a limited opening at the top which could be affectively sealed against the ingress of outside air. When bricks were unwrapped to put Demec disks on them, the wrapping and sealing of the bricks was carefully inspected to see if the sealing was still effective. None of the sealing was found to have failed. After affixing the Demec disks, zero readings were taken and the bricks were returned to the dry container. When re-measuring each brick before loading it in a frame or exposing it to a particular atmosphere, it was found that changes in dimension were negligible being mostly within the range of measuring error, but the highest gain in length was 9×10^{-5} m/m, or 0,09 mm/m. This particular brick gave a negative reading in the transverse direction so that this increase in length could have been because of the settling down of internal stresses within the brick.

From a later comparison with bricks from the same brickfield that were fired in the laboratory at controlled temperatures, it was estimated that these bricks had been fired at about the following temperatures:

(i) well-fired : 1090 °C,
(ii) medium-fired : 1030 °C,
(iii) lightly-fired : 1000 °C.

A relatively hard-burnt blue-black face brick was obtained from another manufacturer about 50 km from the one mentioned above. These bricks had already been removed from the kiln a while before, but were still fairly warm to the touch. They were wrapped, sealed, transported and stored in the same way as the other bricks.

5.1.2 <u>Raw bricks</u>

From two widely separated brickfields in the South Western

Cape, two 100 kg samples of clay as well as raw bricks were obtained. Both wet unfired bricks straight from the factory extruder and air-dried bricks were collected by a colleague and railed to Pretoria. The bricks were very well packed and only four of the air-dried bricks were broken in transit, whereas no damage could be seen on the wet bricks. One of the sources of supply was the same brickfield, from which the first of the fired brick samples had been collected. All these bricks were stored on open racks in the laboratory until required.

5.1.3 Laboratory firing of bricks

After studying the accelerated expansions of the briquettes which at that stage had been steamed for 119 hours, the temperatures at which the raw bricks would be fired were selected. It was decided to fire the Georgedale bricks at 1010 ℃ and 1030 ℃ and the Bellville bricks at 1020 ℃. Having seen that the maximum accelerated expansion of the Georgedale briquettes after 3400 hours of steaming had shifted dramatically to 1085 ℃, a batch of Georgedale bricks was fired at 1100 ℃.

The firing of the bricks took place in the same two furnaces in which the briquettes were fired, as described in 4.2.2. The rate of heating the furnaces was 80 ℃ per hour until the firing temperature was reached. The firing temperature was maintained for a 5 hour soaking period. Three bricks could be fired at a time. After the experience with the briquettes care was taken to ensure that the furnaces were fired at the selected temperatures. Before the first firing at a particular temperature, or if someone else used the furnace between firings, the temperature controls were adjusted and three bricks, from a quantity obtained from a builder, were placed in the furnace for a dummy firing. A calibrated thermocouple and temperature reading instrument used in the fire research laboratory was used to check temperatures. This thermocouple was placed in the furnace between two bricks but not touching either brick. If required, adjustments were made after such a firing and a second dummy firing was carried out. When the correct firing temperature had been obtained, batch after batch was fired after being dried for 24 hours in an oven at 110 °C. It was found that on occasions the firing temperature would be up to 5 °C above or below the selected temperature, but did remain steady at that temperature during the soaking period.

The specimens were removed when at about 100 °C and were placed in a desiccator to cool. After cooling they were transferred to bins with air-tight lids and containing trays of calcium chloride.

5.2 <u>Properties of the Fired Brick Materials</u>

5.2.1 <u>Elastic modulus of bricks</u>

The bricks had the following average moduli of elasticity when tested on their ends:

Blue-black face bricks : 11,600 GPa
Well-fired bricks (1090 °C) : 22,800 GPa
Georgedale bricks (1030 °C) : 11,200 GPa
Bellville bricks (1020 °C) : 14,500 GPa

5.2.2 <u>Thermal expansion</u>

The coefficient of thermal expansion was determined between -17 °C and 40 °C and ranged from 5,26 x 10^{-6} per °C to 5,89 x 10^{-6} per °C.

This means that thermal expansions in a 10 m long wall in which the temperature ranges from 5 °C in winter to 40 °C in summer could be approximately 2 mm, or to express it in the same units as the brick expansions on the graphs, 0,2 mm/m.

5.2.3 Reversible moisture expansion

The reversible moisture expansion of the well-fired clay bricks was found to be negligible. For the medium-fired bricks, i.e. fired at 1020 ℃ it was 0,58 mm/m (Bellville) and when fired at 1030 ℃ it was 0,38 mm/m (Georgedale).

5.2.4 Compressive strength

The following were the compressive strengths of the bricks:

Blue-black face brick : 45 MPa.
Well-fired stock brick : 65 MPa.

The compressive strengths of the laboratory-fired bricks have still to be determined when it is decided to stop measuring their expansions.

5.2.5 Linear firing shrinkage

Linear firing shrinkage was measured on the Georgedale bricks and was found to be:

Firing temperature (℃)	Firing shrinkage (per cent)	Firing shrinkage Briquettes (per cent)
980	2,5	1,9
1030	5,2	4,9
1100	10,1	9,5

The linear firing shrinkage of the Bellville bricks fired at 1020 ℃ was 4,62%. The firing shrinkage of the bricks was higher than that of the briquettes. This might to some extent be due to the much smaller specimens being more affected by friction with their supports, whereas the bricks which were fired on their sides were perhaps not much affected by support conditions 50 mm above the supports.

5.2.6 Weight loss during firing

Dried raw bricks were weighed just before firing and again after firing and cooling in a desiccator. The results are each the average of six bricks. The following were the percentage losses in weight:

(i) Georgedale bricks fired at 1030 °C lost 5,38%,
(ii) Bellville bricks fired at 1020 °C lost 6,7%

There was very little scatter in the results for each type of brick.

5.2.7 Percentage absorption

The percentage absorption, after 24 hours soaking in water, of the well-burned bricks on which moisture expansion measurements had been completed was determined and found to be 24,4%. This is many times higher than the percentage absorption (4,6%) measured on the specially extruded and fired specimens made from Georgedale clay fired at 1085 °C. The small specimens contained no visible firing cracks whereas the bricks had many fine visible cracks on their surface.

5.2.8 Examination with scanning electron microscope

This was carried out by a colleague[22] experienced in the use of this instrument. The corners of four bricks were split off with a hammer and chisel. Those that had not been exposed to moisture previously were placed in a desiccator, whereas those broken off bricks under nil load in the fog room were first dried in an oven at 110 °C before being placed in the desiccator containing silica gel. The two Georgedale bricks had been fired at 1030 ℃ and the one had been in the fog room for 915 days. The Bellville bricks had been fired at 1020 ℃ and the one had been in the fog room for 1255 days.

The preparation of the specimens for examination by the scanning electron microscope (SEM) involved breaking off and trimming pieces of the bricks to approximately 10 x 10 x 10 mm for insertion in the apparatus. A gold-palladium film about 200 Å thick was evaporated onto the surface of each specimen for conductivity and to produce secondary electrons. A photograph was taken of an area which typified the general structure of the surface of the specimen. These photographs are shown in Figures 19a, 19b, 20a and 20b.

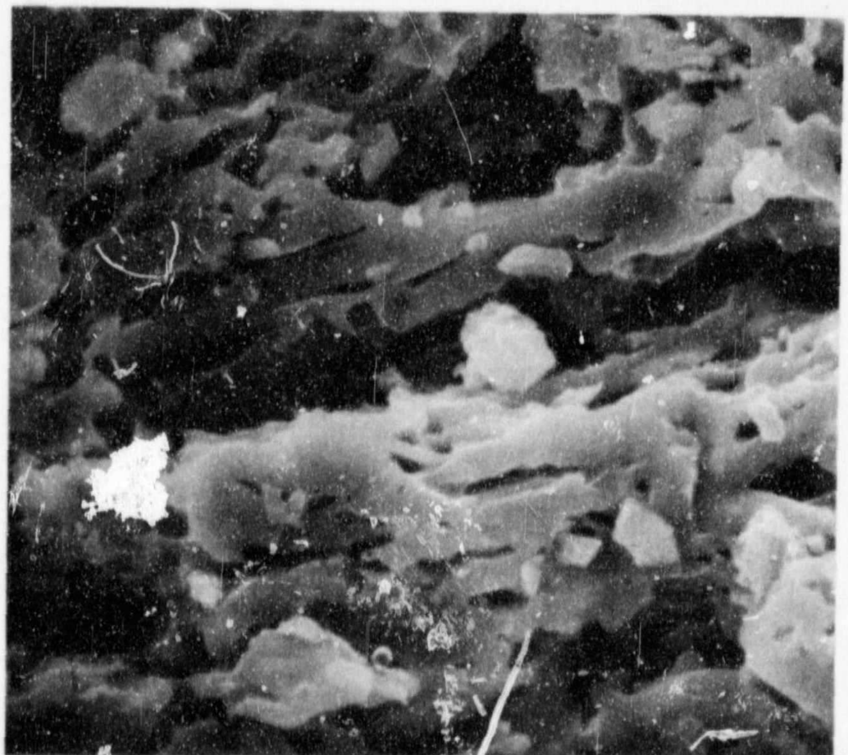
As can be seen there is no noticeable difference between the material that has expanded and the unexpanded material. The pore structure can be clearly seen. Material that had been fired at slightly lower temperatures usually had many more finer pores, than this fairly well-vitrified material.

5.3 Measurement of Dimensional Change

The dimensional change was measured by means of a Demec demountable strain gauge. The disks or targets between which measurements were taken were firmly fixed to the specimens. The strain gauges, targets, methods of fixing the targets, method of taking measurements and the accuracy of readings are fully described and discussed in Appendix B.

5.4 Loads Applied to Bricks

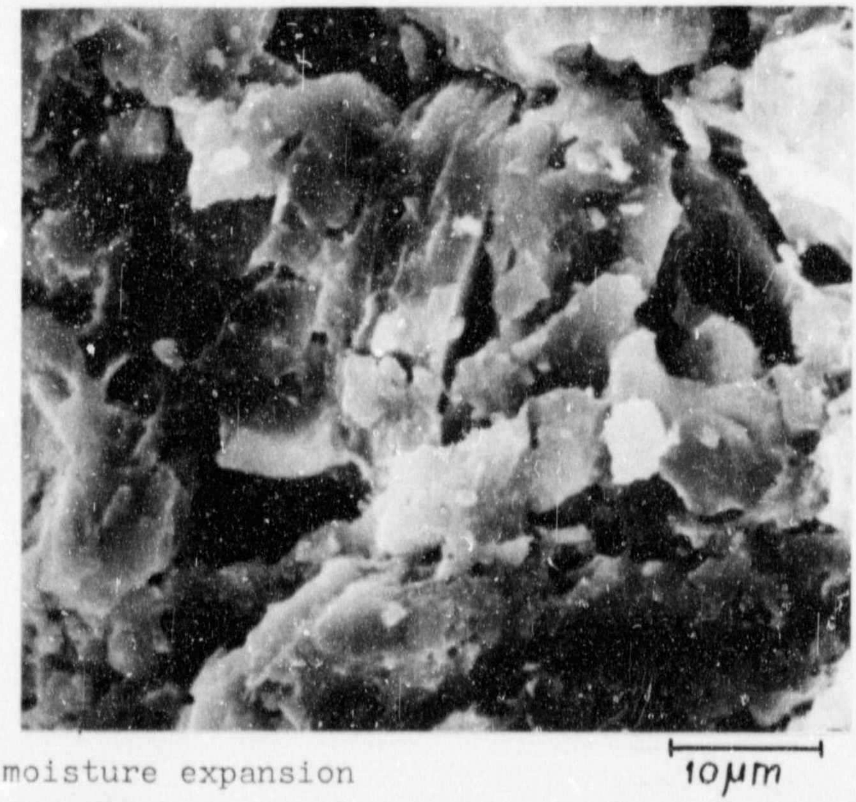
The method of loading the bricks including the design of the loading frames, the preparation of brick specimens and the placing of the long-term loads on the bricks are described in Appendix C.



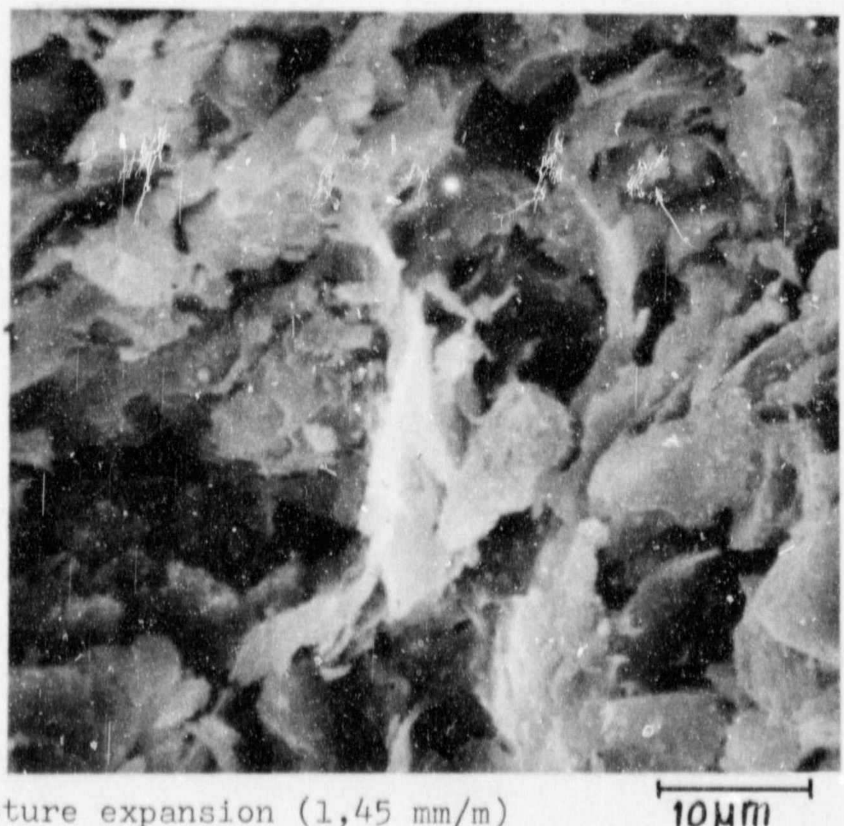
(a) No moisture expansion

(b) Moisture expansion (1,27 mm/m)

FIGURE 19. SEM pictures of Georgedale clay fired at 1030 °C



(a) No moisture expansion



(b) Moisture expansion (1,45 mm/m)

FIGURE 20. SEM pictures of Bellville clay fired at 1020 °C

The load placed on each brick and the exposure conditions are set out in Table 8. The well-burnt stock bricks, the blue-black face bricks and the Bellville bricks fired at 1020 ℃ were subjected to ranges of loads, whereas the Georgedale bricks fired at 1030 ℃ were only subjected to a few loads, but these bricks were used to give information on the effect of different firing temperatures on full bricks. Because of the change in the rate of expansion on a log time scale of some of the briquettes after more than 100 hours steaming, it was decided to leave most bricks in their loading frames for really long periods to see whether an unexpected change would occur in their behaviour. This meant that loading frames were not available for loading further specimens. When specimens are removed from time to time from the loading frames raw Georgedale bricks will be fired at appropriate temperatures and loaded.

5.5 Behaviour of Non loaded Bricks

5.5.1 Effect of relative humidity on expansion

Bellville bricks fired at 1020 ℃ and Georgedale bricks fired at 1030 ℃ were exposed to four relative humidity and temperature conditions, namely:

(i) in a fog room at 22 ℃ as described in Appendix D,

(ii) in a humidity cabinet at 21 ℃ and 81% relative humidity,

(iii) in a constant temperature (21 ℃) and constant relative humidity (50%) laboratory as described in Appendix D, and

(iv) in an office where the temperature and relative humidity changed daily.

Dimensional / ....

TABLE 8 Loads and exposure conditions of bricks

Type of brick	Firing temp. (℃)	Where exposed	Load (MPa)	Type of clamp	Number specimens exposed
Stock brick well-burnt	1090	FR	Nil	-	1
	"	"	0,69	i	3
	"	"	1,38	i	2
	"	"	3,45	ii	2
	"	"	13,79	iii	2
	"	"	41,37	iv	2
Stock brick medium-burnt	1030	FR	Nil	-	1
	"	"	27,58	iv	1
Stock brick lightly-burnt	1000	FR	Nil	-	1
Blue-black face bricks		FR	Nil	-	1
		"	6,90	ii	1
		"	13,79	iii	2
		"	27,58	iv	2
Georgedale	1010	FR	Nil	-	2
	"	Roof	Nil	-	1
	1030	Office	Nil	-	2
	"	50 HR	Nil	-	1
	"	81 HR	Nil	-	2
	"	FR	Nil	-	3
	"	FR	1,5	ii	1
	"	FR	10,0	iii	2
	"	Roof	Nil	-	3
	"	"	0,7	i	2
	1100	FR	Nil	-	1
Bellville	1020	Office	Nil	-	2
	"	50 HR	Nil	-	1
	"	81 HR	Nil	-	2
	"	FR	Nil	-	3
	"	"	0,7	i	2

TABLE 8 Loads and exposure conditions of bricks

Type of brick	Firing temp. (°C)	Where exposed	Load (MPa)	Type of clamp	Number specimens exposed
Bellville	1020	FR	1,5	i	2
	"	"	10,0	iii	2
	"	"	20,0	iv	2
	"	Roof	Nil	-	2
	"	"	0,7	i	1
	"	"	1,5	i & ii	2
	"	"	20,0	iv	2

NOTE: FR = fog room

50 HR = 50% humidity room

81 HR = 81% humidity room

Appendix C for type of clamps

Dimensional changes were measured with a Demec at suitable intervals. The expansion of the Bellville bricks at the different relative humidities is shown on Figure 21 and the expansion of the Georgedale bricks on Figure 22. As can be seen the bricks all expanded, the expansion at 50% relative humidity and in the office after 700 days being just more than half of that in the fog room. The expansions have been plotted against relative humidity on Figures 23 and 24 and it can be seen that the slowing down of the rate of expansion in the fog room is less than that at the lower relative humidities.

Although from these graphs damage to external walls can be expected to be severe because such walls will become wet when it rains, it can also be expected that the expansions of internal walls will cause damage, yet very few cases of such damage have been identified in South Africa. It appears from the graphs that moisture expansion of brickwork will take place even at very low relative humidities but at a much reduced rate. This means that the bricks on the roof should continue expanding right through the dry winter months but the colder temperatures will slow down the expansion and because the bricks have lower temperatures they will shorten, so that very little dimensional change if any will be measured during the cold dry winter months.

5.5.2 Effect of firing temperature on expansion

As with the briquettes, the firing temperatures of the bricks had a marked effect on their moisture expansion. Figure 25 illustrates this. All these bricks were fired in the kilns at brickfields. The heavy lines show longitudinal expansion and the thin lines show the average expansion on the 70 mm and 110 mm wide faces. The lightly-fired (about 1000 °C)

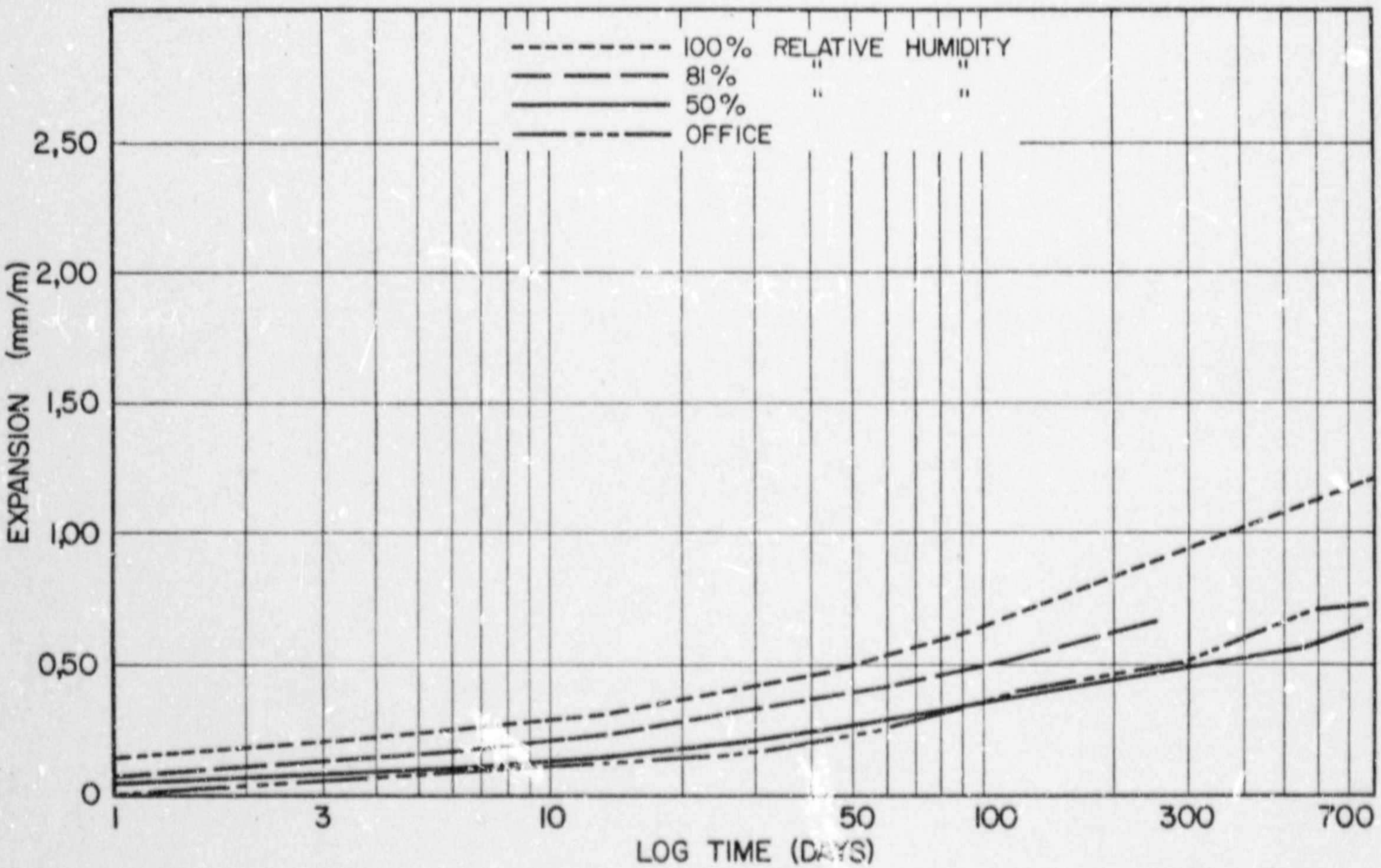


FIGURE 21

Expansion at different relative humidities: Bellville bricks

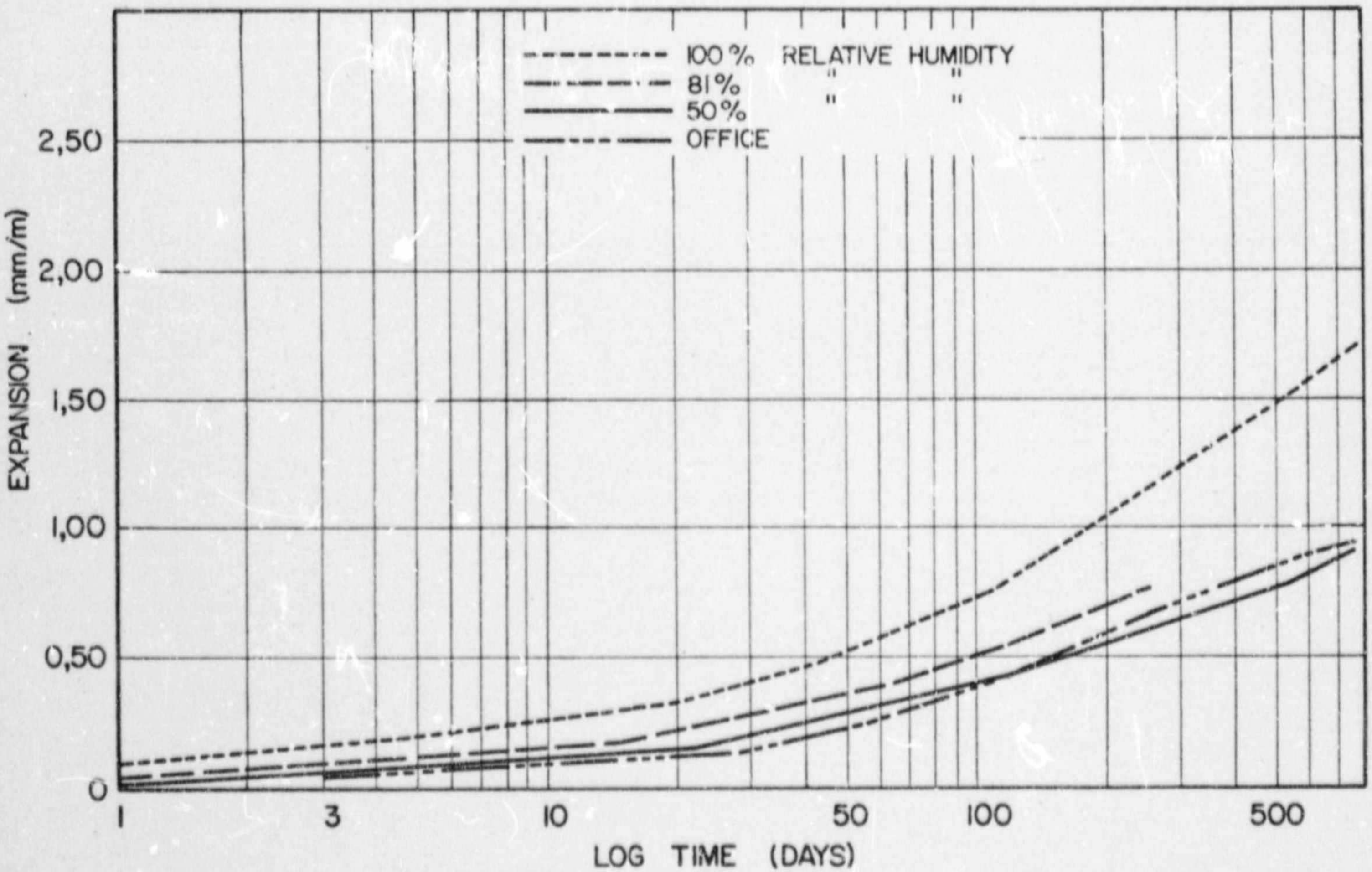


FIGURE 22

Expansion at different relative humidities: Georgedale bricks.

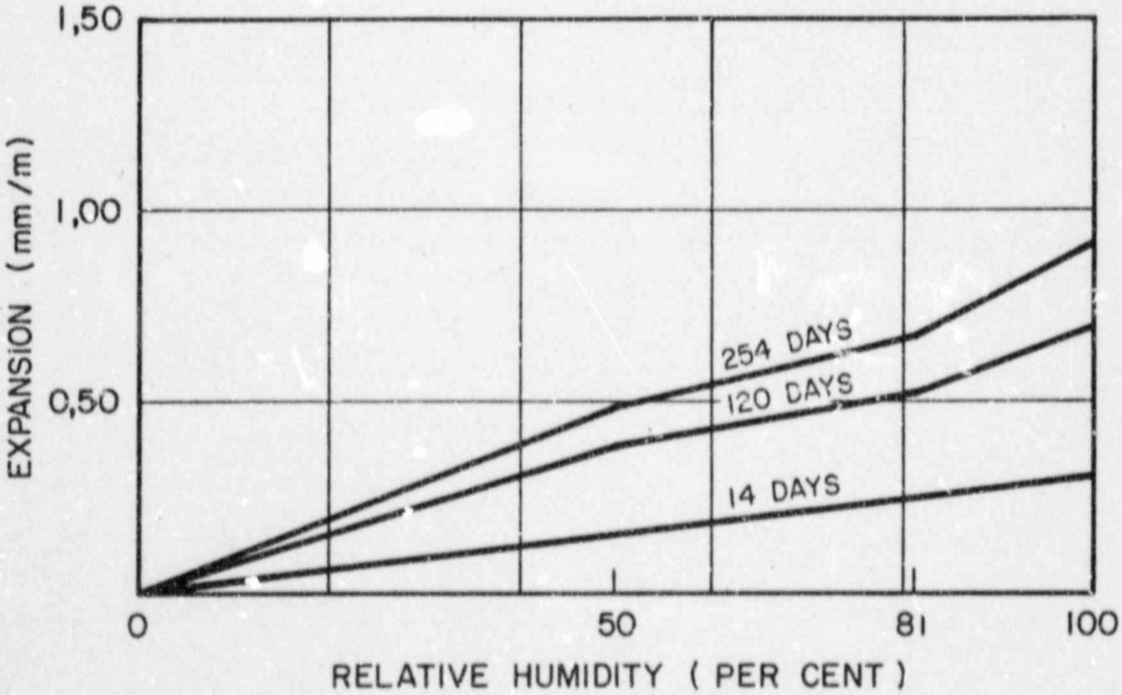


FIGURE 23
Effect of relative humidity on expansion: Bellville bricks

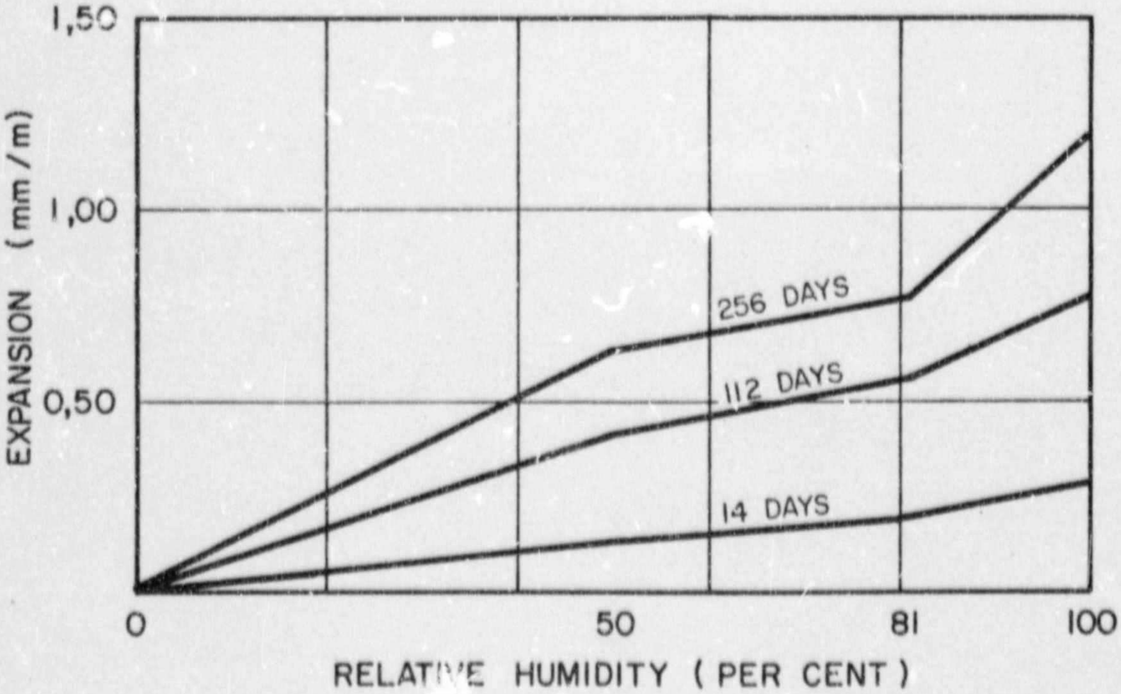


FIGURE 24
Effect of relative humidity on expansion: Georgedale bricks

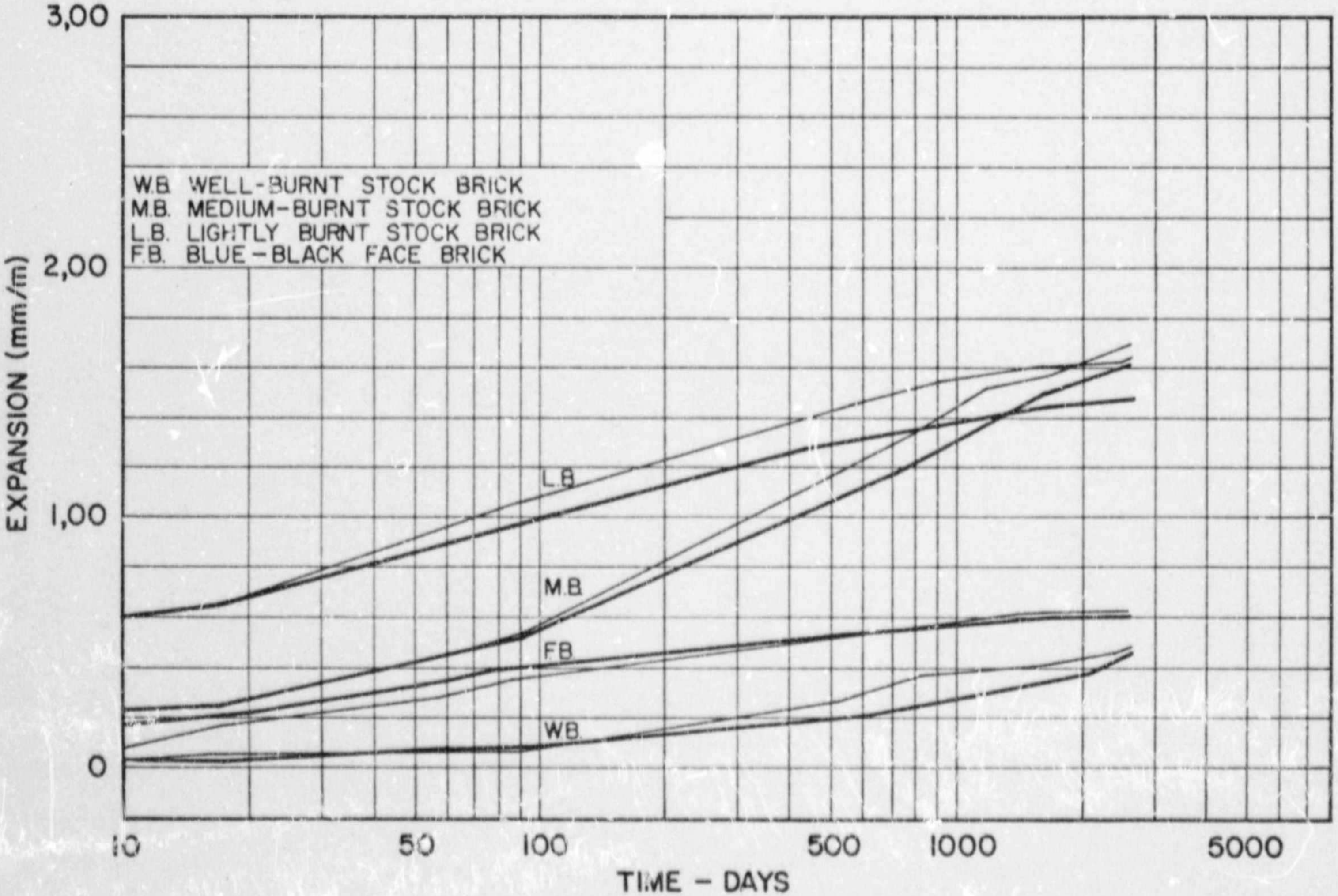


FIGURE 25

Expansion of unloaded bricks

stock brick initially had the highest expansion, but the medium-fired (about 1030 ℃) brick underwent a change in rate of expansion after about 90 days and after 1200 days had expanded more than the lightly-fired brick which by the downward curvature of its expansion against log time shows that its rate of expansion is reducing significantly. The well-fired (about 1090 ℃) bricks had the least initial expansion but are still expanding steadily. The transverse expansions of all three bricks were similar to the longitudinal expansions but slightly higher.

The lightly-fired bricks would have the largest internal surface[9] and the least amount of glass present, so that, if the internal surface reactivity was high, they would initially expand rapidly but soon slow down as the surface energy reduced. The medium-fired bricks would have a smaller internal surface area and, initially, from the shape of the curve a lower internal-surface reactivity than the lightly-burned bricks. However their change in rate of expansion after 90 days could have been because most of the highly reactive amorphous aluminosilicates were thinly coated with glass during firing and until this impermeable thin layer with its low reactivity had been altered by hydration to a more porous substance, the surfaces of the amorphous aluminosilicates would not be exposed to moisture. Once the moisture reached the highly reactive material, because of partial chemical breakdown of the coating or micro-cracking of the coating during expansion, more rapid expansion would take place. Extending this supposition to the well-fired bricks, the coating of glass might have been thicker and more widespread (there would have been more glass formed at this temperature) and the internal surface area would certainly have been comparatively small. Under these conditions the onset of expansion would be very slow but would continue for a very long time. When alkali ions are leacked from the surface of glass these sites have high energy and chemisorption of water takes place which causes expansion.

Further / ....

Further slow leaching out of alkali ions causes further chemisorption of water.

The expansion of the blue-black face brick was low and almost a straight line with log time.

Because the above stock bricks had come from Georgedale, Georgedale raw bricks were fired at various temperatures and exposed under the same fog room conditions. Figure 26 shows the expansion of bricks fired at 1010 ℃, 1025 ℃ and 1100 ℃. The expansion of these bricks was slightly higher than those fired at the brickfield but the shapes of the curves were similar and the brick fired at 1025 ℃ showed the same change in expansion rate after 90 days as the medium-fired brick.

Bricks fired at the same temperatures and exposed on the roof are also shown on Figure 26. The expansions of two of these bricks on normal time plots for 500 days are shown on Figures 27, 28, 29 and 30, including daily rainfall, daily maximum and minimum relative humidities averaged weekly and weekly averages of daily maximum and minimum air temperatures.

On Figure 26, it can be seen that, in all cases after the first 200 days, the expansion on the roof lagged behind the expansion in the fog room as was to be expected with the dry winter season. However, the one brick fired at 1030 ℃ and exposed on the roof had a faster rate of expansion for the first 190 days than the brick in the fog room. This was because the regular rainfall and high relative humidities kept the brick wet and the high summer temperatures caused more rapid expansion than the 22 ℃ temperature of the fog room. On Figure 26 is also shown the significantly different expansion of two bricks fired at 1030 ℃ and 1025 ℃ and exposed on the roof. The brick with the lower expansion was placed on the roof about 18 months after the other brick, during a much drier period, with a resultant lower expansion over the

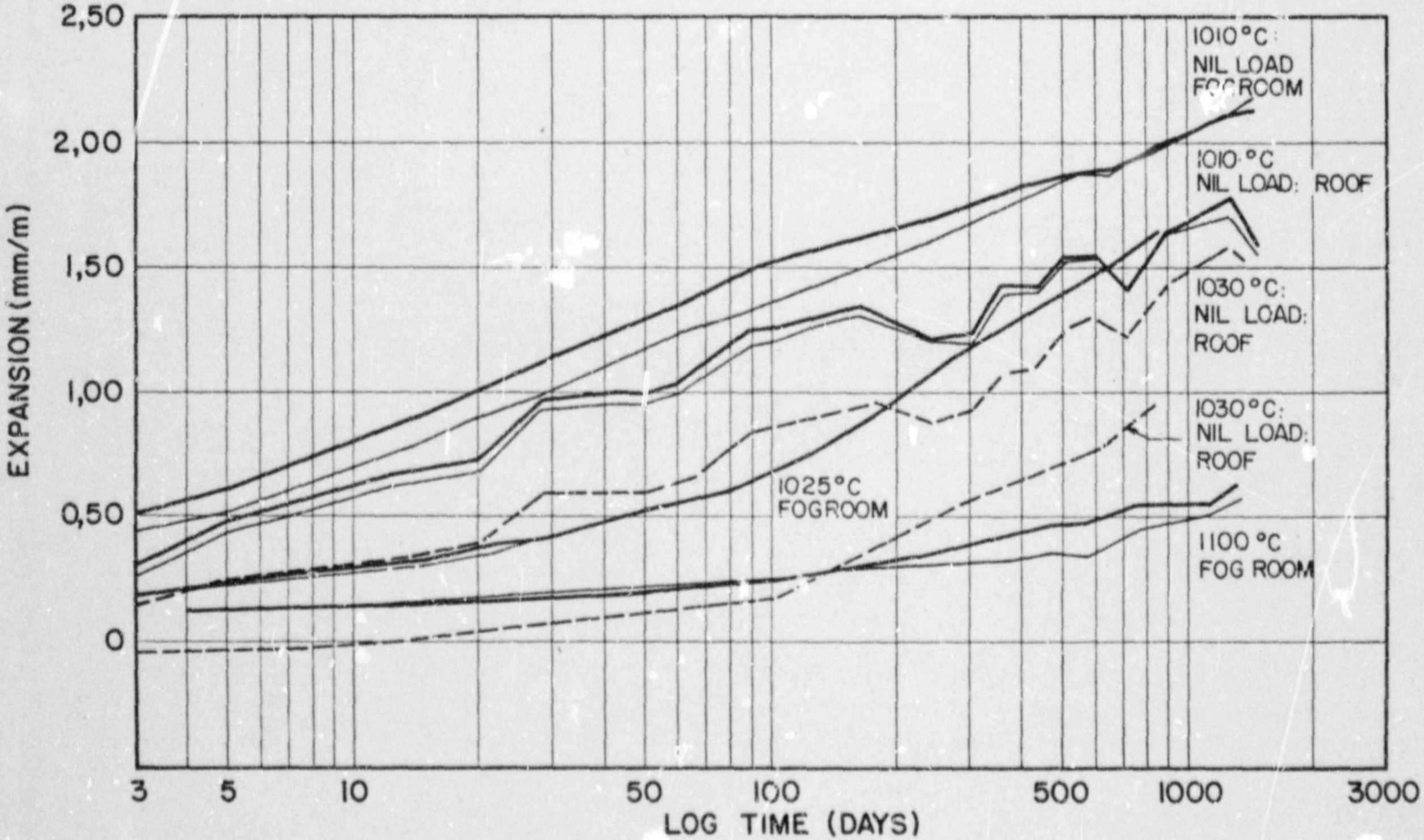


FIGURE 26

Georgedale clay bricks fired at different temperatures: nil load

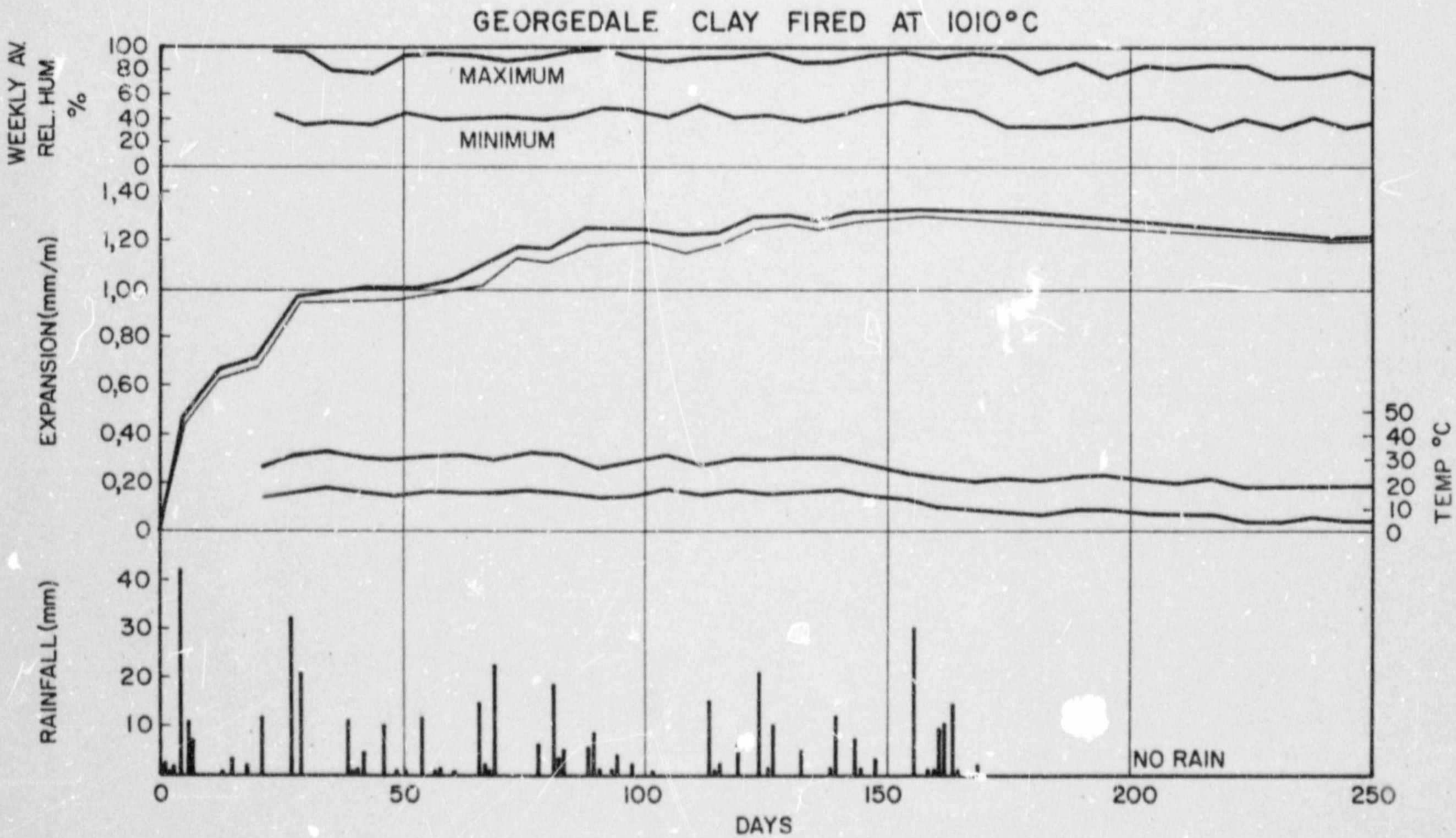


FIGURE 27
Brick exposed on roof - no load

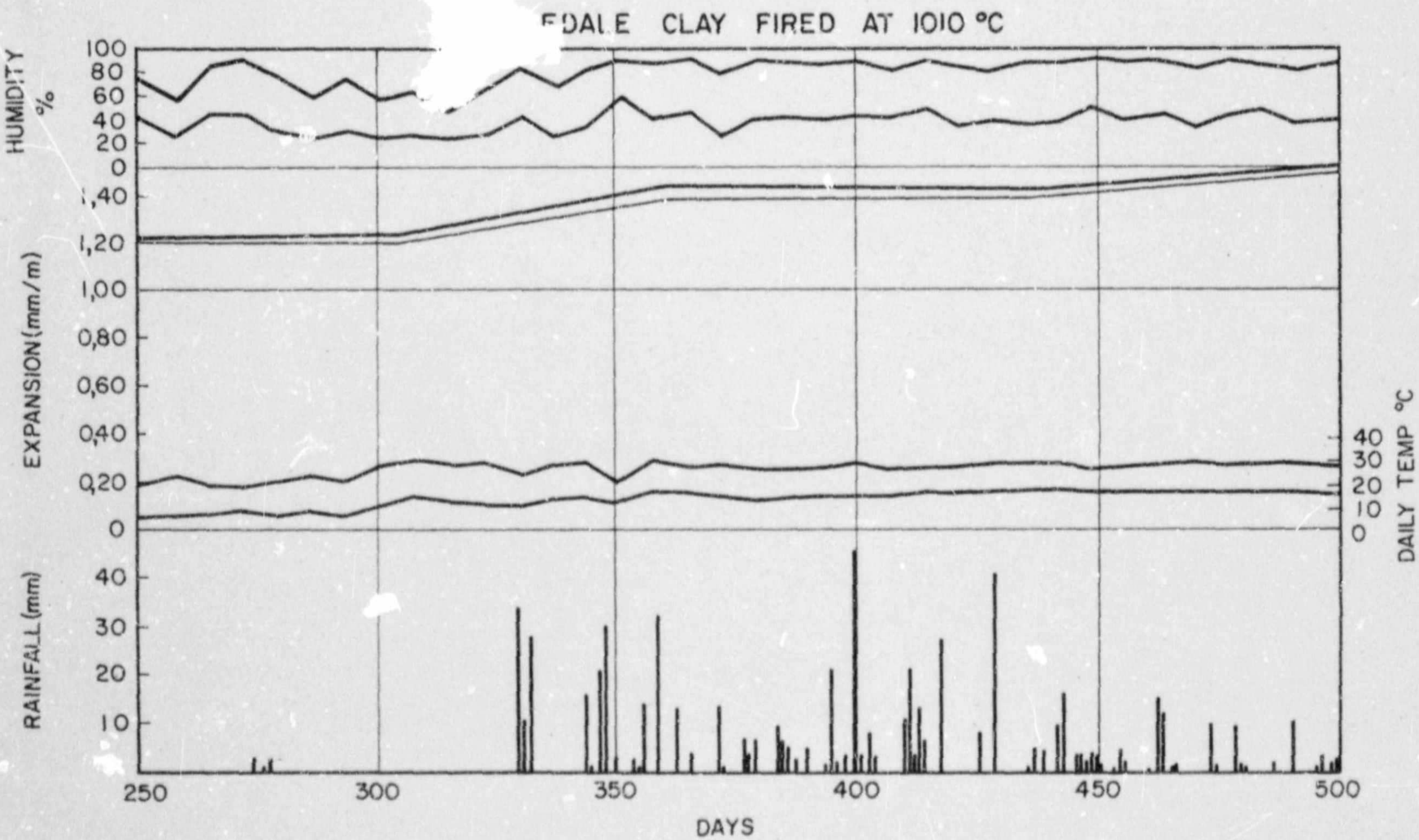


FIGURE 28

Brick exposed on roof - no load

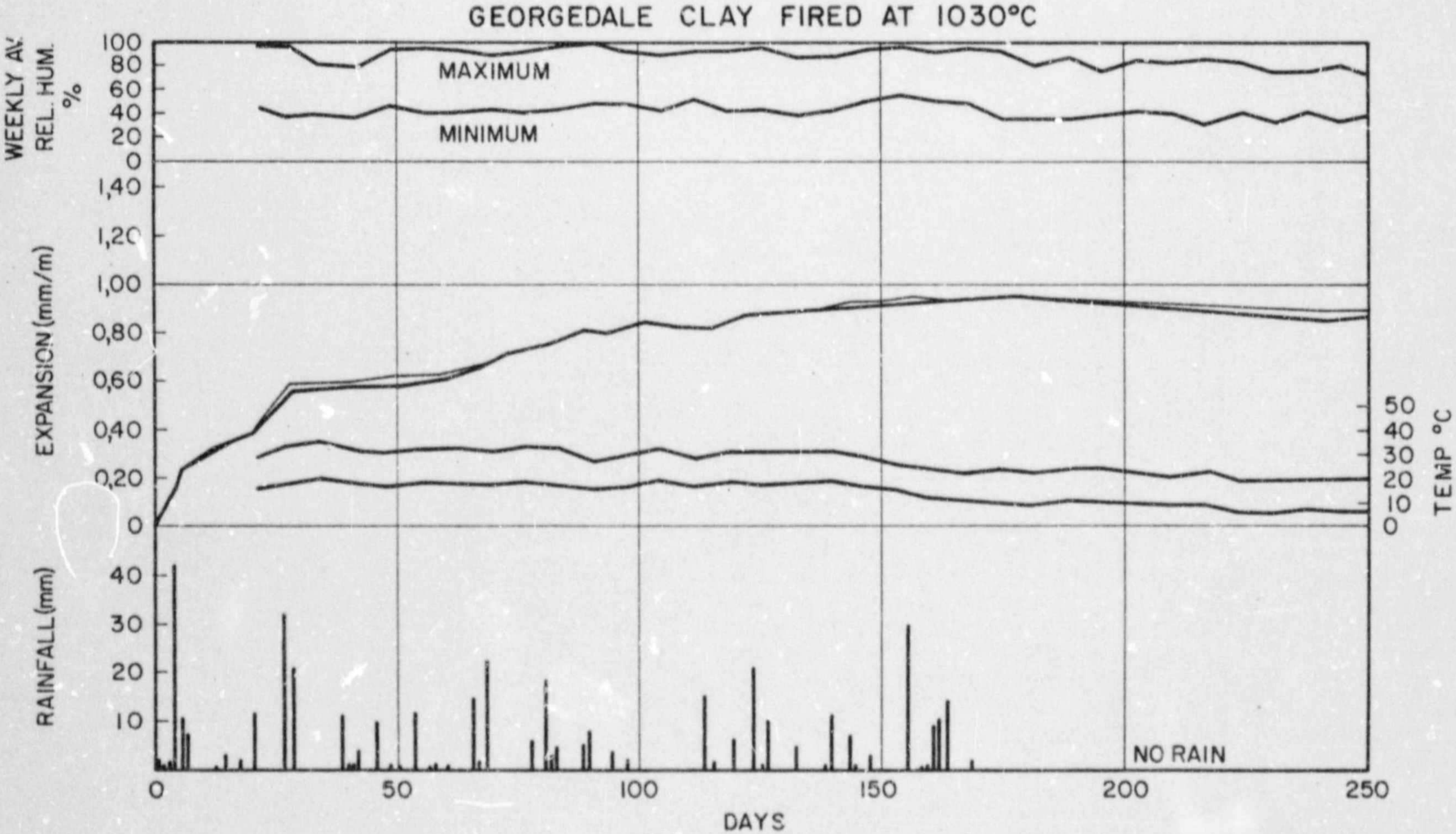


FIGURE 29

Brick exposed on roof - no load

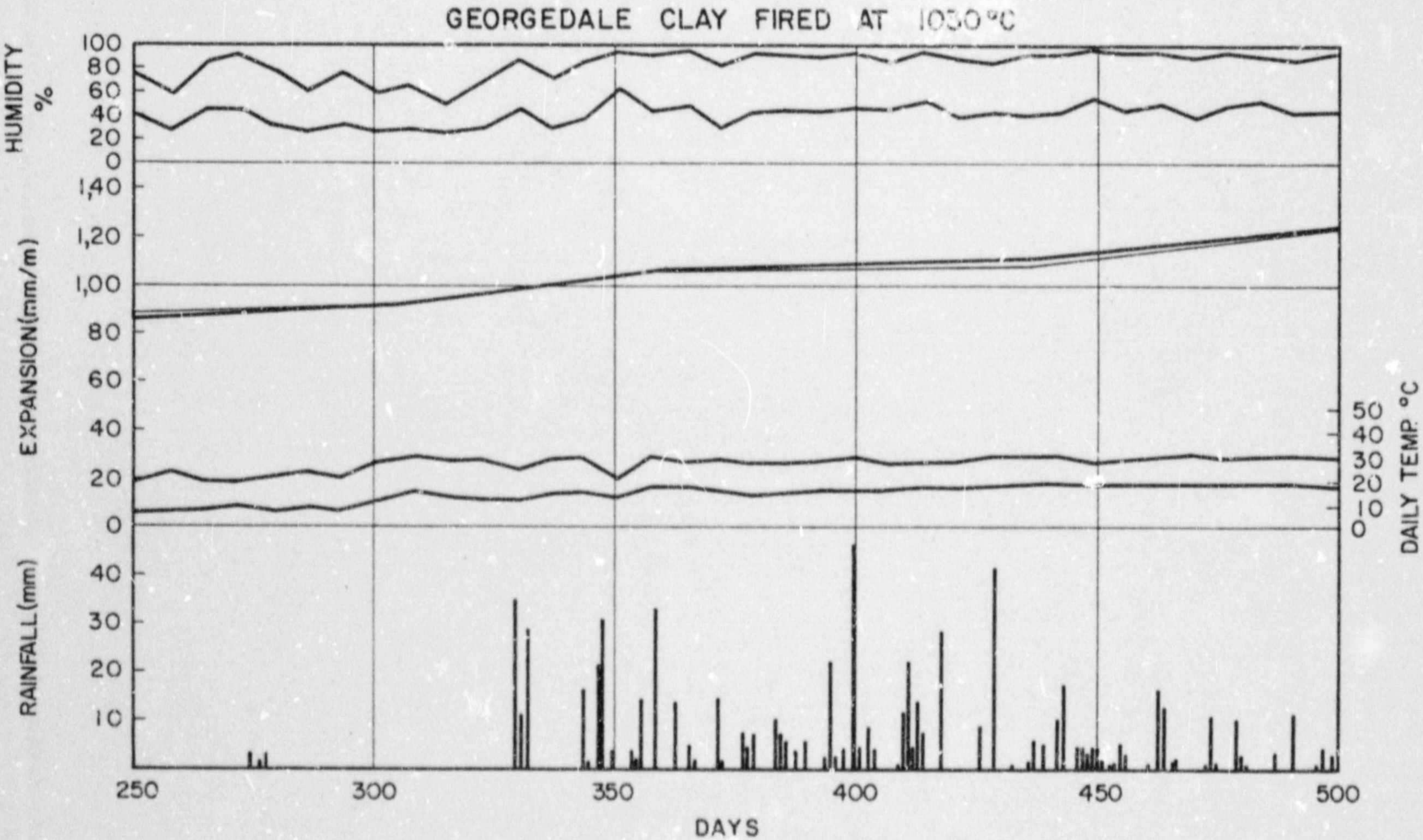


FIGURE 30

Brick exposed on roof - no load

first 100 days. Even after 800 days it has still expanded much less than the other bricks, although it appears to be steadily catching up.

To predict the expansions of bricks built into external walls of buildings from the expansions of bricks in controlled laboratory conditions is difficult to perform accurately, but as brick kept continuously wet under laboratory conditions will in the long-term expand more than bricks in buildings, it will be on the safe side to predict expansions equal to those measured in a fog room, for the purpose of allowing expansion joints.

Regarding the exposure of bricks on the roof, the sun shone for periods in the morning and afternoon on the bricks, therefore expansion measurements were taken early in the morning on all bricks on the roof, while the bricks were still in the shadow of a lift machinery room above roof level. This was done to avoid scattered readings because of uneven heating of bricks once the sun shone on them. The humidity and temperature recorders were housed in a Stevenson screen and the rainfall was measured with a continuously recording rain gauge.

The Georgedale bricks, fired at 1010 ℃ and 1030 ℃ and exposed on the roof, at the same time, had very similar expansion patterns as shown on Figures 27 to 30. At the end of the first rainy season 170 days after first exposure, when the temperatures also fell, both the longitudinal and transverse dimensions reduced slightly, but the brick fired at 1030 ℃ again started expanding at 240 days. Between 240 and 500 days it expanded at a faster rate than the brick fired at 1010 ℃.

5.6 Behaviour of loaded bricks

5.6.1 Effect of restraint on bricks fired at brickfields

Figure 31 shows the dimensional change in the well-fired stock bricks while under different loads on their ends and stored in the fog room. What is not understood in view of later results on loaded bricks fired in the laboratory is the prevention of expansion by even the relatively low load of 3,5 MPa, whereas the medium-fired brick loaded to 27,6 MPa still expanded, as shown on Figure 32, about half the expansion of the unloaded brick after 2 500 days. This lack of expansion however happened on two separate bricks loaded to 3,5 MPa as well as on two bricks loaded to 13,8 MPa, the results of which were not plotted. On loading to 41,4 and 13,8 MPa there was a shortening creep of these bricks; thereafter the bricks loaded to 13,8 MPa expanded slightly. Two bricks were initially loaded at 41,4 MPa, but the one failed in compression explosively under the load after 90 days. The other brick showed rapidly increasing transverse strain after 440 days and when this increased sharply at 570 days the brick was removed from the loading frame.

There was an immediate large elastic recovery in length to within 11% of the original length and afterwards a rapid creep recovery to within 3% of the original length. This brick continued expanding in the humidity room until compression tested.

The blue-black face bricks also exhibited creep the first two days after loading and loads of 27,6 and 13,8 MPa prevented expansion, but under loads of 6,9 and 3,5 MPa these bricks expanded. As a horizontal load of 6,9 MPa from a wall will not be able to be resisted by normal structural elements no reliance can be placed on containing expansions by restraint. See Figure 33.

5.6.2 / .....

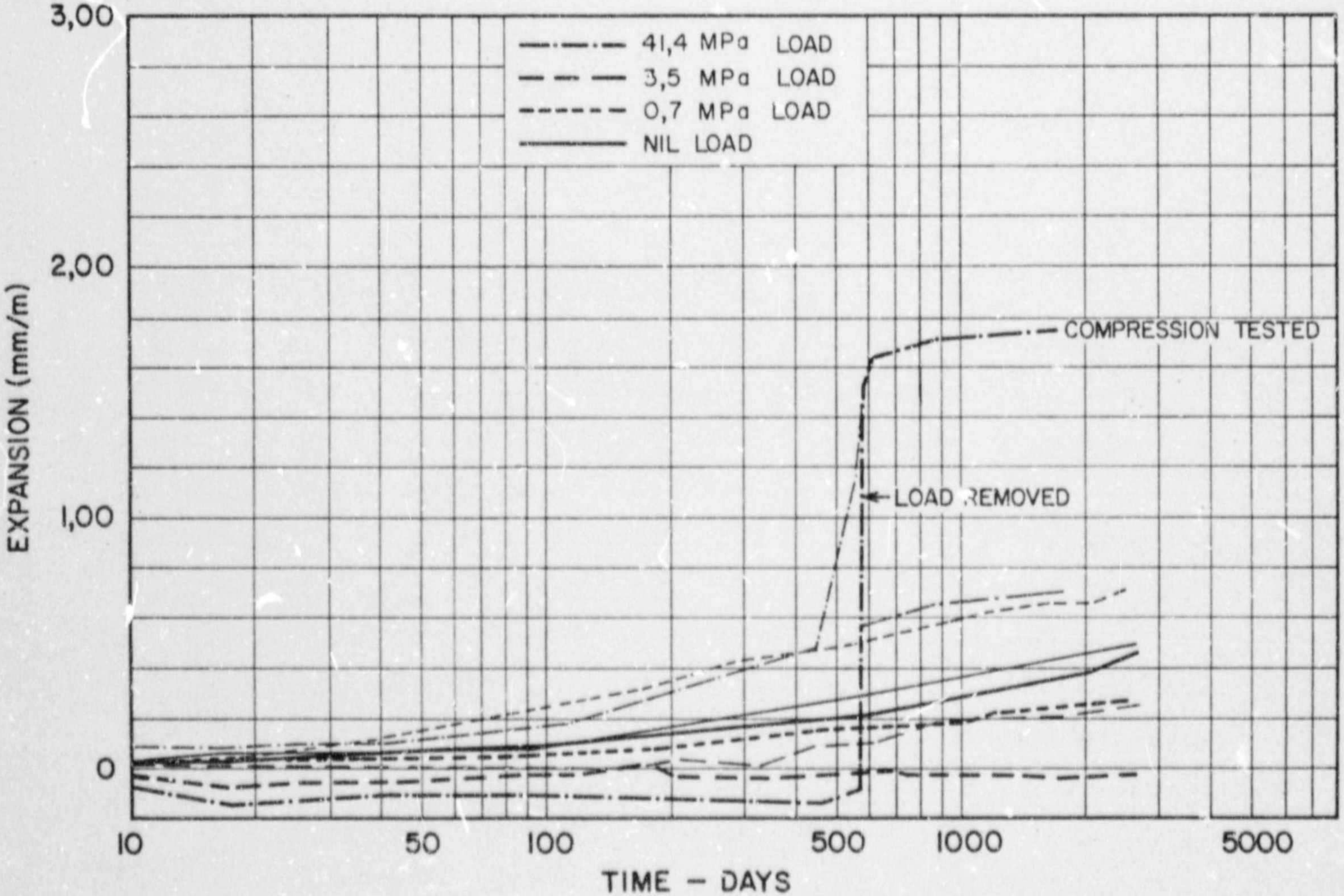


FIGURE 31

Expansion of well-burnt stock bricks - load on ends

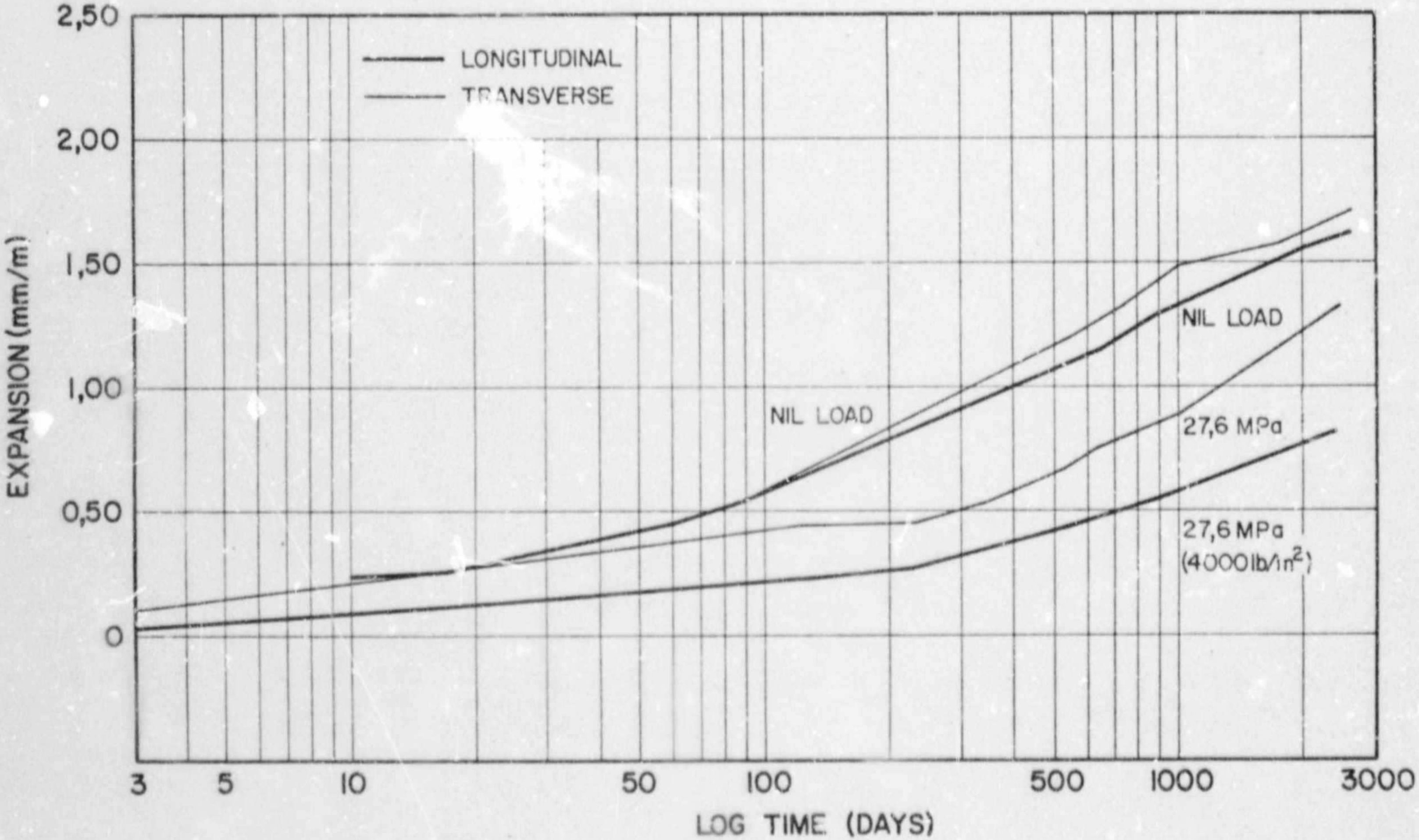


FIGURE 32

Expansion of medium-burnt stock bricks : load on ends in fog room

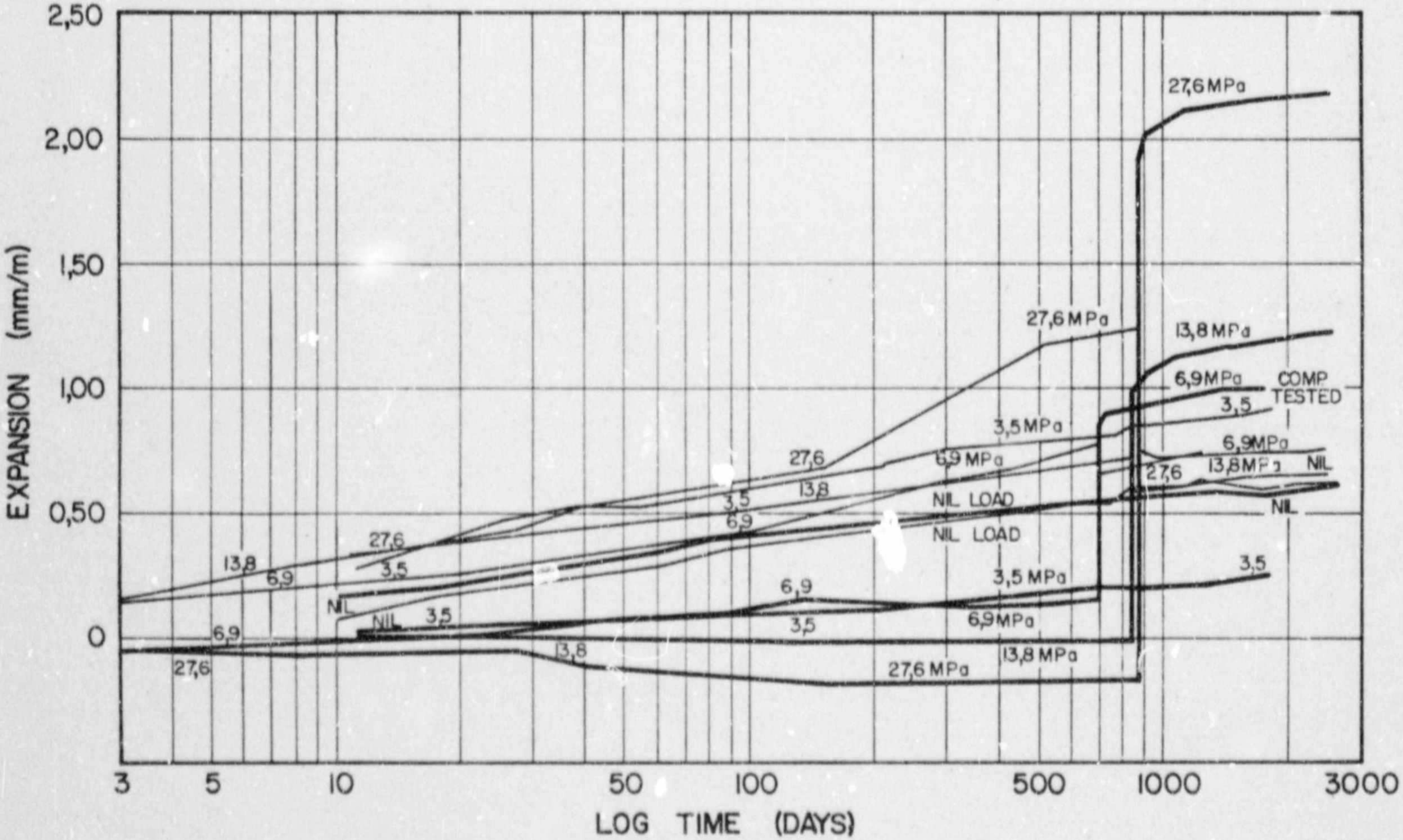


FIGURE 33

Expansion of blue-black face-bricks: load on ends in fog room.