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by

G. T. Tamura and A. G. Wilson

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PREFACE

The Division has been aware, for many years, of many of the difficulties presented by domestic chimneys. Not only must a chimney operate satisfactorily as a gas venting device, for which purpose it must produce draft, but it must also provide protection against the ignition of materials adjacent to it. The problems are greatly increased because the conventional chimney is constructed as a part of the house, and yet must serve any fuel-burning appliance that may subsequently be connected to it.

A small laboratory has been developed for the study of the thermal and fire hazard aspects of chimneys. A first report on the work carried out over the past several years is now presented. It deals with the difficult matter of the test methods and criteria to be applied to chimneys to determine their fire safety, and presents the results of experiments which have been carried out to date. This work is continuing. The authors are mechanical engineers; Mr. Tamura is a research officer with the Building Services Section and Mr. Wilson is Head of that Section of the Division of Building Research.

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N. B. Hutcheon
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G.T. Tamura and A.G. Wilson

The function of a chimney is to provide for the safe discharge to outdoors of flue gases from heat-producing appliances. To do this the chimney must not only provide adequate draft at all times, but it must also prevent overheating of adjacent construction and must remain gas tight and structurally sound under the extreme conditions to which it may be exposed. This has long been recognized by building officials and Code authorities, and standards for construction of masonry chimneys and clearance requirements intended to ensure safety have gradually evolved.

Standardization of masonry chimney construction has been encouraged in Canada by publication of the National Building Code (NBC). Both the 1941 and 1953 issues of this advisory document, following the approach of the National Board of Fire Underwriters (NBFU) of the United States, have specified in detail a method of designing and constructing masonry chimneys considered suitable for the venting of appliances burning any fuel. As do most Codes, the NBC envisages less restrictive requirements for the protection of flues serving gas appliances that produce flue gas temperatures not exceeding 550°F. Further standardization of vents for gas appliances has resulted from the publication in 1958 by the Canadian Standards Association of the Installation Code for Gas Burning Equipment.

The descriptive requirements for the standard masonry chimney generally envisage solid unit masonry or concrete carried to footings and self supporting, usually with a clay tile flue lining. In recent years chimney materials and methods of construction have been developed which cannot always be evaluated in terms of these descriptive requirements. There are two general groups of chimney constructions in this category. One group consists of preformed masonry chimney blocks of different materials, forms, and thicknesses. Those forming the second group are factory-built chimneys, which in general are light, insulated structures, usually metal covered, intended to be supported from the house framing.

Preformed masonry chimney blocks are usually made of concrete, pumice or expanded slag aggregate and usually form either a whole, or half, segment of a chimney. The mating horizontal surfaces of the units may be flat or may interlock to improve the mortared joint. The concrete surrounding the central hole may be solid or contain air spaces. The assessment of various forms of precast masonry blocks is simplified to the extent that chimneys constructed of these closely resemble standard masonry chimneys. So long as the walls are 3 3/4 in. of solid concrete, and separate clay chimney liners are used, the intent of the descriptive requirements for the standard masonry chimney appear to be met. However, when the walls provide less than 3 3/4 in. of solid concrete, when lightweight aggregates are used, or when units are intended for use without separate clay tile liners, the extent to which the assemblies are equivalent to the standard masonry chimney with regard to thermal resistance, dimensional stability and structural strength, and gas tightness may be in question.

It is not possible to assess factory-built chimneys in terms of the descriptive requirements for the standard masonry chimney and this has led to the development of performance tests and requirements by Underwriters Laboratories Inc. These are published as "Standards for Safety of Chimneys, Factory Built", UL103. This has become the basis of listing of factory-built chimneys by Underwriters Laboratories of Canada. In addition to general design requirements, it outlines tests for the structural sufficiency of the assembly and durability of the liner, and a fire hazard test in which a chimney installation is simulated.

In the fire hazard test the chimney is enclosed in a typical construction. The initial test consists of three thermal shock tests of 1700°F flue gas temperature for 10 minutes with each test starting with the chimney at room temperature or four hours after the test, whichever occurs first. No temperature reading on the enclosure is taken. With the flue gas input at 1000°F the chimney is tested until equilibrium condition is reached, followed by a flue gas input of 1400°F for one hour. Temperatures of the enclosure and combustibles in contact with the chimney must not exceed 160°F at 1000°F flue gas input during the period ending 4½ hours of test and 185°F for any subsequent period, and must not exceed 210°F when flue gas input is maintained at 1400°F for one hour. The soot burnout test consists of flue gas input of 1000°F until equilibrium temperatures are attained followed by 1700°F for 10 minutes. The maximum temperature limit on the combustible is 242°F during this test and after the generator is shut off. Chimney assemblies passing the tests are regarded as acceptable for use with gas, liquid or solid-fuel-fired heating appliances and domestic incinerators in which flue gas temperatures generally do not exceed 1000°F.

Tests conducted on standard masonry chimneys (1) indicate that these fail to meet the U.L. thermal performance requirements for factory-built chimneys. It can be assumed that most chimney block constructions would similarly fail. This has led to questions about the adequacy of the standard masonry chimney construction and clearance requirements.

To assist in the further development of masonry chimney construction requirements, based on performance, the Division of Building Research has been engaged in a program of chimney testing. The tests have been designed to obtain further information on the thermal performance of the standard masonry chimney and the temperatures of combustibles in typical surrounding construction, to determine the relative thermal resistance of various masonry chimney constructions and their stability under thermal stressing, and to obtain some information on the behaviour of clay tile liners.

CONSIDERATIONS IN SELECTING TEST CONDITIONS

One of the major difficulties in assessing the safety aspects of chimney constructions is the selection of conditions that represent reasonable extremes to which the constructions are likely to be subjected. For purposes of developing information it was thought desirable to obtain performance records with extended exposure to flue gas temperatures of 500, 750 and 1000°F representing the range in extremes to be anticipated from various appliances under severe conditions. The value of 500°F relates to the maximum (550°F) usually specified in safety standards for gas-fired central heating equipment. The value of 750°F is the maximum selected for oil-fired central heating equipment by the Canadian Standards Association subcommittee developing standards for this equipment. A corresponding subcommittee on oil-fired space heaters has selected 1000°F as the maximum permissible flue gas temperature. This also appears to be representative of flue gas temperatures with forced firing of coal burning appliances where values of 800 to 1200°F are reported. Peak temperatures in excess of this occur with both coal and wood firing according to available information.

It will be recognized that under normal circumstances substantial reductions in flue gas temperature from the outlet of the appliance to the inlet of the chimney occur as a result of heat loss from the flue or vent pipe and bleeding of room air through draft hoods, barometric draft regulators, or plate dampers. As a result the temperature of flue gas at entry to the chimney may have a value only one half that at the appliance outlet. It is difficult to take this into account in selecting test conditions, since the effect is variable. The conditions referred to above, however, can be regarded as abnormally severe for the respective appliances.

Highest temperatures in chimneys are most likely to occur as a result of chimney fires. Chimney fires are unlikely with gas-fired equipment and well adjusted oil-fired central heating units. Fires do occur in chimneys venting some oil- and coal-fired units and are quite common with wood-burning appliances. Investigations in Norway (2) have shown that flue temperatures during chimney fires may range from 1250 to 2200°F over periods from 10 minutes to 1 hour. The highest mean temperature recorded during any one hour period was 1760°F. Based on this, and other information, conditions of 1400°F for 1/2 hour followed by 1800°F for 1/2 hour were chosen to represent chimney fire conditions for the tests reported herein.

Description of Equipment and Test Chimneys

The chimney studies were carried out in a small laboratory shown in Figs. 1 and 2. The portion of the laboratory in which the chimneys were tested was over two stories high and was separated into two spaces by a floor $14\frac{1}{2}$ ft above ground floor level. This was intended to permit the simulation of surrounding construction for inside chimneys serving $1\frac{1}{2}$- and 2-story houses. For the tests reported herein both upper and lower spaces were maintained at the same conditions.

A special propane furnace with forced air supply was used to generate flue gas. Its flue gas output could be controlled between 15 and 300 cfm (at standard conditions) at temperatures from 150°F to 2000°F. The propane was fired tangentially into a central chamber through four burners with individual controls. The quantities of propane and of primary and secondary air, and the temperatures of fuel, air and flue gas were measured. Propane quantities were measured with a wet test gas meter. Air volumes were measured with calibrated sharp edged orifices located in the end of a small orifice tank connected to the suction side of the furnace blower.

To obtain a uniform velocity distribution of flue gas entering the chimney, a metal egg crate straightner was placed in the insulated metal connecting pipe upstream of the thermocouple measuring the flue gas inlet temperature.

The temperatures of the chimneys and any adjacent construction were measured with chromel-alumel thermocouples connected to recording potentiometers for continuous records and a portable potentiometer for spot readings. Bare chromel-alumel thermocouples were used for flue gas temperature measurements and were checked with an aspirating thermocouple arrangement.

Initial measurements were made on a full scale brick chimney conforming to requirements in the 1953 N.B.C., the details of which are shown in Fig. 3. It was constructed of a single course of dry pressed solid clay brick (2 1/4 by 3 3/4 by 8) with $8\frac{1}{2}$ by $8\frac{1}{2}$ vitrified clay flue liner fully grouted.

The chimney was 27 ft in height, measured from the floor, with the thimble 3 ft 4 in. from the floor. Floor constructions built to National Building Code minimum requirements were located 1 ft 9 in. and 10 ft 6 in. from the bottom of the joists to the thimble level, to simulate 1st and 2nd floor locations. For one series of tests an enclosure was fitted around the chimney between floors, as shown in Fig. 3. The enclosure was constructed of 3/8-in. plaster board nailed to 2- by 4-in. wood studs fixed to the corners of the chimney.

The remainder of the test chimneys were only 6 ft long. It was thought that the short chimneys would be adequate for purposes of comparative testing and that significant savings in time and expense would result. It was possible to construct the short specimens on heavy metal pallets and to move them into position for testing on a dolley. During test they were vented into a metal factory built chimney suspended from the roof above. As shown in Fig. 4, the short test chimneys were not provided with cleanout openings and the height of the thimble opening was correspondingly less. To date, tests have been conducted on the following five short test chimneys.

1. Single course dry pressed clay brick with 3 13/16-in. diameter holes in brick with $8\frac{1}{2}$ by $8\frac{1}{2}$ vitrified clay flue liner fully grouted.

2. Single course dry pressed clay brick with frog in brick and $8\frac{1}{2}$ by $8\frac{1}{2}$ vitrified clay flue liner fully grouted.

3. Single course dry pressed clay brick with frog in brick and $8\frac{1}{2}$ by $8\frac{1}{2}$ vitrified clay flue liners mortared at joints, but with only enough mortar between liner and brick to locate the liner.

4. Double course dry pressed clay brick with frog in brick with no liner.

5. Concrete block chimney with $8\frac{1}{2}$ by $8\frac{1}{2}$ vitrified clay flue liner fully grouted. Wall thickness of concrete block 3 3/4 in.

A standard mortar mix of one part lime, one part cement and six parts sand was used for all test chimneys. Standardization of clay liners, however, was more difficult. All clay liners were obtained from a local supplier. Those used for the full scale chimney were produced by manufacturer A. The results for short chimneys Nos. 1 and 5, which were the first tested, indicated significant differences in the thermal resistance of the liners. It was subsequently established that the liners of short chimney 1 were produced by manufacturer A, but those of short chimney 5 were produced by manufacturer B.

It was clear that some standardization of clay liners was necessary so that differences in observed chimney performance were not mainly the result of differences in the properties of the liners used. Some exploratory thermal tests on liners produced by both manufacturers were carried out, but differences observed were not great. However, liners of manufacturer A were more uniform in dimensions and appearance, and a number of them were hand-picked from the stock of the local supplier for the construction of other short chimneys.

Conditions of Test and Procedure

The full-scale masonry chimney, with the first and second floor constructions and without an enclosure, was exposed to the following inlet flue gas conditions. Essentially steady state conditions had been established at the end of the test period indicated.

Inlet temp., °F	Flue gas flow, cfm	Duration of test hr
350	100	24
500	100	27
750	100	22
1000	100	28½
350	50	27
750	50	26

The flue gas flow rates of 100 and 50 cfm at standard conditions correspond approximately to that produced in burning 1 imperial gallon of oil per hour with 4 per cent and 8 per cent CO_2 respectively. The rate of 100 cfm was selected for subsequent tests since it seemed to represent a reasonable extreme for the small chimneys involved.

With the enclosure, as shown in the cross-section of Fig. 3, between 1st and 2nd floor levels the full scale chimney was exposed to the following inlet flue gas conditions.

Inlet temp., °F	Flue gas flow cfm	Duration of test hr
500	100	14
750	100	14
900	100	14

The period of 14 hours was chosen because steady state conditions were approximated in this time and also tests could be completed in one extended work period by the same laboratory technician.

The short masonry chimneys were exposed to flue gas inlet conditions of 500, 750 and 1000°F at a flow rate of 100 cfm for 14 hr. This was followed by two or more thermal shock tests of one-half hour at 1400°F and one-half hour at 1800°F. Chimneys 1 and 5 were tested both with and without surrounding floor construction. The remainder were tested without the floor construction. The effect on chimney and floor construction surface temperatures of insulation between joists and chimney and of metal firestopping between the chimney and underside of joists was determined at 750°F and 100 cfm inlet flue gas conditions with chimney 5.

Observations of surface temperatures of chimney and surrounding construction and temperature gradients across the components of the chimneys were made with all chimneys at each condition of test. Temperatures under a 6- by 6- by 3/16-in. felt pad glued to the surface of the short test chimney No. 1 just above the first floor level were also measured. The pad, perhaps of doubtful value, was intended to give a comparative surface temperature measurement less affected by variations in outside surface conductance. At each test condition measurements were made of dimensional changes, both horizontally and vertically, on the surface of several of the short test chimneys and all chimneys were inspected for cracks in masonry and liners. As a further index of cracking the air leakage rates of the short chimneys were measured following exposure to each condition at pressures up to 4 in. water gauge. This was done by connecting a blower and calibrated variable area flowrater to the chimney thimble and sealing the outlet of the chimney with a gasketed cap clamped in position.

In the thermal tests on the chimney liners three sections were cemented one above the other to provide a test specimen 6 ft high. The specimen was surrounded by a wire cage, as a safety precaution, and vented into the factory built chimney. Continuous records of inside and outside surface temperatures and observations of cracking were made under a variety of flue gas inlet conditions.

TEST RESULTS

Temperature Measurements

Temperatures of the chimney components and the surrounding combustibles were measured with chromel-alumel thermocouples. Thermocouples were placed on the outside surface of chimney and held in place with saurerizen cement. Thermocouples for the liners were embedded flush with the respective surfaces and held in place with saurerizen cement with the exception of the outer surface of the liners of the full scale masonry chimney and chimneys No. 1 and 5 where the thermocouples were placed on the surface and held with mortar. Temperatures of the surrounding combustibles were measured with thermocouples embedded flush with the surface and held in place with plastic wood. Thermocouple locations were in most cases duplicated on the four sides of the chimney, but only the maximum temperatures are recorded in this report.

Temperatures differed somewhat on the various sides due to the variations in convection air currents in the laboratory and, also, due to the non-uniformity of the flue gas temperature distribution within the flue. A metal shield with an asbestos backing was placed on top of the connecting pipe to divert its heat away from the chimney and the floor section.

Since the baseboard was made with hinges at the corners and clamped around the chimney and not attached to the floor boards, a gap of 1/4 in. in width occurred between the baseboard and the floor boards with the vertical expansion of the chimney during the test. This air gap probably allowed more convection air to flow up through the floor section and may have resulted in lower framework temperatures than with the baseboard fixed to the floor boards.

Full-Scale Clay Brick Chimney. - With first and second floor sections in place, temperature measurements obtained on the full scale masonry chimney are shown in Figs. 5, 6 and 7. Maximum temperatures were recorded at the first floor level, and as the time temperature curves indicate, equilibrium temperatures of the chimney and the surrounding framework were reached after 22 to 28 hours of steady operation. It will be noted that equilibrium temperatures are approached within 10 to 15°F after 14 hours of operation.

A comparison was made between the chimney surface and the framework temperatures obtained with flue gas flow of 50 and 100 cfm. The results are presented in Fig. 8. As expected, lower temperatures occur at the lower flow rate for corresponding inlet flue gas temperatures. This is due to the lower surface conductance and, also, to greater cooling of the flue gas at the lower heat input.

The results of the tests with the plasterboard enclosure between first and second floor levels are given in Fig. 9. Higher framework temperatures were obtained at the second floor level. This is due to the vertical temperature gradient in the air inside the enclosure as a result of convection. The maximum combustible temperature was obtained at the wood firestop located between the joist and the chimney surface. The maximum temperature of the studs attached to the corners of the chimney was found to be lower than the floor or joist temperatures at the second floor level.

Chimney surface and joist temperatures at the second floor level with the enclosure are compared with those at the first floor level of the chimney without the enclosure in Fig. 10. Temperatures with the enclosure were found to be significantly higher. Temperatures of joist, floor, plasterboard and firestop at the second floor level are plotted versus time in Figs. 11, 12, 13 and 14. Comparison of these with time temperature curves in Figs. 5, 6 and 7 for the chimney without an enclosure indicates that the slopes of the curves at the end of 14 hours are greater for those of the chimney with an enclosure, and that the time required to reach steady state is probably much longer.

Short Single Course Clay Brick Chimneys. - The results of thermal tests at the end of 14 hours on short chimney No. 1 are shown in Fig. 15 and these are compared with chimney surface and framework temperatures for the full scale chimney in Fig. 16. These temperatures were found to be higher for the short chimney. Similarly, the flue gas temperatures at the first floor level were found to be lower at corresponding inlet flue gas temperatures for the full scale chimney. Chimney surface and framework temperatures for the full scale and the short chimney are replotted against the flue gas temperature at the first floor level in Fig. 17. Temperature relationships for both chimneys are similar with only slightly higher temperatures for the short chimney. The higher flue gas temperature drop from inlet to first floor level obtained with the full-scale chimney is probably due to leakage air from the cleanout door and the longer flue length below the thimble level which provided greater cooling area.

As shown in Fig. 15 the baseboard temperature is reduced 15 to 20°F with cement asbestos insulation between the baseboard and the chimney surface.

The thermal performance without floor section of clay brick chimney No. 1 with fully grouted liner and clay brick chimney No. 3 with just enough mortar to locate the liner are compared in Fig. 18. Surface temperatures were found to be almost the same with values for the chimney with liner not grouted approximately 10°F lower. Temperature under the 6- by 6- by 3/16-in. felt pad located just above the first floor level approximated the surface temperature of short chimney No. 1 with floor section. The clay brick chimney No. 2 with the liners fully grouted was subjected to one thermal test at a 1000°F flue gas inlet temperature. Surface temperatures at the end of 14 hours of test were similar to those of the clay chimneys No. 1 and No. 3. Clay bricks with cored holes were used for the construction of chimneys No. 1 and clay bricks with frogs for the chimneys No. 2 and No. 3.

Short Double Course Clay Brick Chimney. - Thermal test results on the double course clay brick chimney without a liner (No. 4) are given in Fig. 19. At the end of 14 hours of test with 1000°F inlet flue gas temperature, the chimney surface temperature is 70°F lower than that of the single course clay brick chimney with liner.

Short Concrete Block Chimney. - Surface temperatures of the concrete block chimney (No. 5) without a floor section are shown in Fig. 20. Comparing this with Fig. 18 surface temperatures of concrete block and clay brick chimneys are found to be similar with the former giving slightly lower values.

Results of thermal tests carried out at an inlet flue gas temperature of 750°F and a flue gas flow of 100 cfm to determine the effect of insulating the joist and the use of a sheet metal firestop are also shown in Fig. 20. With mineral wool between the joist and chimney the joist temperature was lower during the initial part of the test but at the end of 14 hours it was the same as that of the joist without any insulation. If the test had been continued beyond the 14-hr period, the temperature of the joist with insulation would probably have exceeded that of the joist without insulation. With a sheet metal firestop at the bottom of the joist, the joist temperature at the end of 14 hr was 60°F higher than that of the standard floor section. These higher framework temperatures are caused by the restriction of the convection of air around the framework. Baseboard temperatures were the same, either with the joist space insulated or with the metal firestop and were 50°F higher than with the standard floor section. The higher baseboard temperatures are a reflection of lower heat losses from the chimney in the vicinity of the floor section below which leads to higher chimney surface temperatures.

Short Test Chimney Time-Temperature Relationship. - The rates of surface temperature rise of the short test chimneys are compared in Figs. 21 and 22. Although at the end of 14 hr at 1000°F inlet flue gas temperature the surface temperature of the concrete block chimney No. 5 is almost the same as that of the single course clay brick chimneys No. 1 and No. 3, the curves indicate that the former has greater thermal capacity and that the surface temperature of the concrete block chimney may be higher at steady state condition. The surface temperature of the double course chimney No. 4 is lower by 75°F and it is expected that the time to thermal equilibrium is much longer than for the other short test chimneys. The time temperature curve of the clay brick chimney No. 2 tended to flatten at 4 hr of test. This was probably caused by the latent heat of evaporation of the moisture in this chimney. Since no thermal test was run prior to the 1000°F test, this chimney probably contained more moisture than the other chimneys.

Surface temperatures recorded during and after the 1-hr thermal shock tests are shown in Fig. 22 for the single and double course clay brick chimneys without a floor section and the concrete block chimney with a floor section. The maximum surface temperatures for the concrete block and single course clay brick chimneys, which occurred $1\frac{1}{2}$ hr after the end of test, were approximately 200°F. The maximum surface temperature for the double course clay brick chimney, reached $3\frac{1}{2}$ hr after the end of the test, was 125°F.

After four thermal shock tests, a 1000°F thermal test was repeated with the concrete block chimney. Although the chimney was cracked severely, the surface temperature readings were found to be unaltered from the previous 1000°F thermal test.

Temperature Gradients Through Chimney Sections. - Temperature gradients through the short test chimneys at the end of 14 hr of test are given in Table I. The resistances to heat flow of the components of the chimney are proportional to the ratio of the temperature drops across the components to the over-all temperature drop, under steady state conditions. The ratio of the temperature drops across masonry and liner to the temperature difference between flue gas and ambient air are also given in Table I, indicating the relative resistances of these components. It can be seen that approximately half of the over-all thermal resistance is provided by the chimney walls and the remainder by the inside and outside film resistances. The clay brick chimney with liners ungrouted (chimney No. 3) shows a slightly higher resistance than with the liners grouted (chimney No. 2), assuming the resistance of inside and outside films essentially the same in both tests. It is seen that the thermal resistance of the concrete block chimney No. 5 is higher than that of the clay brick chimney No. 1, again assuming that the film resistances were essentially the same in both test series. The liner in the concrete block chimney, however, represents a greater portion of the chimney wall resistance. This may have been due at least in part to the greater wall thickness of the liners in the concrete block chimney (3/4 in. as compared to 5/8 in.). The thermal resistance of the concrete block would appear to be comparable to that of the brick.

The over-all wall resistance of chimney No. 2 (brick with frog) is slightly greater than that of chimney No. 1 (brick with cored holes). However a substantial difference in the ratio of the liner and masonry resistances was obtained. This may be due largely to the different method used in locating the thermocouples on the outside surface of the liner. The thermocouple was placed on the surface and held with mortar for chimney No. 1 and flush with the surface in a groove and held with cement for chimney No. 2, resulting in a higher temperature reading for the latter. The method of mounting the thermocouple on the outside surface of the liner of chimney No. 3 was similar to that for chimney No. 2, while the method used for chimney No. 5 was similar to that for chimney No. 1.

Observations of Structural Properties

Thermal Expansion Measurements. - During the thermal tests vertical and horizontal expansion measurements were taken on the outside surface opposite the inlet opening. As shown in Table II the unit vertical expansion of the clay brick chimneys, Nos. 1 and 4, is twice as great as that of the concrete block chimney No. 5. With the concrete block chimney the vertical and horizontal expansions are identical, whereas the horizontal expansion for the clay brick chimney is less than that of the concrete block chimney. This may be due to the larger number of horizontal mortar joints in the brick chimney, which separate and allow greater vertical movement of the masonry. No expansion measurements were taken on chimneys Nos. 2 and 3.

Cracks in Chimneys. - Chimneys were examined for cracks and results recorded after each thermal test. The severity of cracking was difficult to evaluate by visual observation. Since liners were fixed inside the chimney it was possible to examine them only at inlet and exit. No cracking was observed during the 500°F thermal tests on any clay brick chimneys. Hairline cracks were noted on the concrete block chimney extending vertically through three blocks. During the 750°F thermal test, all chimneys showed hairline cracks in mortar joints and in the masonry. These cracks were more numerous and wider after the 1000°F test. Severe cracks in the masonry of all chimneys appeared during the thermal shock test, with cracks ranging from hairline to 1/8-in. in width. These cracks tended to close up as the chimney cooled down after the test.

No liner cracks were observed after the 500°F and 750°F thermal tests. Hairline cracks appeared in the liners after the 1000°F thermal test in some of the chimneys. Liners in all chimneys cracked during the thermal shock test. No fragment of liners in any chimney was found to have fallen out.

Besides the visual observation of cracks, structural degradation of chimneys was assessed by air leakage measurements before and after each thermal test. To ensure that the inlet fitting for pressurizing the chimney and the outlet opening were properly sealed, the sealing joints were checked with soap solution for extraneous leakage. The air leakages measured were adjusted to standard condition.

The results of air leakage tests are shown in Figs. 23, 24, 25 and 26. Exposure to the various thermal test conditions resulted in reductions in the air leakage resistance of the different chimneys. After the 500°F and 750°F thermal test the increase in air leakage was found to be small. A decided increase in air leakage was noted after the 1000°F thermal test. After the chimney had been subjected to the thermal shock test, the rate of air leakage rose significantly and continued to increase with subsequent thermal shock tests.

A comparison of air leakages for the single course clay brick chimneys with the liners grouted (chimneys No. 1 and 2) and the liners not grouted (chimney No. 3) shows similar rates up to the 1000°F thermal test. After the thermal shock tests, however, the chimney with the liner grouted shows less leakage indicating that the mortar behind the liner assists in the prevention of air leakage. The air leakages of the concrete block chimney No. 5 measured after the steady thermal tests are almost the same as those of the single course clay brick chimney, both with liners fully grouted. However, higher air leakage was measured with the former after each thermal shock test. The air leakages measured after the steady thermal test and thermal shock tests, were greater for the double course clay brick chimney No. 4 without a liner than for the other chimneys. It can be concluded that the liners contribute significantly to the resistance to air leakage of the clay brick chimneys.

Flue Liner Tests

Two sets of vitrified clay flue liners from manufacturer A and one set from manufacturer B were tested with the liners freestanding. Each set consisted of three 2-ft liners placed on top of each other (with ends mortared). Inside and outside surface temperatures were recorded at each inlet flue gas temperature condition, with the flue gas flow maintained at 100 cfm.

With the first set of liners from manufacturer A, cracks occurred initially in the top liner at the 750°F inlet temperature. This was thought to be due to the weight of the factory built chimney on top of the liner. The top liner was replaced and with the weight of the factory built chimney relieved, all liners cracked at 1000°F. All of the second set of liners cracked at the 750°F inlet temperature condition.

Clay liners obtained from manufacturer B also cracked at the 750°F inlet temperature. With the flue gas temperature increased from 900°F to 1900°F in 100°F increments at half hour intervals, the largest crack in the flue liner was 1/4 in. wide and extended vertically from the top to the bottom of the liner.

Although the liners cracked in a number of places when subjected to inlet temperatures above 750°F, the liners remained in one piece, with no fragments of liners falling out.

In Table III surface temperatures of the liners obtained during the liner test are compared with those obtained during tests on the short chimney. Since thermal stress in the liner is a function of the temperature difference between the inside and outside surfaces, temperature drops are also included. Because the maximum temperature drop across the liners in the thermal tests on the test chimneys occurred after two hours of exposure, temperature readings in Table III are recorded for this time.

The temperature drop across liner A was consistently greater than across liner B at the same inlet flue gas temperature. This is due to the greater wall thickness for liner B, and the ratio of the thermal resistances of liner A and liner B approximates the thickness ratio. The relative thermal resistance of the liners increased as the inlet flue gas temperature was increased. This is due to the decrease in the inside and outside surface film resistances with increasing chimney temperatures.

Since a similar method was used in locating thermocouples on free-standing liner A and the liners in chimneys No. 2 and No. 3, temperature drops across these liners may be compared. Maximum temperature differences across liners in chimneys No. 2 and No. 3 are 14°F and 24°F lower respectively than with the liner free standing at 1000°F inlet flue gas temperature. In the free-standing test on liner A cracking occurred with a temperature drop across the wall of 99°F. This temperature drop is exceeded in chimneys No. 2 and No. 3 at an inlet flue gas temperature of 1000°F. Furthermore, the mean temperature of the liners in the chimneys is higher at this inlet flue gas temperature than the mean temperature of the free-standing liner at 750°F inlet temperature. Cracking of the liners in these chimneys can be expected, therefore, at the 1000°F flue gas inlet temperature. Cracking of the liner in chimney No. 2 might be reduced due to the restraint on the outer surface of the liner provided by the surrounding mortar and masonry.

SUMMARY AND DISCUSSION

In thermal tests on the full scale chimney in which typical surrounding construction was simulated, maximum temperatures of framework and other combustibles were higher at the second floor level than at the first floor level. The maximum temperature of combustible construction occurred at the firestop in contact with the chimney. Floor temperatures were almost as high. Temperatures of combustibles attached at the corners of the chimney, as in the case of studs for the enclosure, were found to be lower than the floor or joist temperatures and it would appear that this practice does not materially increase fire hazard.

For purposes of comparative testing, short test chimneys were found to be adequate. Relative thermal resistances, cracks and expansions of masonry chimneys were evaluated with the short test chimneys. A clay brick short chimney was tested with a floor section to compare its thermal performance with that of the full scale chimney. At equal flue gas temperature at the first floor level, chimney surface and framework temperatures were found to be about the same for both chimneys.

The use of 1/8-in. asbestos insulation between the baseboard and chimney surface reduced the baseboard temperature 15 to 20°F. Insulation placed between the joists and chimney resulted in higher floor and baseboard temperatures. Firestops placed at the bottom of the joists had the same effect and also materially increased framework temperatures.

Thermal performance of the clay brick chimneys with the liners grouted was compared with the liners not grouted. The latter gave slightly lower surface temperatures. It is believed that the effectiveness of the insulating air with the liners not grouted is reduced due to gas leakage through cracks and mortar joints of the liners.

Chimney surface temperatures for the concrete block chimney at the end of 14-hr tests gave slightly lower temperatures than those of the clay brick chimney. However, the rate of temperature rise of the two chimneys showed higher thermal capacity for the concrete block chimney and the surface temperatures for this chimney may possibly be higher at steady state condition. The over-all resistance to heat flow of the concrete block chimney determined at 14 hr was higher than that of the clay brick chimney. Liners of greater wall thickness were used for the concrete block chimney and the resistance to heat flow of the concrete block was found to be equivalent to that of the single course clay brick based on results at 14 hours. However, the concrete block may give less thermal resistance than that of the clay brick at steady state condition.

The double course clay brick chimney without a liner gave much lower surface temperatures at the end of a 14 hour test, due to its higher resistance to heat flow and its thermal capacity.

With the clay brick chimney thermal expansion measurements indicated that the vertical expansion is much greater than the horizontal expansion, whereas with the concrete block chimney expansions in both directions are about the same. This may be due to more numerous horizontal mortar joints of the clay brick chimney with the separation at these mortar joints adding to the vertical expansion measurements. The unit horizontal expansion of the clay brick chimney is almost half that of the concrete block chimney, whereas the unit vertical expansion of the former is twice that of the latter.

Measurement of the air leakages of chimneys after the thermal test gives some indication of the relative amount of cracking of the chimneys. Hairline cracks appeared in the masonry during the 500°F thermal test for the concrete block chimney and during 750°F thermal test for the clay brick chimneys. After the 1000°F thermal test, liner cracks were observed at the inlet opening of some test chimneys. Air leakage measurements gave a slight increase in the rate of air leakage after the 500°F and 750°F thermal tests and a decided increase after the 1000°F thermal test. After the thermal shock test, the cracks in the masonry and liners were extensive and the rate of air leakage rose significantly.

Air leakages of the clay brick chimneys measured after the thermal shock tests were much higher with the liners not grouted than with the liners grouted. Air leakages measured after the thermal tests were about the same for both cases. On this basis it is believed that the mortar behind the liners assists in reducing the air leakage of chimneys subjected to severe thermal shock. However, from these tests the effect of the mortar on the cracking of the liner is not known. The report on chimney tests by the National Bureau of Standards (1) recommends no grouting of liners for chimney construction. This recommendation is based on the observation of continuous cracks through the liners and masonry of chimneys with the liners fully grouted. Because of the narrow space between the liner and the chimney, to fully grout the liner it was necessary to tamp the mortar into the space with a steel rod. In practice, the liners are probably only partially grouted.

The concrete block chimney gave higher air leakages after the thermal shock tests compared to the clay brick chimney with the liners grouted. Air leakages of the double course clay brick chimney with no liner were higher for both steady thermal and thermal shock tests than those of all other chimneys. Besides providing additional thermal resistance, the liners assist significantly in providing gas tightness.

Air leakage measurements were made with the short chimneys pressurized up to 4 in. water gauge. The chimney draft is usually less than 0.10 in. water gauge and the rate of air leakage at this pressure differential was found to be about 1 cfm after the steady thermal tests and about 3 cfm after the first thermal shock test. It is believed the rates of air leakage under actual draft conditions will not seriously affect the chimney performance.

The cracking of liners due to thermal stess is dependent on the temperature difference across the liner.

The comparison of the temperature differences across the liner during chimney and free-standing flue liner tests gives some indication of the inlet flue gas temperature at which the liners in the chimney will crack. The clay flue liner in a chimney may crack with steady flue gas input at from 750°F to 1000°F.

The temperatures measured under the felt pad attached to the surface of the clay brick chimney approximated the surface temperature of the chimney with floor section. This leads to the possibility that temperatures of combustibles in contact with the chimney may be approximated by measuring temperatures under the felt pad, thus simplifying the test setup.

Flattening of the time temperature curve observed with clay brick chimney No. 2 during the initial part of the test at inlet flue gas temperature of 1000°F indicates that moisture in the chimney materials may significantly affect chimney temperatures. During conditions of transient heat flow temperatures are likely to be lower with moisture present than with dry materials. Under quasi-equilibrium conditions outside surface temperatures will probably be higher with moisture present, although drying out of the materials is likely to be complete after one or two fourteen-hour tests. The effect of moisture on the deterioration of chimney materials at elevated temperatures may be significant and should be considered in future studies.

According to a report of Underwriter's Laboratories Inc. (3), the ignition temperature of various types of woods for tests of short duration under laboratory conditions is about 400°F. The ignition temperature of wood is much lower if exposed to moderately low temperature for a long period of time. From case histories, these ignition temperatures were found to vary from 212 to 248°F. In isolated cases, wood ignited at a temperature of 134°F. Allowing for a margin of safety, the generally accepted limit for combustibles is 160°F based on the ignition temperature for long-term exposure.

This limiting temperature was reached on the full scale chimney, with an enclosure, in 14 hr of testing at 400°F inlet flue gas temperature. At 1000°F inlet flue gas temperature maximum temperature on the framework at 14 hours was 350°F. It is apparent that masonry chimneys, subjected to flue gas at the maximum temperatures that can be expected at the outlet of heating appliances, cannot pass a test which specifies a limit of 160°F for adjacent construction under thermal equilibrium conditions. If the temperature limit of 160°F is used, it may be more realistic to adjust the test inlet temperature to account for the cooling of the flue gas that normally occurs between appliance outlet and chimney inlet. In practice, the flue gas temperature is reduced before entering the chimney, due to heat loss from the smoke-pipe and the introduction of room air through dampers or hoods used for draft control. According to reference (4) the reduction in temperature due to the diluent air is approximately 40 per cent with oil-fired appliances, 20 per cent with coal-fired appliances and 40 per cent with gas appliances. The reduction in flue gas temperature due to cooling in the flue pipe will depend on the length of passage. This is likely to be substantial in space heater installations where the heater is often located a considerable distance from the chimney.

In automatically fired appliances and in hand-fired solid-fuel appliances, periods of maximum flue temperature are unlikely to persist continuously for several hours. This is also true of domestic incinerators. Under these conditions the thermal capacity of the chimney will affect maximum temperatures of the outside chimney surface and adjacent construction. The effect of cyclical operation of automatically-fired appliances on the chimney outside surface temperature was investigated with the aid of an analog computer simulating 1/8 section of a square chimney. With a typical firing cycle of 10 minutes on, 5 minutes off time, the reduction of chimney surface temperature obtained as compared to the steady flue gas input is given in Fig. 27.

It can be concluded that the masonry chimneys subjected to prolonged exposure under the extreme flue gas temperatures possible from heating appliances will produce temperatures on surrounding combustible material which are higher than the presently accepted limits. Also under these conditions structural damage of the masonry chimneys can be expected. It is evident that the masonry chimneys cannot meet the test requirements presently set out for factory built chimneys. Due to the number of factors involved it is difficult to arrive at a realistic test condition for masonry chimneys. So long as the lined clay brick chimney is regarded as standard, it is necessary to evaluate other types of masonry chimneys by comparison with it.

Further tests on chimneys constructed of precast masonry units are being continued in the chimney laboratory using procedures similar to those described. These tests are intended to provide more information on the effect of variations in wall thickness, materials and moisture content on thermal and structural performance.

ACKNOWLEDGEMENTS

The authors record their thanks to Mr. C. Wachmann for his contribution in designing the furnace and instrumentation, and his assistance in the initial part of the test program, and to Mr. R. G. Evans for carrying out the tests and recording of results. The authors also acknowledge the guidance given to this project by Dr. N. B. Hutcheon.

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(1) Fire Hazard Tests with Masonry Chimneys by Nolan D. Mitchell - National Bureau of Standards 1949.

(2) Temperatures During Fires in Chimneys with Shining Soot by Asbjorn Torp, Vollebekk, Norwegian Building Research Institute 1956.

(3) Performance of Type B Gas Vents for Gas-Fired Appliances, Underwriter's Laboratories Inc. 1959.

(4) Performance of Masonry Chimney for Houses, Housing Research Paper 13, Housing and Home Finance Agency 1952.

TABLE I

Temperatures Through the Short Test Chimneys

(Temperature readings at 14 hours of test)

Chimney No.	Flue Gas Temp.		Liner Surface		Outside surface of masonry, °F	Resistance Ratio	
	at inlet, °F	at 1st floor level °F	inside °F	outside °F		liner	masonry
1	500	456	364	314	173	.133	.374
	750	698	557	476	224	.131	.408
	1000	938	762	643	271	.139	.434
2	1000	916	779	698	275	.098	.505
3	500	443	375	350	166	.069	.490
	750	673	573	522	213	.086	.521
	1000	970	829	748	270	.091	.538
4	500	450	352		127		.609
	750	664	523		162		.619
	1000	902	744		201		.660
5	500	457	368	297	160	.188	.363
	750	676	564	456	211	.181	.410
	1000	903	766	620	256	.178	.442

Description of Chimneys:

1. Single course clay brick with cored holes, liners grouted
2. Single course clay brick with frogs, liners grouted
3. Single course clay brick with frogs, liners not grouted
4. Double course blay brick with frog, no liners
5. Concrete block chimney with liners grouted

TABLE II

Thermal Expansion Measurements

(Expansion in in./ft)

Chimney No.	Inlet Temp., °F	At 6 hr.		At 10 hr.		At 14 hr.	
		Vert.	Horiz.	Vert.	Horiz.	Vert.	Horiz.
1	500	.014	.005	.015	.006	.015	.006
	750	.023	.007	.024	.008	.024	.008
	1000	.038	.010	.040	.012	.040	.012
4	500	.013	.004	.014	.005	.014	.005
	750	.026	.004	.028	.005	.029	.006
	1000	.047	.002	.049	.004	.050	.005
5	500	.006	.007	.007	.008	.007	.008
	750	.012	.013	.013	.014	.013	.014
	1000	.019	.021	.021	.023		

Description of Chimneys:

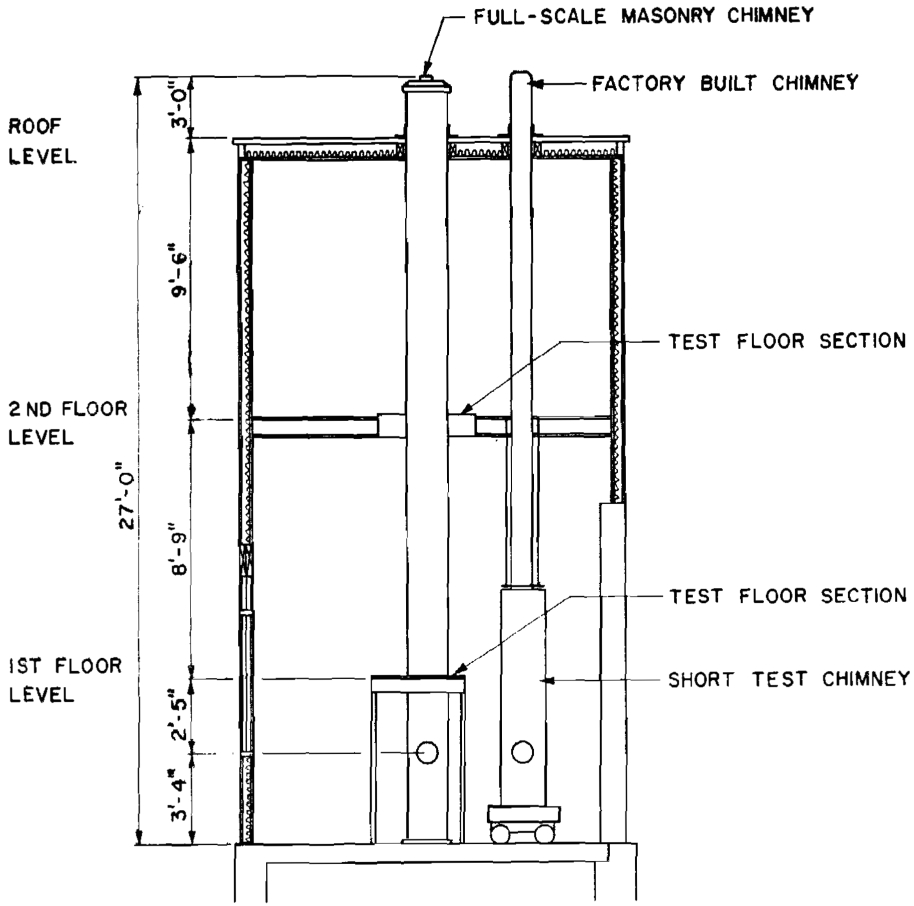
1. Single course clay brick with cored holes, liners grouted
4. Double course clay brick with frog, liners grouted
5. Concrete block chimney with liners grouted

TABLE III

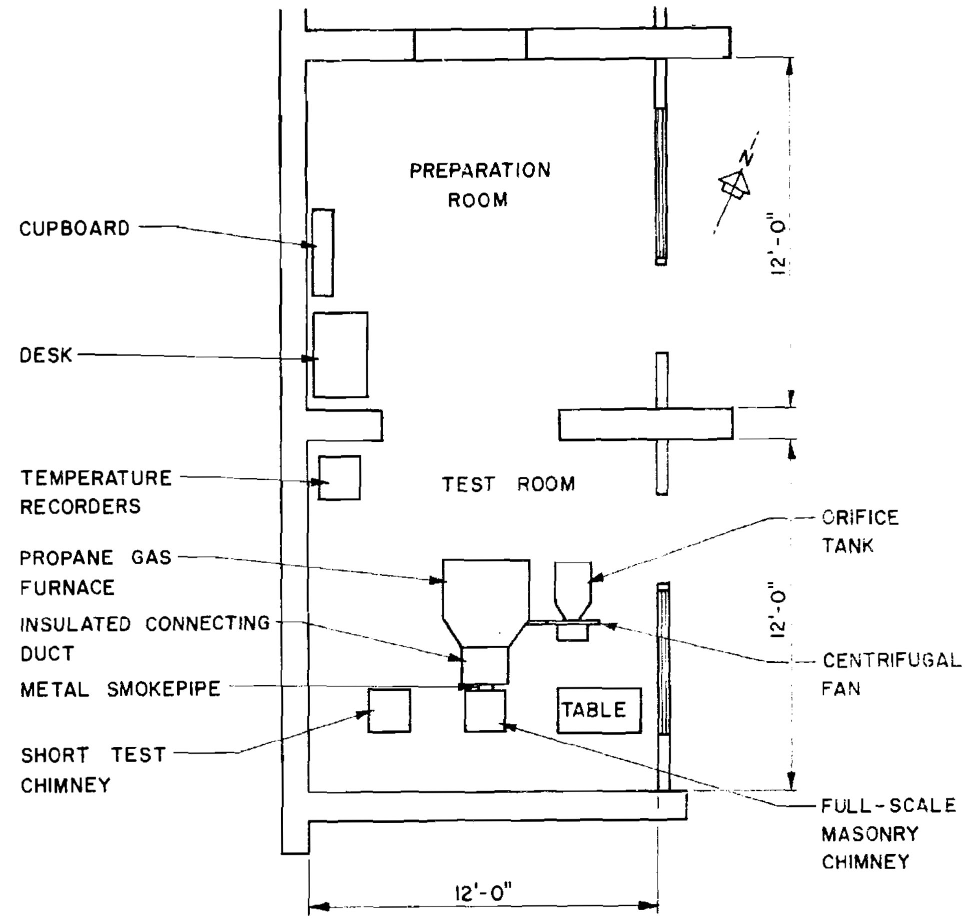
Liner Temperature Measurements

Liner	Flue Gas Temp.		Inside surface, °F	Outside surface, °F	Temp. Drop °F	Resistance Ratio
	at inlet, °F	at 1st floor level				
Liner A 1st set	500 750 1000	424 647 800	314 461 567	268 370 438	46 91 129	.134 .160 .179
2nd set	500 750	458 674	333 476	277 377	56 99	.148 .167
Liner B	500 750 1000	423 606 800	312 448 583	252 344 428	60 104 155	.175 .198 .216
Liner A in chimney #1	500 750 1000	426 670 890	290 460 630	220 350 475	70 (50) 110 (81) 165 (119)	
Liner A in chimney #2	1000	855	610	495	115 (81)	
Liner A in chimney #3	500 750 1000	443 650 922	350 512 723	314 451 619	36 (25) 61 (51) 104 (81)	
Liner B in chimney #5	500 750 1000	428 632 903	305 470 601	205 328 421	100 (71) 142 (108) 180 (146)	

Liner temperatures in chimneys taken at 2 hours
Temperature drops at 14 hours shown in brackets



SECTION OF TEST ROOM
LOOKING SOUTH



PLAN VIEW

FIGURE 1
LAYOUT OF CHIMNEY LABORATORY BUILDING M-13 C

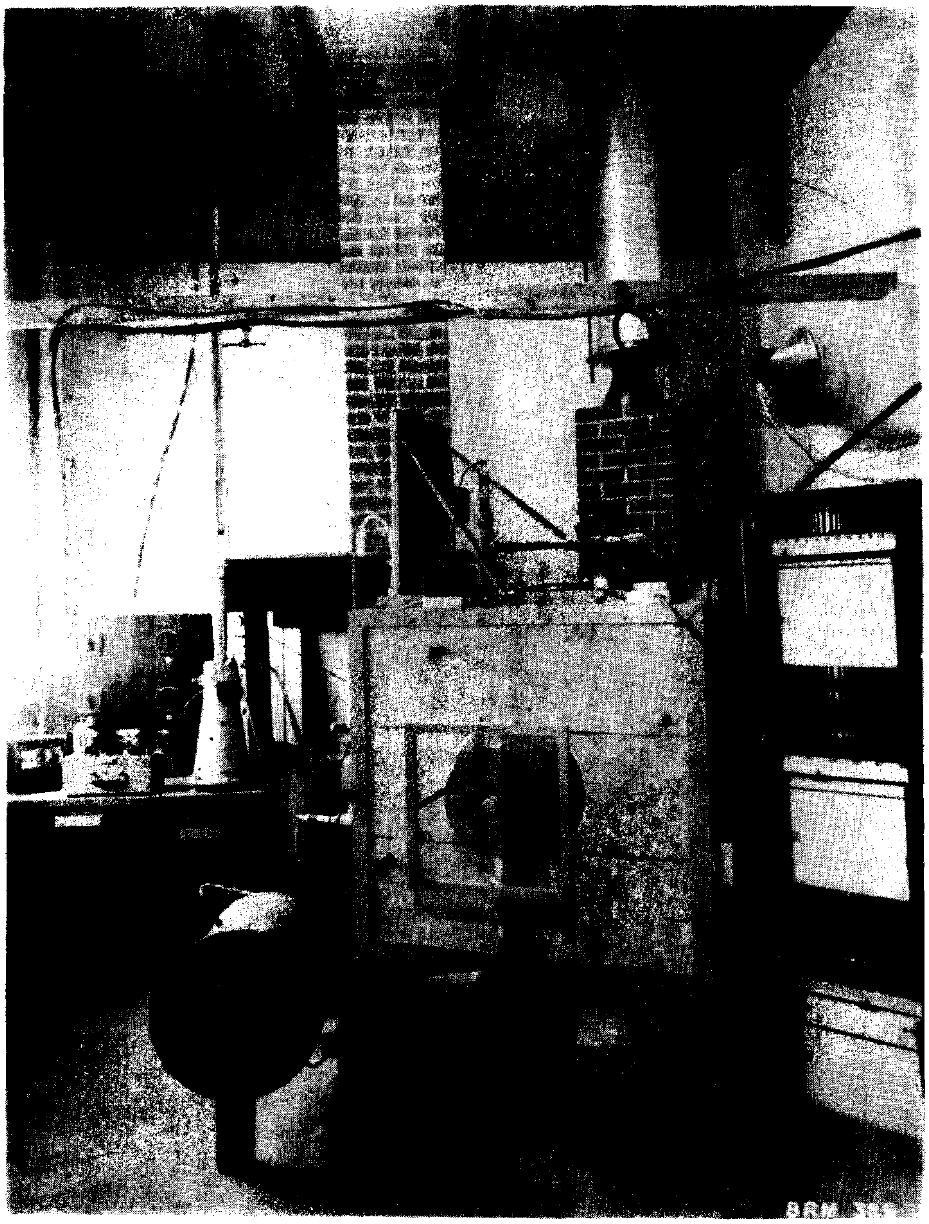


Figure 2 View of chimney laboratory with the propane furnace in the foreground, the full-scale brick chimney at centre and the short test chimney at the right.

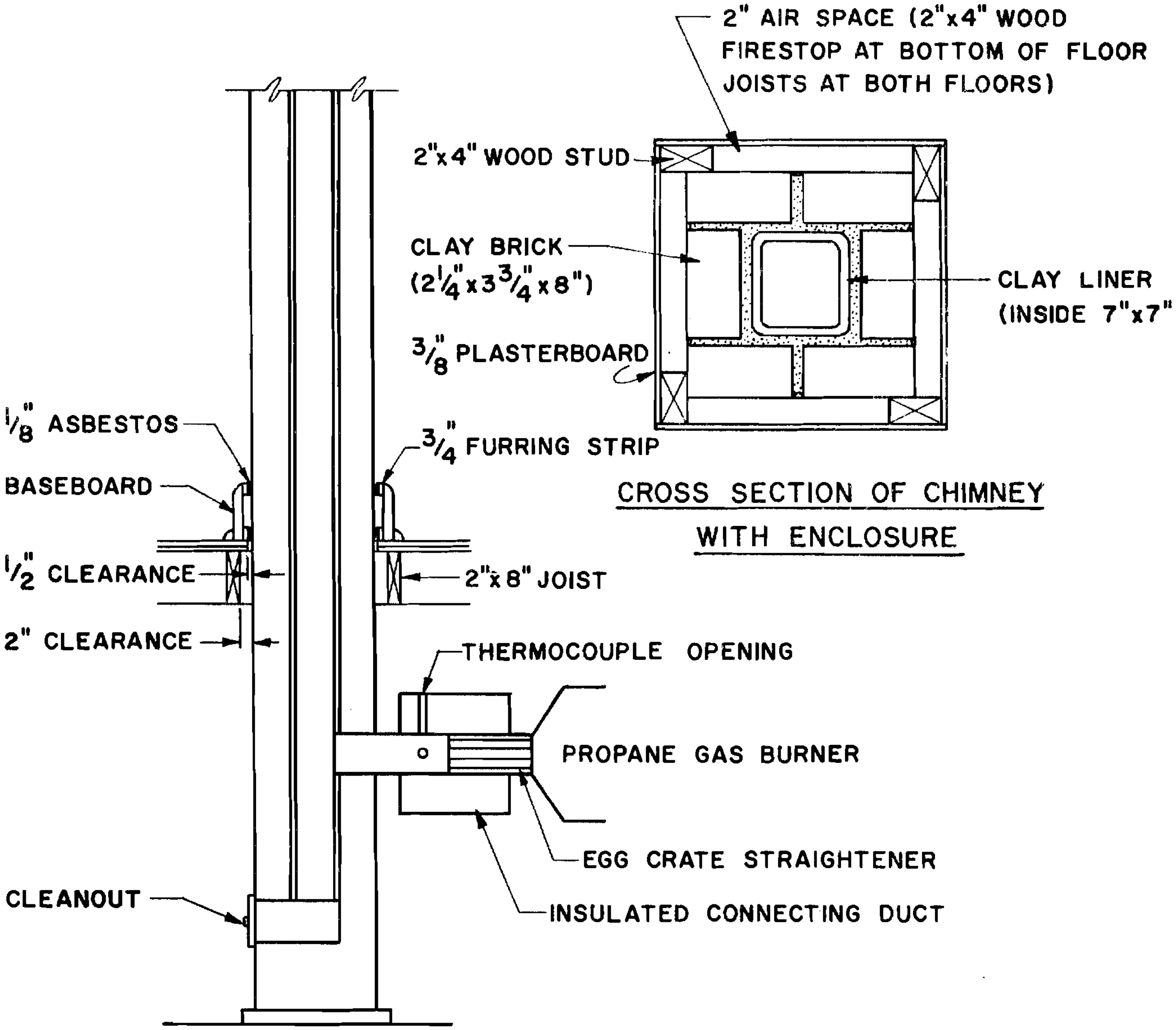
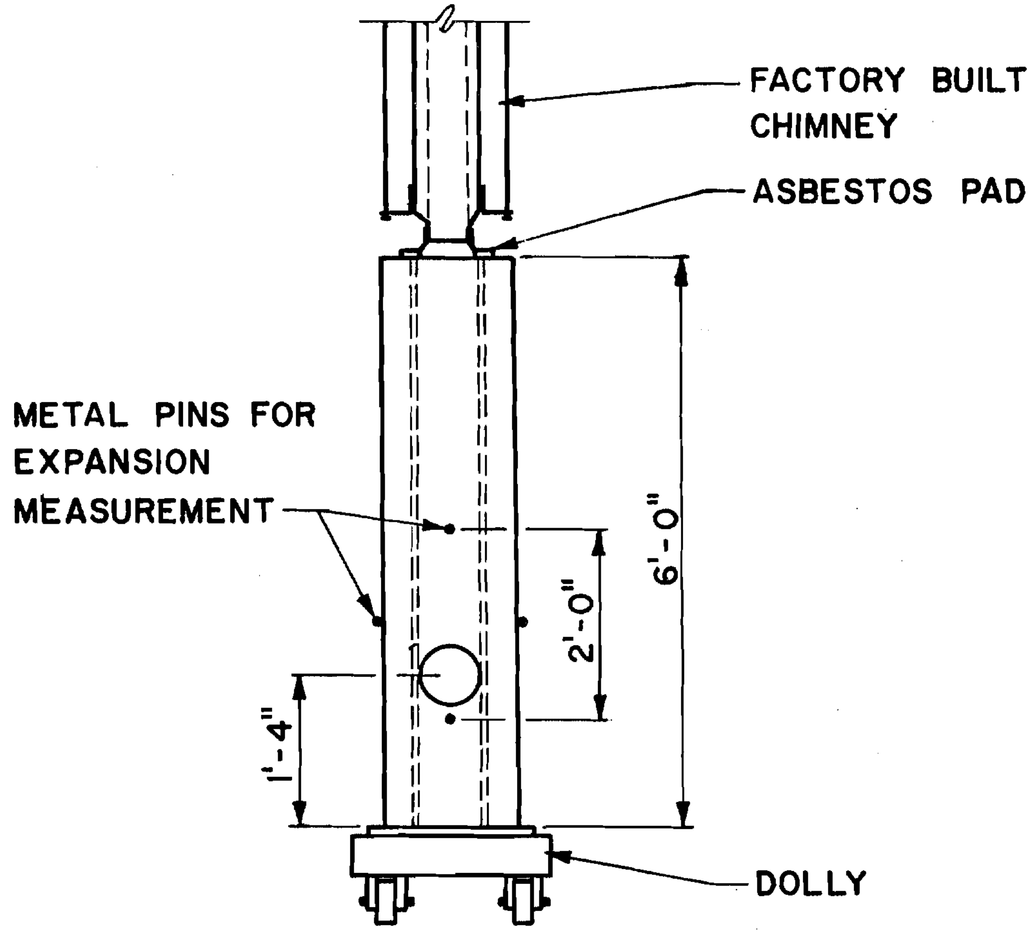


FIGURE 3
SECTION OF FULL-SCALE MASONRY CHIMNEY

BR. 2277-2



VERTICAL AND HORIZONTAL MEASUREMENTS TAKEN AT THE BACK SIDE OF CHIMNEY

FIGURE 4
SHORT TEST CHIMNEY

BR. 2277-3

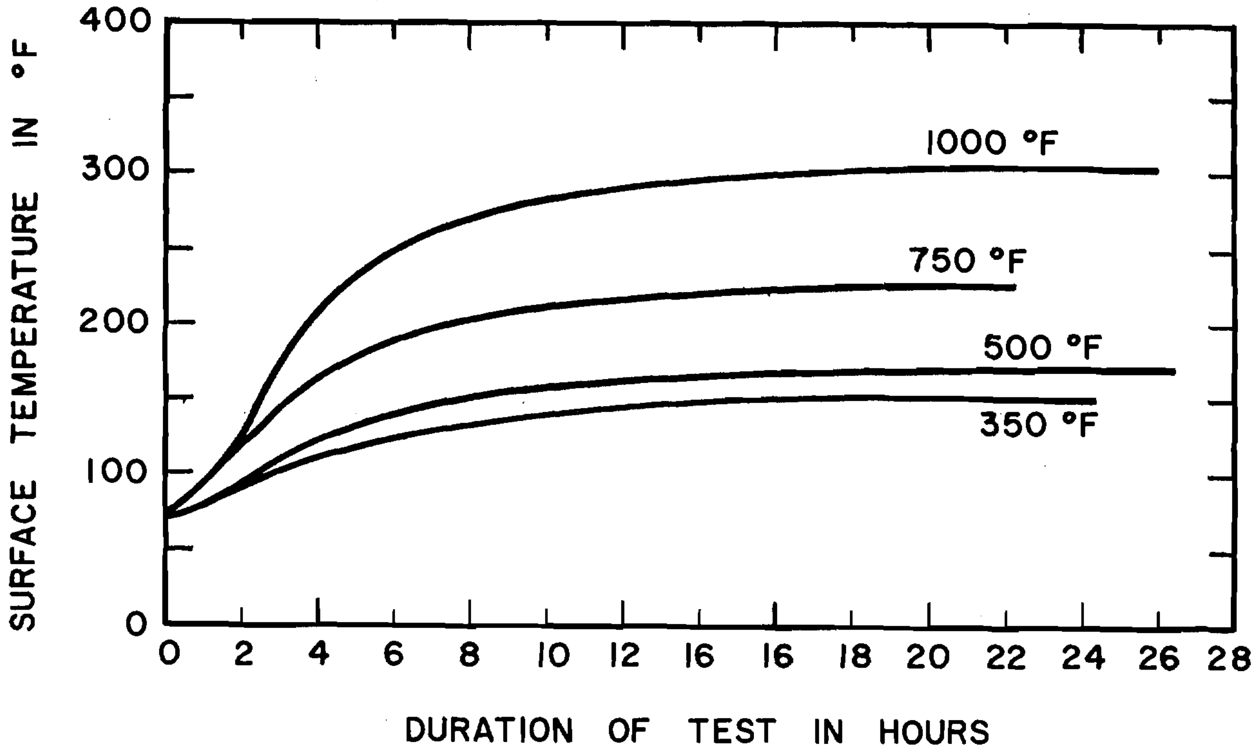


FIGURE 5
SURFACE TEMPERATURE OF FULL - SCALE CLAY - BRICK MASONRY CHIMNEY VS TIME
(AT FIRST FLOOR LEVEL FLUE GAS FLOW - 100 CFM)

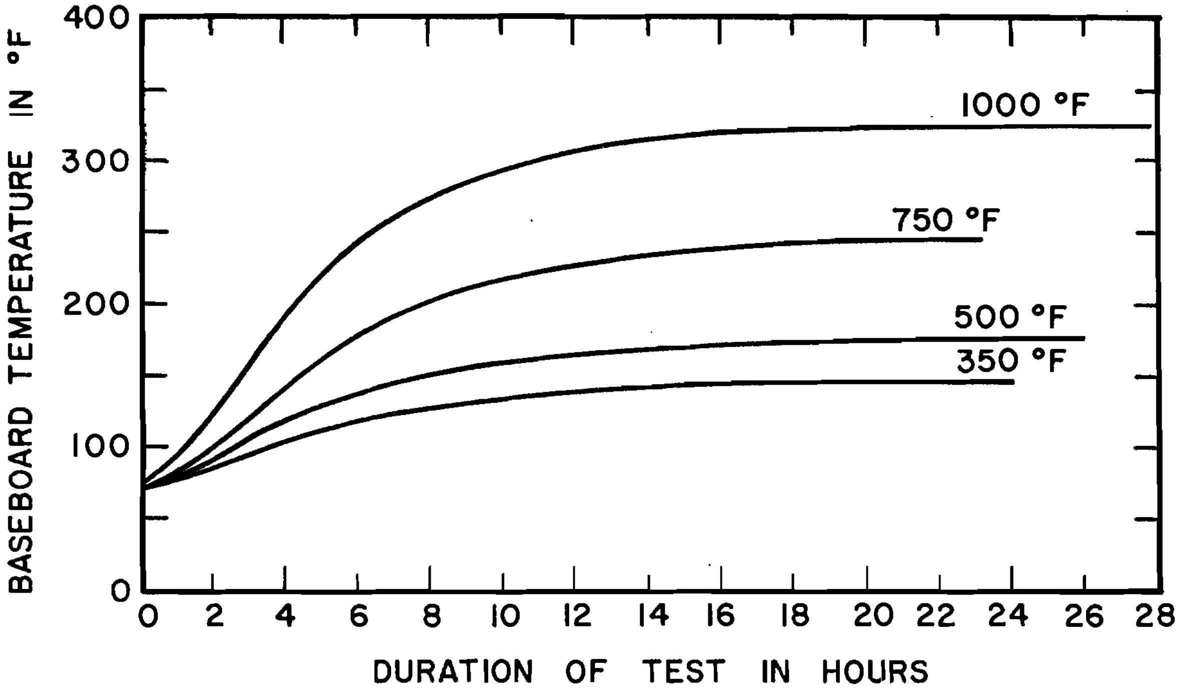


FIGURE 6

BASEBOARD TEMPERATURE OF FULL - SCALE CLAY - BRICK MASONRY CHIMNEY VS TIME

(AT FIRST FLOOR LEVEL FLUE GAS FLOW - 100 CFM)

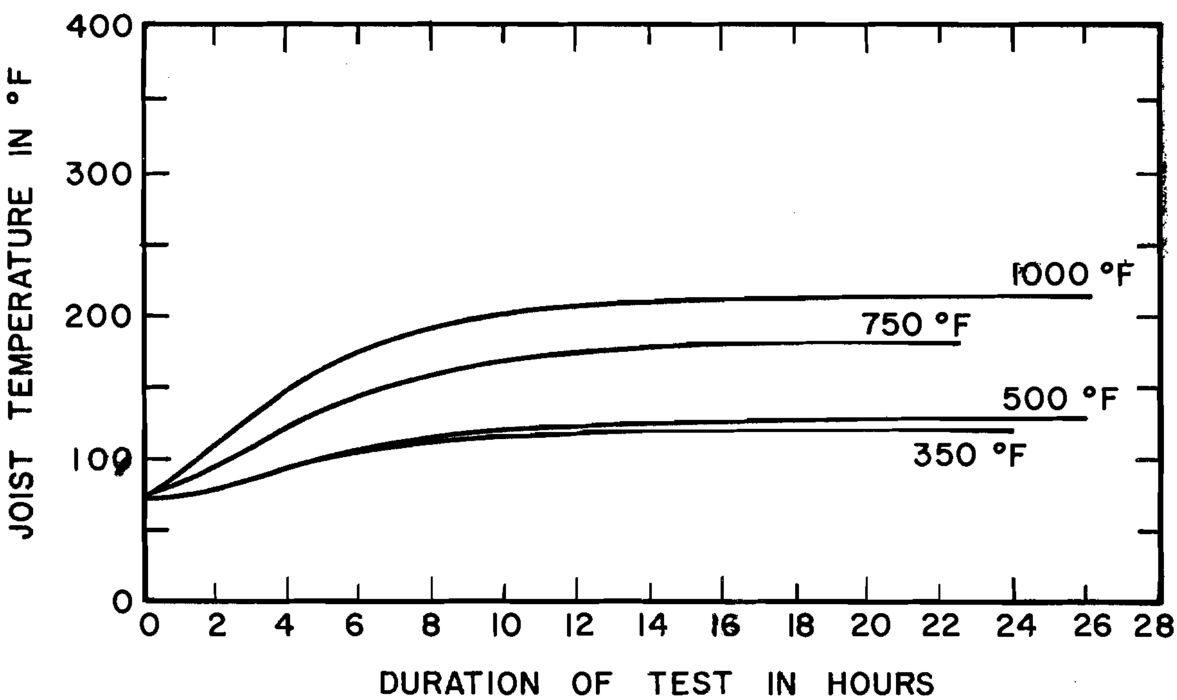


FIGURE 7

JOIST TEMPERATURE OF FULL - SCALE CLAY - BRICK MASONRY CHIMNEY VS TIME

(AT FIRST FLOOR LEVEL FLUE GAS FLOW - 100 CFM)

BR. 2277-5

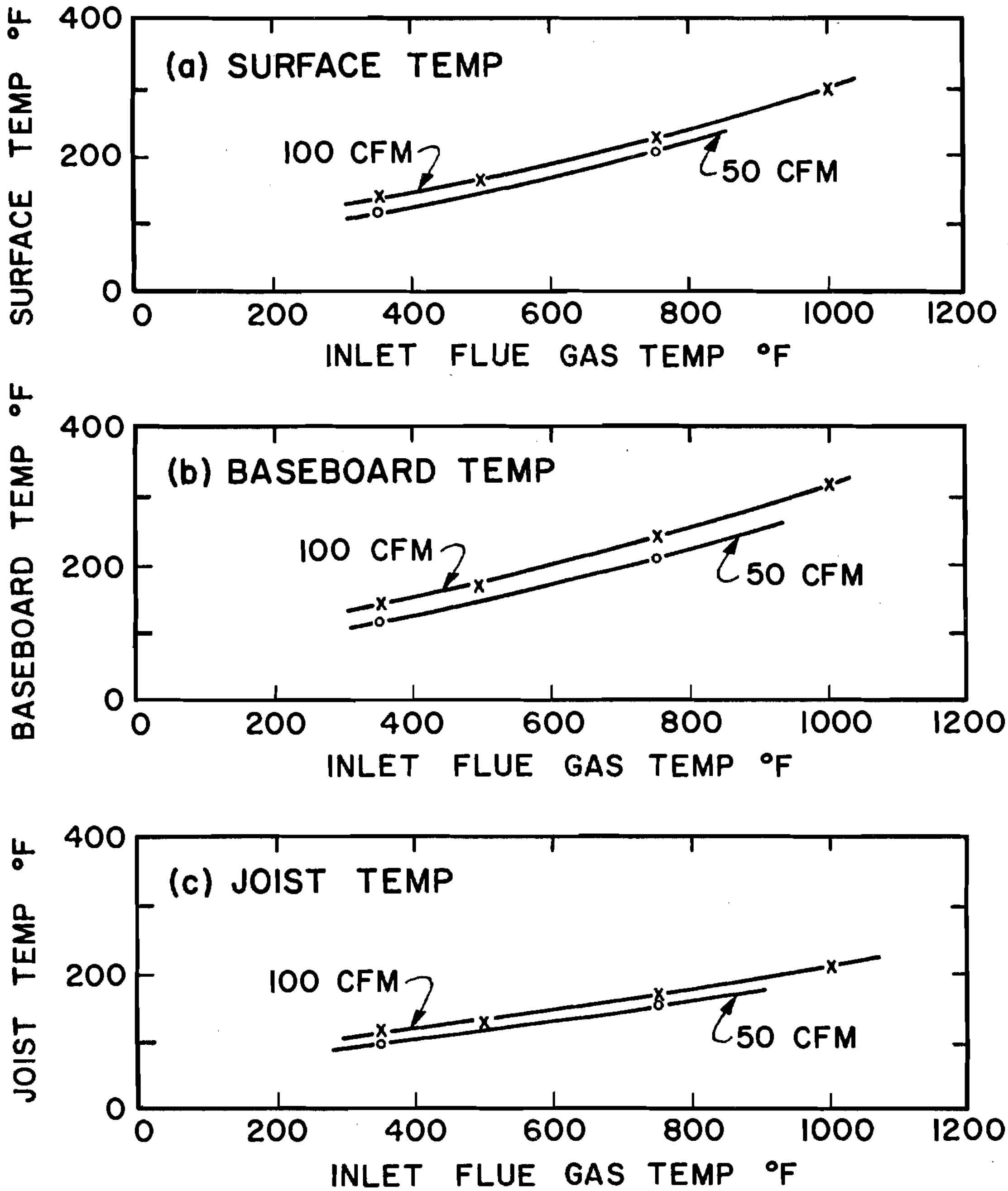


FIGURE 8

FULL - SCALE CLAY - BRICK MASONRY CHIMNEY.

COMPARISON OF SURFACE & FRAMEWORK TEMPERATURE

(DURATION OF TEST - 14 HOURS)

BR 2277-6

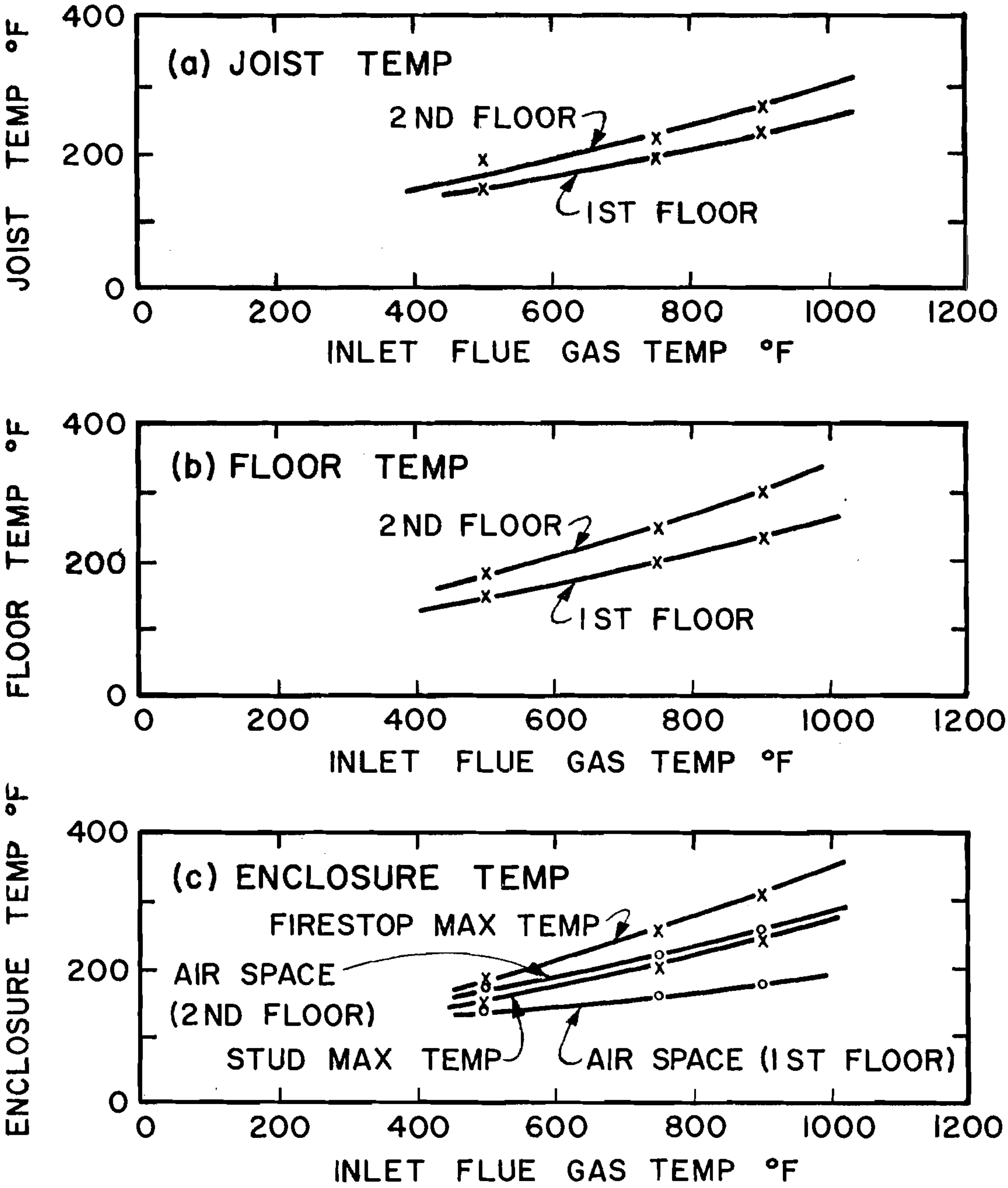


FIGURE 9

TEMPERATURE MEASUREMENT ON A FULL-SCALE CLAY-BRICK MASONRY CHIMNEY WITH AN ENCLOSURE

(DURATION OF TEST - 14 HOURS, FLUE GAS FLOW - 100 CFM)

BR. 2277-?

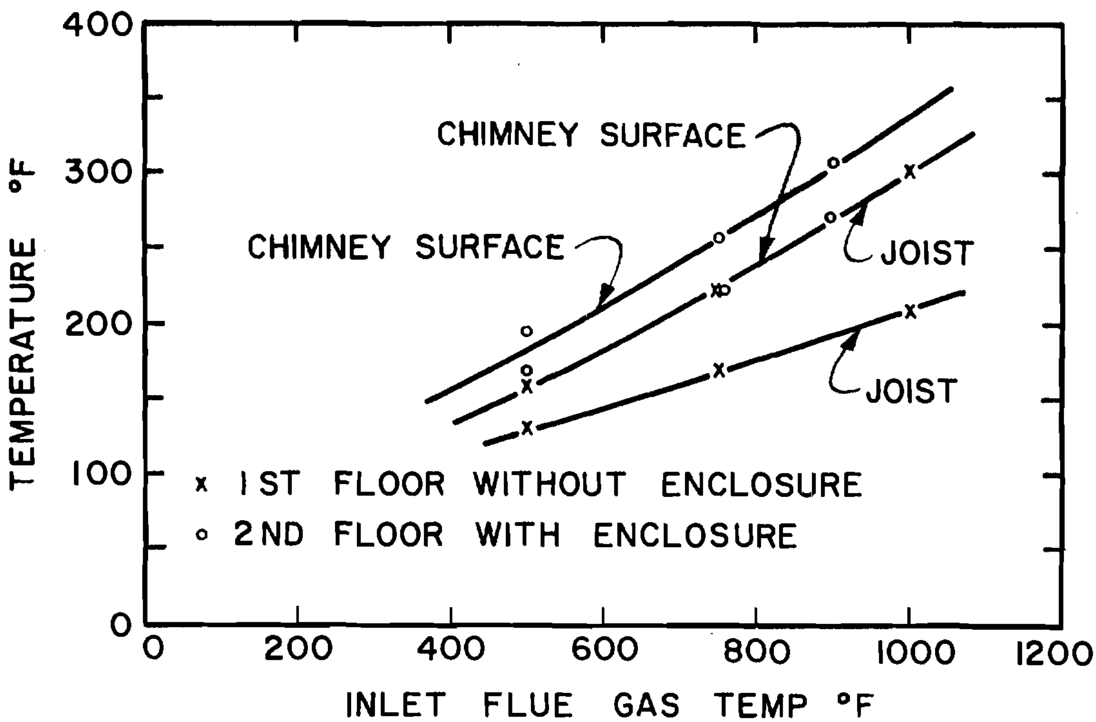


FIGURE 10

FULL-SCALE CLAY-BRICK MASONRY CHIMNEY
COMPARISON OF SURFACE & JOIST TEMPERATURES
AT 1ST FLOOR WITHOUT ENCLOSURE AND AT
2ND FLOOR WITH ENCLOSURE
(DURATION OF TEST - 14 HOURS, FLUE GAS FLOW - 100 CFM)

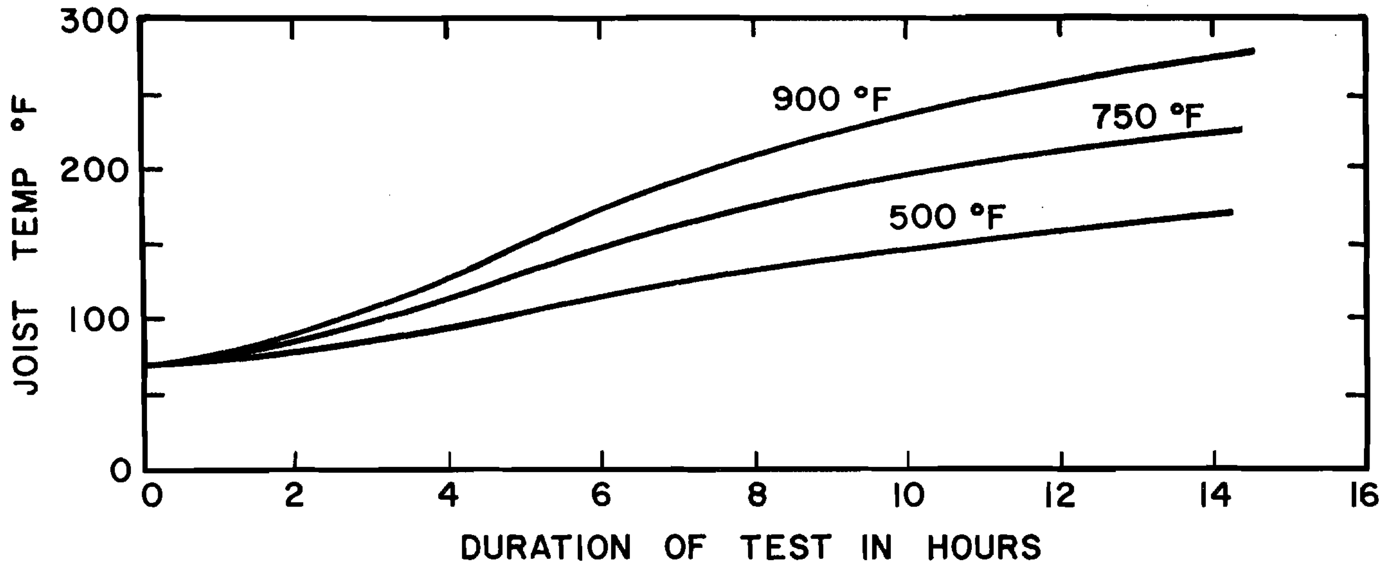


FIGURE 11
FULL-SCALE CHIMNEY WITH ENCLOSURE
JOIST TEMPERATURE VS TIME AT 2ND FLOOR LEVEL
(FLUE GAS FLOW - 100 CFM)

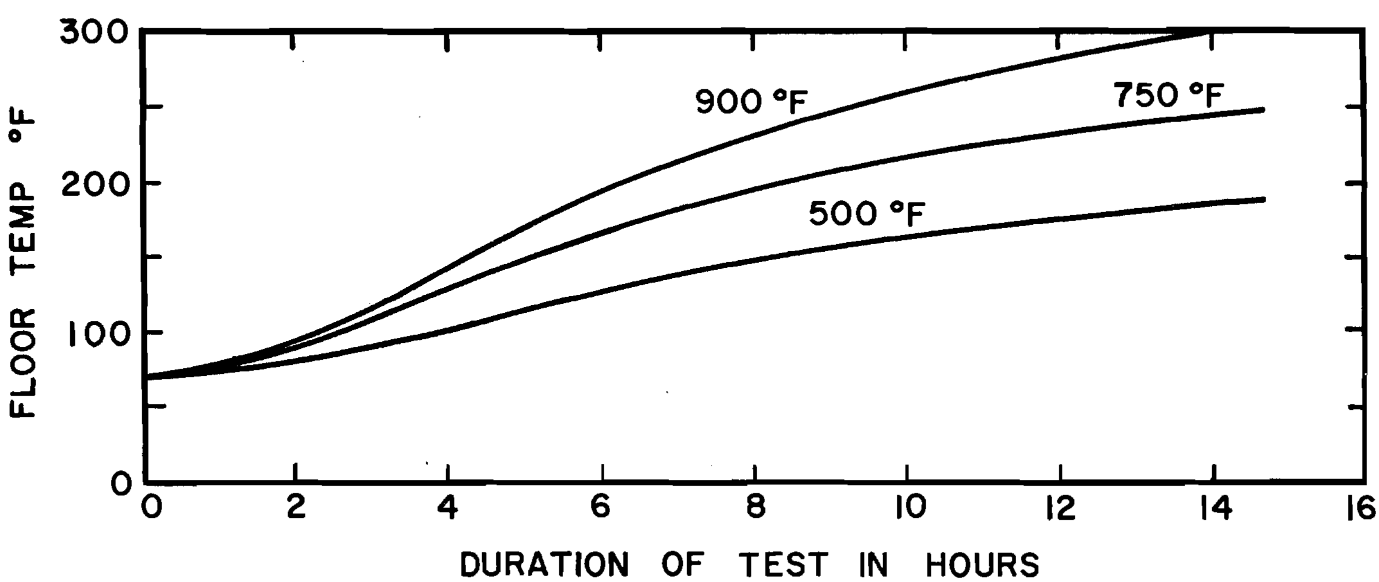


FIGURE 12
FULL-SCALE CHIMNEY WITH ENCLOSURE
FLOOR TEMPERATURE VS TIME AT 2ND FLOOR LEVEL
(FLUE GAS FLOW - 100 CFM)

BR. 2277-9

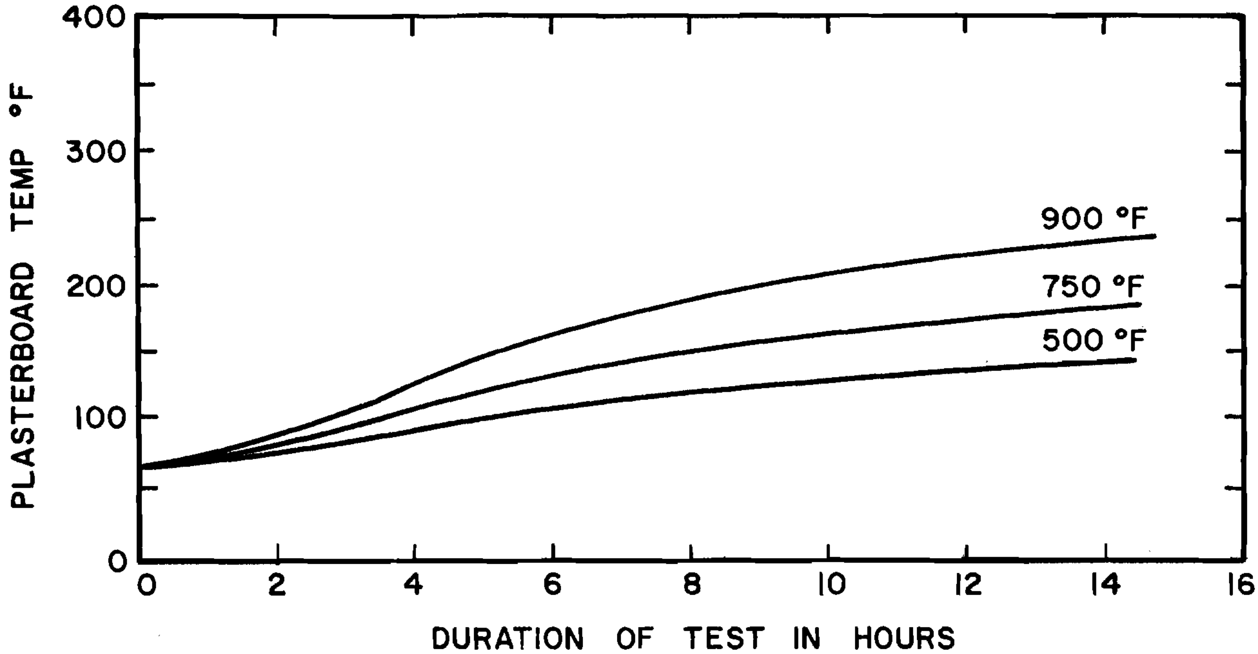


FIGURE 13
FULL-SCALE CHIMNEY WITH ENCLOSURE
PLASTERBOARD TEMPERATURE VS TIME
AT 2 ND FLOOR LEVEL
(FLUE GAS FLOW - 100 CFM)

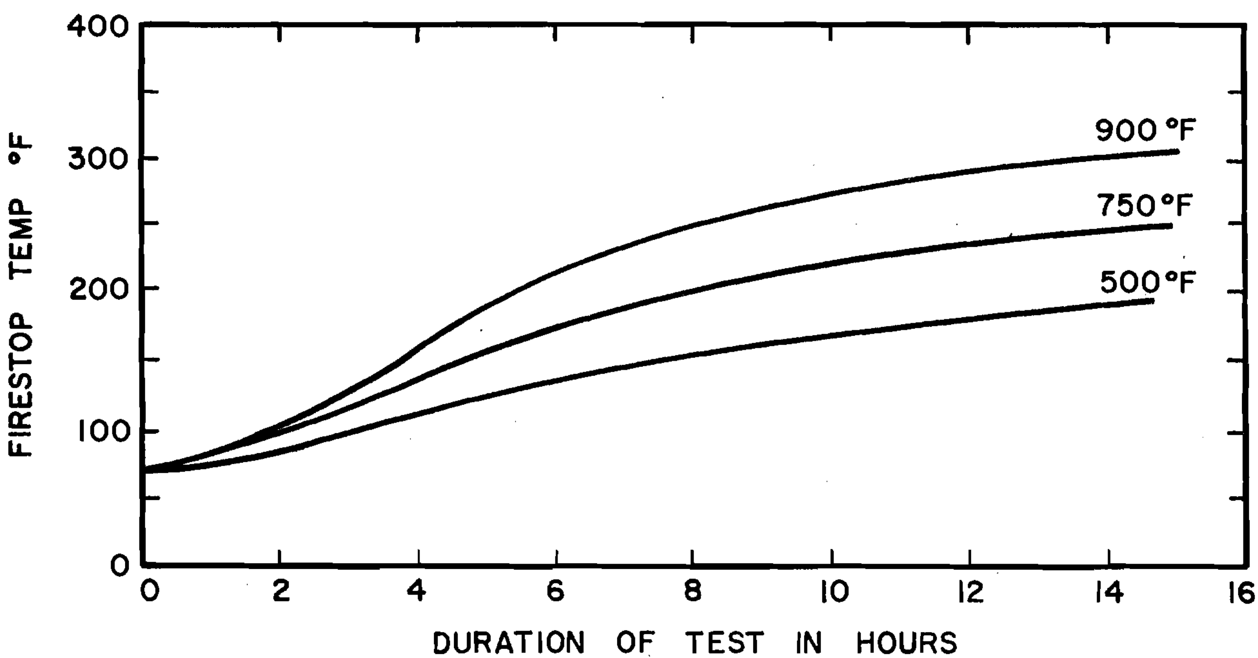


FIGURE 14
FULL-SCALE CHIMNEY WITH ENCLOSURE
FIRESTOP TEMPERATURE VS TIME
AT 2 ND FLOOR LEVEL
(FLUE GAS FLOW - 100 CFM)

BR. 2277-10

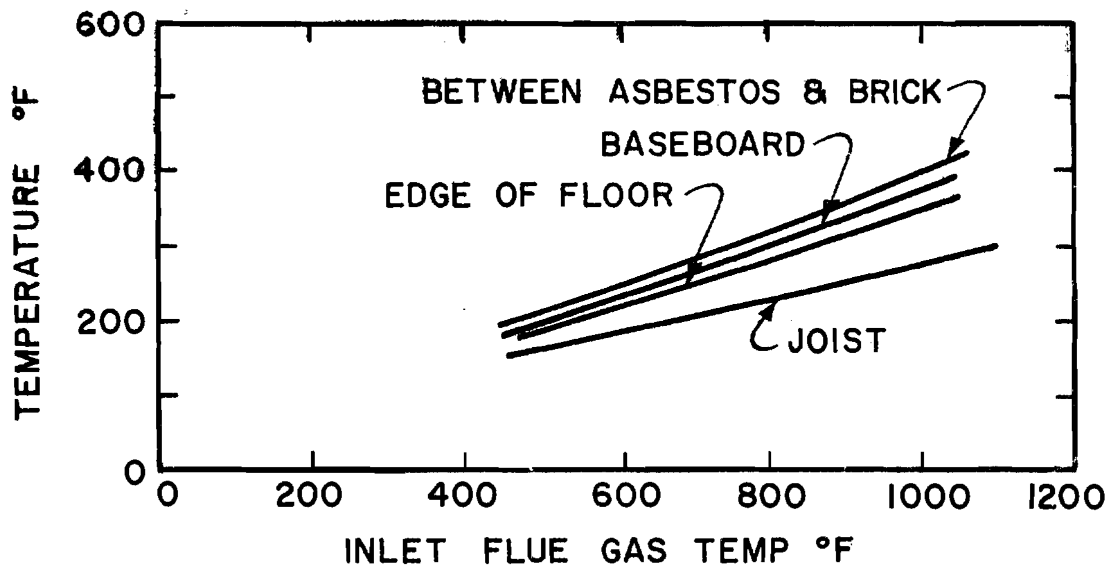


FIGURE 15
SHORT CLAY BRICK CHIMNEY NO. 1
FRAMEWORK TEMPERATURES
(TEMPERATURE READINGS AT 14 HOURS)

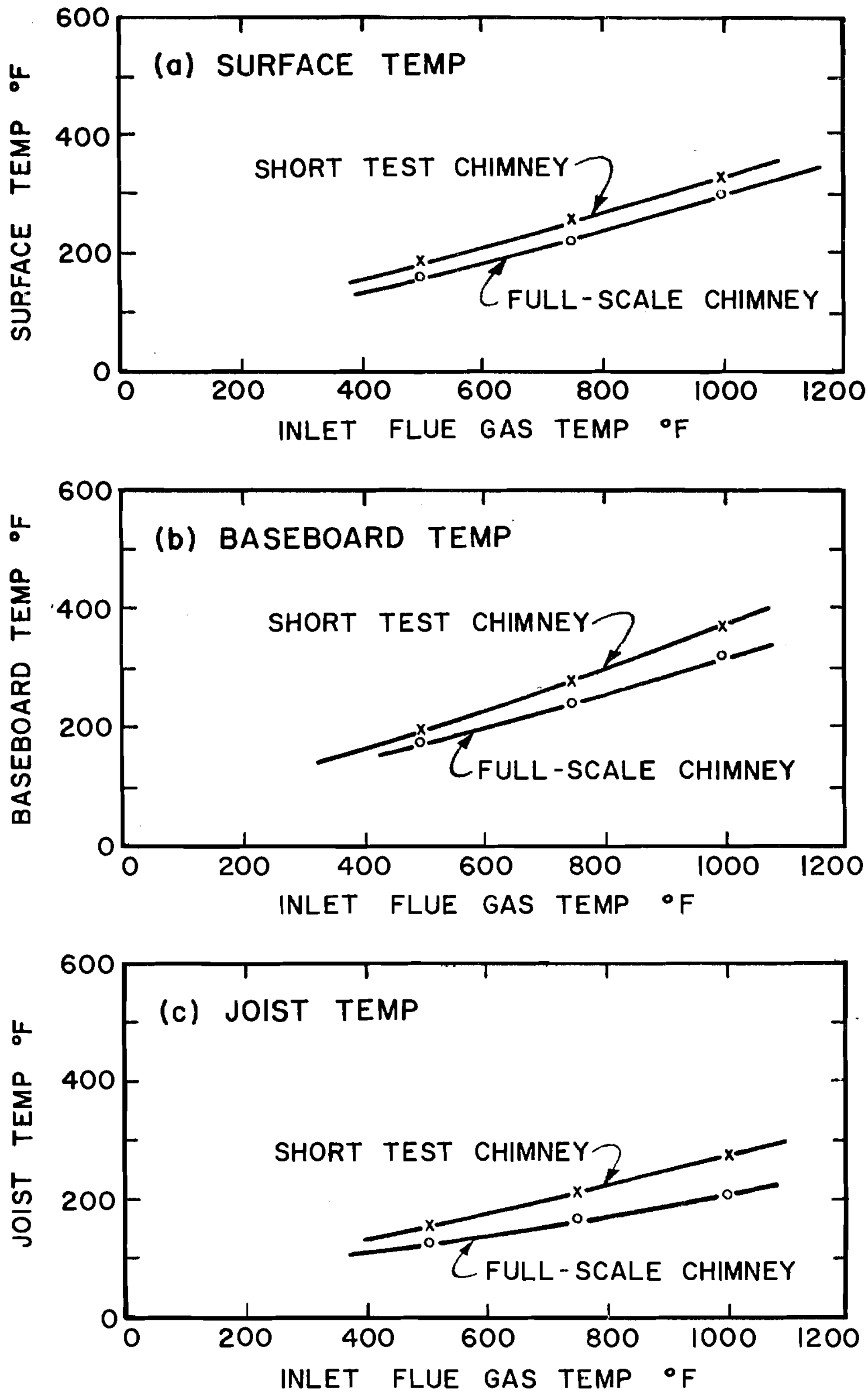


FIGURE 16

COMPARISON OF SURFACE AND FRAMEWORK TEMPERATURE FOR FULL-SCALE CHIMNEY AND SHORT CLAY-BRICK CHIMNEY NO. 1

(FLUE GAS FLOW - 100 CFM, DURATION OF TEST - 14 HOURS)

BR. 2277-12

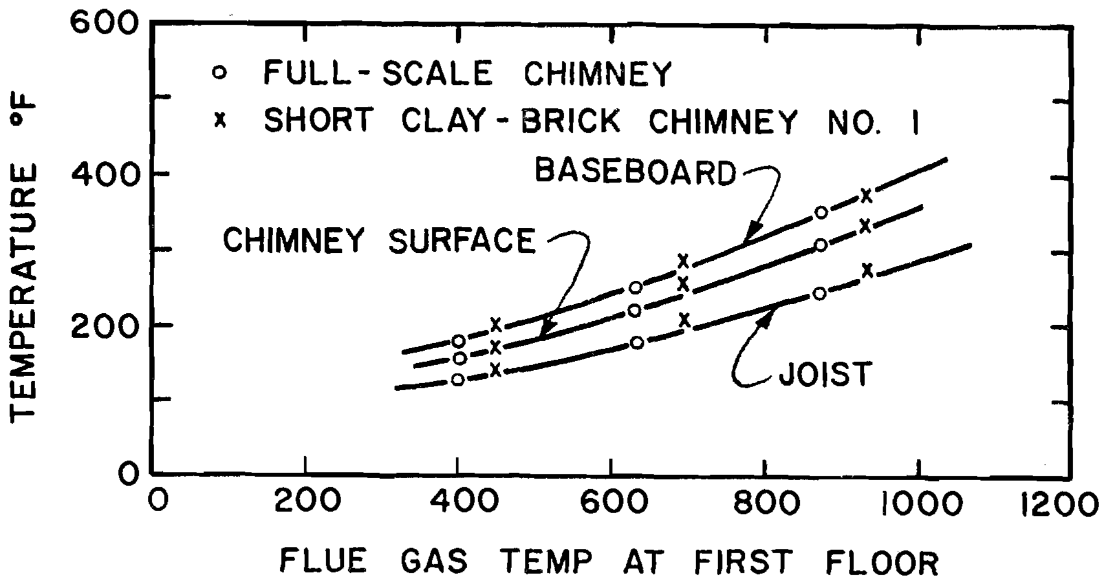


FIGURE 17
COMPARISON OF SHORT AND FULL-SCALE CHIMNEYS AT 1ST FLOOR FLUE GAS TEMPERATURE
(TEMPERATURE READINGS AT 14 HOURS)

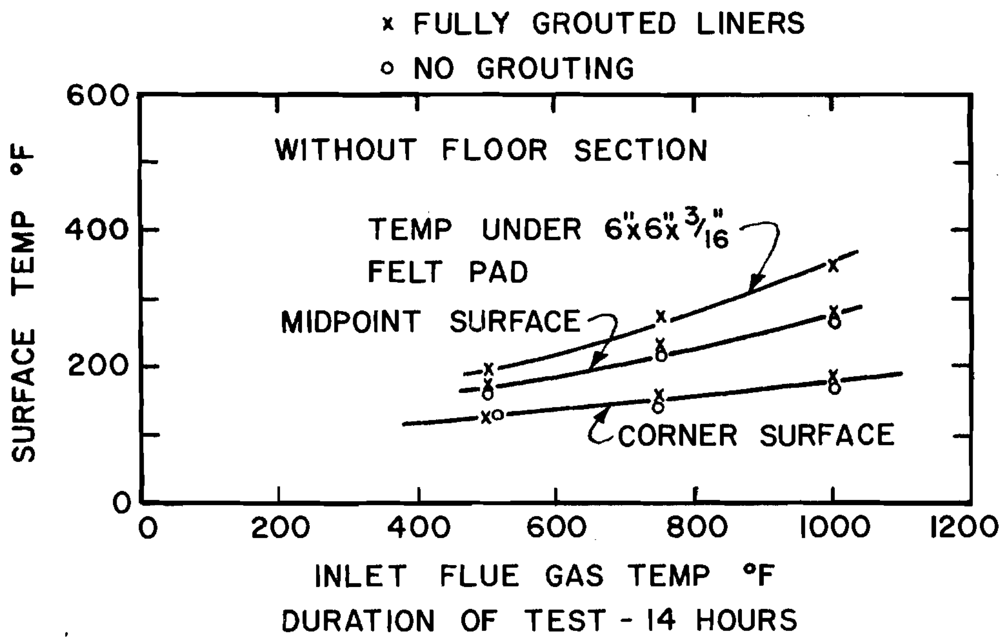


FIGURE 18
SURFACE TEMPERATURES OF CLAY-BRICK CHIMNEYS WITH LINERS GROUTED (CHIMNEY NO. 1) AND WITH LINERS NOT GROUTED (CHIMNEY NO. 3)

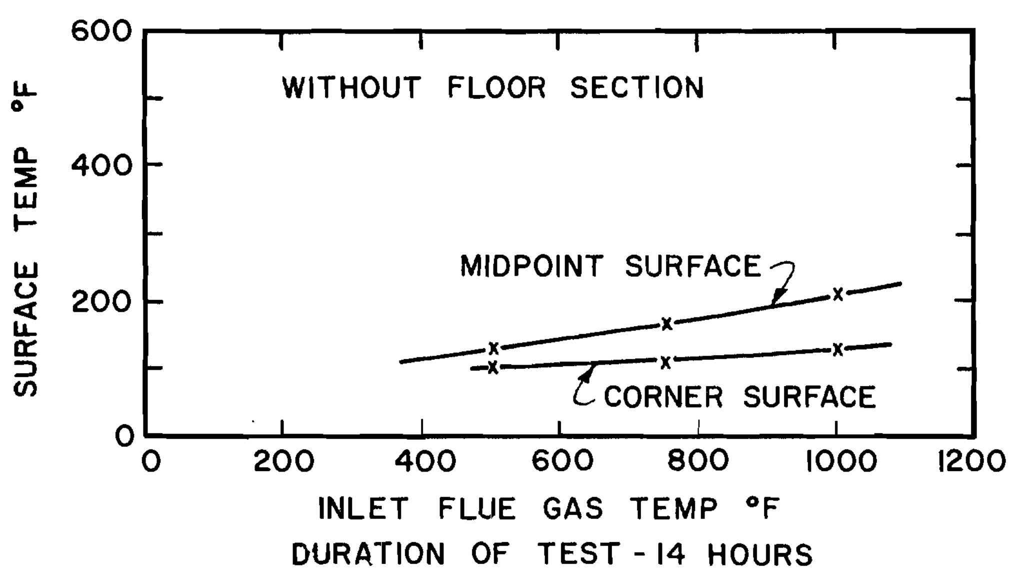


FIGURE 19
SURFACE TEMPERATURES OF DOUBLE COURSE CLAY-BRICK CHIMNEY NO. 4

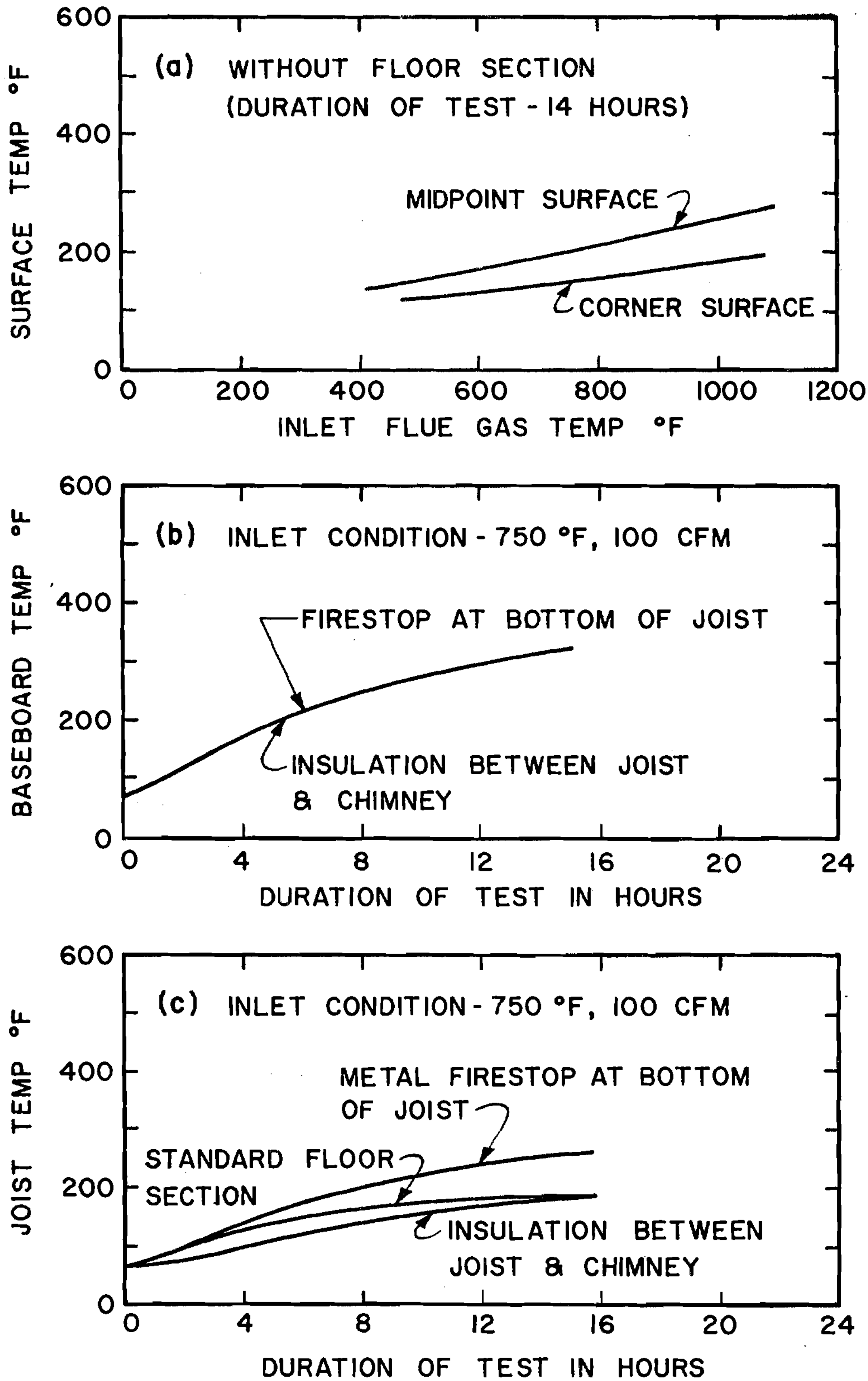


FIGURE 20
SURFACE AND FRAMEWORK TEMPERATURES OF CONCRETE BLOCK CHIMNEY NO. 5

BR. 2277-15

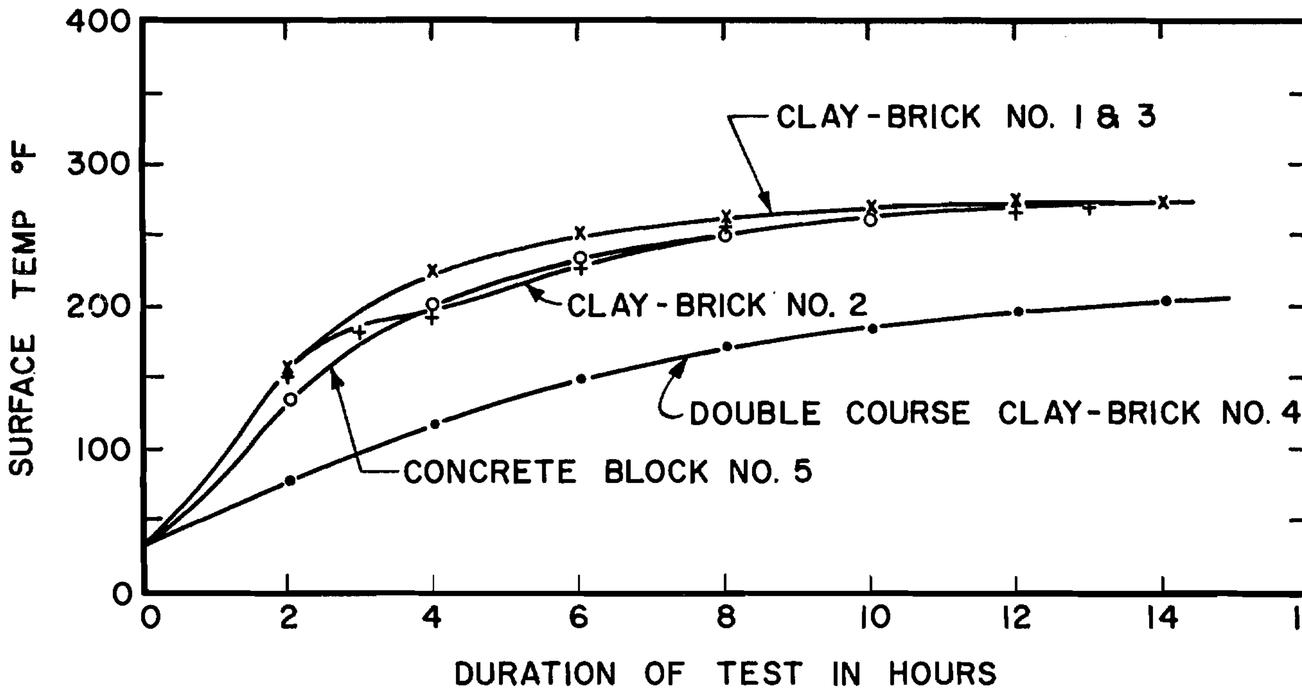


FIGURE 21
SURFACE TEMPERATURE VS TIME FOR SHORT TEST CHIMNEYS
(AT 1000 °F 100 CFM INLET CONDITION WITHOUT FLOOR SECTION)

BR. 2277-16

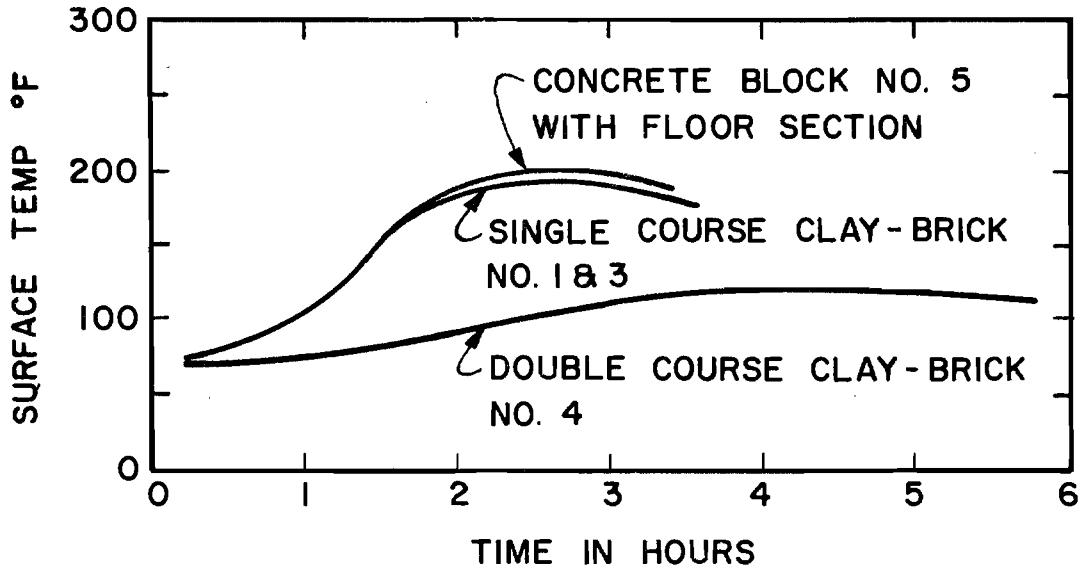


FIGURE 22

THERMAL SHOCK TEST ON SHORT TEST CHIMNEYS - SURFACE TEMPERATURE (TEST - 1/2 HOUR AT 1400 °F, 1/2 HOUR AT 1800 °F)

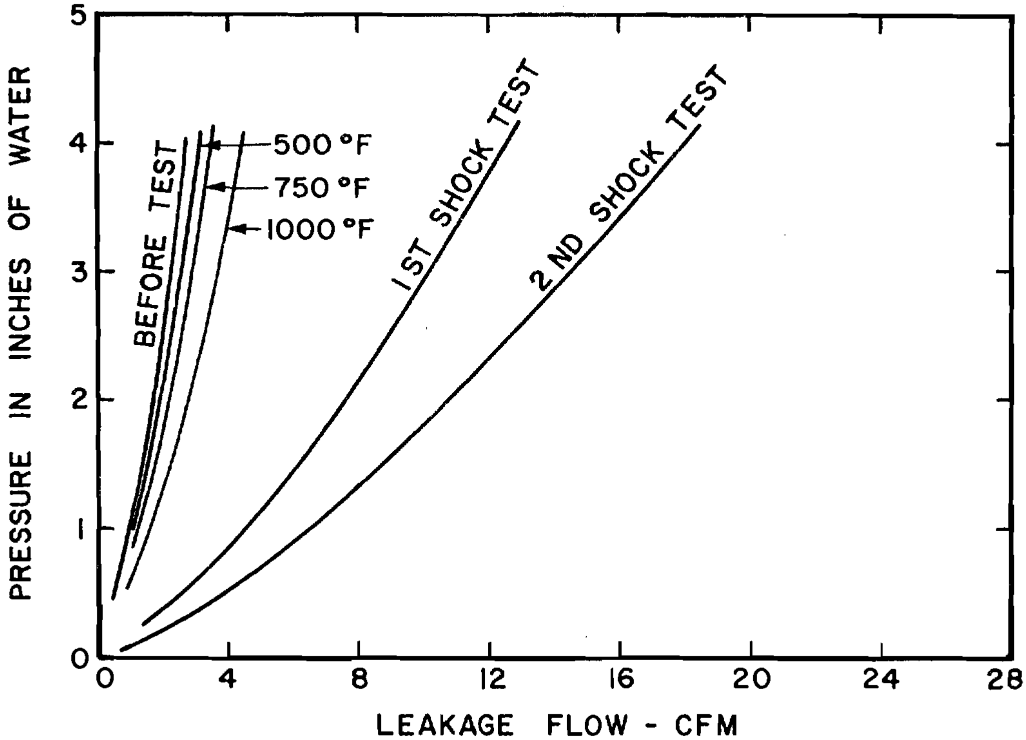


FIGURE 23
AIR LEAKAGE TEST
SINGLE COURSE CLAY - BRICK CHIMNEY NO. 1

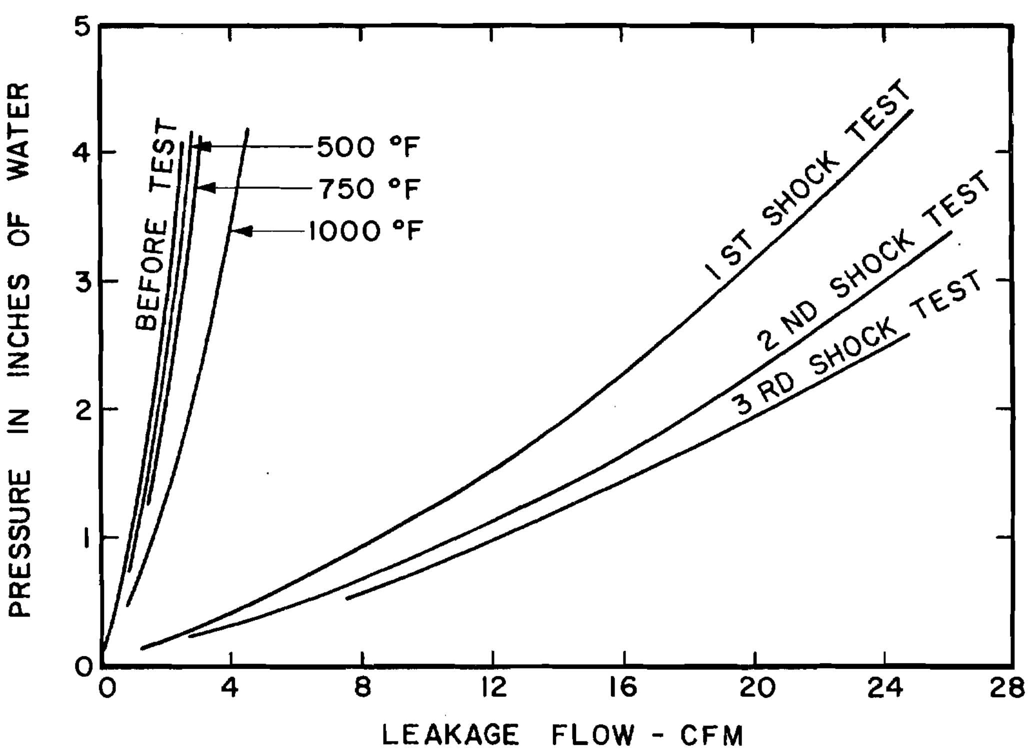


FIGURE 24
AIR LEAKAGE TEST
SINGLE COURSE CLAY - BRICK CHIMNEY NO. 3
(LINERS NOT GROUTED)

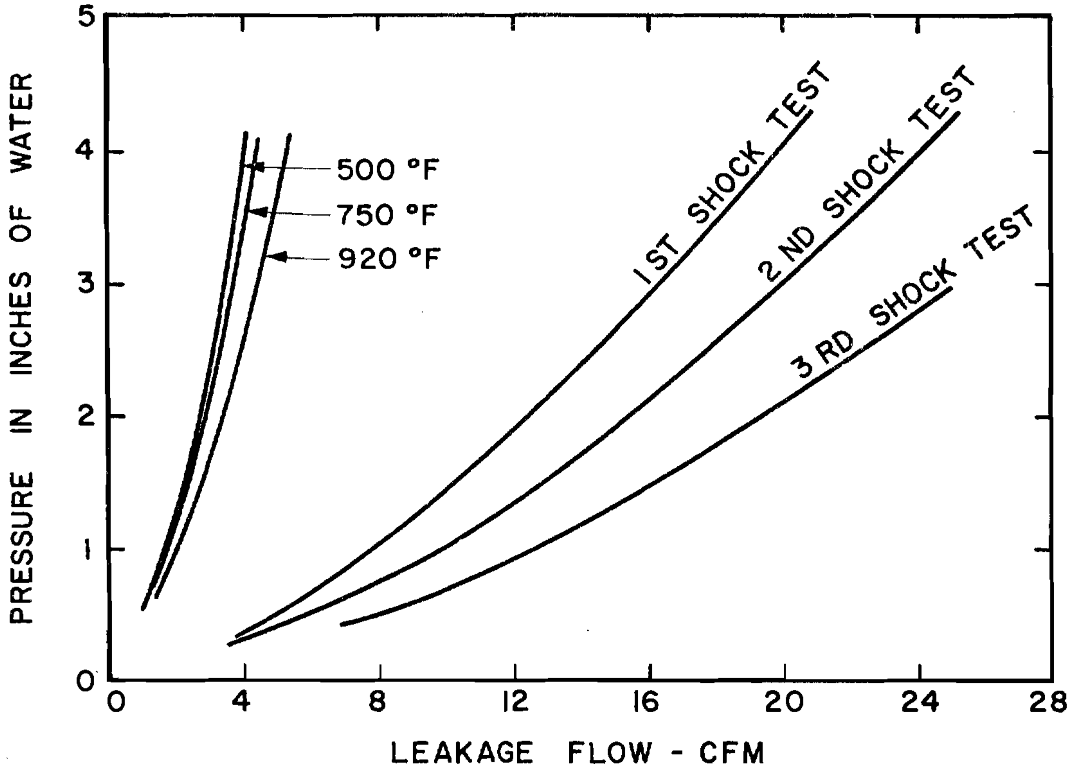


FIGURE 25
AIR LEAKAGE TEST
CONCRETE BLOCK CHIMNEY NO. 5

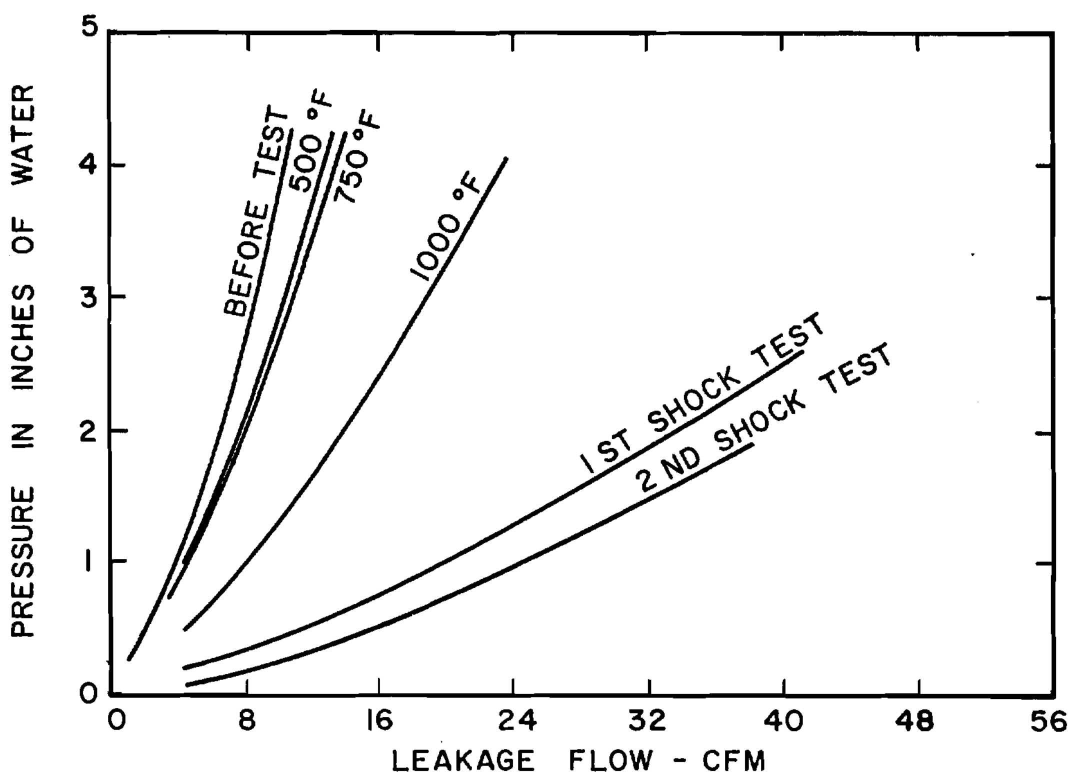


FIGURE 26
AIR LEAKAGE TEST
DOUBLE COURSE CLAY - BRICK CHIMNEY NO. 4

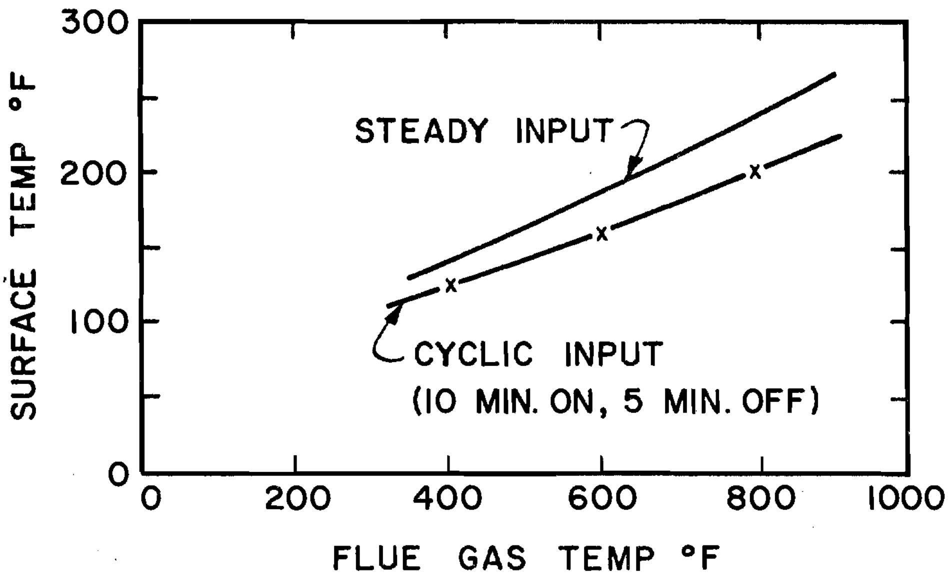


FIGURE 27

COMPARISON OF OUTSIDE SURFACE TEMPERATURE WITH CYCLIC AND STEADY FLUE GAS INPUT

(SINGLE COURSE CLAY - BRICK CHIMNEY)

BR. 2277-20