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HEAT TRANSFER IN FURNACES FOR CIB COOPERATIVE PROGRAM AND HEAT BALANCE ANALYSIS OF WALL FURNACE

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LIST OF NOMENCLATURE

A_B	Interior surface area of furnace including test specimen
A_E	Cross-sectional area of the exhaust stack
A_S	Interior surface area of the test specimen
A_w	Surface area of the furnace walls
C_A	Heat capacity at constant pressure for air
C_i	Heat capacity at constant pressure for the i-th species
C_V	Heat capacity at constant volume for furnace gas mixture
E_t	Total energy contained in furnace gases
h	Convective heat transfer coefficient
H_A°	Enthalpy of the inlet air at the datum temperature T_o
H_B	Radiative heat flux incident at the gray surface element
H_F°	Enthalpy of fuel gas at the datum temperature T_o
H_i	Enthalpy of the i-th species at temperature T
H_i°	Enthalpy of the i-th species at the datum temperature
M_i	Molecular weight of the i-th species
Q_B	Heat loss to both test specimen and furnace walls
Q_C	Heat loss to both test specimen and furnace walls by convection
Q_F	Heat supplied by fuel combustion
Q_L	Heat loss to the bounding surfaces
Q_R	Heat loss to both test specimen and furnace walls by radiation
Q_S	Heat loss to test specimen
Q_W	Heat loss to furnace walls
T	Absolute temperature
T_B	Temperature of exposed walls including test specimen
T_E	Temperature of exhaust gases

T_I	Temperature of inlet air
T_M	Temperature of furnace gases
T_o	Datum temperature
T_S	Surface temperature of the test specimen
t	Time variable
U_E	Velocity of exhaust gases
V	Volume of furnace
w_A	Mass flow rate of the inlet air
w_F	Mass flow rate of fuel gas
w_i	Mass flow rate of the i-th species
X_i	Mole fraction of the i-th species
α_B	Absorptivity of gaseous mixture at T_M for radiation emitted from interior walls at T_B
α_S	Total absorptivity of the furnace gases to be evaluated at the surface temperature of the test specimen
α_W	Total absorptivity of the furnace gases to be evaluated at the surface temperature of the furnace walls
ε	Effective surface emissivity of furnace walls including test specimen
ε_B	Surface emissivity of furnace walls including test specimen
ε_M	Emissivity of gaseous mixture
ε_S	Surface emissivity of the test specimen
ρ_M	Density of gaseous mixture
σ	Stefan-Boltzmann constant

HEAT TRANSFER IN FURNACES FOR CIB COOPERATIVE PROGRAM AND HEAT BALANCE ANALYSIS OF WALL FURNACE

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Tests were conducted in the NBS wall panel furnace as part of a CIB international cooperative program to measure and compare heat transfer in fire endurance furnaces. Additionally, a heat balance analysis showed that a cellular concrete block wall specimen absorbed more heat by convection than by radiation. The rate of radiant heat transfer was found to decrease slowly, while the furnace exhaust heat loss increased during the test from 42 to 58 percent of the heat output. The calculated radiant heat fluxes incident at furnace walls was found to be somewhat lower than the experimental values measured at the test wall.

Key words: Fire resistance ratings; fire test furnace; heat balance; heat transfer; temperature-time curve.

1. INTRODUCTION

These preliminary tests were performed as part of a cooperative effort to correlate the fire resistance of reference specimens obtained by various testing laboratories. This project was initiated following the ninth meeting of CIB (Conseil International du Bâtiment) Commission W.14 in Paris in May 1970 where it was decided to continue the work on the comparison of the performances of fire test furnaces.

Previous efforts to compare furnaces had shown wide variability among laboratories in fire resistance determinations for ratings up to 90 minutes. [1][1] Recently, Castle [2] made radiant and total heat flux measurements in several test furnaces operated in accordance with ASTM E-119 method, and reported a wide variation in the radiation and convection levels to the specimen determined in these furnace environments. The primary reasons for these differences were that fuel properties and its input rate, amount of air introduced, furnace geometry, thermal properties of furnace walls and test specimen, the operating pressure, and the positions of burners and the exhaust stack, were varied among the furnaces, even though the same prescribed temperature-time curve was followed.

A method for measuring the heat transfer rate and comparing the performance of various furnaces was described by van Keulen in his report on "Comparison of Heat Transfer in Furnaces."[3] The report provided testing

[1]Numbers in brackets refer to the literature references listed at the end of this paper.

and measurement details for determining heat transfer rate along with the theory for correlating test results between furnaces.

Three tests were conducted at NBS to measure the rates of heat transfer by radiation and convection using two TNO heat flux meters [3] set in a cellular concrete block wall. In these tests, measurements were restricted to heat flux into the elements separating the heated furnace from the outside.

The application of an overall heat balance concept to a wall panel furnace was first introduced by Harmathy.[4] He studied the effect of thermal properties of a test specimen on the fuel consumption in a temperature-programmed fire test furnace. Therefore, additional measurements were taken to provide information for a heat balance analysis of the wall panel furnace.

The intent of the thermal analysis was to provide relative indications of the level and mode of heat transfer processes taking place in the furnace, and to obtain a better understanding of the various phenomena involved in the determining of the fire endurance rating of a panel assembly.

2. TEST EQUIPMENT

A 4.9 x 3.0 m (16 x 10 ft) high test wall was constructed of precast cellular concrete blocks. The blocks were 22.9 x 45.7 x 15.2 cm (9 x 18 x 6 in) in size, had a density of 0.50 g/cm^3 (31 lbs/ft^3) and a thermal conductivity of 0.117 W/m-°K (0.0675 Btu/hr-ft-°F). The test wall had two TNO heat flux meters and two radiometers built into it as shown in figure 1. The radiometers were commercial water-cooled 150 degree viewing angle instruments of the Gardon circular foil type with a saphire window to measure the radiant heat flux component.

The TNO heat flux meters were constructed of refractory sillimanite. Two identical slabs were joined to form a 19.5 x 30 x 3 cm thick (7.7 x 11.8 x 1.2 in) heat flux meter. The exposed surface of the meter was enameled and one-half of it treated with a gold paste in order to provide a difference in emissivity between the two halves. Three thermocouples were imbedded in each half of the meter while additional thermocouples monitored the temperature 5 cm in front of the exposed surface and 5 cm behind the unexposed side of the heat flux meter. All thermocouples were of 0.5 mm diameter chromel-alumel wires. A diagram of thermocouple locations is shown in figure 2.

The furnace temperature was measured by 12 metallic sheathed mineral insulated fast response thermocouples symmetrically arranged within the furnace and 10 cm from the test specimen to provide an approximation of its average temperature. These thermocouples comprised 1 mm diameter chromel and alumel wires insulated with magnesium oxide from a closed end 6.4 mm (1/4 in) OD stainless steel (type 310) sheathed tube. For comparison purposes the furnace temperature was also monitored using 12

ASTM thermocouples mounted within heavy iron pipes and symmetrically distributed 10 cm from the test wall. The time constants of the sheathed and the ASTM thermocouples were found to be approximately 1.2 and 6.2 minutes respectively, using a gas fired furnace maintained at a constant temperature of 900 °C.

Specimen surface temperatures were measured using eight thermocouples arranged as shown in figure 3. Other temperatures monitored during the test were the furnace wall, the exhaust gas and the room temperature.

Inlet air and exhaust gas velocities were measured by means of pitot tubes in conjunction with a differential pressure transducer.

Furnace gas concentrations of O_2, CO_2 and CO were measured during the tests. Exhaust gas samples were taken using a stainless steel tube positioned in the exhaust stack. The gas was drawn through a trap filled with glass wool and was cooled with dry ice to remove smoke particles and water vapor. The gas was divided into three streams which passed through individual instruments of the following types: non-dispersive infrared analyzers for CO and CO_2, and a magnetic susceptibility analyzer for O_2.

Details of the wall test furnace including principal dimensions, are given in figure 4. The furnace is of the natural updraft type. The fuel was natural gas containing approximately 95% methane and having a specific gravity of 0.595 and a higher heating value of 38.5 J/cm^3 (1,033 Btu/ft^3). The gas composition and its thermochemical data are tabulated in table 1 along with some information on furnace walls and test specimen. This natural gas was supplied through 92 air-aspirating burners mounted in the wall opposite the specimen. The gas flow rate was measured every 5 minutes during Test No. 1.

3. TEST METHOD

3.1. Comparison of Furnaces

To promote uniform test conditions the test wall was dried during Test No. 1. The ISO R-834 standard time-temperature curve was followed for one hour. The furnace was left closed until it cooled down in order to avoid water uptake in the test wall.

Two tests were then conducted in the wall panel furnace with Test No. 2 being of 60-minute duration and Test No. 3 being a 90-minute test. A constant pressure of 1.5 mm of water column was maintained at a height of 2.3 m above the bottom of the test wall during both tests. Periodic recordings were made of various instruments on a data logger and later processed and plotted by computer.

3.2. Heat Balance in Furnace

A description of the method and equations used for the heat balance calculations are given in appendix A. Determination of the terms in the heat balance equation were made by experimental measurements and by calculations using developed heat transfer formulae. The results of the fully instrumented first test were used for the heat balance analysis.

4. TEST RESULTS AND DISCUSSIONS

4.1. Comparison of Furnaces

The variations of temperature readings of TNO heat flux meters with time for each test are shown in figures 5 to 10. It can be seen that the temperature of furnace gases near the meters was considerably higher than the exposed surface temperature throughout the test. Figures 11 to 13 illustrate time sequence of average furnace gas temperature measured during the tests along with the ISO R-834 standard curve plotted for comparison. An inspection of these figures show a significant difference in the temperatures measured using sheathed versus ASTM thermocouples. The results indicate over a 100 °C difference between the temperatures measured after 20 minutes during Test No. 1 with similar results obtained in the other tests. This temperature difference was attributed to high thermal capacitance of the iron protection tubes utilized in ASTM thermocouples and significant radiation loss from the tubes to the cooler furnace walls.

The average surface temperatures of furnace walls and the test specimen, and the flue gas in the exhaust stack for the three tests are shown in figures 14 to 16 as a function of time. It is important to note that the surface temperature of the test specimen was approximately equal to that of furnace walls. Figures 17 to 19 show plots of radiation flux densities determined at two locations of the test specimen versus time. As shown in the figures, there was little variation in the measured radiant fluxes between tests 1 and 2. The reason for the higher irradiance observed at the lower portion (radiometer No. 2) of the test wall than that at its upper part (radiometer No. 1) as shown in figure 19 was not known.

Time variations of the velocities of air entering into the furnace through the inlet ports, and combustion gases flowing inside the exhaust stack of Test No. 1 are given in figure 20. The results of gas analysis demonstrated that a process of complete combustion of fuel gas occurred in the test furnace since no CO was detected in flue gas. The concentrations of CO_2 and O_2 in the exhaust stream were found to be relatively constant after approximately 10 minutes after the start of the test. The flue gas composition averaged over the last 50 minutes of the test was 8.7% CO_2, 8.4% O_2 and 82.9% N_2 (dry basis).

The test results tabulated in tables 3 through 5 were forwarded to van Keulen for data analysis with the other participating laboratories. Summary data of the test series were given in his report along with construction details of TNO heat flux meter, and the procedure for furnace performance evaluation.[5] He compared the performance of each test furnace based on the amount of heat accumulated in the standardized wall test material versus time curve, and concluded that a correction factor to reduce differences between furnaces was not presented due to wide scattering of test results, and insufficient data for justification. The determination of separate contributions of radiation and convection components to the heating of the test specimen was unsuccessful because of evaporation of the gold coating on TNO heat flux meters.

4.2. Heat Balance in Furnace

Using the equations developed in appendix A, determinations were made of the heat input and output terms. Figure 21 provides a graph of each term in the heat balance equation. Inspection of the curves showed a decreasing rate of heat supply from the fuel while there was a slight increase in heat loss through the exhaust stack. Convective and radiative heat losses decreased during the test. The sensible energy supplied by the inlet air and the heat stored in the furnace gases were very small and were neglected.

The determined convective heat transfer coefficient, h, ranged from 89 to 180 W/m^2-°C (16 to 32 Btu/hr-ft^2-°F). These h values seem to be comparable with values determined by other experiments.[6] A check of the convective and radiant heat transfer throughout the test with the calculated h values, assumed thermal properties of furnace wall material as given in appendix B, and measured furnace gas temperatures using a method described in reference 7 showed that the deviation between the estimated average surface temperature of the furnace walls and the actual measured value varied from 0.2 to 11.3% with an average of 3.7%.

Since there were some difficulties in calibration of the oxygen analyzer, the composition and mass flow rate of combustion products were calculated based on the measured gas composition and mass rate of the fuel gas, and the concentration of CO_2 in the exhaust stream. It was found that the flue gas consisted of 7.3% CO_2, 14.9% H_2O, 5.1% O_2 and 72.7% N_2, and the fuel burned with approximately 36% in excess of the air required for complete combustion. The total emissivity and absorptivity for furnace gases were derived from H_2O and CO_2 emissivity charts developed by Hottel and his coworkers [8] with a correction to account for spectral overlap of emission bands. The gas emissivity was found to range from 0.30 to 0.22, decreasing with an increase in gas temperature, and the absorptivity varied between 0.33 and 0.22.

Listed in table 2 are the average heat transfer contributions for each of the terms in the heat balance equation along with their percentage contribution to heat input or output. For this furnace, the largest heat loss was due to the flow of hot combustion products through the exhaust stack, and this increased from 42% at 10 minutes to 58% at 60 minutes. Convective heat loss to the furnace walls was found to decrease with time from 42 to 34% of the total heat input, and the rate of radiant heat transferred into furnace walls was also seen to decrease gradually with increasing wall surface temperature during the test.

Figure 22 shows a comparison plot of time variation of calculated radiant heat flux incident at the furnace walls and the measured radiant flux obtained at the test wall for Test No. 1. The calculated values were computed on the basis of the rate of radiant heat loss shown in figure 21, and the average interior wall temperature using a surface emissivity of 0.8 for all furnace walls. It can be seen from the figure that the calculated values were approximately 15% less than those determined experimentally. This discrepancy in radiative heat transfer to the surface element may be due to non-uniformity of the temperature and composition of furnace gases. Also there might have been introduced some errors with higher readings on the radiometer as a result of reradiation from the heated sapphire window attachment to the foil sensing element.

The fire resistance rating of a structural element depends upon its physical and thermal properties and the heat flux incident at its bounding surfaces from the surrounding furnace walls and the furnace gas. The magnitude of the incident heat flux is determined by the furnace geometry, the surface emissivity and thermal properties of the furnace walls, the radiative properties, the gas flow and turbulence characteristics of the furnace gas as well as its temperature. The incident heat flux to the test wall appears to be a more appropriate parameter to be measured during the test than the gas temperature for characterizing and monitoring the furnace fire intensity.

The results of this study are limited to the single test which involved one material and one set of test conditions. Future testing with additional instrumentation by including water-cooled total heat fluxmeters and gas purged radiometers will make possible a verification of the results obtained. Extension to other materials of different thermal properties will provide data for better comprehension of the fire endurance testing since thermal properties determine the temperature level of the exposed surface, and the amount of heat absorbed by the test wall.

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Table 1. General Test Information

Fuel:	Natural Gas
Gas Composition:	95.1% CH_4, 3.0% C_2H_6, 0.76% C_3H_8 0.29% C_4H_{10}, 0.14% C_5H_{12}, 0.70% CO_2 0.01% N_2
Specific Gravity:	0.595
Heating Value (corrected to 14.2 °C (60 °F), 762 mm (30 in) Hg dry):	38.5 J/cm^3 (1,033 Btu/ft^3) (Gross) 34.7 J/cm^3 (931 Btu/ft^3) (Net)
Furnace Walls:	Fire Brick
Test Wall:	Cellular Concrete Blocks Density = 0.50 g/cm^3 (31 lbs/ft^3) Thermal Conductivity = 0.117 W/m-°K (0.0675 Btu/ft-hr-°F)
Gas Flow Data:	226 m^3 (8,000 ft^3) for 1 hour test

Note: For additional information see figures 1-4.

Table 2. Average Heat Contribution for Test No. 1

	Term	Rate of Heat Flow		Percent	
		Kw	(10^6 Btu/hr)	Average	Range
Energy In	Q_F	2,180	7.45	100	---
Energy Out	$\sum(w_i H_i)$	1,155	3.95	53	42-58
	Q_R	243	0.83	11	7-16
	Q_C	782	2.67	36	34-42

Table 3. Measured Data for Test 1

Times (min)	Room Temp (°C)	Furnace Temp (°C)		Pressure (inch of H_2O)		Top HFM I (°C)								Bottom HFM II (°C)							
		mean	extreme	upper HFM	lower HFM	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
0	17	16	14-28	---	---	18	16	16	16	15	15	13	17	14	14	13	13	13	13	13	15
2	18	276	234-324	---	---	80	29	19	82	31	19	431	19	77	23	18	87	26	21	352	16
4	19	365	324-421	---	---	110	42	27	126	51	30	486	22	108	33	26	124	46	32	418	18
6	19	483	436-554	---	---	180	81	39	188	90	45	610	25	169	55	37	202	73	47	606	20
10	20	689	635-791	.068	.014	300	125	82	330	138	94	684	31	338	118	78	388	160	101	770	25
15	21	761	707-844	.058	000	428	212	146	458	243	168	757	42	474	214	150	528	277	195	820	44
20	21	797	765-866	.064	000	526	295	213	550	327	237	786	58	562	299	219	614	374	275	844	53
25	22	841	791-885	---	---	607	371	268	623	404	294	814	75	636	372	276	676	444	329	866	67
30	22	846	811-900	.062	.002	671	436	318	679	461	337	834	92	701	436	325	720	500	373	874	80
35	24	867	832-918	---	---	719	490	357	717	509	372	858	106	754	492	368	758	543	403	892	94
40	25	885	852-933	.063	.000	760	533	390	752	545	400	877	121	790	535	399	790	574	425	920	106
45	25	903	870-950	---	---	791	566	414	782	576	421	894	134	816	566	419	815	598	442	927	112
50	27	910	877-956	.062	.002	809	597	433	800	601	438	904	150	832	588	435	830	616	459	929	121
55	28	922	887-967	---	---	822	615	447	812	618	451	917	160	850	605	450	846	630	468	936	123
60	28	930	896-972	.065	.006	844	630	460	833	632	464	922	173	860	616	461	855	641	476	940	130

Table 4. Measured Data for Test 2

Times (min)	Room Temp (°C)	Furnace Temp (°C)		Pressure (Inch of H_2O)		Top HFM I (°C)								Bottom HFM II (°C)							
		mean	extreme	upper HFM	lower HFM	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
0	19	20	17-26	---	---	21	21	21	21	19	19	18	21	18	15	16	17	17	16	17	17
2	19	289	253-328	---	---	86	27	20	86	28	21	446	22	83	20	17	89	26	19	376	18
4	20	506	469-619	---	---	170	50	31	170	54	34	599	24	175	41	27	184	53	33	586	19
6	22	587	550-685	---	---	224	79	46	231	87	50	630	25	240	71	42	262	90	54	643	20
10	22	688	661-790	.064	.004	336	150	100	350	165	109	681	33	378	150	96	397	180	119	732	26
15	23	768	729-859	.060	.000	460	240	172	470	260	185	742	53	508	247	176	530	286	201	791	40
20	24	801	762-886	.060	.000	552	325	238	558	343	254	780	72	597	335	248	611	377	273	818	57
25	25	825	794-907	---	---	624	398	295	628	413	308	809	89	662	408	305	671	446	330	842	72
30	25	850	819-929	.062	.002	675	456	336	679	470	351	819	105	710	464	348	716	496	373	864	85
35	25	865	839-932	---	---	715	500	374	713	511	384	848	120	749	508	380	750	536	400	880	94
40	26	879	859-935	.060	.002	750	536	401	746	542	859	859	133	776	537	407	775	567	426	895	100
45	27	893	875-946	---	---	782	570	421	774	575	880	880	140	798	565	423	796	590	440	906	113
50	27	904	887-955	.060	.002	802	593	436	792	587	888	888	156	819	583	435	813	607	453	920	120
55	27	918	899-966	---	---	821	613	450	812	616	908	908	163	833	598	449	828	619	462	926	126
60	28	927	908-968	.060	.002	835	626	458	824	629	461	922	170	846	612	456	841	630	471	936	130

Table 5. Measured Data for Test 3

Times (min)	Room Temp (°C)	Furnace Temp (°C)		Pressure (Inch of H_2O)		Top HFM I (°C)								Bottom HFM II (°C)							
		mean	extreme	upper HFM	lower HFM	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
0	18	19	16-25	---	---	20	21	20	21	18	18	17	19	17	14	15	16	16	15	16	16
2	18	281	243-326	---	---	78	30	20	80	36	26	380	20	74	29	20	74	29	20	320	17
4	19	483	442-539	---	---	156	48	30	171	57	36	564	22	185	54	29	185	56	29	589	19
6	19	629	596-738	---	---	216	72	42	234	88	50	620	24	258	85	52	258	90	55	666	20
10	20	695	653-774	.060	.010	326	135	94	352	164	113	674	30	382	163	104	382	178	114	722	27
15	23	761	719-847	.060	.010	450	220	161	472	258	187	744	45	512	257	176	512	276	192	795	37
20	24	791	762-858	.060	.010	542	301	224	565	342	255	782	65	600	346	247	600	367	260	820	52
25	25	818	784-882	---	---	609	371	278	625	411	310	806	80	659	418	300	659	436	315	839	64
30	26	843	816-894	.062	.004	660	427	322	673	468	352	824	97	704	474	342	699	490	356	854	72
35	26	861	838-906	---	---	706	472	357	711	507	384	858	116	740	520	376	748	530	385	875	83
40	27	878	856-916	.065	.004	742	511	388	746	549	430	810	195	776	554	400	770	560	409	888	90
45	28	893	873-934	---	---	770	542	414	774	584	458	881	208	804	580	419	794	585	426	899	103
50	28	897	877-936	.066	.006	786	571	434	789	607	475	892	212	812	599	432	804	605	438	901	107
55	29	911	899-954	---	---	809	590	452	812	626	490	903	216	830	612	442	820	618	448	916	111
60	29	921	900-964	.072	.006	822	608	466	825	641	500	910	220	843	626	455	832	630	460	923	114
65	29	931	902-972	---	---	846	620	474	849	654	506	929	220	861	640	462	848	640	468	937	119
70	29	942	909-981	.062	.008	859	634	482	862	664	513	940	221	870	651	468	859	651	473	942	122
75	29	952	921-993	---	---	873	645	490	876	677	524	953	224	887	660	474	874	600	479	962	126
80	29	961	929-997	.063	.008	887	655	496	890	690	530	960	226	898	669	480	882	669	485	968	129
85	29	972	939-1006	---	---	902	665	504	906	700	544	971	234	913	676	486	897	676	491	982	131
90	30	983	952-1018	.065	.007	914	676	512	917	712	550	980	240	922	685	492	908	685	497	984	136

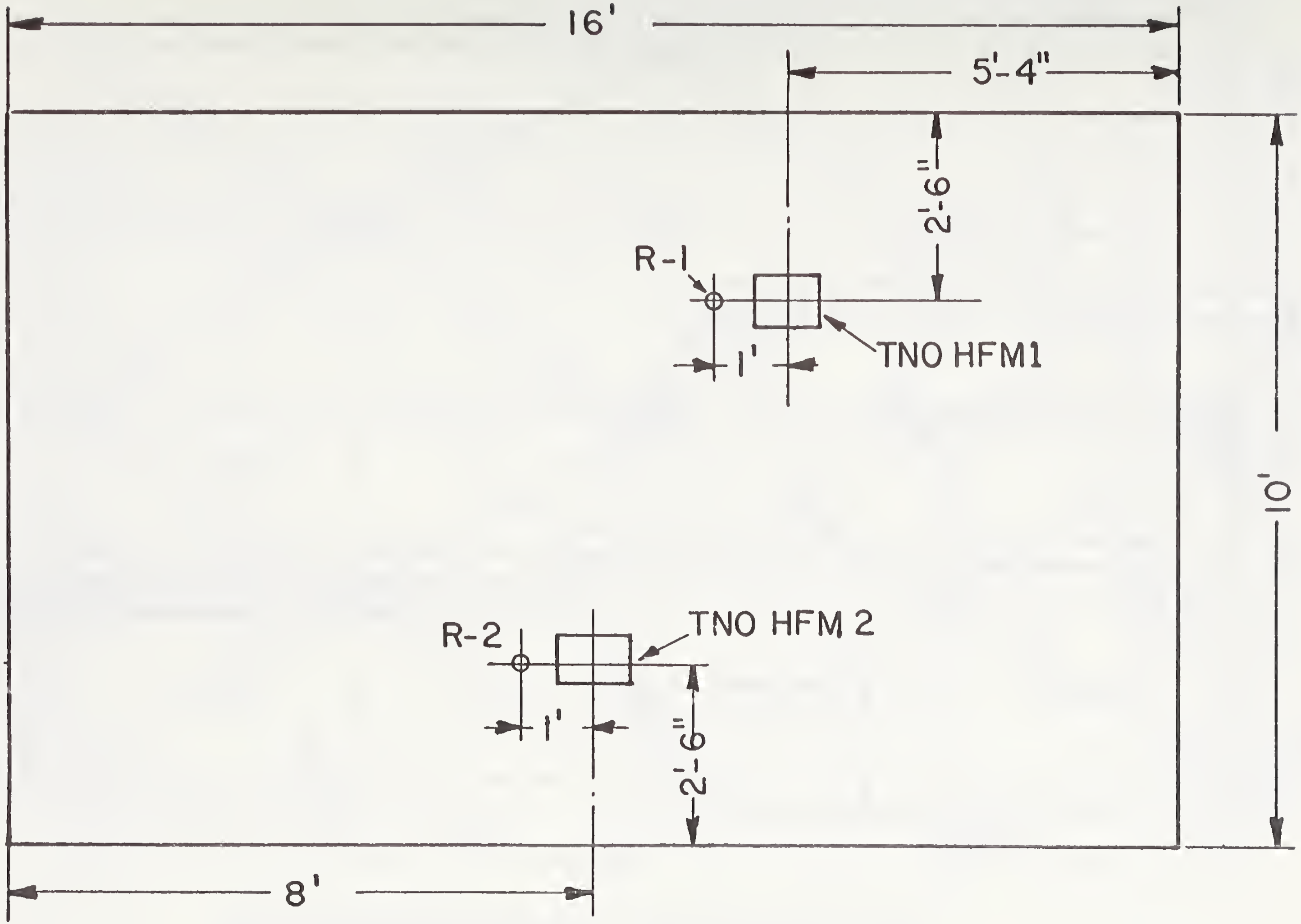

Figure 1. Location of Radiometers and TNO Heat Flux Meters in Test Wall.

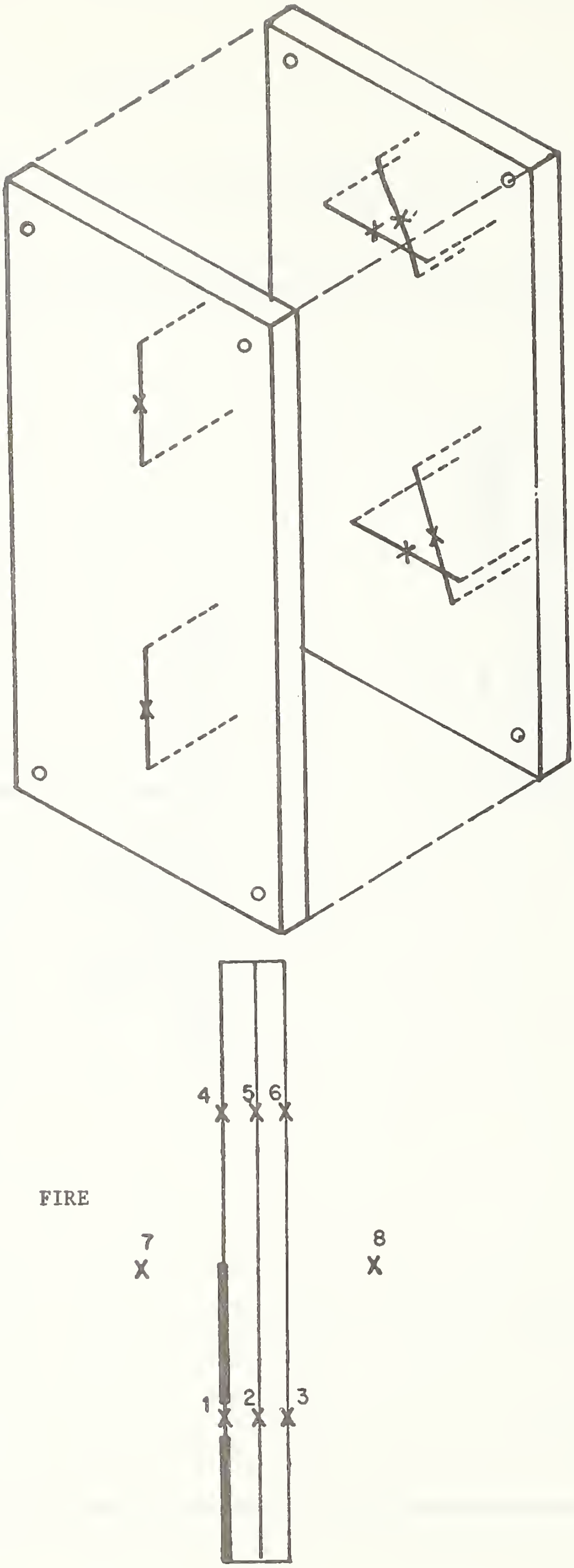

Figure 2. TNO Heat Flux Meter With Thermocouple Locations.

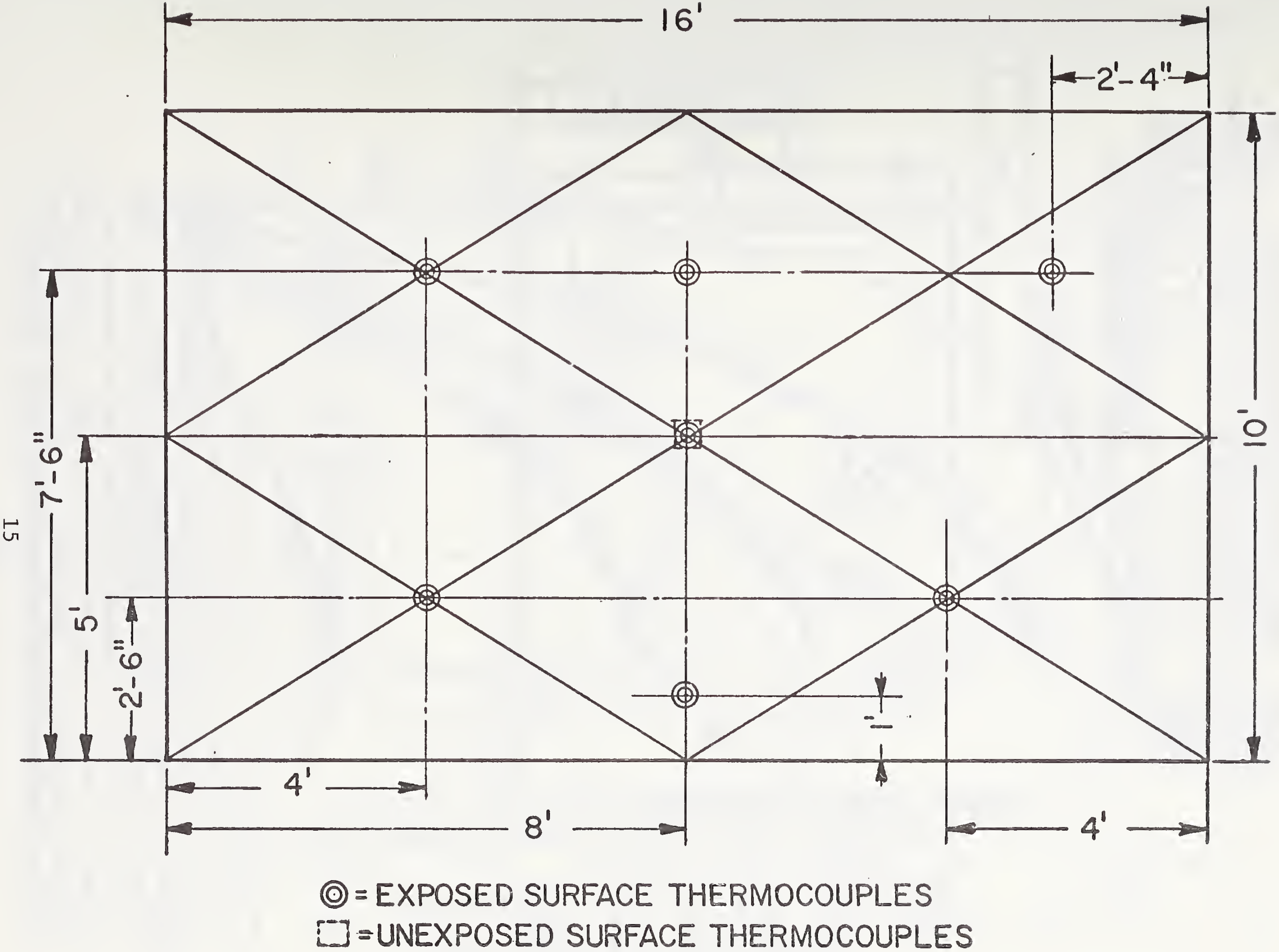

Figure 3. Test Wall Thermocouple Locations.

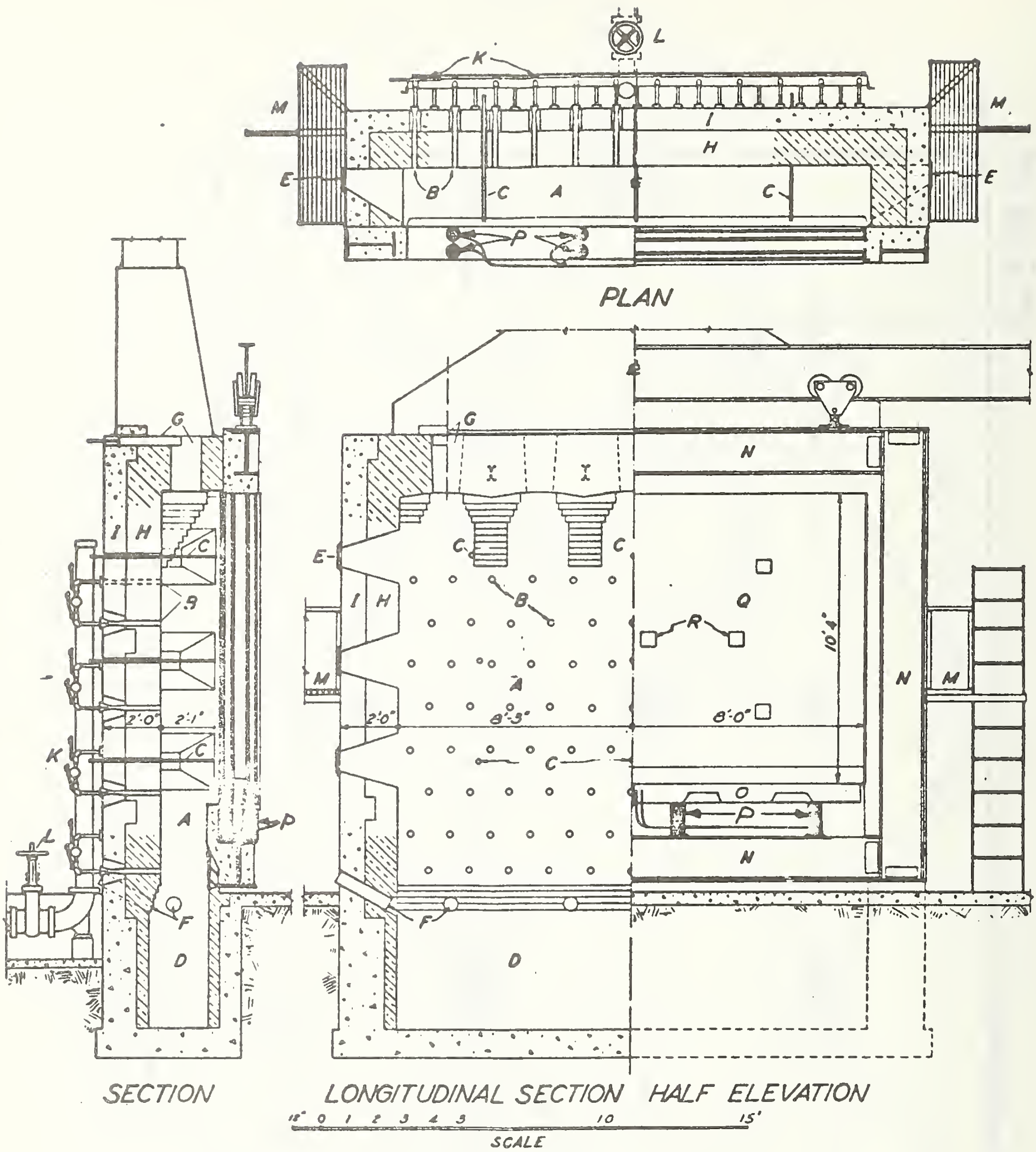

Figure 4. Details of Wall-Testing Furnace.

A, Furnace Chamber; B, Burners; C, Thermocouple Protection Tubes; D, Pit for Debris; E, Observation Windows; F, Air Inlets; G, Flue Outlets and Dampers; H, Firebrick Furnace Lining; I, Reinforced Concrete Furnace-Shell; K, Gas Cocks; L, Control Valve; M, Ladders and Platforms to Observation Windows; N, Movable Fireproofed Test Frame; O, Loading Beam; P, Hydraulic Jacks; Q, Test Wall; R, Asbestos Felted Pads Covering Thermocouples on Unexposed Surface of Test Wall.

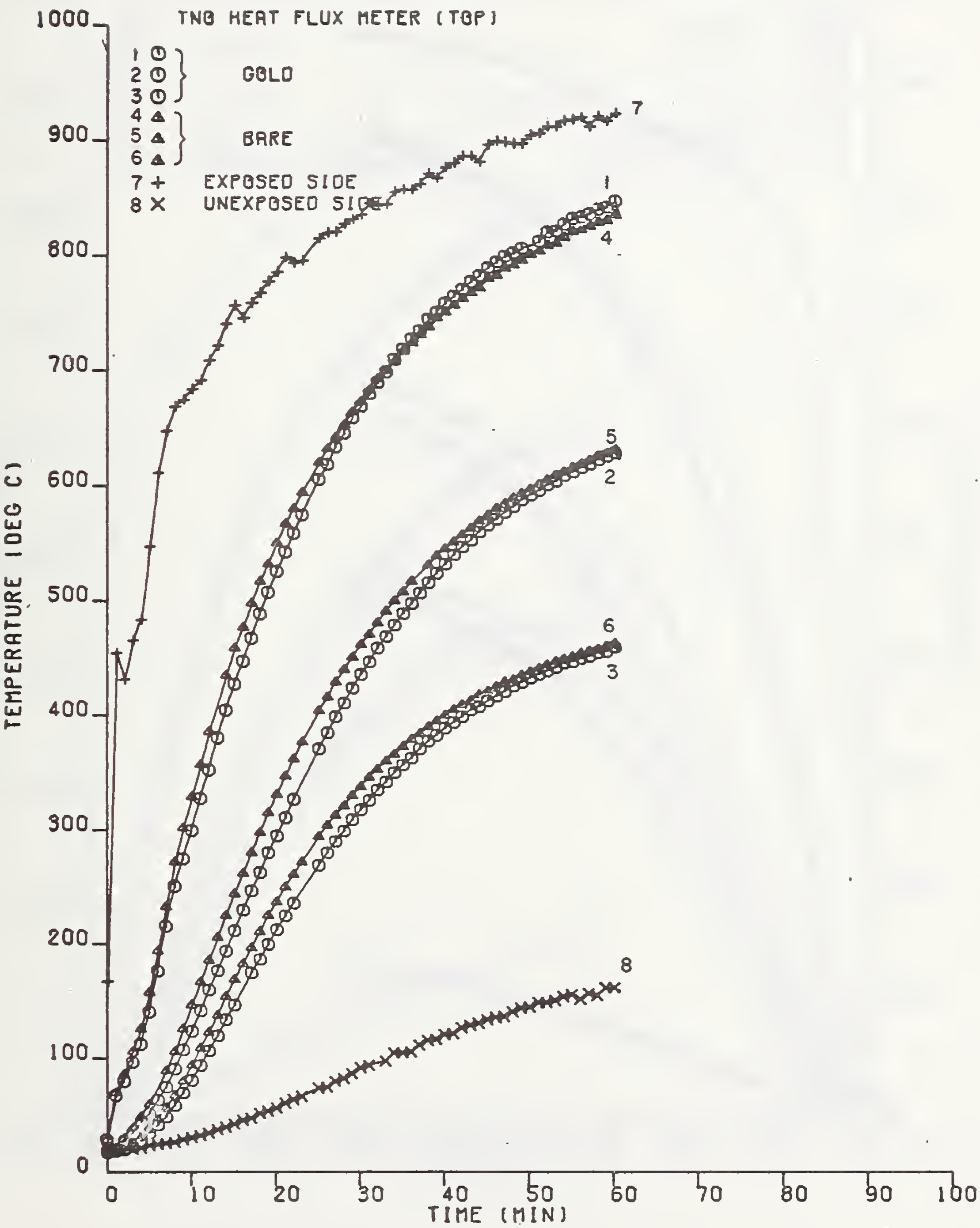

Figure 5. Upper TNO Heat Flux Meter Readings.

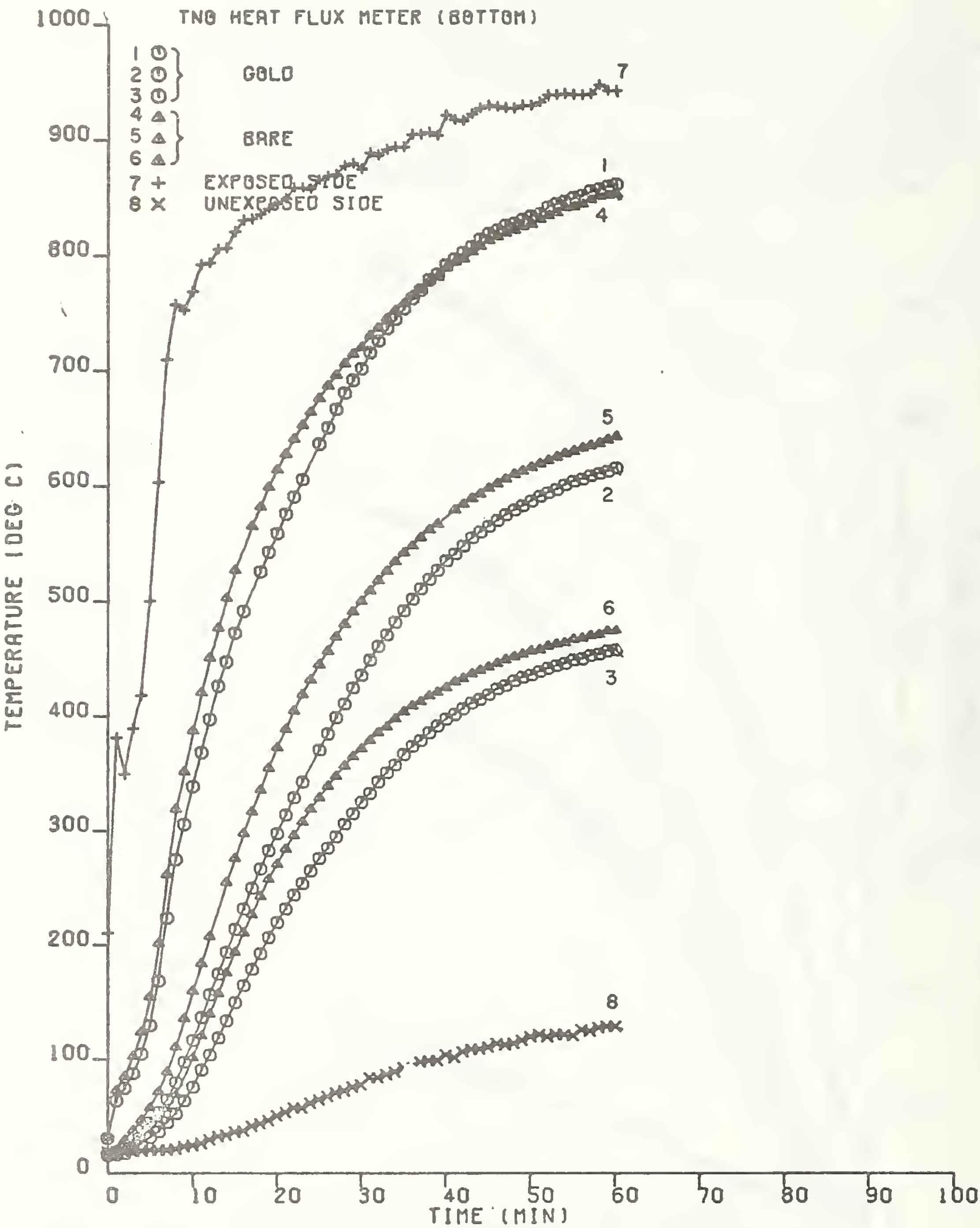

Figure 6. Lower TNO Heat Flux Meter Readings in Test No. 1.

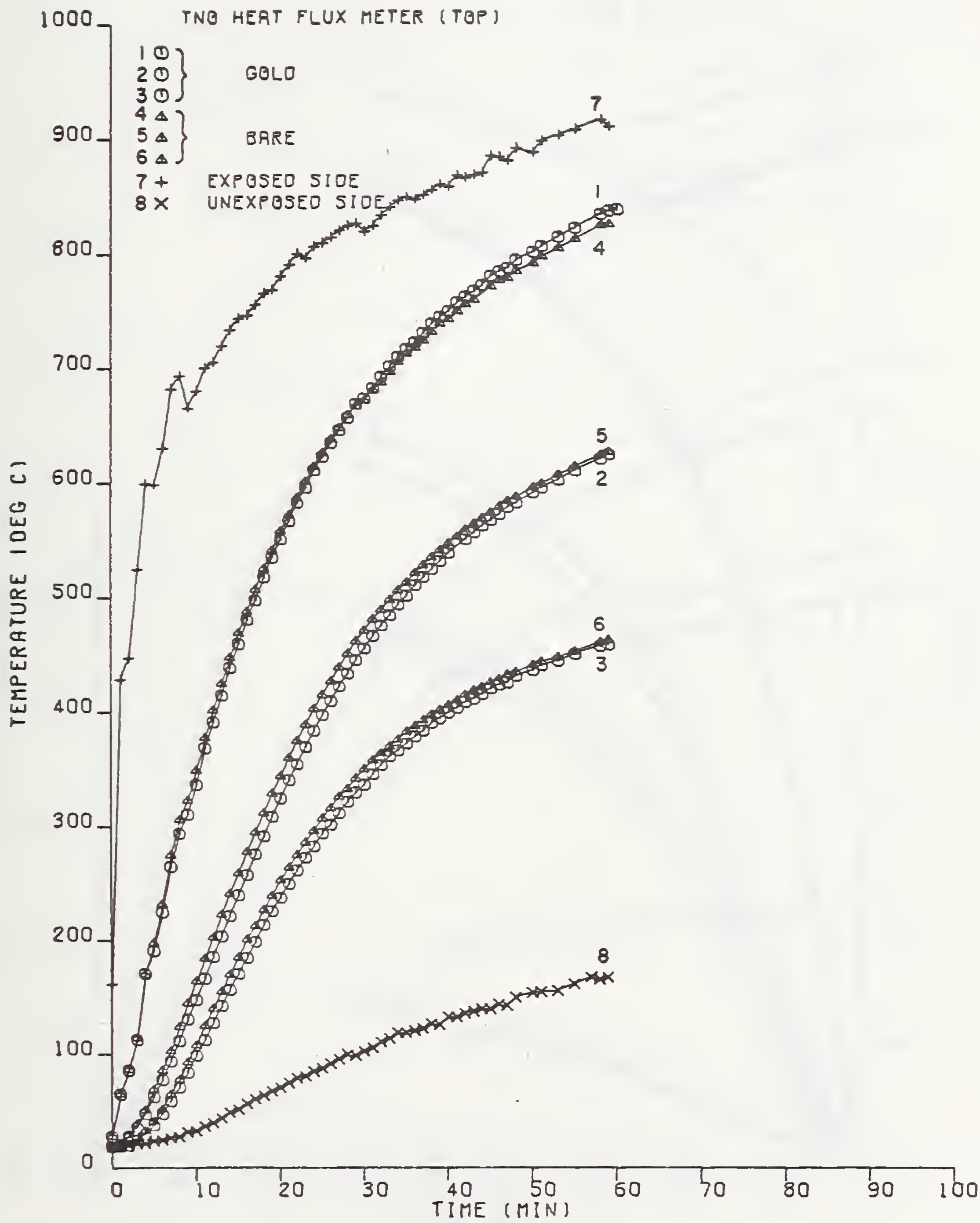

Figure 7. Upper TNO Heat Flux Meter Readings in Test No. 2.

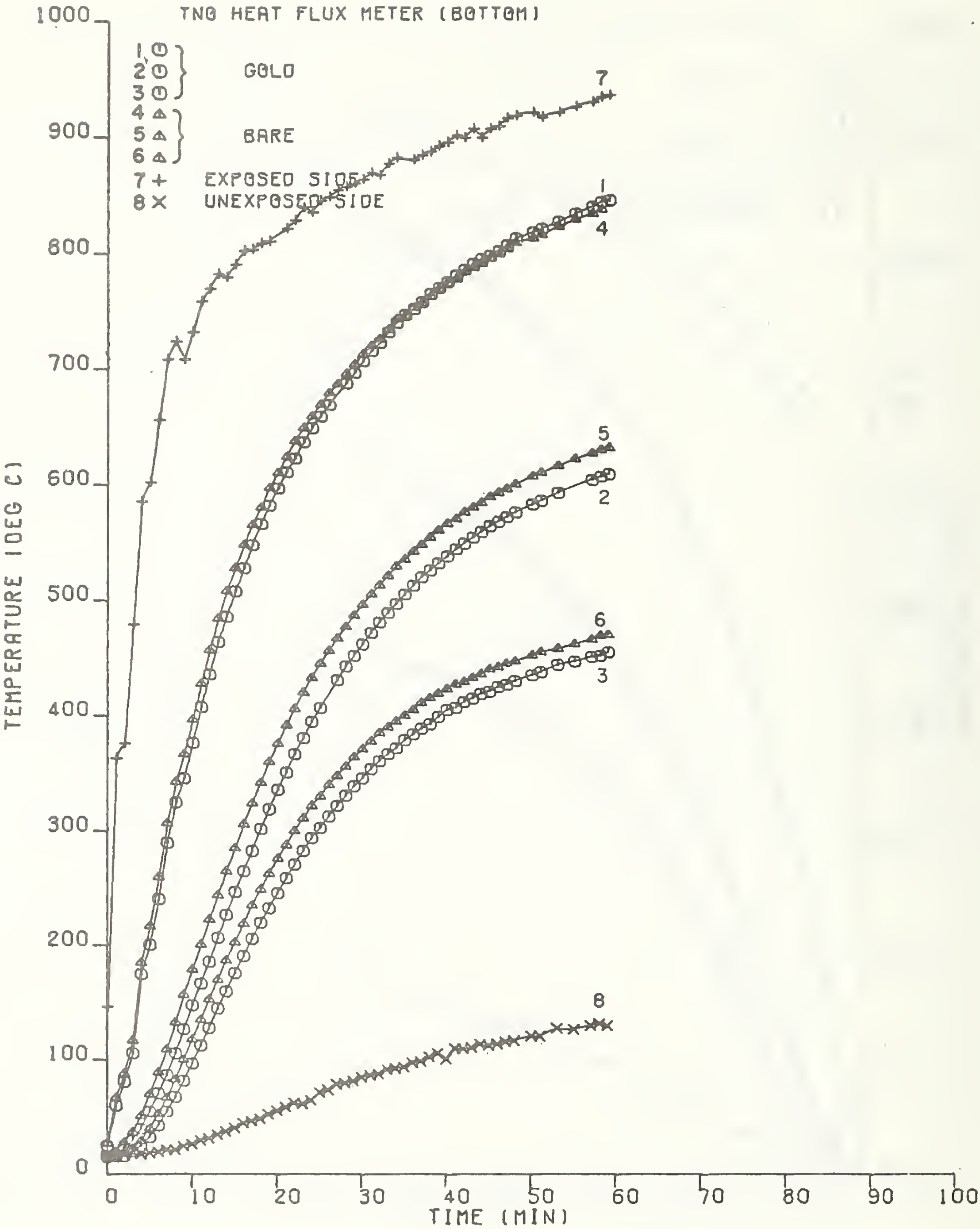

Figure 8. Lower TNO Heat Flux Meter Readings in Test No. 2.

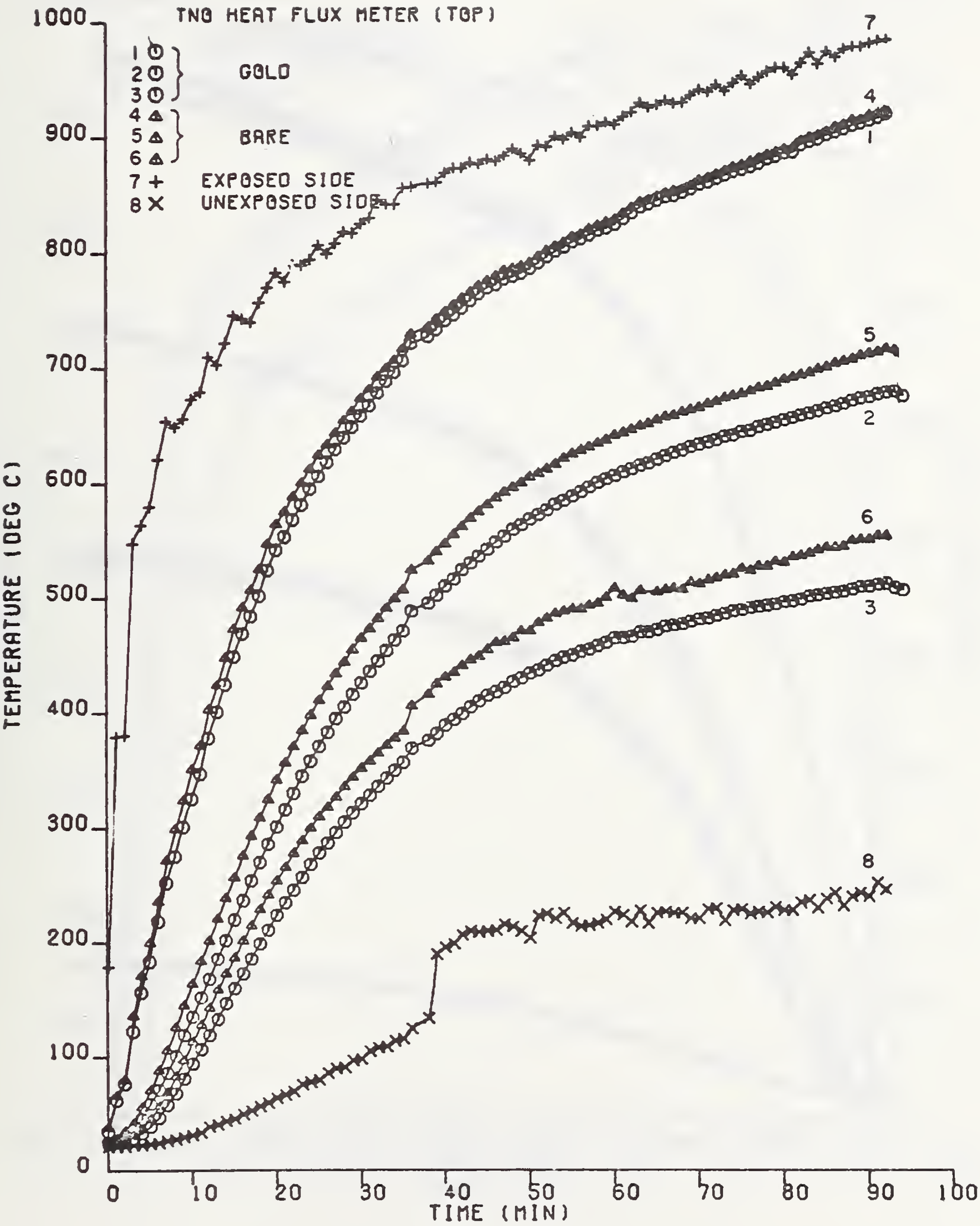

Figure 9. Upper TNO Heat Flux Meter Readings in Test No. 3.

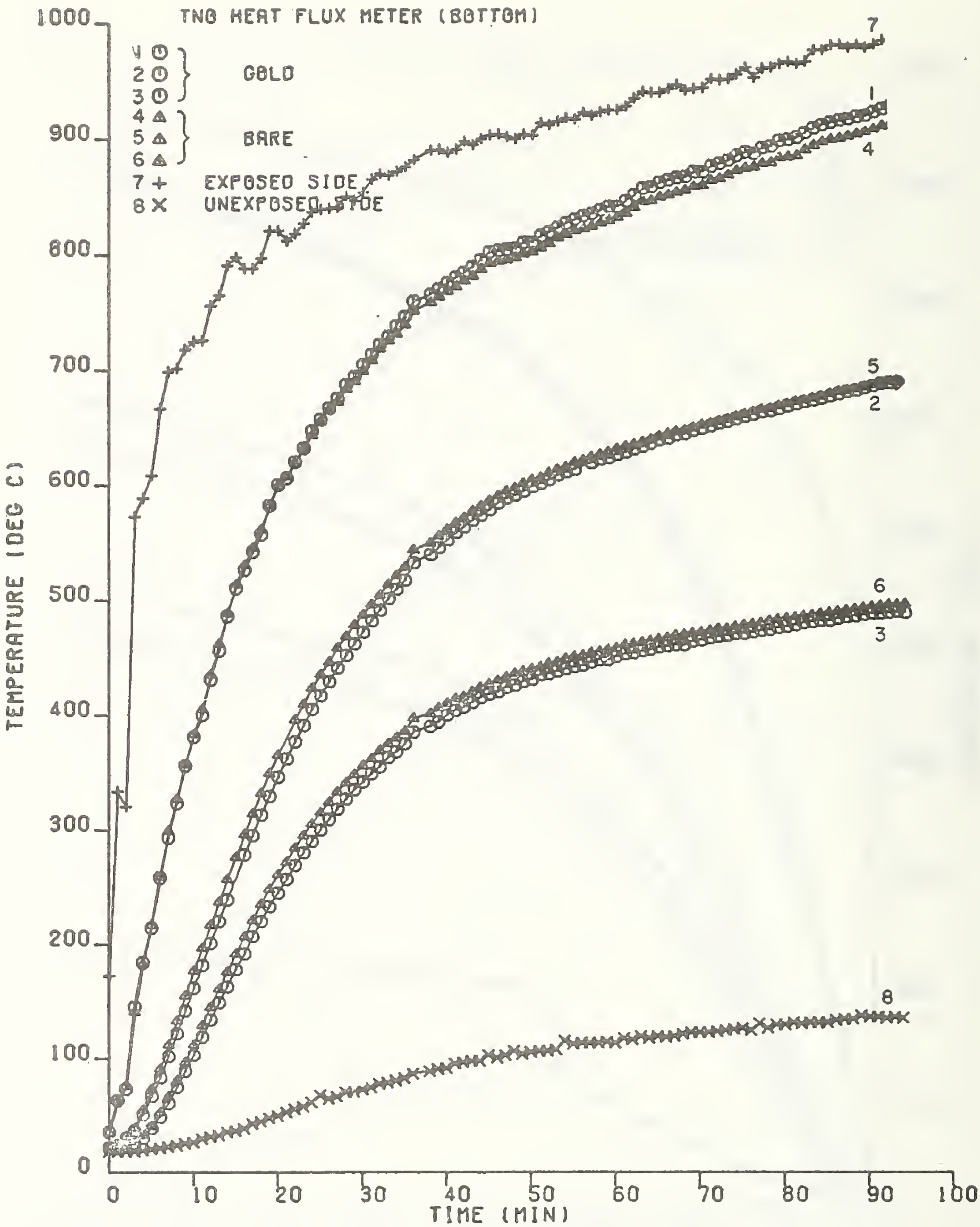

Figure 10. Lower TNO Heat Flux Meter Readings in Test No. 3.

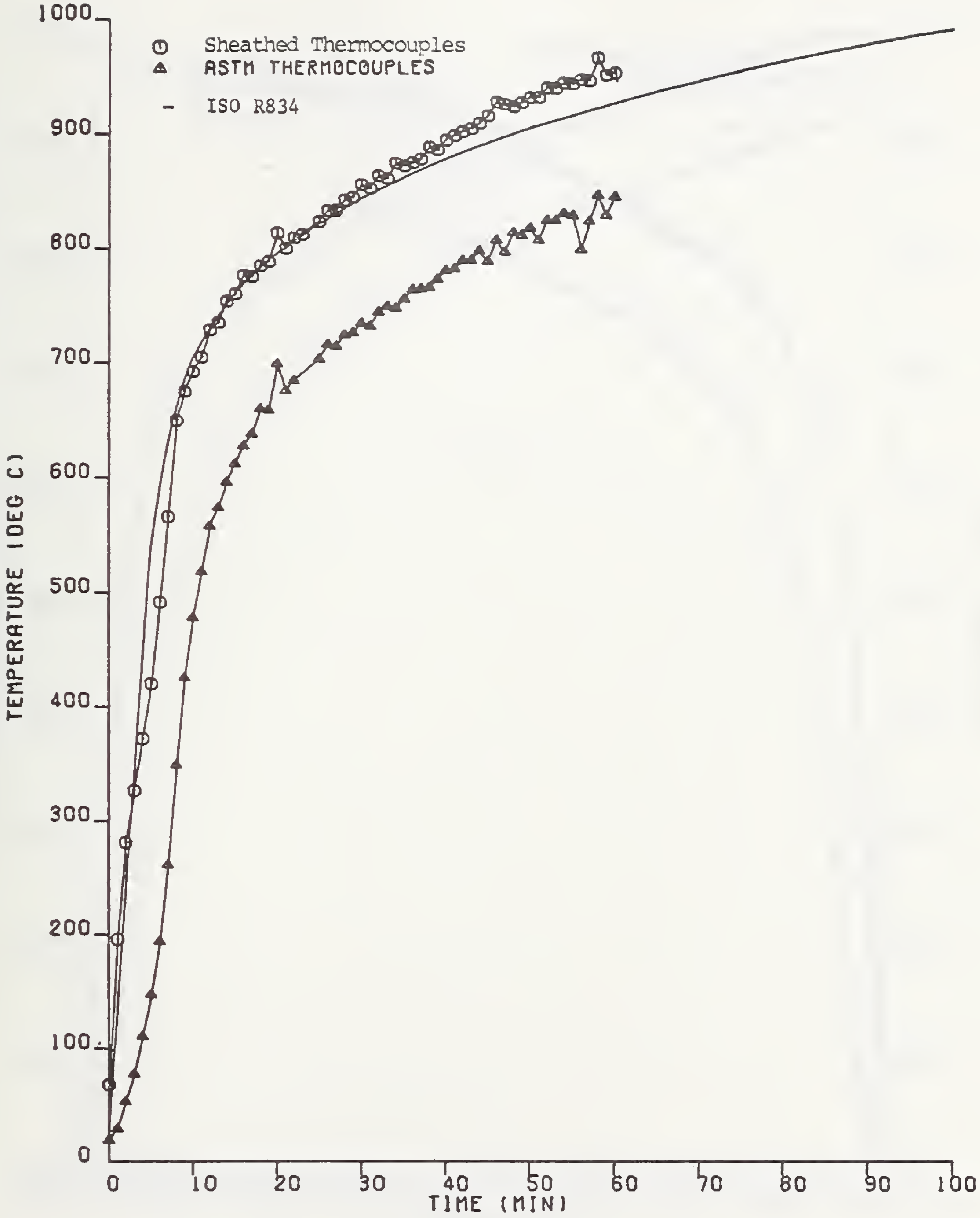

Figure 11. Furnace Temperatures in Test No. 1.

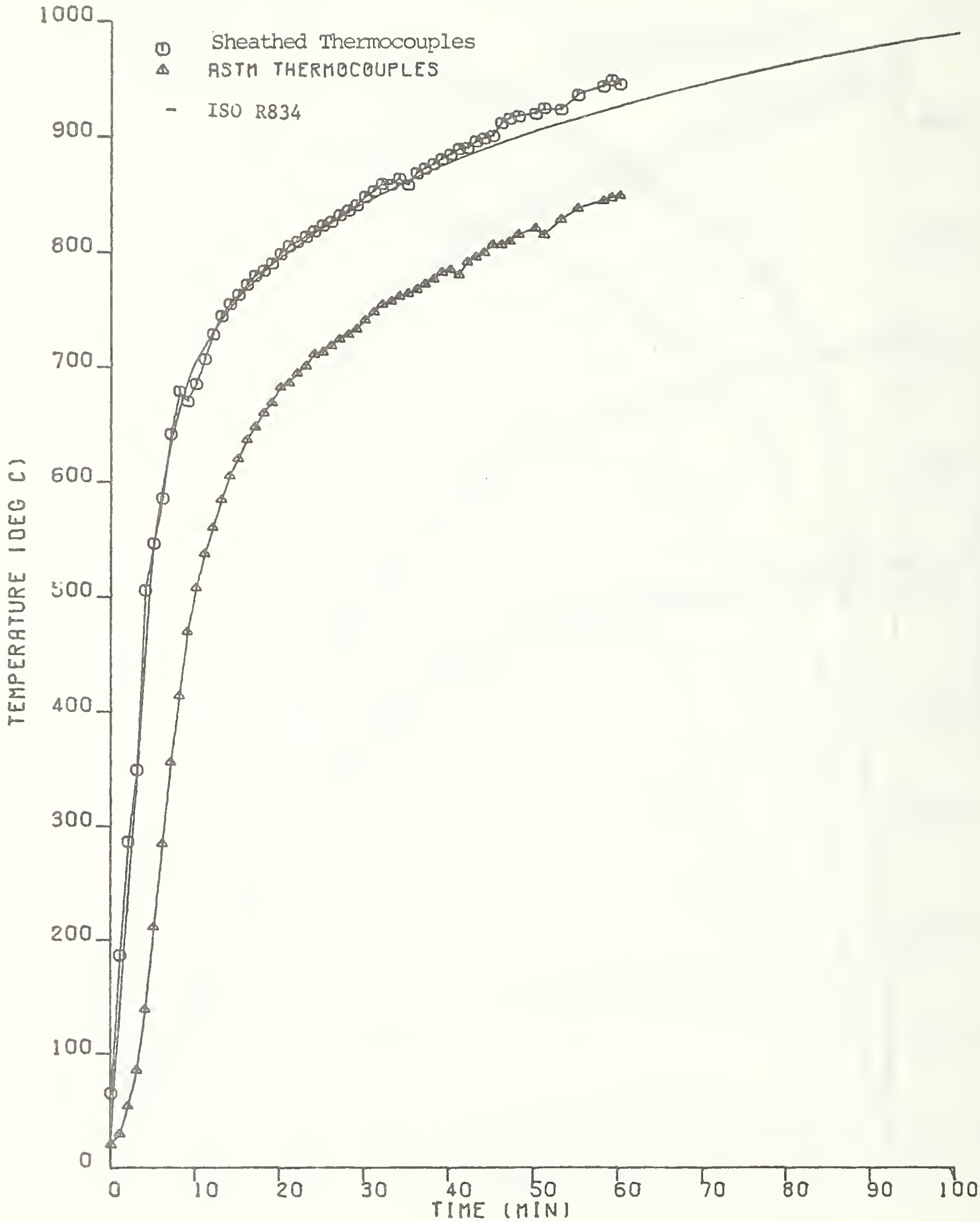

Figure 12. Furnace Temperatures in Test No. 2.

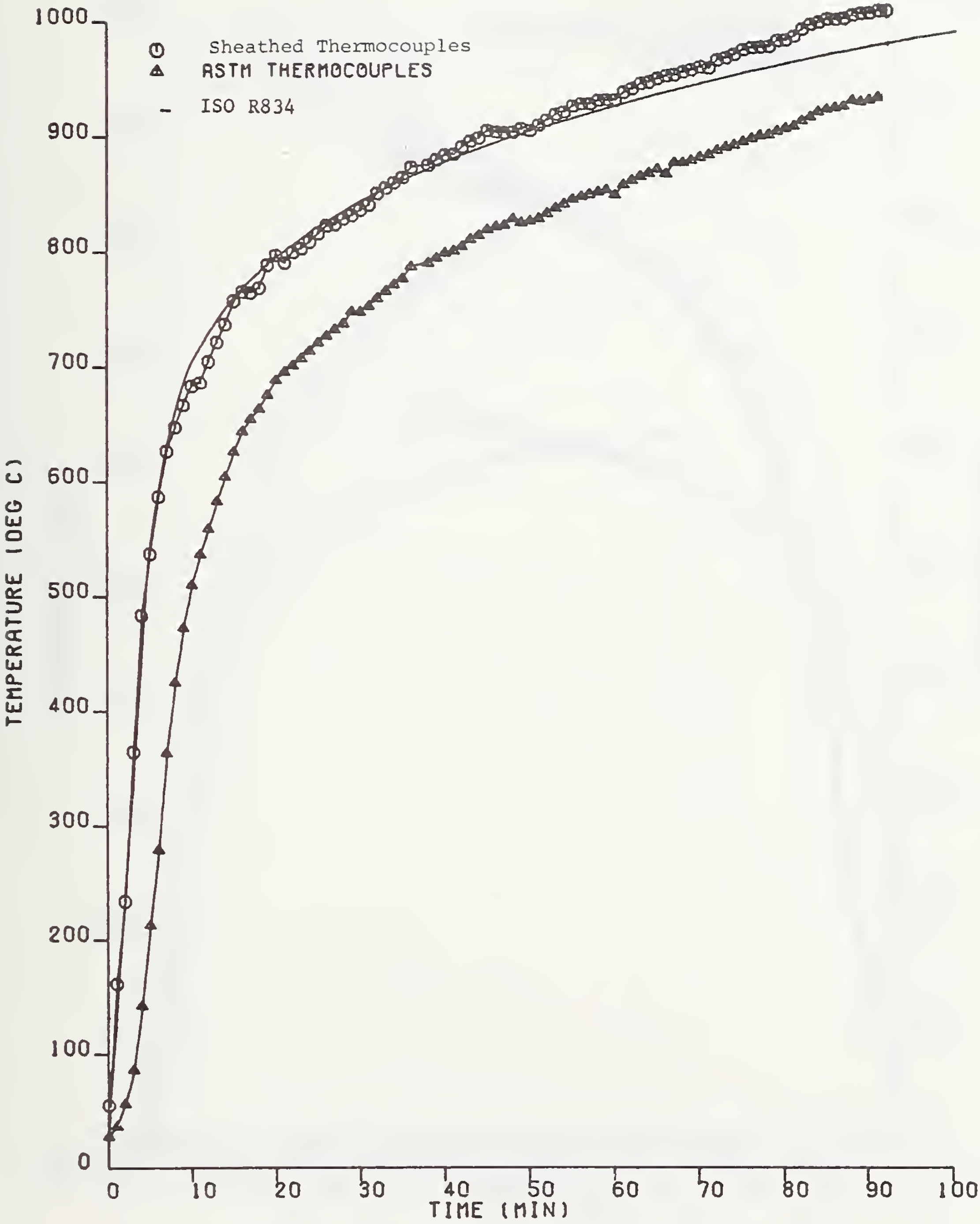

Figure 13. Furnace Temperatures in Test No. 3.

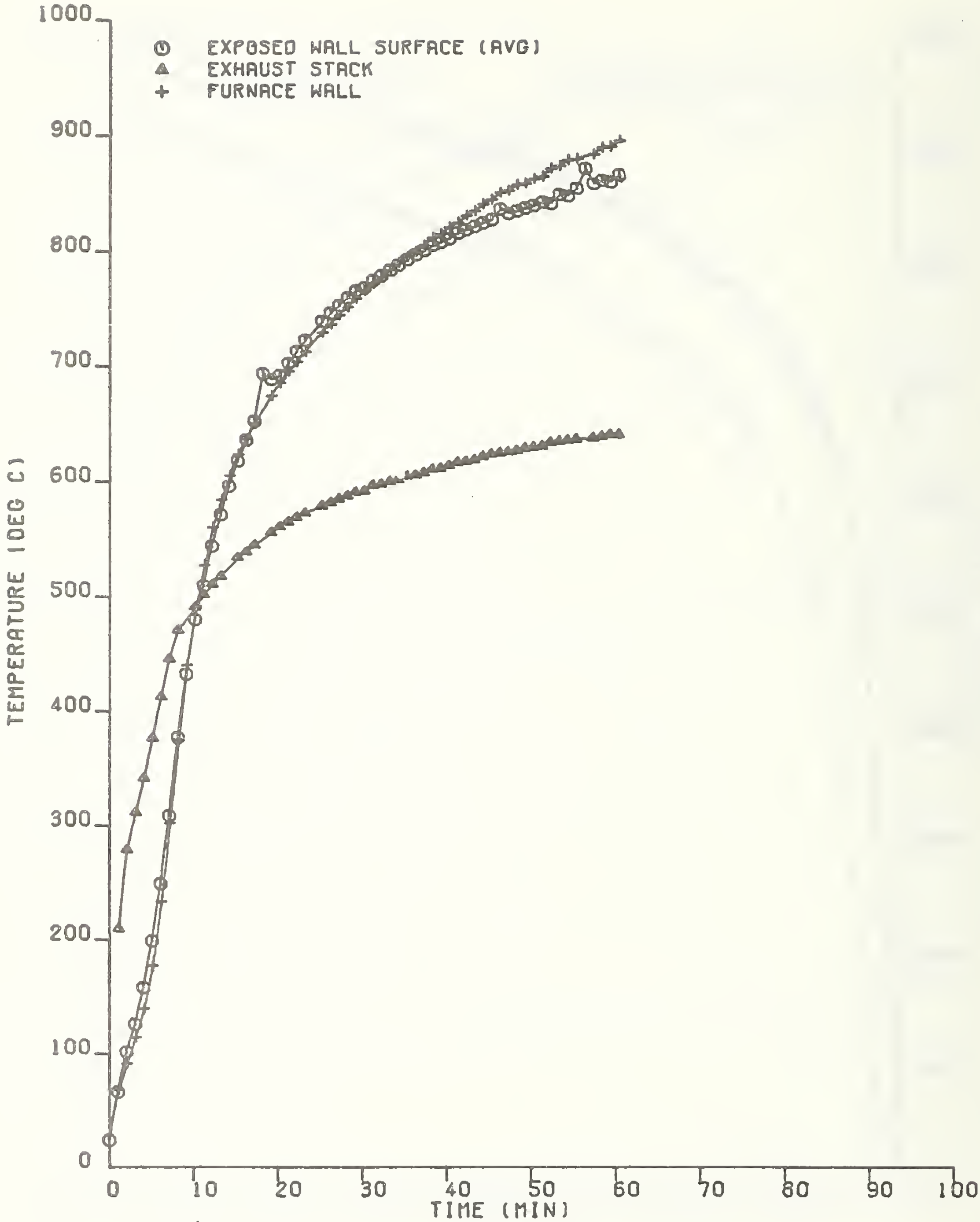

Figure 14. Stack and Wall Temperatures in Test No. 1.

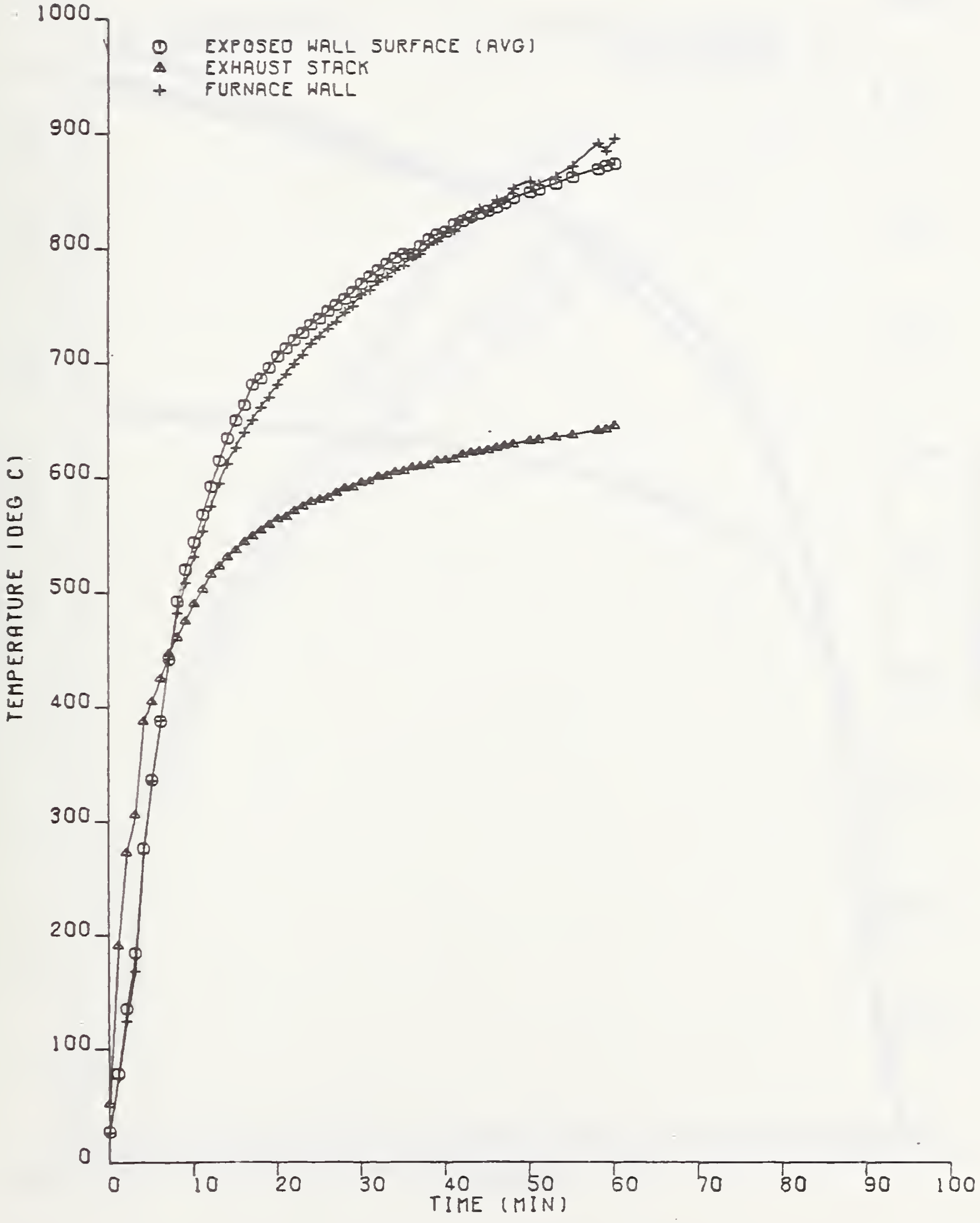

Figure 15. Stack and Wall Temperatures in Test No. 2.

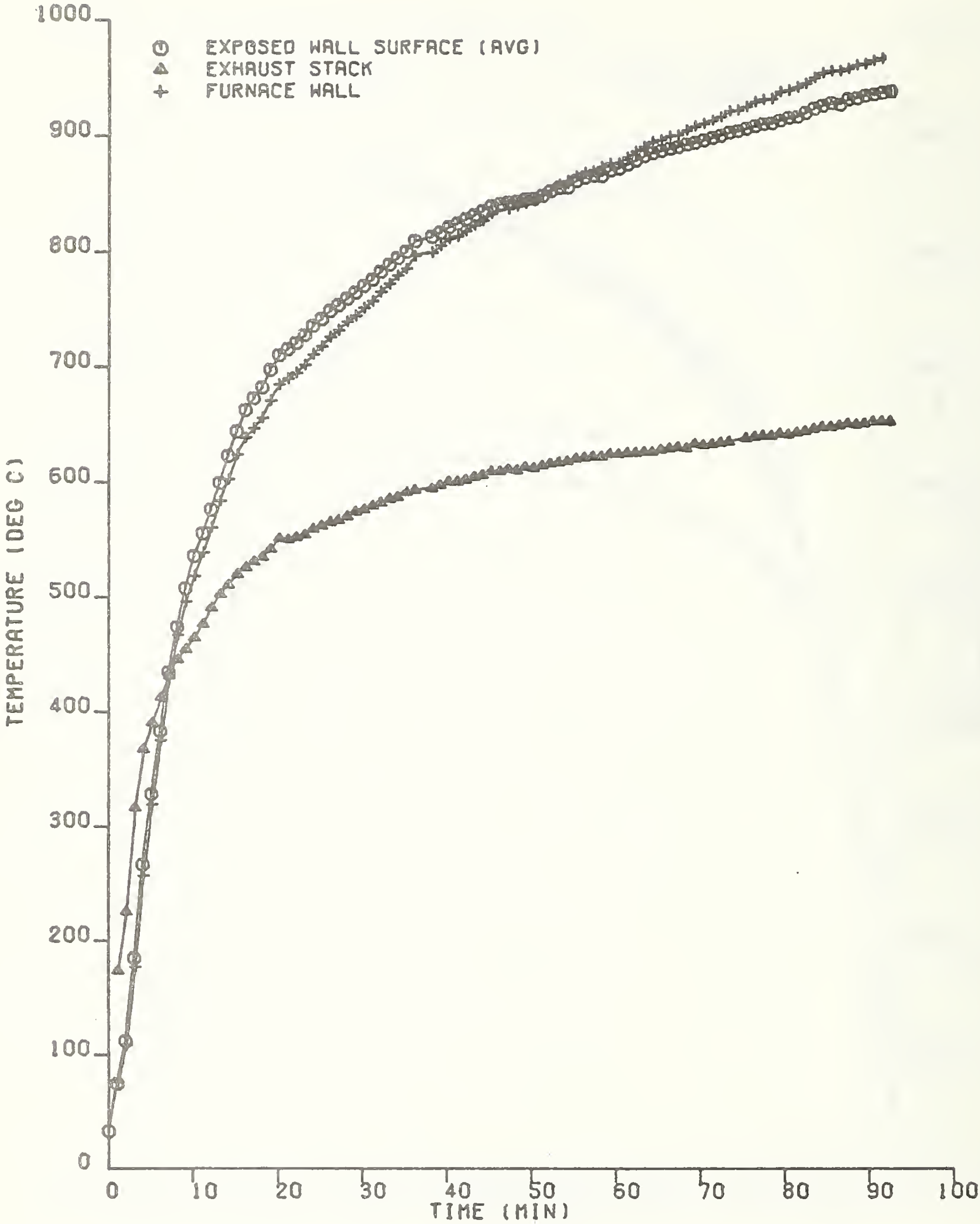

Figure 16. Stack and Wall Temperatures in Test No. 3.

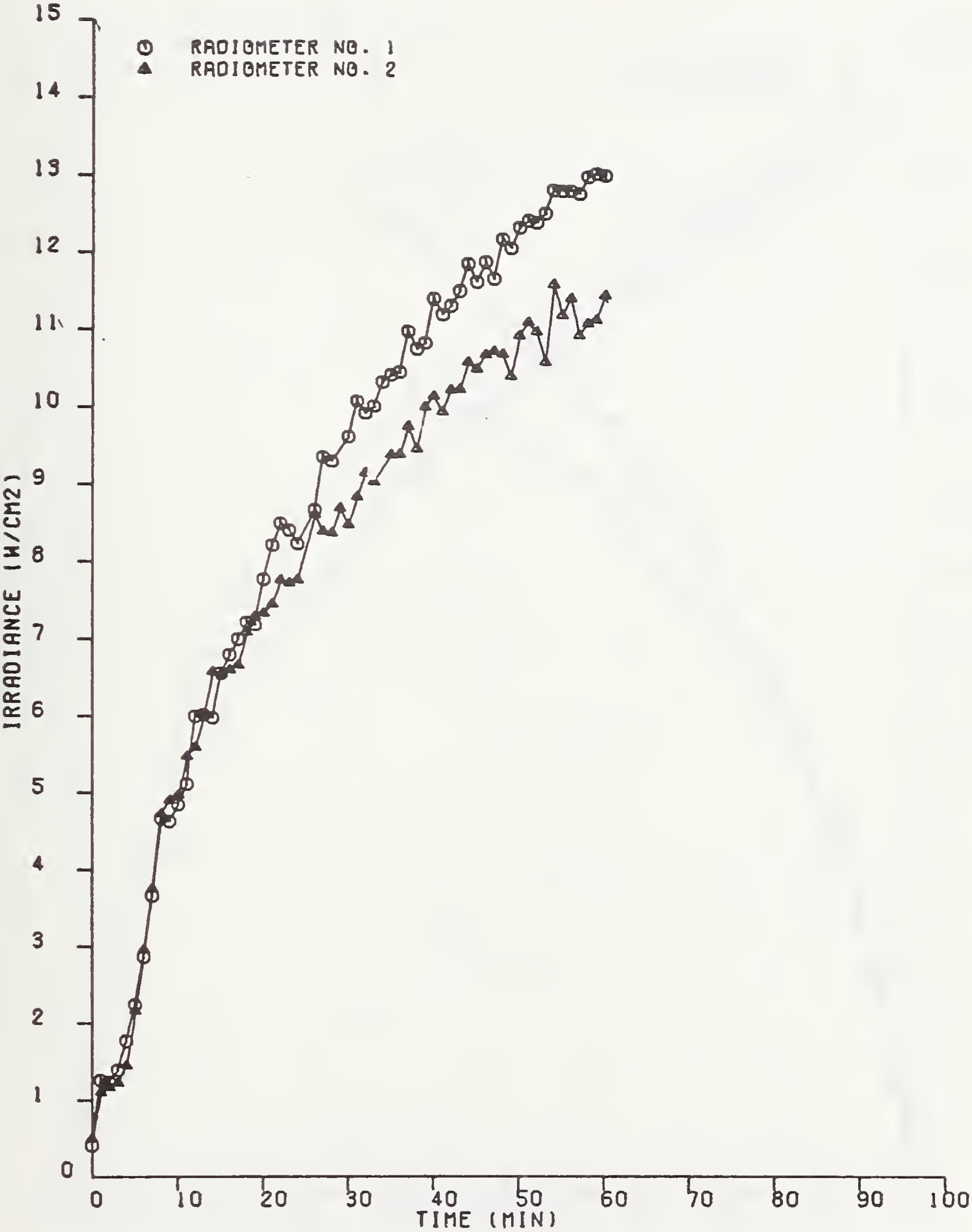

Figure 17. Radiometer Readings in Test No. 1.

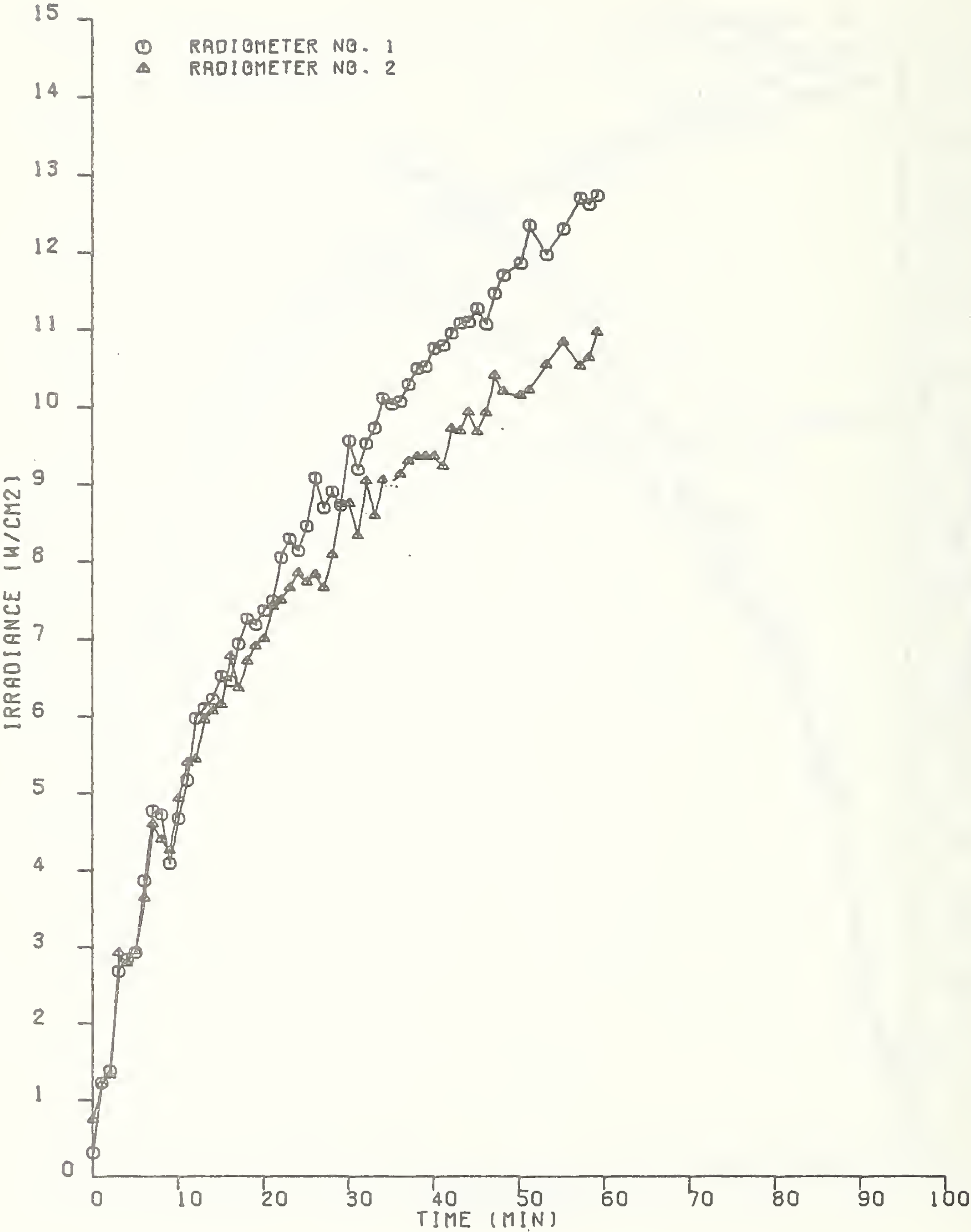

Figure 18. Radiometer Readings in Test No. 2.

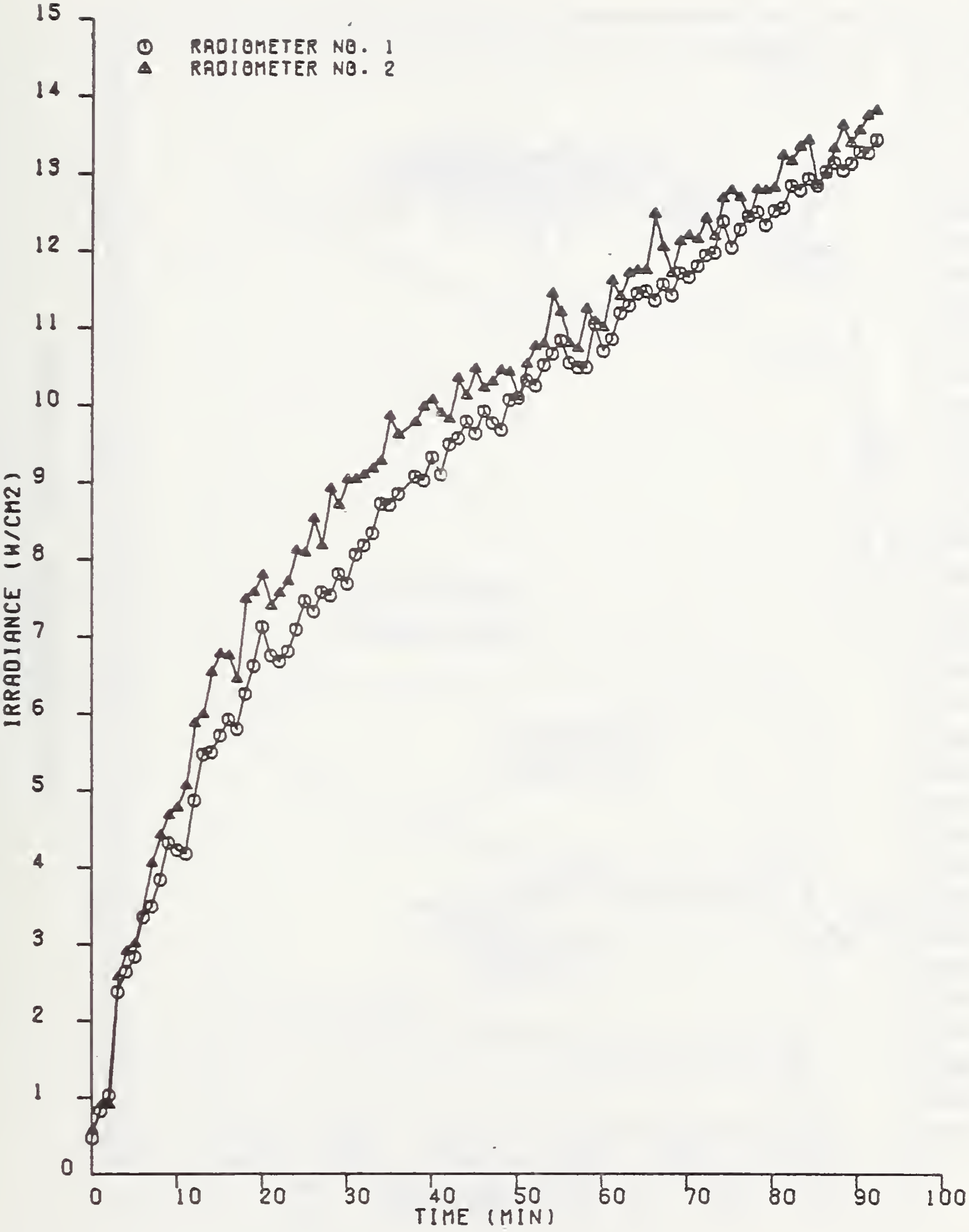

Figure 19. Radiometer Readings in Test No. 3.

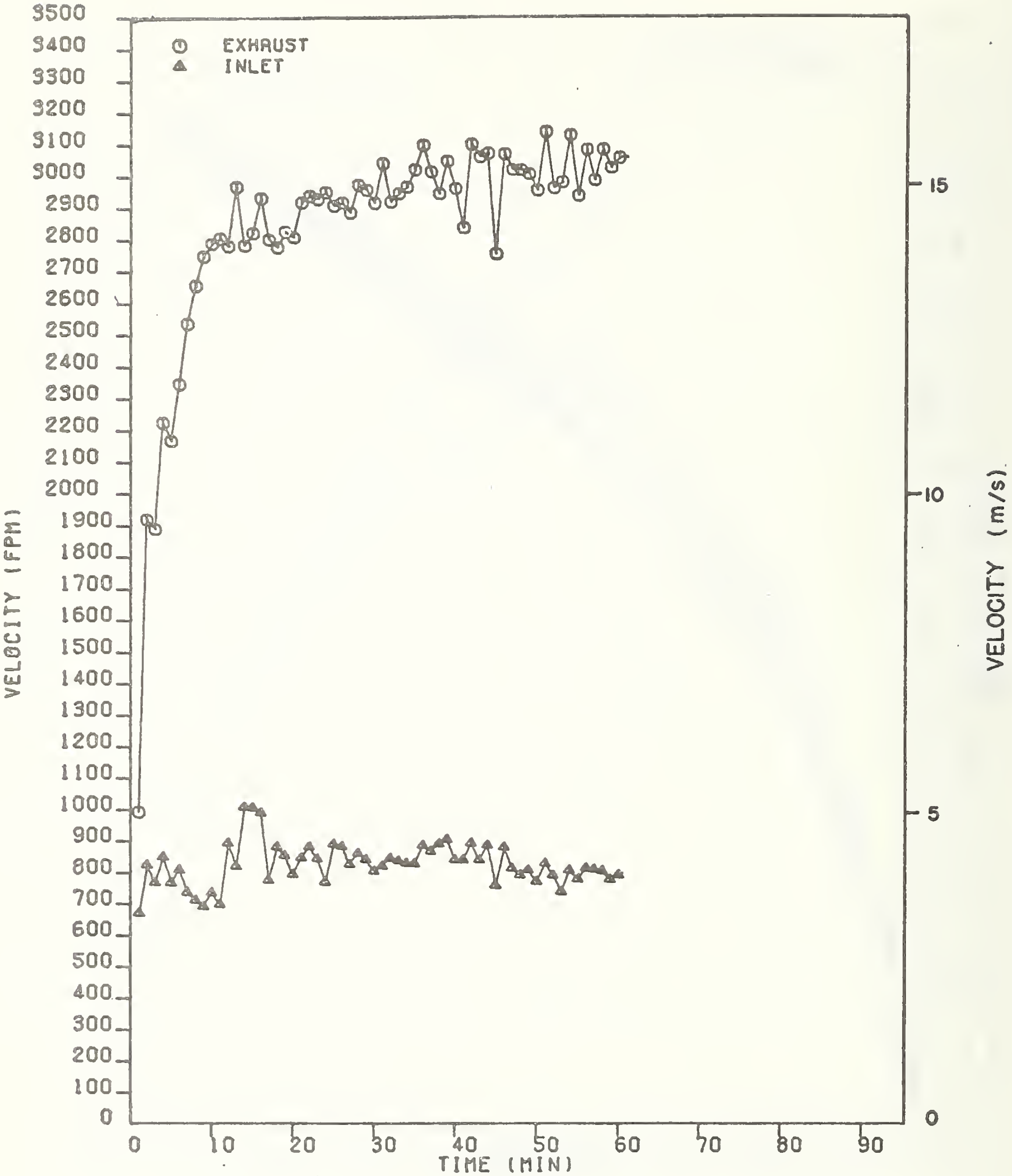

Figure 20. Inlet Air and Exhaust Gas Velocities in Test No. 1.

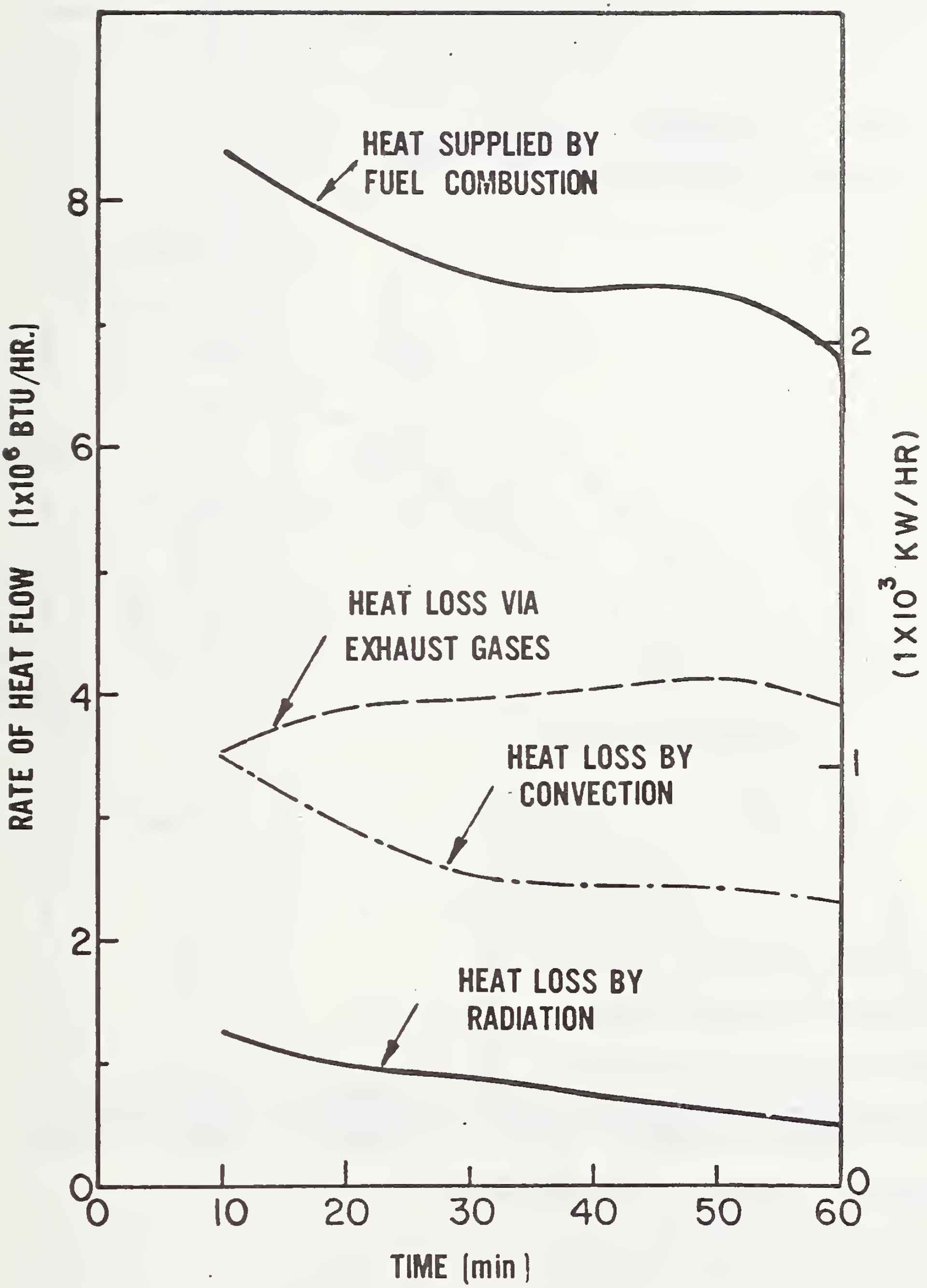

Figure 21. Calculated Heat Input and Output Curves for NBS Wall Furnace Using a Lightweight Masonry Block Test Wall (Test No. 1).

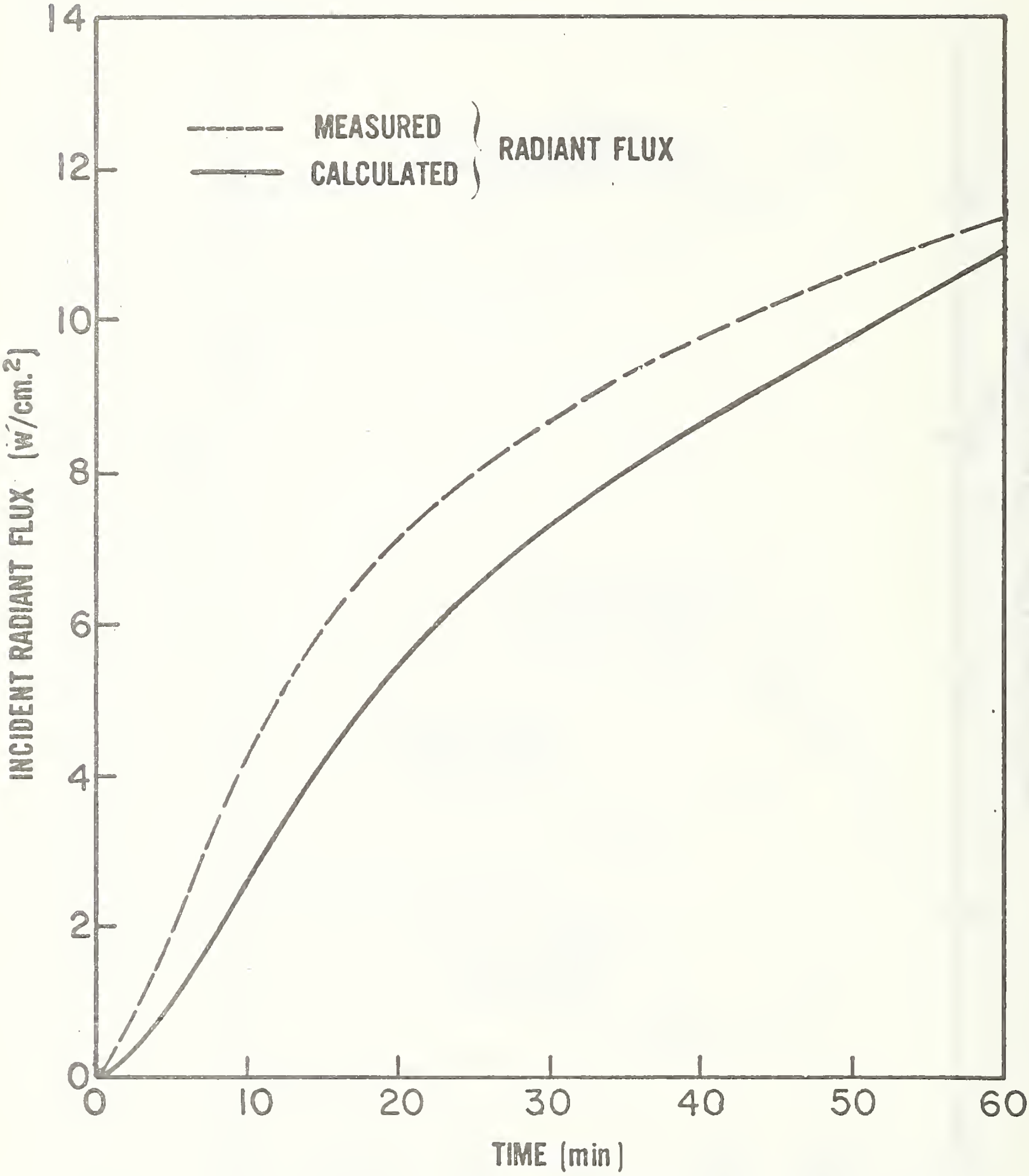

Figure 22. Comparison of Calculated Radiant Heat Flux Incident at Furnace Walls and Radiant Flux Measurement (R-2) on Test Wall for Test No. 1.

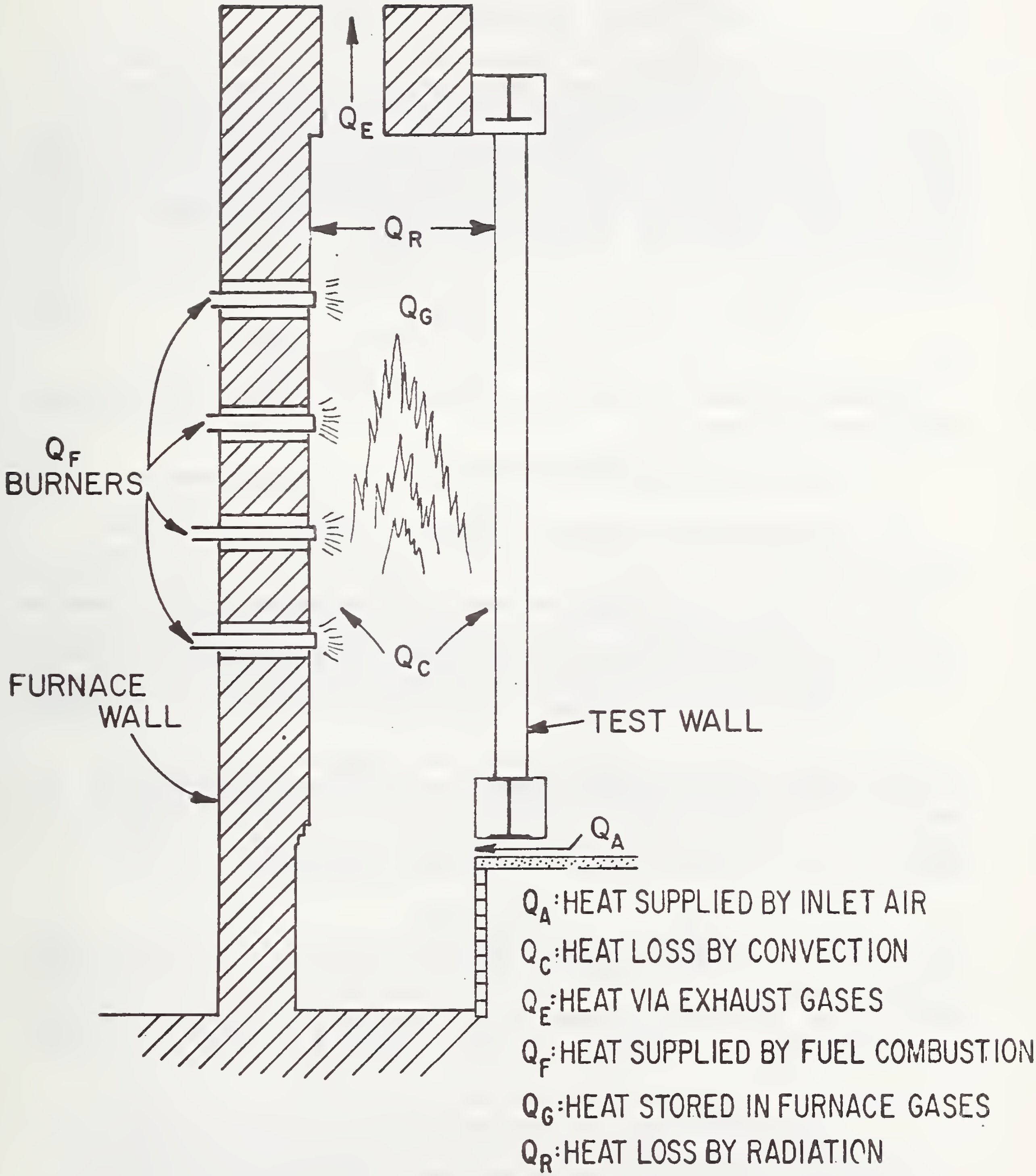

Figure 23. Schematic Diagram of Furnace and Heat Transfer.

APPENDIX A. HEAT BALANCE IN FURNACE

The law of conservation of energy applied to the test furnace, which is considered as a control volume, expresses the fact that the rate of increase of total energy contained in the furnace gases will equal the sum of (a) the net rate of energy transport into the system associated with the mass flow and (b) the rate of heat generation by fuel combustion, minus the rate of energy removal across the bounding surfaces. Accordingly a macroscopic energy balance equation for the test furnace illustrated in figure 23 can be written in the form:

$$\frac{dE_t}{dt} = \sum(w_i H_i)_{in} - \sum(w_i H_i)_{out} + Q_F - Q_L \qquad (1)$$

In order to make the analysis mathematically feasible, the following assumptions were made:

1. There is no temperature variation in the furnace gases.

2. A stoichiometric complete combustion process occurs in the furnace.

3. The heat loss by radiation through openings can be neglected.

4. The furnace walls and test specimen are gray-bodies, and the entire furnace walls have substantially uniform surface temperatures and can be assigned a single mean temperature.

The total energy accumulated within the furnace gases comprises internal, kinetic and potential energy, the last two of which may be neglected in comparison with the remaining one. The rate of energy stored in the furnace gases and the sensible heat supplied by inlet air and fuel were calculated from the following expressions:

$$\frac{dE_t}{dt} = V\rho_M C_V \frac{d(T_M - T_I)}{dt} \qquad (2)$$

$$\sum(w_i H_i)_{in} = w_F\left(H_F^\circ + \int_{T_o}^{T_I} C_F dT\right) + w_A\left(H_A^\circ + \int_{T_o}^{T_I} C_A dT\right) \qquad (3)$$

The velocity and temperature of the inlet air and the volumetric flow rate of fuel into the furnace were measured throughout the test. The contributions of these two terms, which were evaluated in reference to standard conditions at a datum temperature of 15 °C (60 °F), were found to amount to less than one percent of the total heat transfer supplied. Since these quantities were of negligible impact and were on opposite sides of the heat balance equation, equation 1 reduced to:

$$Q_F = \sum (w_i H_i)_{out} + Q_L \tag{4}$$

The rate of heat provided by the fuel combustion was equal to the rate of fuel consumed multiplied by its net heating value. The composition of the exhaust gases can be determined either by direct experimental measurement or by calculation from air overall material balance for each chemical species present, based on the measured fuel gas composition and concentration of one of the component gases in the exhaust stream along with the assumption of complete combustion for the fuel gas reacted with air. The heat loss due to the venting of the exhaust gases was calculated from:

$$\sum (w_i H_i)_{out} = \sum w_i (H_i^\circ + \int_{T_o}^{T_E} C_i dT) \tag{5}$$

where $$w_i = (\rho_M U_E A_E) \left(\frac{X_i M_i}{\Sigma X_i M_i} \right) .$$

Heat loss to the bounding surfaces consisting of the test specimen and the walls of the test furnace occurred mainly by convection and radiation from the hot furnace gases. The radiation incident at the test specimen consisted of direct emission from the furnace gases, and radiative contribution from surrounding furnace walls through the gases. The net rates of radiation and convection losses to the test specimen can be expressed by

$$Q_S = \sigma A_S \varepsilon_S' (\varepsilon_M T_M^4 - \alpha_S T_S^4) + \sigma A_S \varepsilon_S \varepsilon_W [(1 - \alpha_W) T_W^4 - (1 - \alpha_S) T_S^4]$$
$$+ hA_s (T_M - T_S) \tag{6}$$

where α_W and α_S are the total absorptivities of the furnace gases, to be evaluated at the furnace wall and test specimen temperatures, respectively. [8] A_S, ε_S', ε_S and T_S are the surface area, effective surface emissivity, surface emissivity, and absolute surface temperature of the test specimen, respectively.

Similarly, the net rates of radiative and convective exchange for the furnace walls with furnace gases and the test specimen are

$$Q_W = \sigma A_W \varepsilon_w' (\varepsilon_M T_M^4 - \alpha_W T_W^4) + \alpha A_S \varepsilon_S \varepsilon_W [(1 - \alpha_S) T_S^4 - (1 - \alpha_W) T_W^4]$$
$$+ hA_W (T_M - T_W) \tag{7}$$

where A_W and T_W are the surface area and surface temperature of the furnace walls, respectively. ε_W and ε'_W denote the surface emissivity and effective surface emissivity of the furnace walls, respectively.

A review of figure 14 showed that there was little variation between the surface temperatures of furnace walls and test specimen. Incorporating this information, the test specimen and furnace walls were treated as a single zone. Defining Q_B to be the sum of Q_S and Q_W, and combining equations 6 and 7 yields

$$Q_B = Q_R + Q_C = \alpha A_B \varepsilon (\varepsilon_M T_M^4 - \alpha_B T_B^4) + h A_B (T_M - T_B) \qquad (8)$$

A simplified equation describing the overall heat balance for the test furnace can be obtained by introducing the above relationship into equation 4. Thus,

$$Q_F = \Sigma(w_i H_i)_{out} + (Q_R + Q_C) \qquad (9)$$

Both the total emissivity and absorptivity for the furnace gases were determined in accordance with the procedures recommended in the text [8] taking into account the concentrations of CO_2 and H_2O vapor, gas temperature, furnace geometry and size, and surface temperatures of furnace walls. A value of $(1 + \varepsilon_B)/2$ was used for the effective surface emissivity, ε, of the entire boundary walls. [8] The geometric beam length used in gas radiation calculation was equivalent to 4 times of the furnace volume divided by its internal surface area.

All parameters in equations 8 and 9 were either known or measured except for the convective heat transfer coefficient (h). By calculating all the other quantities, it was possible to determine the convective heat transfer coefficient. The above equations were solved at 10 minute time intervals from 10 to 60 minutes. A plot of the heat input and output terms in the overall heat balance equation is shown in figure 21.

The net radiant heat flux density at a gray surface element of total emissivity ε_B and at temperature T_B due to incidence of radiative heat flux H_B coming from the surroundings was expressed by

$$\frac{Q_R}{A_B} = \varepsilon_B (H_B - \sigma T_B^4) \qquad (10)$$

Evaluation of the radiant flux incident at furnace walls at any time was possible using the above equation along with known or measured values for all the other parameters. Figure 22 was derived from these results.

APPENDIX B. A LIST OF ASSUMED PROPERTIES FOR TEST FURNACE

Furnace Walls:

Heat Capacity: 0.84 J/g-°K (0.2 Btu/lb-°F)

Thermal Conductivity: 0.52 W/m-°K (0.3 Btu/hr-ft-°F)

Density: 1.25 g/cm^3 (78 lb/ft^3)

Surface Emissivity (ε_B): 0.8

Effective Surface Emissivity (ε): 0.9

Furnace:

Total Volume (V): 14.2 m^3 (492 ft^3)

Total Internal Surface Area (A_B): 55.7 m^2 (600 ft^2)

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Tests were conducted in the NBS wall panel furnace as part of a CIB international cooperative program to measure and compare heat transfer in fire endurance furnaces. Additionally, a heat balance analysis showed that a cellular concrete block wall specimen absorbed more heat by convection than by radiation. The rate of radiant heat transfer was found to decrease slowly, while the furnace exhaust heat loss increased during the test from 42 to 58 percent of the heat output. The calculated radiant heat fluxes incident at furnace walls was found to be somewhat lower than the experimental values measured at the test wall.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Fire resistance ratings; fire test furnace; heat balance; heat transfer; temperature-time curve.

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