures measured within the rig structure.

Although the chimney design was intended for use on the external wall of a house, the rig was wholly contained within the laboratory and so no attempt was made to measure the influence of true external ambient temperatures and, perhaps more importantly, wind conditions. It is considered a safe assumption that the laboratory conditions represent the worst case in this context.

The operator of the rig may influence performance principally through the way in which fuel is added to the fire. In both the open fireplace and the insert heater, the orientation of the fuel piece (in the case of timber) influences the way in which the fire burns and hence may influence surface temperatures on the wall framing. If for example fuel was stacked near the front of the grate or firebox more heat would be radiated towards the position of the lintel and timber trimmer. These effects however tend to be transient and to even out over time if fuel pieces are added randomly.

Although in the insert heater the fire as a heat source is more confined and therefore easier to control or define, there are a number of parameters that can influence heat output and therefore heat flow patterns around the installation. This has considerable importance when trying to assess, without testing, the comparative behaviour of two different heater models.

Some of these parameters are:

- the means of air inlet control to the firebox,
- the firebox capacity and design (including the relative size and position of primary and secondary combustion chambers),
- the materials of construction of both firebox and flue (which influence emissivity) and,
- the design of the flue system (to allow for ventilation of the chimney cavity which in turn influences convective heat transfer from flue to chimney wall and so to framing timber).

See Figure 20 for a quantification of the hazard resulting from inadequate ventilation of the chimney cavity.

The physical dimensions of the firebox obviously determine the proximity of hot metal surfaces to the fireplace construction. Some manufacturers advise the use of an insulation blanket, usually of glass or mineral fibre, to lag the firebox. Depending upon some of the parameters listed above this can have the effect of lowering or raising timber surface temperatures in the structure. For example, a heater which, either by accident or design, allows some secondary combustion to occur in the lower part of the flue, will tend to have more such combustion occurring after the fitting of an insulation blanket which allows more heat to be retained in the firebox leading to hotter flue gases. This can lead to higher timber surface temperatures at the level of weatherboards and rafters. Another model, designed and operated differently, can yield quite different results. This highlights the need to be careful in extrapolating the results of a test on one heater to another of different design. Although many of the available heaters have a maximum heat output rated in the range 12-15 kW, the actual levels of heat delivered from different parts of the heater body and flue can vary considerably from one model to another.

There are two aspects of the test method which need further consideration prior to a recommendation that it become part of a performance oriented Standard, for example as an Appendix to NZS 7421. These are the relationship of the method to real usage of open fireplaces and insert heaters and, the repeatability of the method. It is always possible to criticise a test method for being out of touch with the real world.

As a means of comparison with "real usage", temperatures were measured on the top (front) of the firebox of an insert heater installed in a representative dwelling. During "normal" domestic usage of the heater these temperatures reached a maximum of 420 °C, two hours after start-up. This compares with the 590 °C reached during the laboratory runs, arguably a worst case usage.

Since it was the intention of this test method to assess the performance of a typical open fireplace, with and without an insert heater installed, during worst case usage we believe that the test method is a reasonable one.

Of more concern is the influence of the ageing of the test rig on the repeatability of the method. It was shown above that repeatability was good in comparing results from two consecutive runs when the rig was used as an open fireplace. These runs were carried out when the rig was still relatively "young" - having been used for about 75 hours, albeit under accelerated ageing conditions. Some evidence has been gained that as the rig has aged timber surface temperatures have tended to drift upwards. Suggestions are offered here as to possible causes of this effect.

During the first runs after a rig has been built some of the heat entering both concrete and timber is used in driving off in-situ water. Pumice concrete is particularly porous and would be expected to retain relatively large quantities of water from the drying stage of fireplace manufacture. However with drying and exposure to heat comes shrinkage and varying degrees of cracking. Several cracks have developed in the rig used for testing in this series. Such cracks may affect the rate of heat transfer through the concrete and, in the extreme case, may allow direct communication between the firebox or chimney and adjacent framing timber. These effects have not been fully investigated for the rig used in this experimental series.

Model Predictions

The experimental result of 75 °C (trimmer surface temperature) at 25 mm clearance was obtained in the first open fireplace run performed in the rig. The mathematical model predicted a trimmer surface temperature of 85 °C at 25 mm clearance but it was calibrated on the fifth and sixth runs. If a re-run had been performed on the rig at this stage, with 25 mm clearances, a temperature of 80-85 °C might have been expected because of the trend for temperatures to rise with rig use. Generally, because the model has been calibrated using data from the existing experimental rig, confidence can be placed in the reliability of its predictions for fireplaces of this design.

However as discussed above, the predictions must be treated with caution for other fireplace designs for, without experimentation, it is unclear what boundary conditions should be used to account for the heat transfer from the fire and combustion gases. Clearly the model predictions (Figure 17) show unambiguously that a fireplace built to the design used in the 40 experiments, but with 1.4 W m^{-1} $°C^{-1}$ conductivity concrete, (i.e. "normal weight" concrete) will have critical temperatures on combustible surfaces far in excess of those considered safe. Brick fireplaces of the type analysed (Figures 18 and 19) are probably safe if built at the 25 mm clearances currently recommended by NZS 1900 Chapter 7.

Attempts to use the model to predict the performance of an insert heater when installed in fireplaces of different design have not been pursued beyond the point of identifying some of the physical parameters thought to influence heat flow around the installation. It is not likely that many heater manufacturers would have the required data on the performance of their particular heater model which would be needed to enable acceptably accurate predictions to be made. Such data include mass flow rates, combustion efficiency, internal firebox temperatures and flue gas temperatures, and their dependence on fuelling rate and air inlet control.

Correlation with Other Work

In efforts to assess the reproducibility of the test rig, confidential data, supplied by members of the solid fuel heating industry in New Zealand, have been examined and compared where appropriate with the findings of the present work. Correlation has been found, within the apparent experimental error range of 5-10 °C for temperature maxima at stability. Similarly the times to reach stability are in good agreement.

It has not been considered worthwhile to look for correlation of the present work with some, superficially similar, work carried out overseas. Peacock (1987c) reported the results of experimental work involving an open fireplace construction with and without an insert heater installed. However there are sufficient differences in the detail of construction, fuelling and appliance type to make comparison of data with the present work meaningless.

The same argument holds in regard to the work by Walker and Fletcher (1987) and reinforces the need for caution in using data from this field of research for comparative purposes. Only the most general of conclusions can be drawn and, from a safety viewpoint, it is apparent that all workers accept the need for protection of wood-based materials from long-term exposure to temperatures of 100 °C, as an upper limit, see for example McGuire (1969), Matson, Dufori and Breen (1959) and Forest Products Laboratory (1958). This is reflected in current New Zealand Standards and a major outcome of the present work has been to confirm that existing construction and installation requirements will meet internationally accepted levels of safety.

Recommendations for Future Work

As discussed above, before the test method used in this work could be recommended for inclusion in a current Standard, further work would be needed to establish its repeatability and reproducibility with particular attention paid to the effect of ageing of the rig components on heat transfer characteristics.

Further progress is possible with the mathematical model. When solid fuel heaters are inserted into existing fireplaces it is possible to make some useful approximations in modelling the performance of the fire within the heater which cannot easily be done for the case of an open fire. Empirical information exists connecting mass flow rates and combustion temperatures, see for example Neulicht (1982), which allow calculation of the flow of the flue gases and simultaneous heat transfer from them. This can be done using a simple one-dimensional model with stack buoyancy pressure driving the gases through the various flow resistances in their flow path. A model of this type has been constructed during the present work and some preliminary data collected of flow resistances through a heater and up the chimney. Probably the heater, fireplace and surrounds would need to be modelled three-dimensionally, which confronts the modeller with complex geometrical problems.

The model described here has obvious applications in other areas of heat flow through structures at fire temperatures. The capacity to handle phase change would have to be added if accurate transient data were required.

For any useful comparison of incident data between New Zealand and other countries, and indeed for adequate analysis of local data, changes to the coding and reporting system used by the New Zealand Fire Service would be required. Recommendations for such changes will be made in due course. In reporting incidents it is of course true that a final analysis can only be as good as the data entered and so continuing emphasis will be placed on the need for education and awareness of all of those involved in the reporting of fires as well as those engaged in construction and installation of fireplaces and insert heaters.

CONCLUSIONS

Present requirements for timber to concrete/masonry clearances, being 25 mm for open fires and 50 mm for insert heaters, have been confirmed as adequate. If New Zealand Standards and Manufacturers' Installation Instructions are not complied with, a fire safety hazard exists.

It is possible to correlate some hazards identified experimentally with field incidents for both open fireplaces and insert heaters.

A test rig has been developed for assessing the performance of an open fireplace and an insert heater. Knowledge has been gained of the repeatability and reproducibility in using the rig for both open fireplaces and insert heaters.

A mathematical model has been described to extend the range of useful predictions that can be made on the temperatures on combustible materials around fireplaces. No claim is made for high accuracy of the predictions of the model, for much important information, particularly the performance of the fire itself, is not well known. However the model predictions are accurate enough to allow decisions to be taken on what clearances are likely to be safe for a range of designs and clearances that have not been tested experimentally. The model has been written in a very general fashion, allowing it to be used in other fire situations.

An attempt was made to compare data from the testing of inserts and open fireplaces in New Zealand, USA and UK. Reasons have been identified for the general incompatibility of the data.

Recommendations have been made on the need for further work in the areas of reproducibility of the test method, improved mathematical modelling techniques and fire incident data collection.

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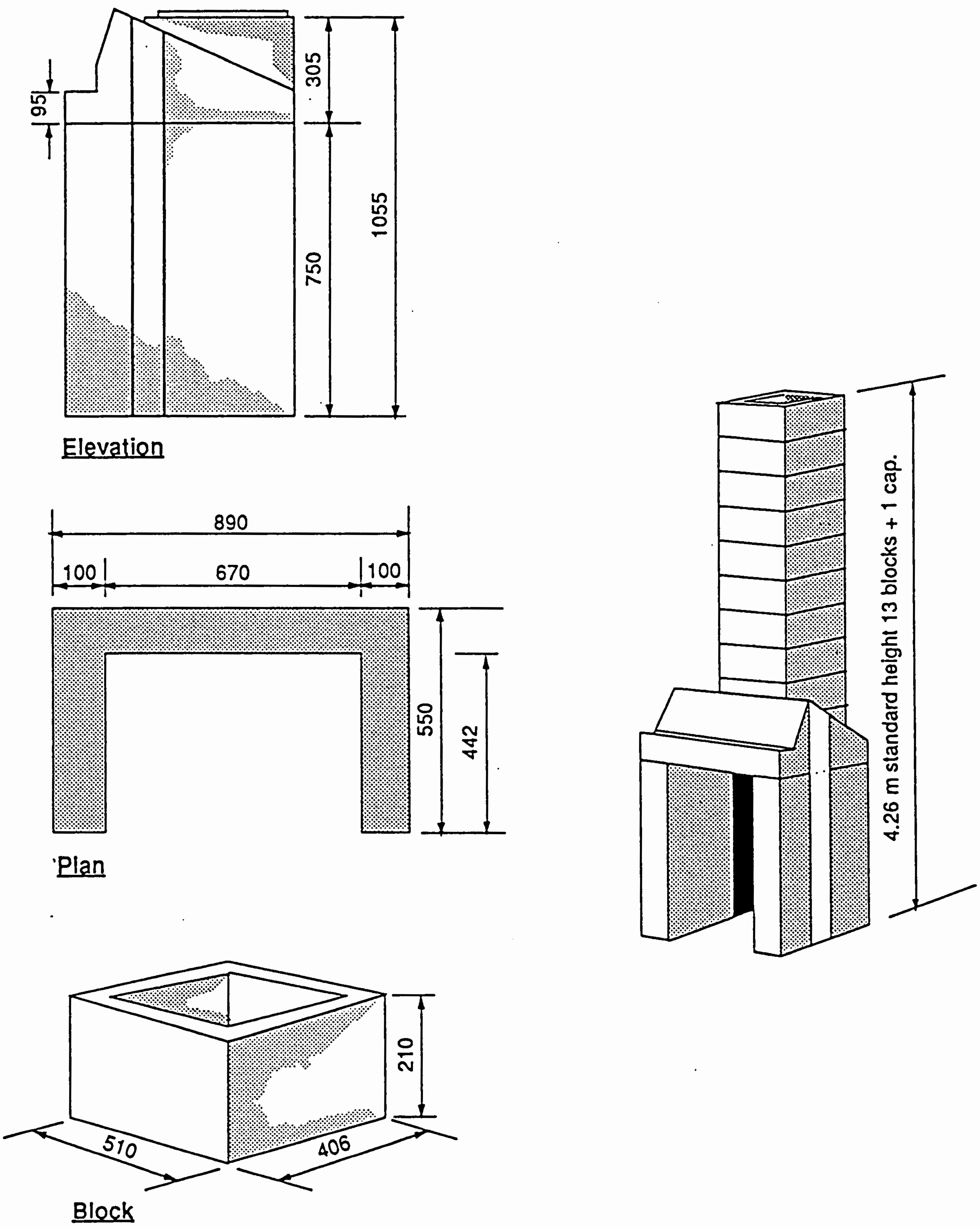


Figure 1: Data sheet for 'Firth Industries' precast pumice concrete chimney.
Standard exterior design, as built dimensions.

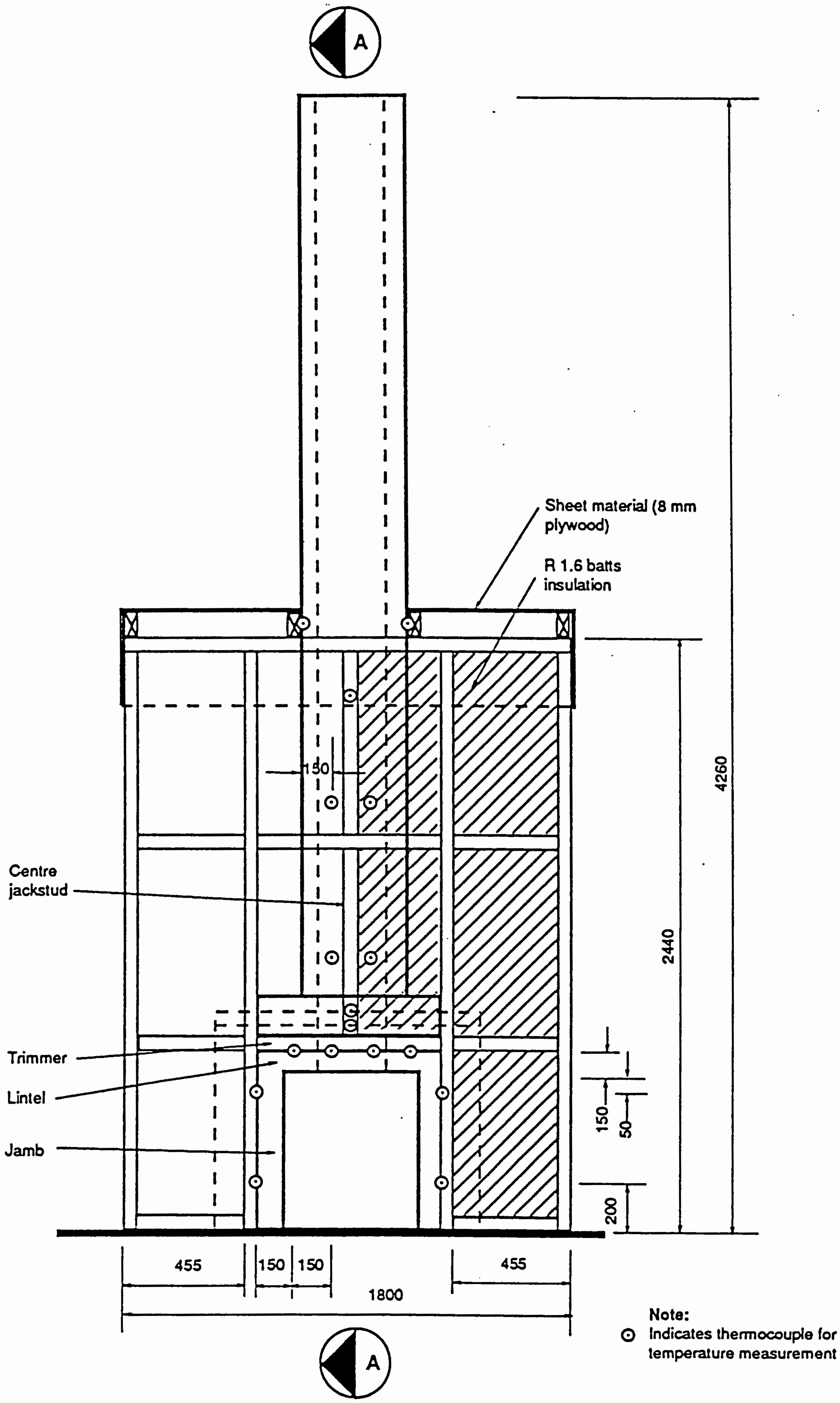


Figure 2: Elevation of Fireplace, Chimney, Framing and Thermocouple Arrangement

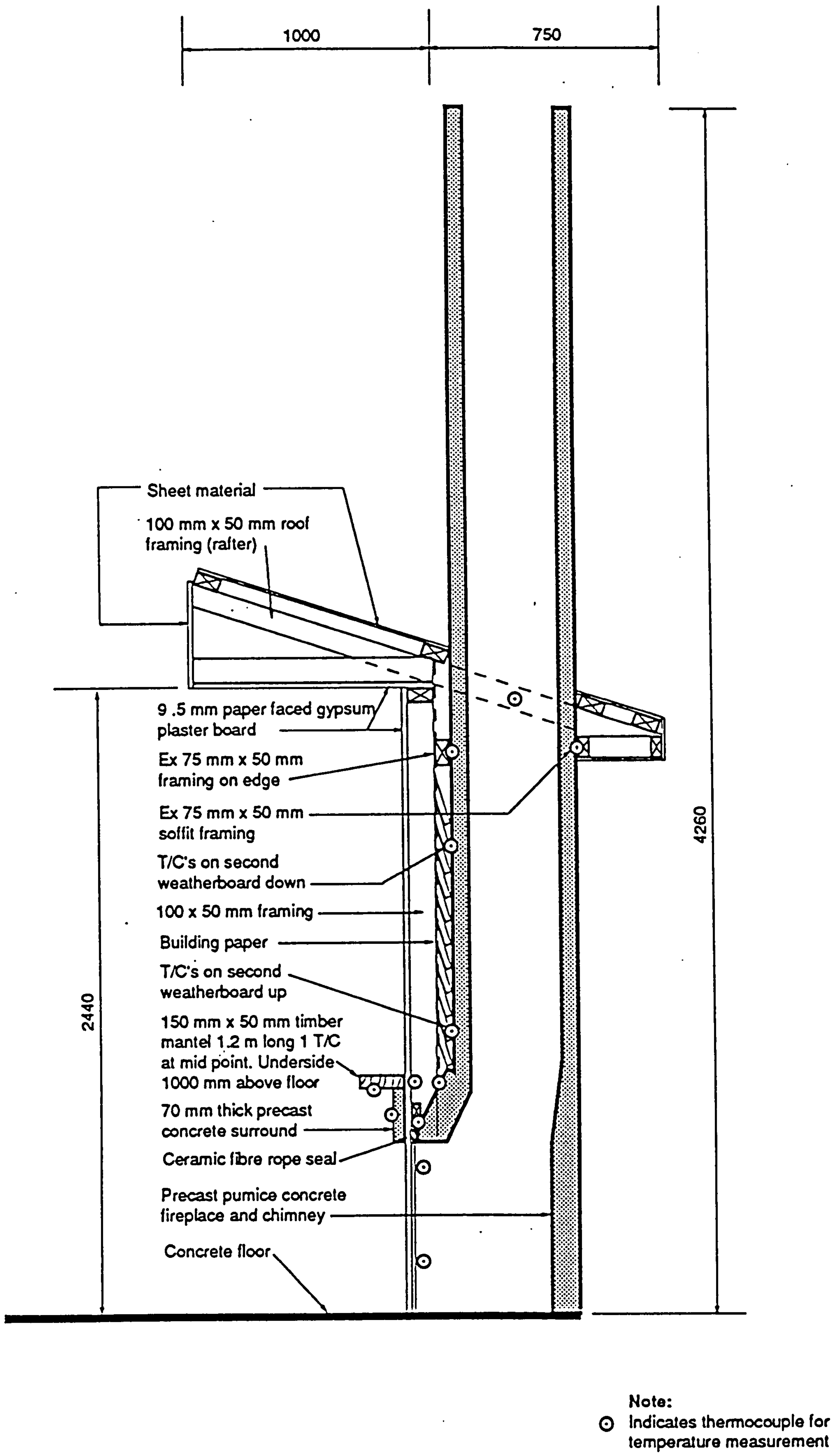


Figure 3: Section A-A of the Experimental Rig

Figure 4: Test rig during construction, with framing at 25 mm clearances.

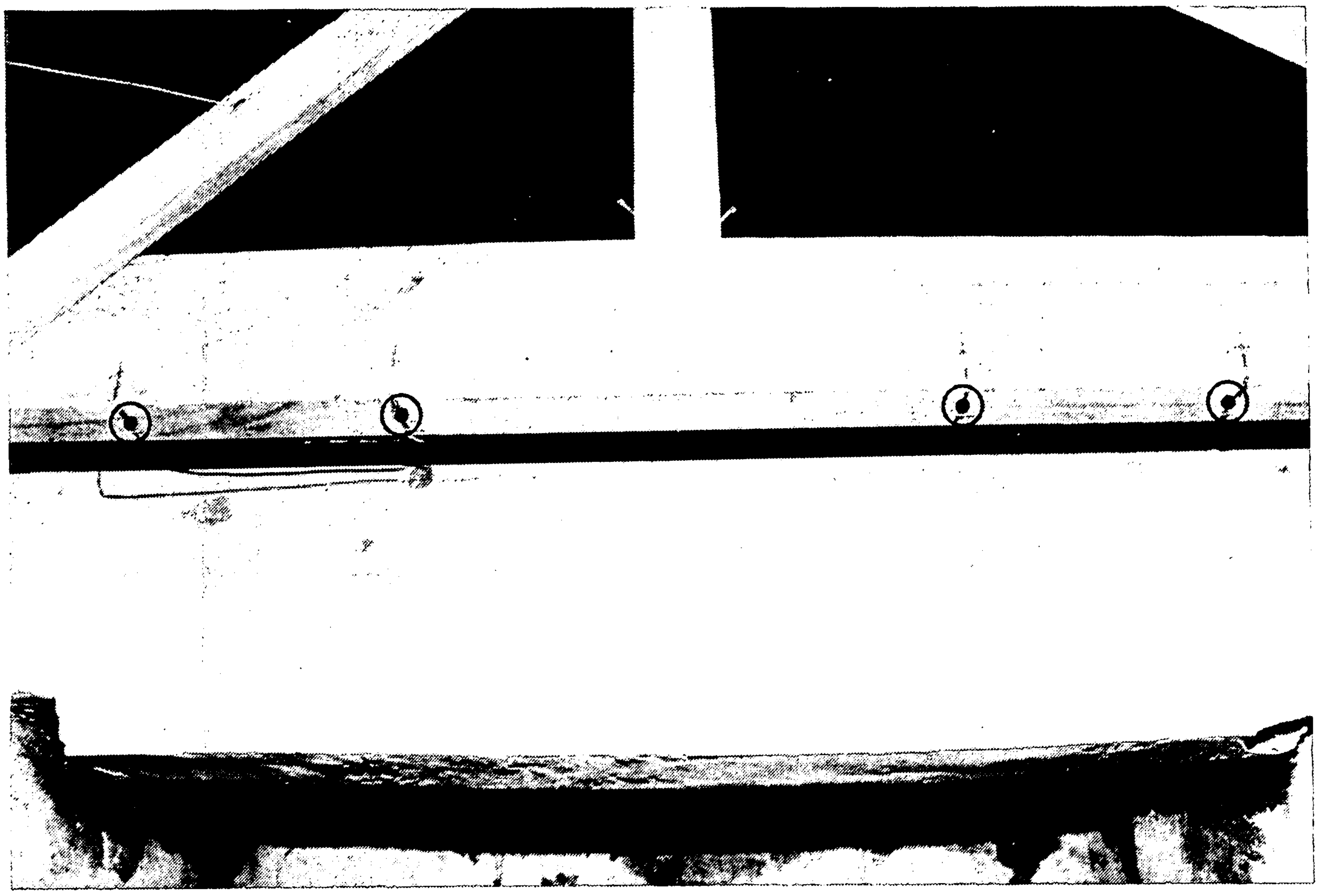


Figure 5: Test rig detail of trimmer and lintel area showing 25 mm clearance and position ⊙ of thermocouples on timber.

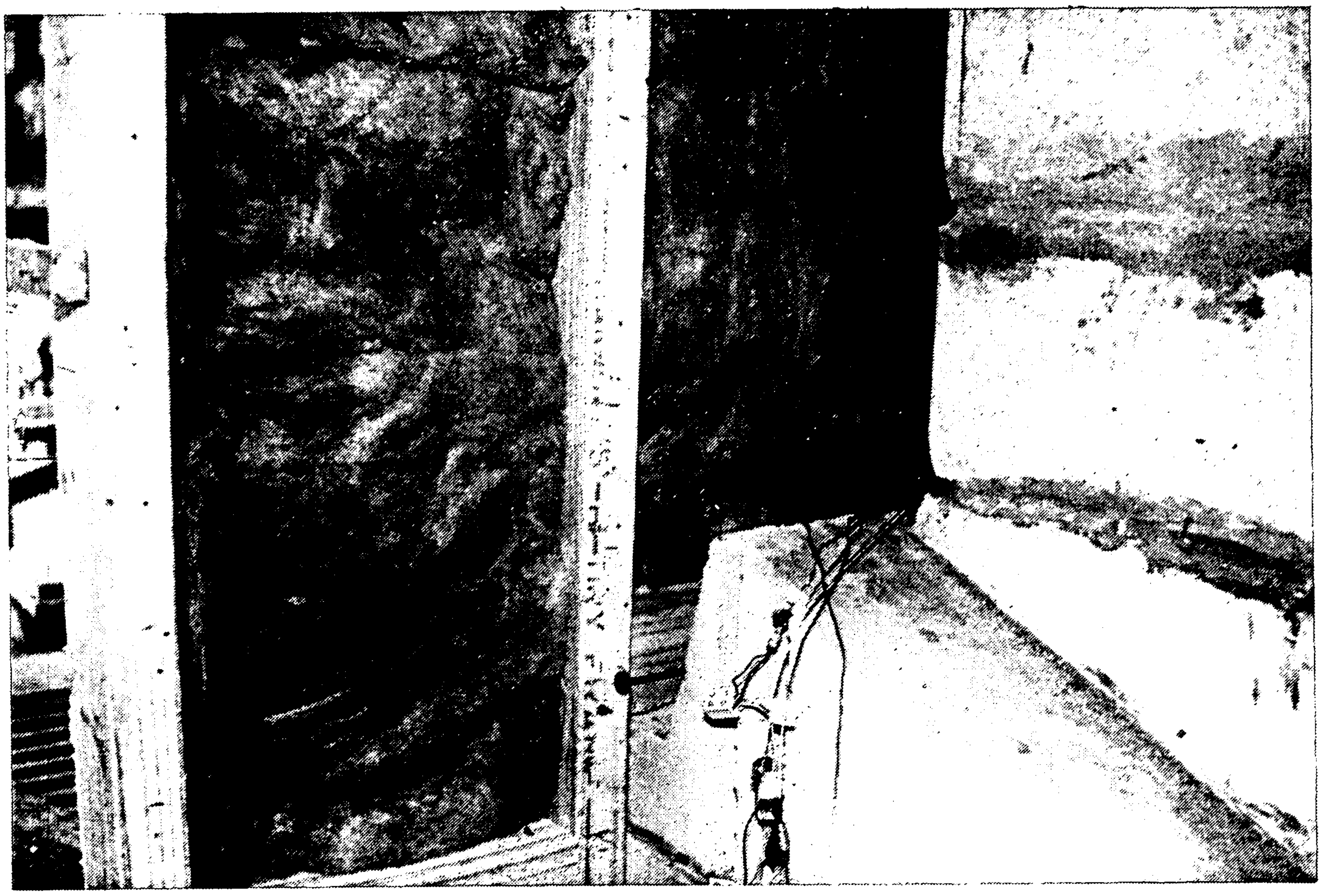


Figure 6: Test rig detail prior to weatherboard installation.

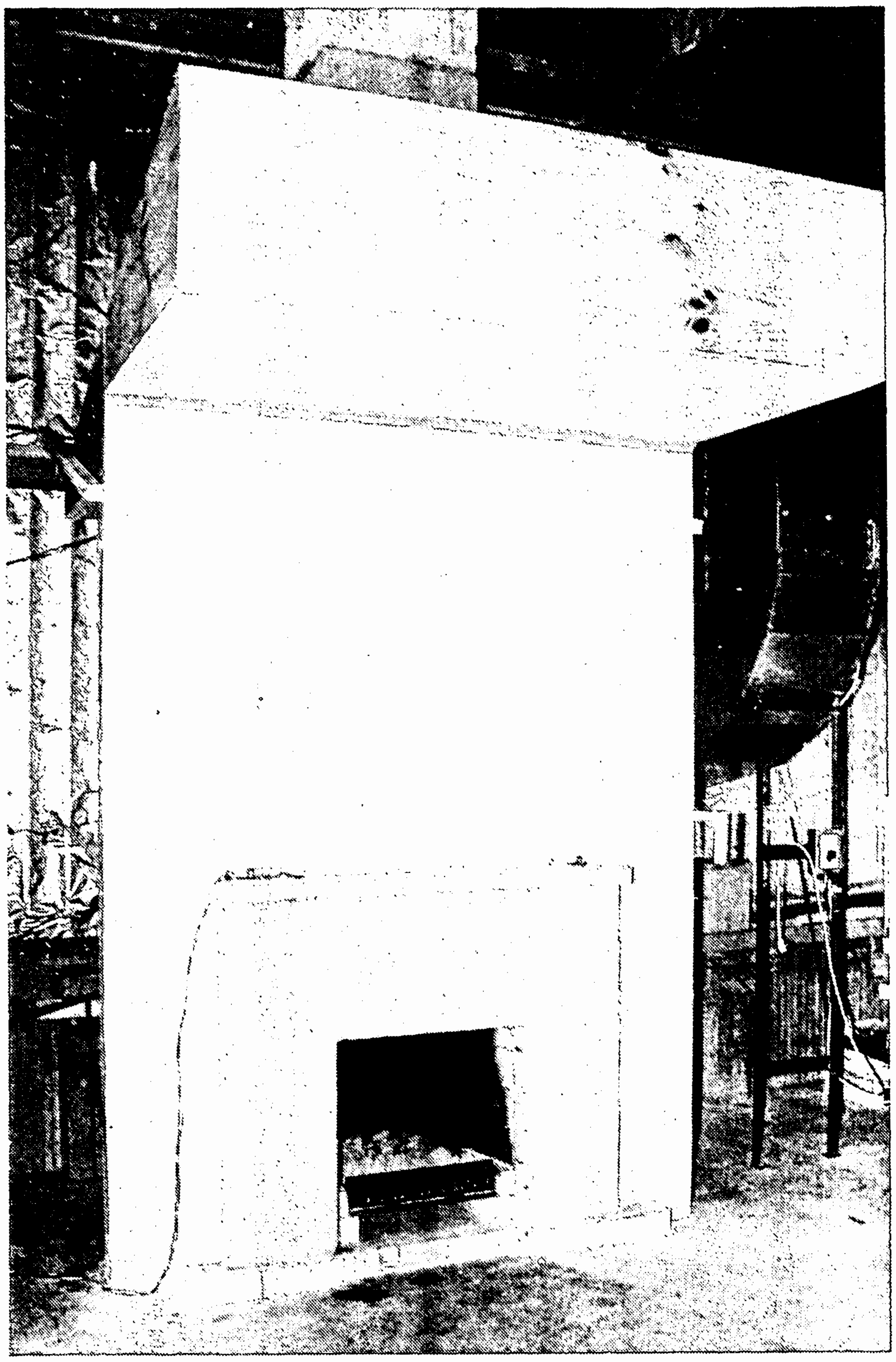


Figure 7: Test rig used as an open fireplace, (before addition of side walls and extension of ceiling).

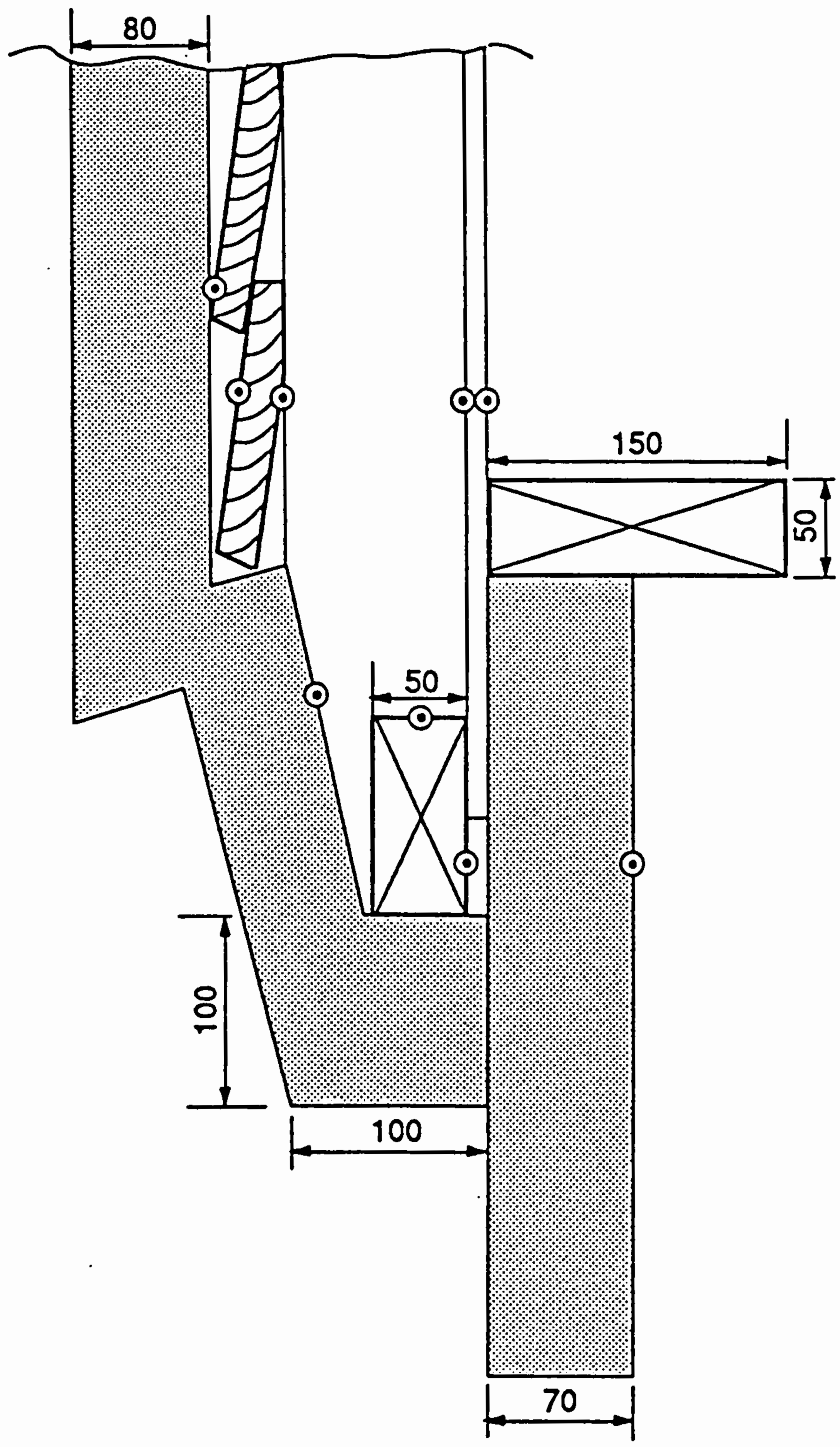


Figure 8: Thermocouple placement (⊙). Uninsulated side, 75 mm from edge of centre jackstud.

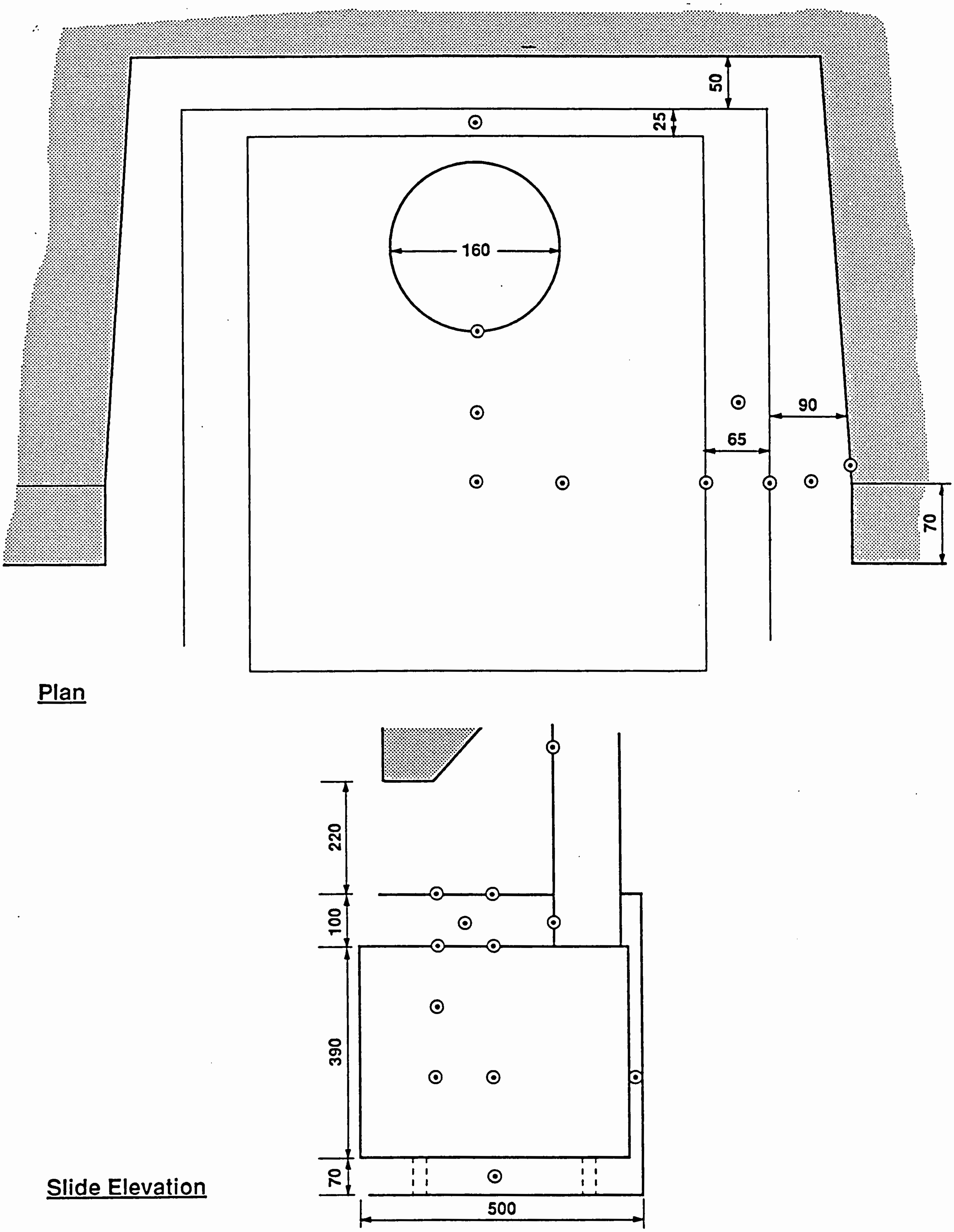


Figure 9: Thermocouple placement (⊙). Insert heater.

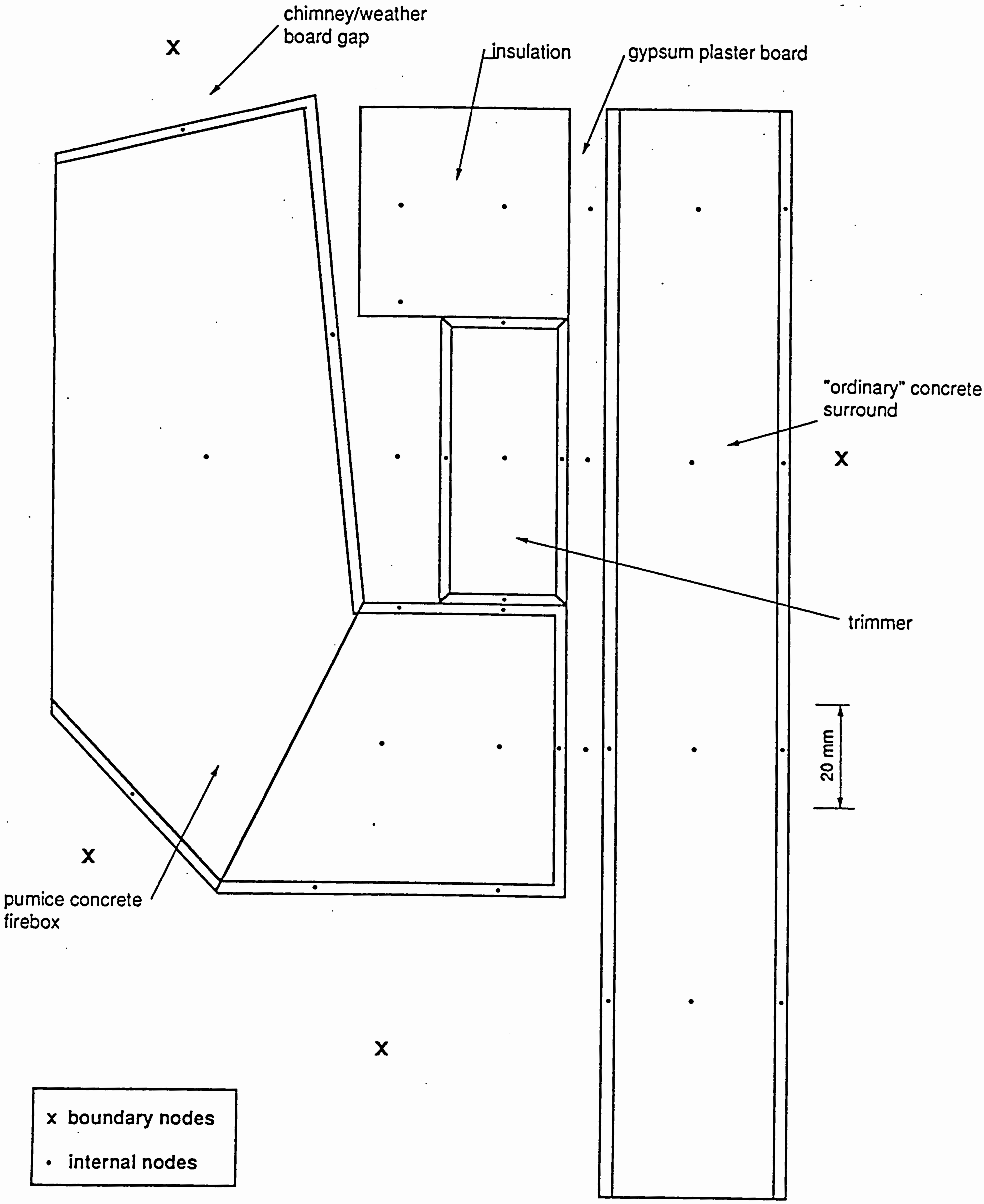


Figure 10: Vertical section through pumice concrete fireplace and surround showing position of nodes (zero clearance) in the lintel region.

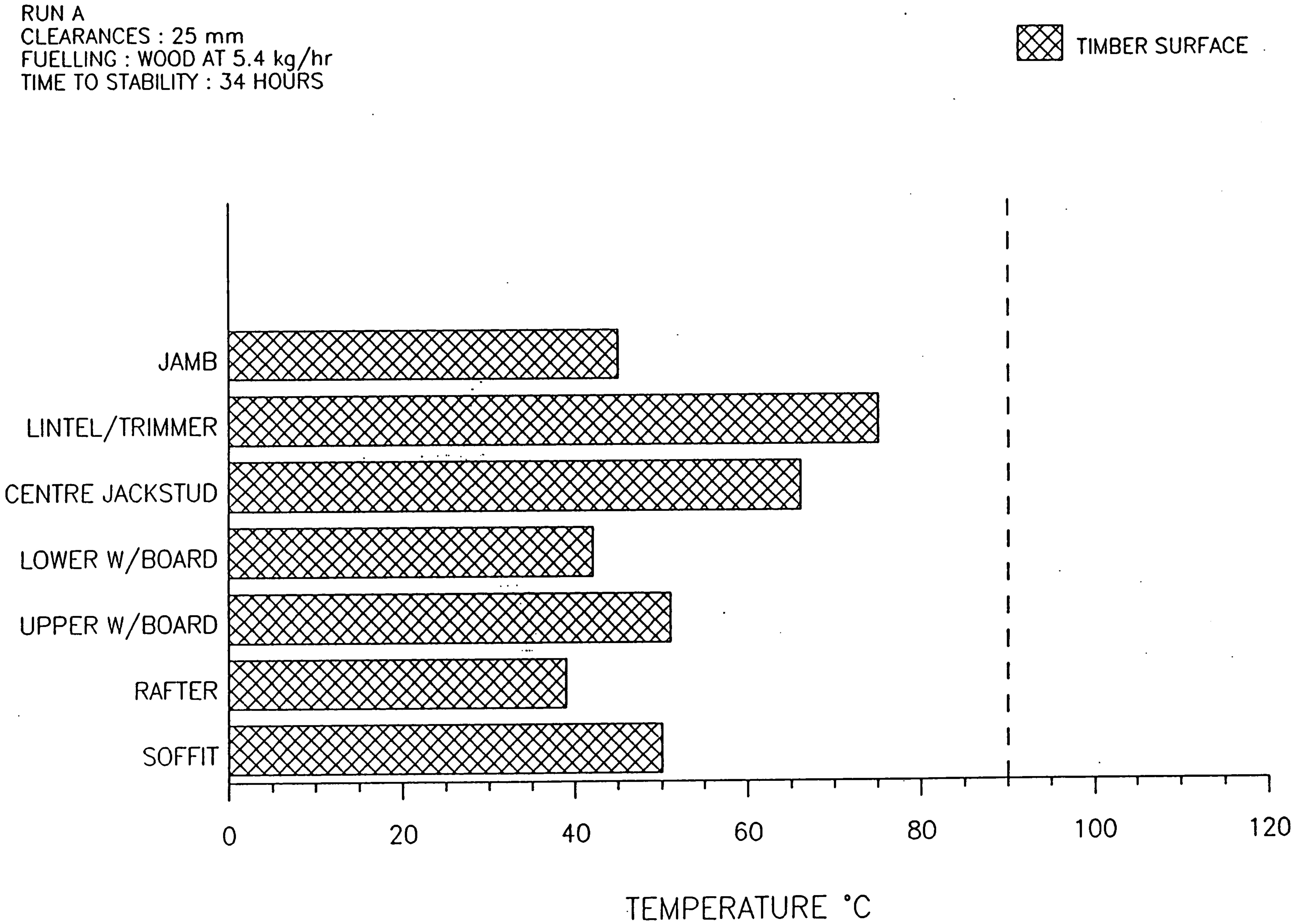


FIGURE 11 : TYPICAL TEMPERATURES IN RIG
– OPEN FIREPLACE

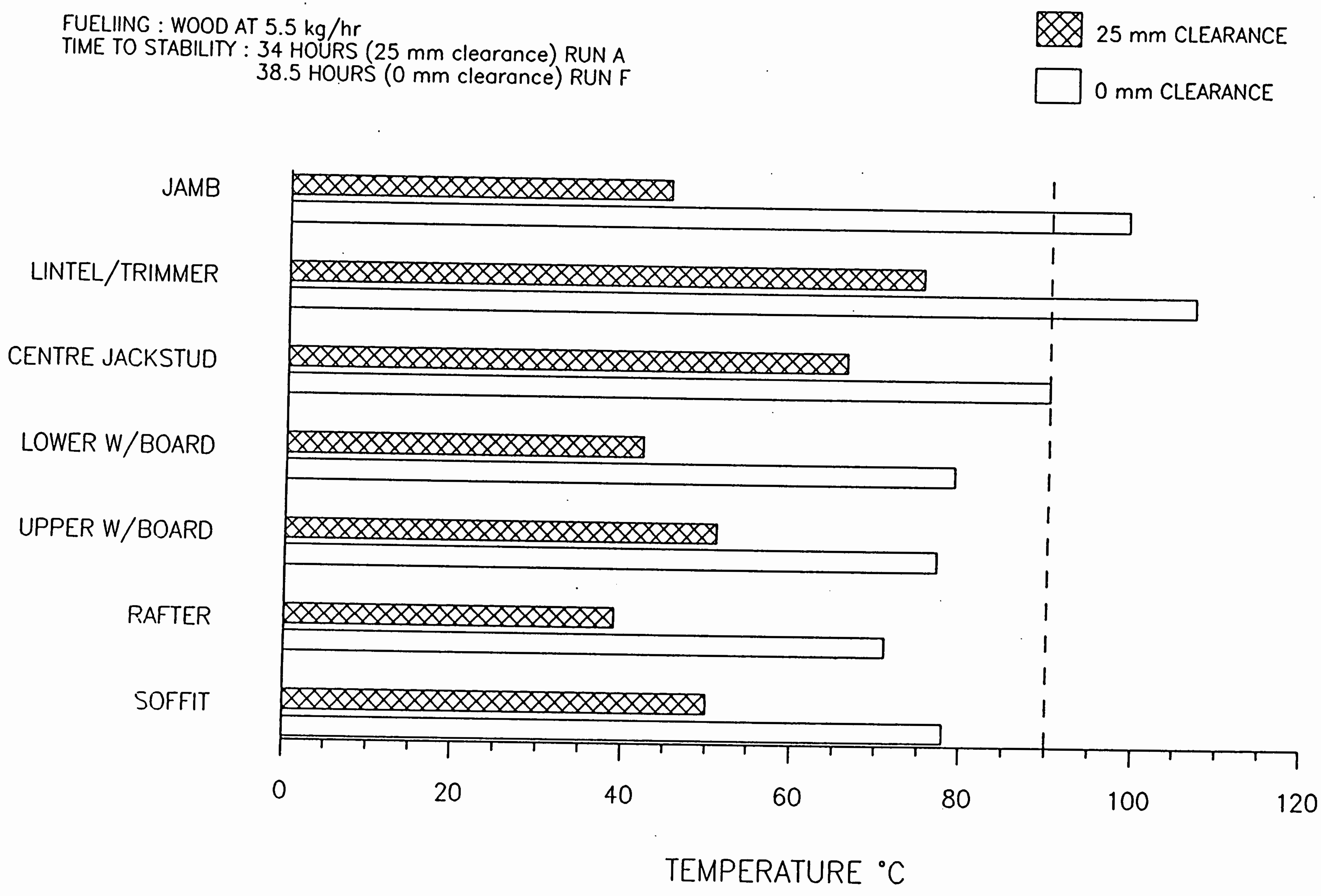


FIGURE 12 : RELATIONSHIP BETWEEN MEASURED TIMBER SURFACE TEMPERATURE AND TIMBER-TO-CONCRETE CLEARANCES – OPEN FIREPLACE

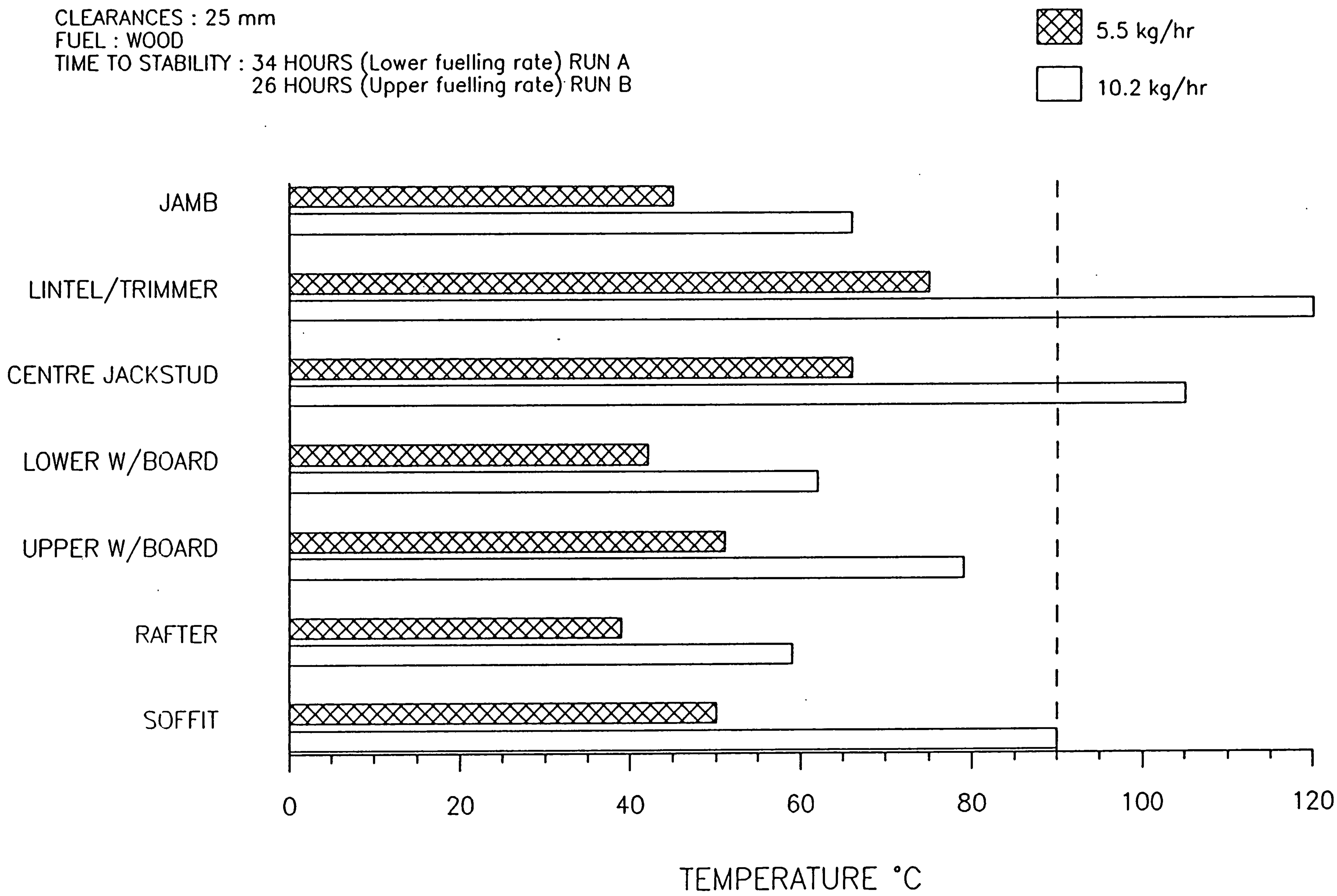


FIGURE 13 : RELATIONSHIP BETWEEN FUELLING RATE AND MEASURED TIMBER SURFACE TEMPERATURES – OPEN FIREPLACE

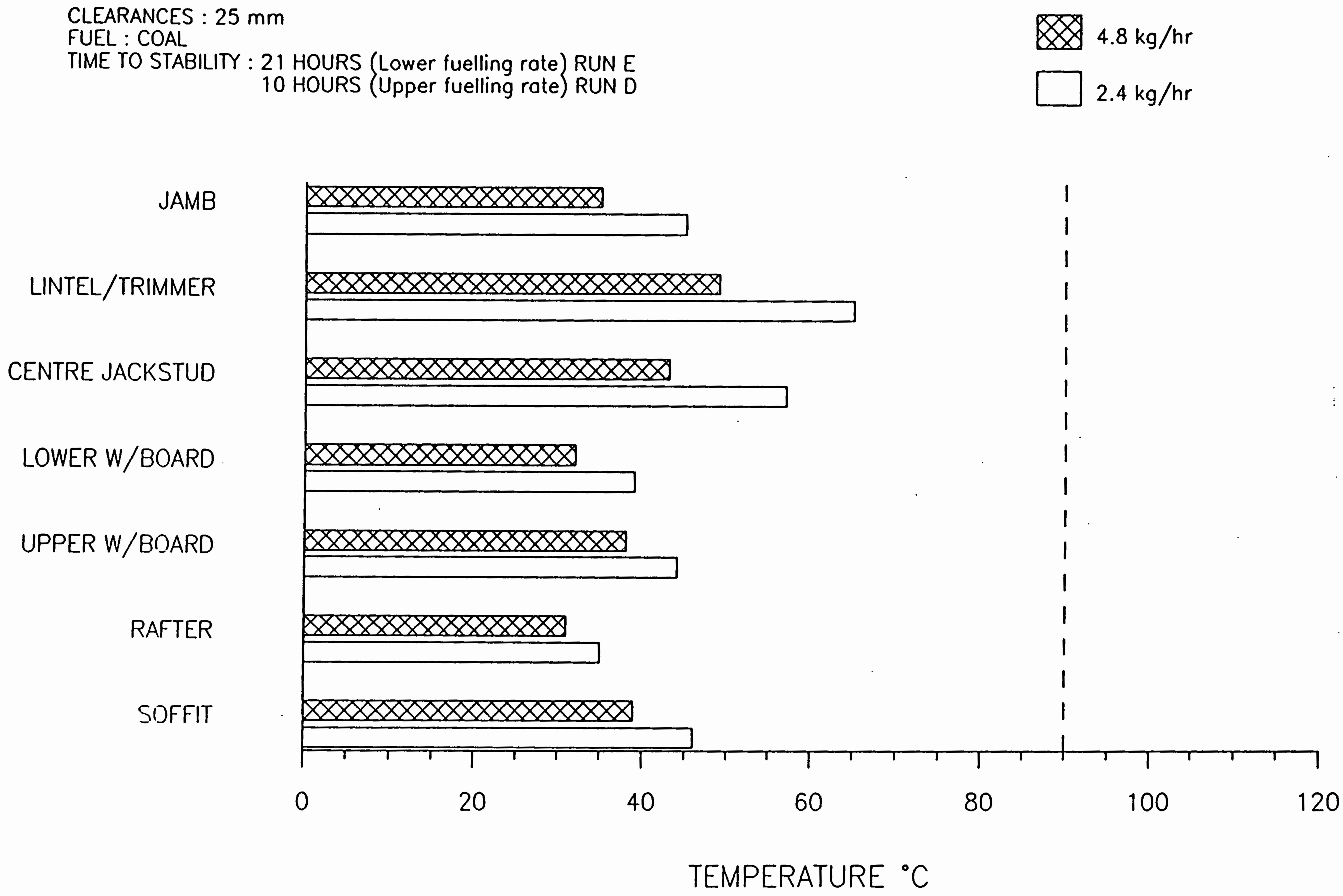


FIGURE 14 : EFFECT ON TIMBER SURFACE TEMPERATURES OF FUEL TYPE
– OPEN FIREPLACE

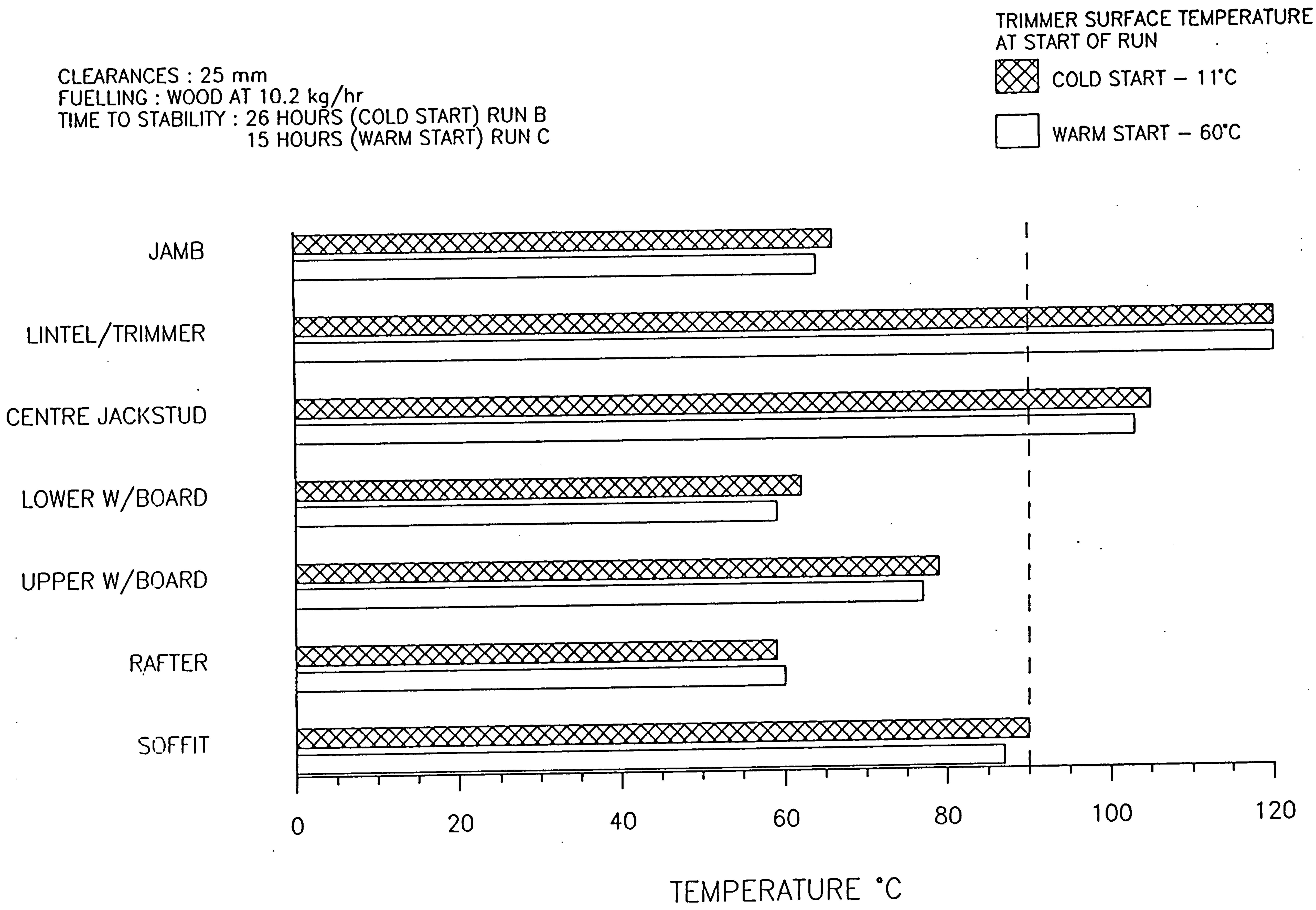


FIGURE 15 : EFFECT OF RIG STARTING TEMPERATURE ON TIMBER SURFACE TEMPERATURES – OPEN FIREPLACE

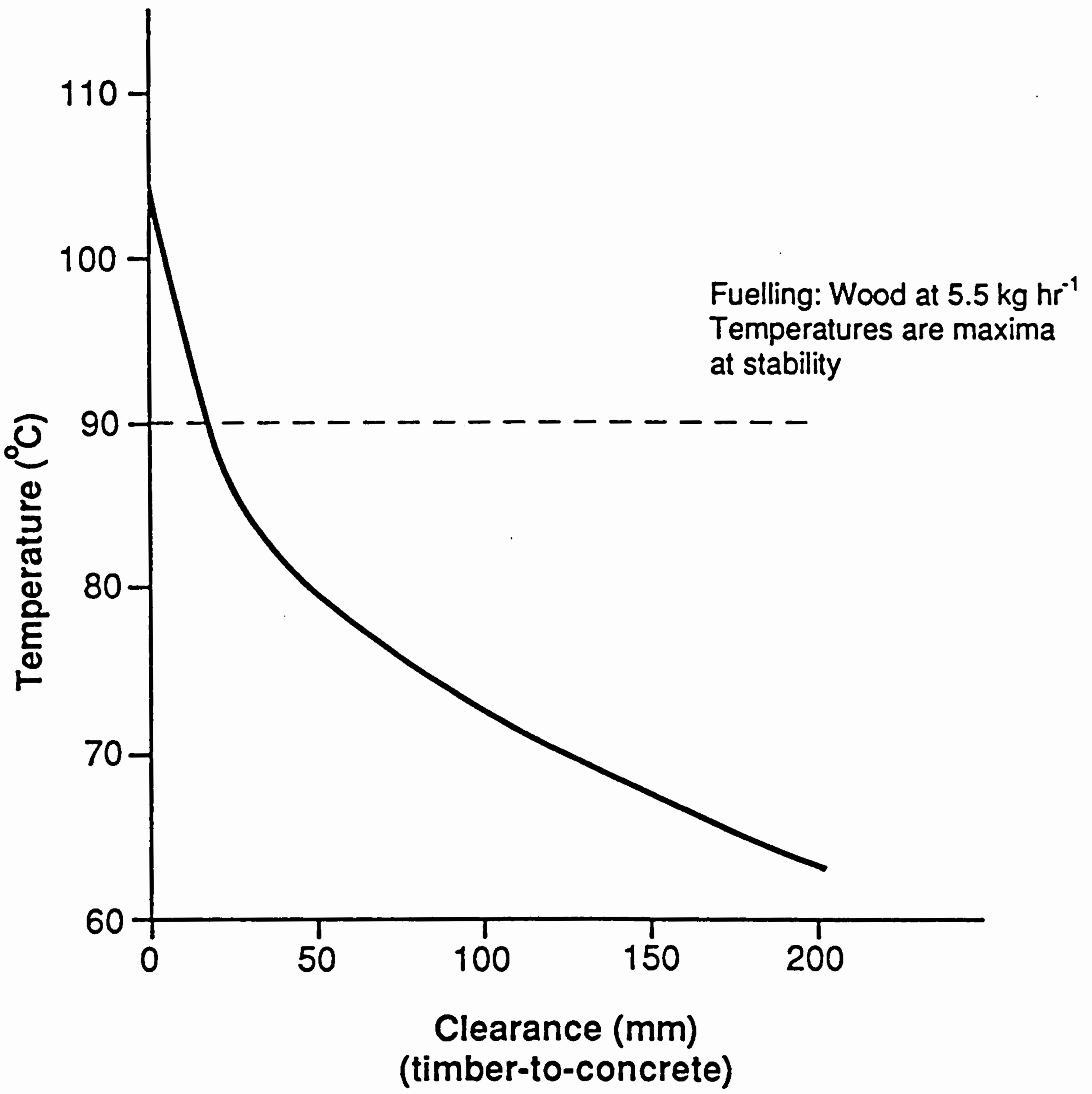


Figure 16: Predicted temperature of trimmer surface in pumice concrete open fireplaces

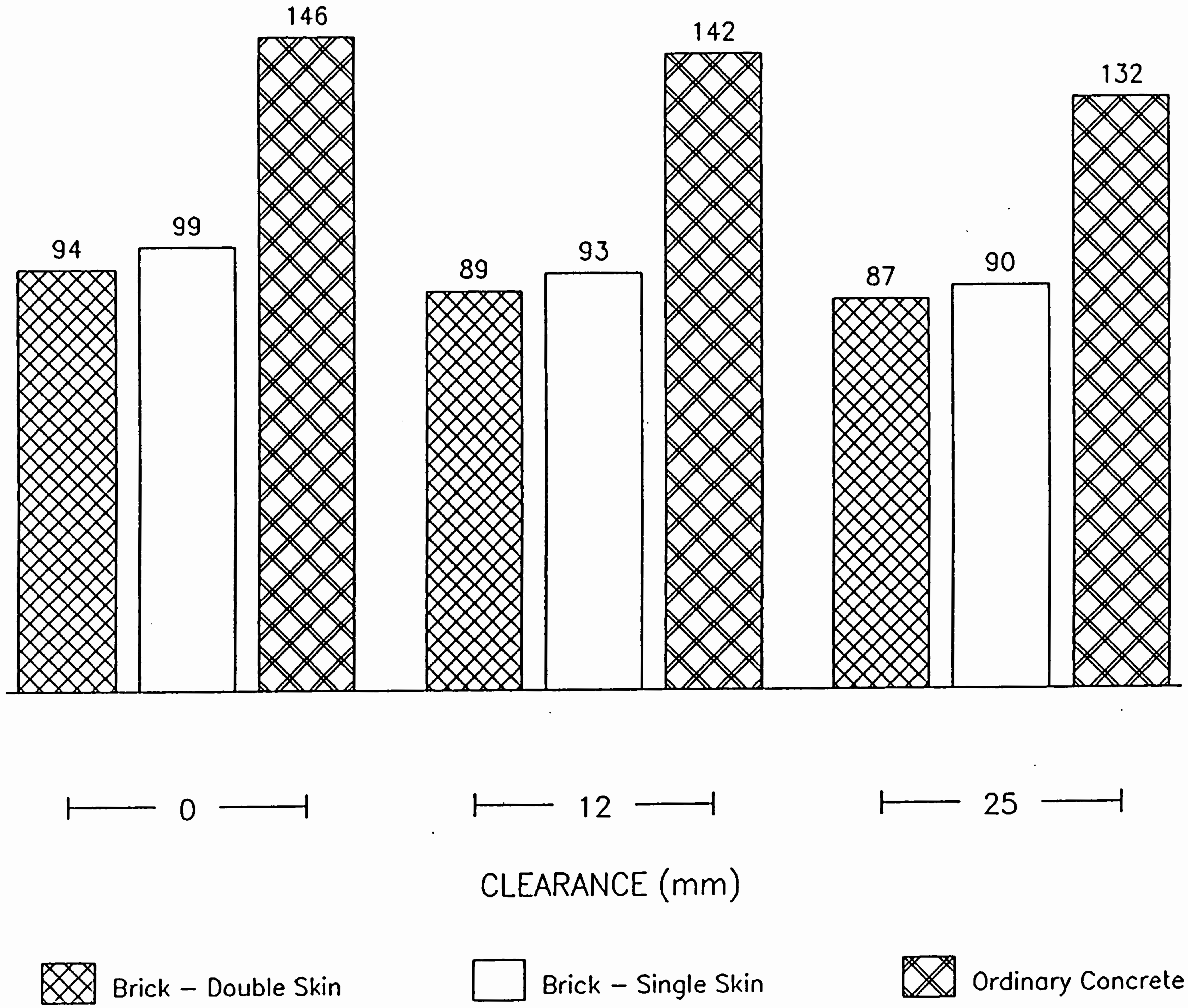
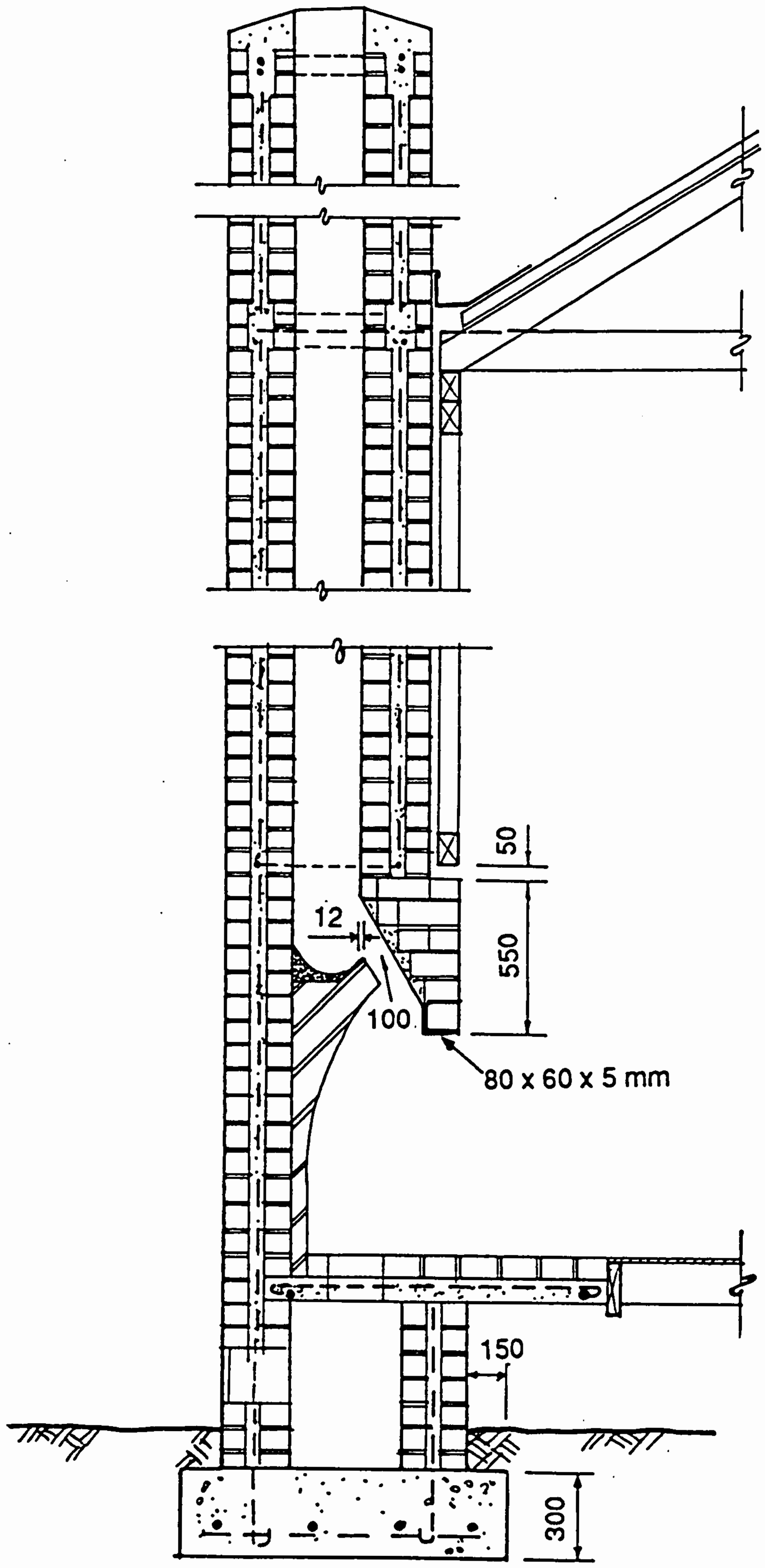
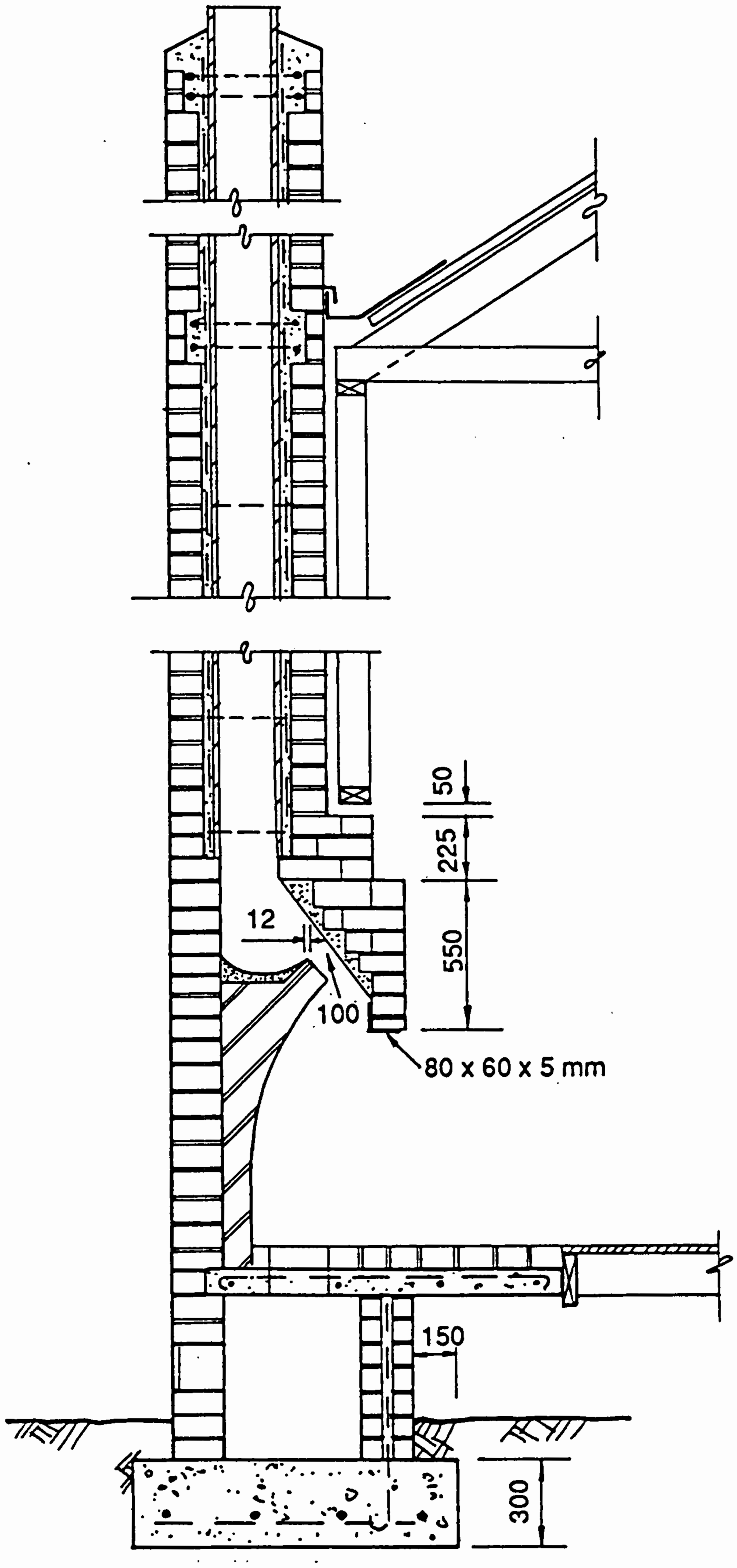


FIGURE 17 : PREDICTED TEMPERATURE (°C) OF TRIMMER SURFACE IN BRICK AND ORDINARY CONCRETE OPEN FIREPLACES



Vertical Section

Figure 18 : Reinforced brick chimney using half bricks/full bricks or half bricks on edge (PACRA, 1981)



Vertical Section

Figure 19 : Reinforced brick chimney with flue liner (PACRA, 1981)

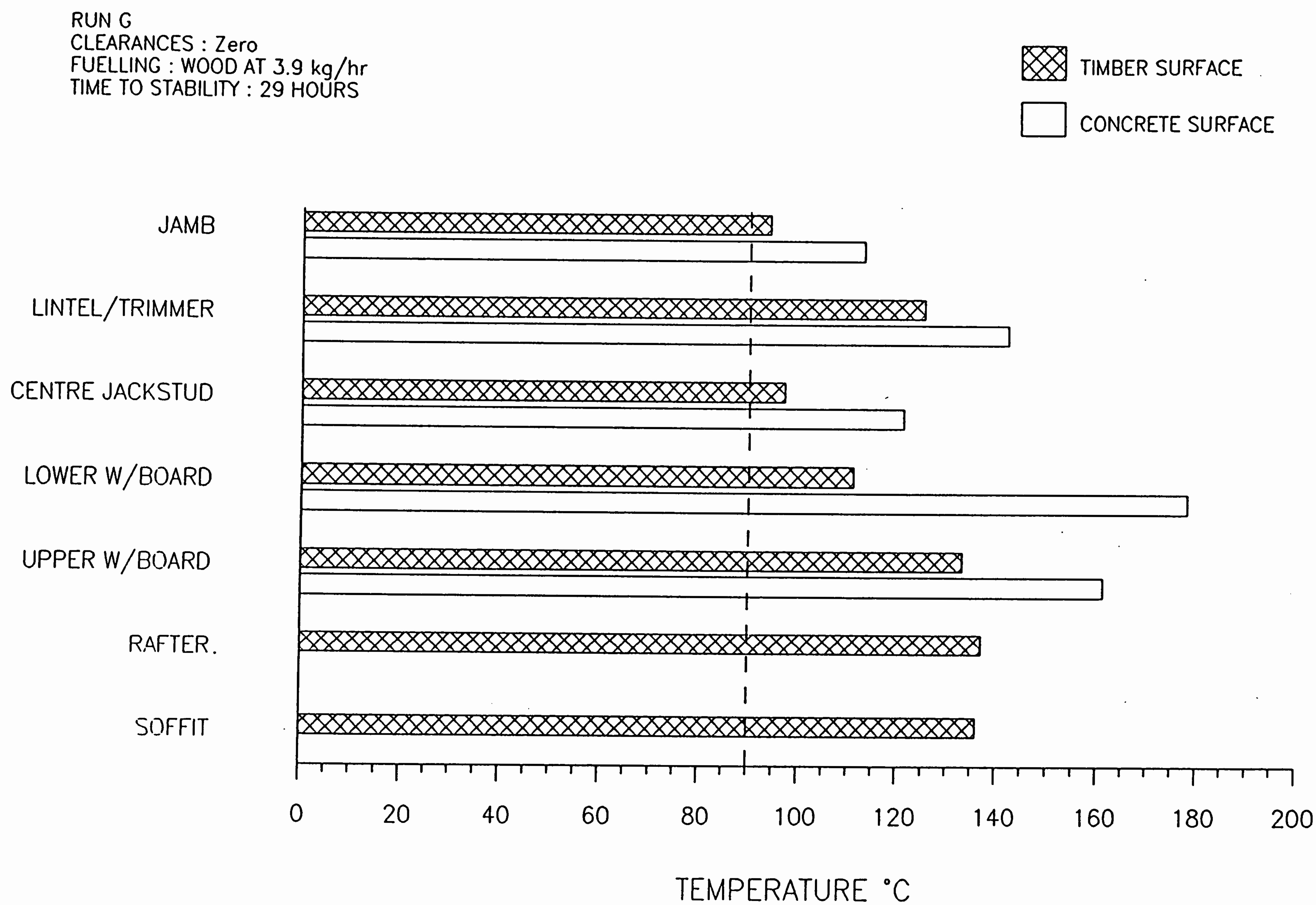


FIGURE 20 : TYPICAL TEMPERATURES IN RIG
– INSERT HEATER, "HAZARDOUS INSTALLATION"

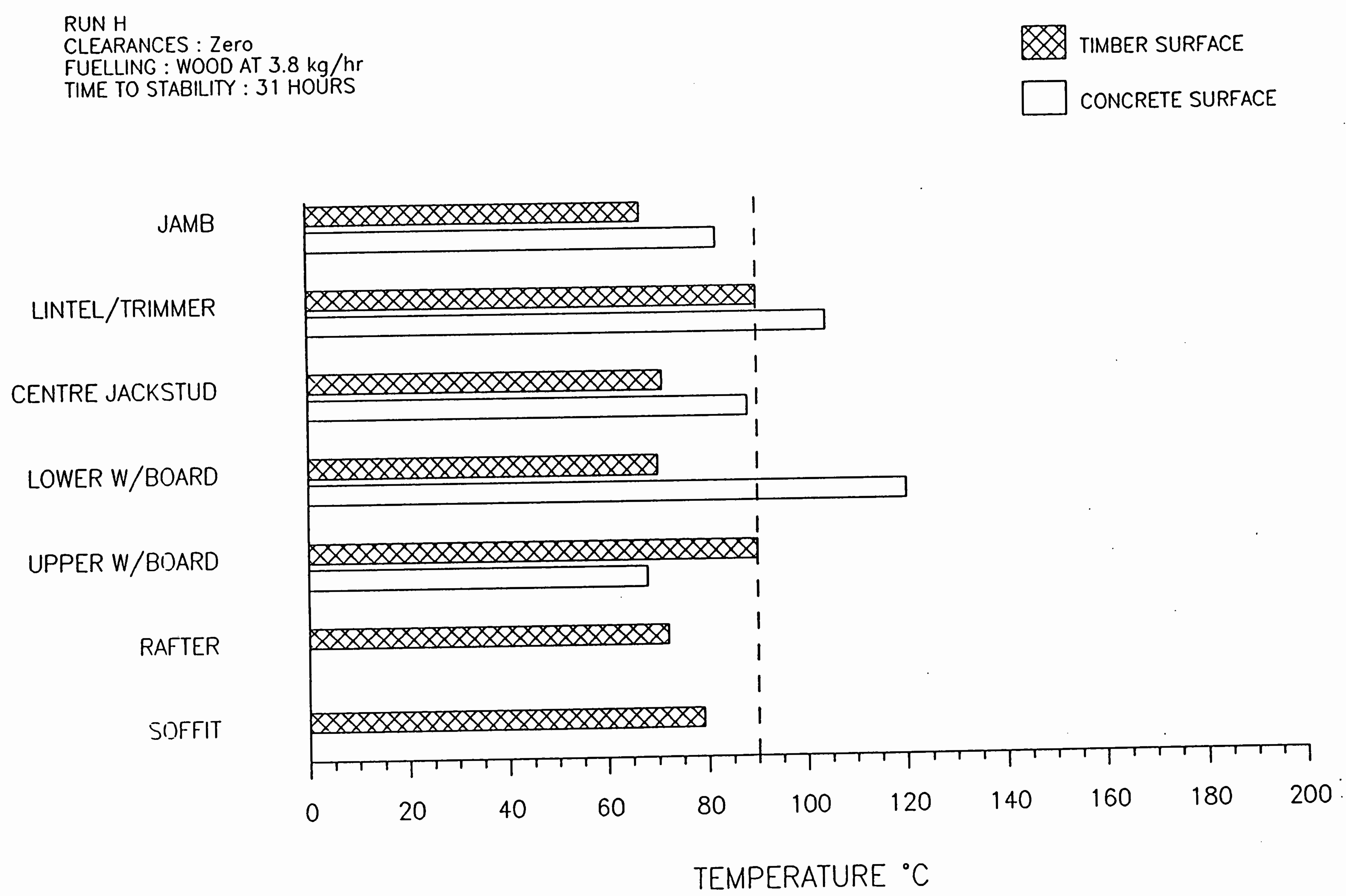


FIGURE 21 :TYPICAL TEMPERATURES IN RIG
– INSERT HEATER, "RECOMMENDED INSTALLATION"

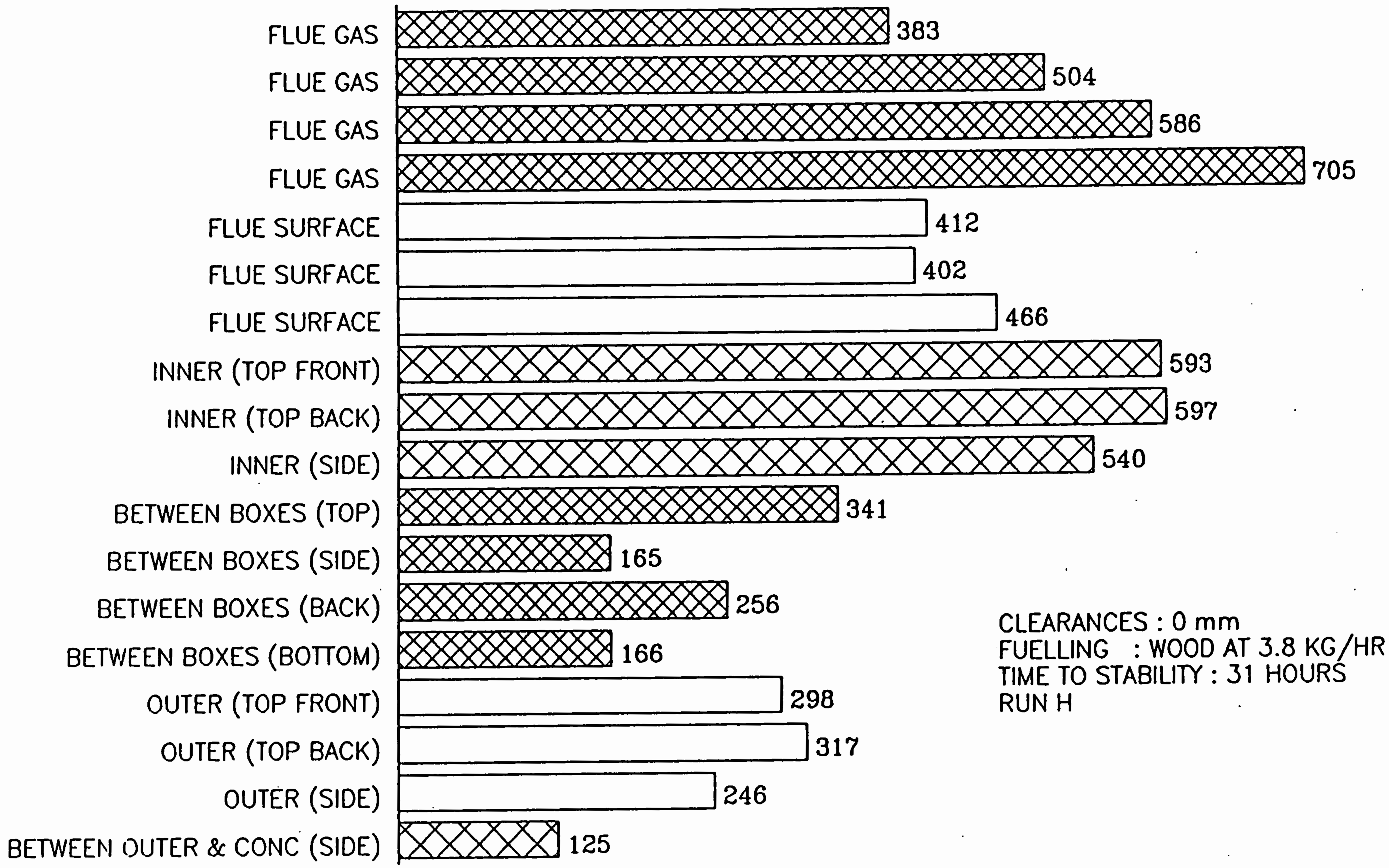


FIGURE 22 : TEMPERATURES (°C) OF INSERT HEATER, FLUE AND FLUE GASES
(RECOMMENDED INSTALLATION)

Open fireplaces and inser
t solid fuel stoves : an

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