

**ENERGY ANALYSIS OF A RETROFITTED SCHOOL BUILDING  
WITH A SOLAR AIR HEATER**

Sukhbir Mahajan, California State University  
Lanfranco Soma and Simonetta Fumagalli  
ENEA, FARE

Sergio Zobot, Regione Lombardia, Servizio Edilizia Scolastica  
Ashok Kumar Bhargava, Ramjas College, Delhi University

**ABSTRACT**

A low cost methodology is used to evaluate the thermal performance of a retrofitted school with a solar air heater. The main aim of the analysis is to determine with a reasonable accuracy the performance of the various subsystems and to make suggestions for improvements.

Hourly data for weather variables, indoor temperatures, fuel consumption and heat delivered to the building (both from auxiliary and solar heater) are collected using an automatic Data Acquisition System (DAS).

The infiltration rate was determined using tracer gas techniques and overall conduction heat loss was determined using night time data during a long cloudy period (5 days). A constant temperature difference (between indoor and outdoor) was maintained throughout this period. The ambient temperature was nearly constant during this period. Using these measured quantities and hourly data, the passive solar gains are calculated. A subtractive approach is used to obtain these quantities. The results of 12 day periods (7 to 18 March and 14 to 25 November 1985) are reported. For these periods, the passive and active solar contributions make up 39% and 30% respectively of the total heat load. Suggestions for improvements to enhance these contributions are presented.

The analysis of the data presented here, indicate that the methodology is simple and reliable for large scale monitoring using short time periods (10-15 days).

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**I - INTRODUCTION**

The passive solar gains in buildings are difficult to calculate. Available models predict very different numbers for slightly different climatic conditions.

For policy making purposes and to encourage investment in solar (passive and hybrid) design, it is necessary to have a reliable method and a transparent procedure to determine solar contributions to the total heating load.

In order to achieve this goal, a methodology<sup>1,2,3</sup> has been developed. Using this methodology one can calculate the passive gains and evaluate the thermal performance of the various subsystems.

This methodology<sup>4</sup> has been tested on the Elementary School of Montorfano (Como, Italy). The results show that the methodology is simple, reliable and that it is possible to arrive at a definite conclusion about long term performance using short term data.

If performed in real time, a closed loop network model can be used to drive various systems for controlling the energy performance.

**II - SITE AND BUILDING DESCRIPTION**

The Lanzada Elementary School is located 20 km. north of the city of Sondrio in Regione Lombardia (see Fig. 1). It is at the end of Val Malenco (a side valley of Valtellina), below the Bernina Range - in the Alps. Winter and spring seasons are sunny and cool. Summers are moderately warm.

The school is a masonry building made with massive stones, internally covered with bricks (average thickness 70 cm.). The school has a compact shape with all the classrooms facing south. It is a three story building with a small gymnasium at the lower level.

Figure 2 shows the floor plan and a section of the building. In order to decrease energy consumption, the following major retrofit measures were installed in 1983:

- o Increased envelope insulation on North side
- o Double glazed all windows on North side
- o Insulated the ceiling
- o Installed solar air heaters on South facade connected with a ventilation system

Table I lists the physical parameters of the school.

### III - METHODOLOGY AND DATA COLLECTION

A methodology is developed to determine the passive gains and to evaluate the solar air heater thermal performance. All the energy sources, like auxiliary heater, solar air heaters and internal gains are monitored. Using this monitored data, energy balance for the whole building is performed. The following equation is used to determine passive solar gains:

$$Q_{\text{passive}} = Q_{\text{loss}} - Q_{\text{auxiliary}} - Q_{\text{internal}} - Q_{\text{collector}} \quad (1)$$

$Q_{\text{loss}}$  is made up of three parts:

$$Q_{\text{loss}} = Q_{\text{conduction}} + Q_{\text{infiltration}} + Q_{\text{ventilation}} \quad (2)$$

The infiltration rates were measured with tracer gas technique. The detail of this technique is presented at the end of this section. The ventilation rate is calculated by subtracting injected air from aspirated air. The data on aspirated air are obtained from the ventilation unit placed at lower level; 3025 m<sup>3</sup>/h of air is aspirated through the stairwell and 1200 m<sup>3</sup>/h is reinjected through the ventilation openings.

Due to the heating system design it is difficult to determine the conduction heat loss coefficient (UA) with the coheating method. Therefore an indirect method has been used. During a long cloudy period the indoor-outdoor temperature difference was held constant. The auxiliary delivered at night (10 hours) and temperature differences during this period were monitored.

The measured infiltration heat losses are subtracted to obtain the conduction losses. The conduction losses are then divided by inside-outside temperature differences to obtain the overall conduction loss coefficient (UA). The average value for 5 nights is assumed as the true UA value. It was found that the UA value is 34% lower than the calculated value (Italian

Standard UNI-CTI). Table II shows calculated and measured UA values. Auxiliary is calculated from the measured outlet and inlet water temperatures and water flow rates. Solar collector contributions are similarly obtained from air temperatures and air flow rate.

For internal gain calculations, 75 W per student during the lesson hours is assumed. The heat gains from lighting are also added to internal gains. Steady state conditions are assumed throughout the calculations. The thermal time constant of the walls is of the order of a few days (130 hours<sup>5</sup>), and initial and final conditions should be considered in order to deal with short periods of time. For periods greater than 10 days the thermal mass effects are small. For seasonal performance evaluations the errors due to thermal mass effects should be negligible.

The data collection was limited to a level adequate for assessing performance evaluations of subsystems. A complete list of measured quantities is given in Table III. All probes were calibrated in the laboratory before field installation. The Solartron Schlumberger ORION is used for data logging. It allows some conversion on probes, counters unit and measures of events. It is a high accuracy system and has many possibilities for programming and interfacing with other systems. The data were recorded on a cassette tape and later transferred on to the VAX 11/750 system via modems and telephone line.

During back-up operations, logger operations were interrupted. There were a lot of disadvantages by working in this mode. However, there were no other options available.

#### Tracer Gas Measurements

The tracer gas measurements were done at 4 places: classroom and corridor at first floor, classroom at second floor and gymnasium at lower level. The tracer gas ( $SF_6$ ) was injected in the rooms, corridor and gymnasium. After waiting for half an hour, four to five air samples from each of the spaces were taken at 15 minute intervals.

The concentration of  $SF_6$  was measured using gas chromatography. From the  $SF_6$  concentration decay rates, the air exchange rates were obtained. These measurements were done with fan off. In Table IV the air exchange rate values for three different parts of the school are listed.

#### IV DATA ANALYSIS

The main objective of the data analysis is to calculate the total heat losses, auxiliary energy used, internal gains and solar energy contributions. The solar energy contributions consist of two parts: the energy provided by the solar air heater and passive solar gains. A short description of the procedure used to calculate these quantities is described below.

##### Total Heat Loss

The heat loss from the building occurs through conduction, infiltration and ventilation. All these loss calculations assume steady conditions. As mentioned earlier, this assumption is valid for periods longer than the time constant of the building.

The conduction heat losses were calculated using the value of conduction loss coefficient (UA) as determined above and the measured indoor-outdoor temperature differences.

$$Q_{\text{conduction}} = \sum_i (UA)_i * \Delta T * t \quad (3)$$

The infiltration heat losses were calculated using the infiltration rate determined from tracer gas measurements and indoor-outdoor temperature difference.

$$Q_{\text{infiltration}} = \sum V_j * R_j * \rho_a * C_a * \Delta T_j * t \quad (4)$$

where  $V_j$  = Volume of the  $j$  th space

$R_j$  = Air Infiltration Rate for the  $j$  th space

$\Delta T_j$  = Temperature difference between the  $j$  th space and outdoor

$\rho_a$  = Density of air

$C_a$  = Specific Heat Capacity of air

$t$  = Duration

The ventilation losses are calculated using the ventilation rate as determined above (difference between aspirated rate and injected rate) and indoor-outdoor temperature differences. An equation very similar to Eq. (3) is used to calculate ventilation rate for the fan on periods.

### Auxiliary Energy

Auxiliary energy is provided by hot water radiators. The energy supplied by the hot water was calculated from the information on inlet-outlet water temperature differences and water flow rates, and the time for which the pump was on.

$$Q_{\text{auxiliary}} = F * \rho_w * C_w * T * t \quad (5)$$

where

F = Water Flow Rate

$\rho_w$  = Density of Water

$C_w$  = Specific Heat Capacity of Water

T = Inlet-Outlet Water Temperature Difference

t = Time for which Pump is On

### Internal Gains

The information on the number of occupants, time of occupancy and the lighting level was used to calculate internal gains.

### Boiler Efficiency

The burner flow rate and the burner on-off time give the total oil burned and finally the oil burned along with the auxiliary energy delivered gives the heating system efficiency.

### Solar Contributions

The measured values of the air flow rate through the collector, the inlet-outlet air temperature difference and the time for which the fan is on, are used to calculate solar contributions provided by the solar air collectors. An equation similar to Eq. (4) is used for this calculation. Finally the passive solar contributions are calculated subtractively using Equation (1). However, any errors made in the calculation of  $Q_{\text{loss}}$  and  $Q_{\text{aux}}$  are lumped into the passive contributions.

## V - RESULTS AND DISCUSSION

Two 12 day periods were analyzed. These two periods are representative of typical spring and fall climate.

During the twelve day period in Fall (November) six days were sunny and six days were overcast. In March, eight days were sunny and four days were overcast. The average ambient temperature is nearly the same during these periods. The insolation values on collector plane, indoor temperatures and outdoor temperatures are plotted in Figures 3 and 4 for a three day period (November 7-8-9 1985). This is a relatively clear period with insolation peaking at  $850 \text{ W/m}^2$ .

The bar chart in Figure 5 shows the hourly auxiliary delivered to the building and the solar energy incident on the collector plane for the same three day period.

There were considerable temperature variations in different parts of the building primarily due to the stack effect: classrooms at lower floors have lower temperatures. The increased ceiling insulation decreased the heat loss at the second floor. This means the radiator system needs to be recalibrated. The corridors have generally lower temperatures than adjacent classrooms due to the fact that corridors do not have direct gain (corridors face north) and have higher infiltration rates.

In Figure 6 the average temperatures in different parts of the building are graphed for a twelve day period in November 1985. The heat balance calculations are performed for the whole building. The results for the 12 day periods in March and November 1985 are presented in Table V and Table VI respectively.

Only values and totals of  $Q_{\text{loss}}$ ,  $Q_{\text{in}}$ ,  $Q_{\text{aux}}$  and  $Q_{\text{sol}}$  (both passive and active) are listed in this table. The listed percentages are with respect to the total load.

The daily energy balance has little meaning, because of different shifts in the various contributions due to the transient effects through the thick walls, but the twelve day periods presented are nearly free of thermal mass effects. The building collects a considerable amount of solar energy: the south facade has  $84 \text{ m}^2$  of direct gain aperture (windows) and  $130 \text{ m}^2$  of collector area out of a total of  $380 \text{ m}^2$  of the south facade area. The collector efficiency in the two periods doesn't exceed 30% and 20% respectively. This low efficiency is mainly due to the low flowrate of hot air removed from the collectors. The measured air flowrate is  $1200 \text{ m}^3/\text{h}$  leaving the collectors versus  $3200 \text{ m}^3/\text{h}$  ( $3025$  from inside plus  $175$  from outside) of air forced into collectors by the fan and pushed through. The designed value is  $5000 \text{ m}^3/\text{h}$  with 60% efficiency. The discrepancy is attributed to the following factors:

- o Leakages through collector trimmings
- o Cracked ducts. Ducts are made of polystyrene and the cracks are due either to vibrations from fan-engine and accidental breaking of ducts.

There is a definite need to improve the collector performance.

- o The ventilation unit should be moved to the attic and the external air intake should be closed. The air would be aspirated from the collectors and the fresh air would then be taken from collector leaks.
- o The distribution ducts should be redesigned and protected from accidental damages.
- o A better calibration of the air distribution system is also needed.

The total solar contribution (30% in November and 39% in March) is quite good and with the modifications suggested, should easily reach 35-45% of the total load. The collector contribution will increase if the existent ventilation unit is moved to the attic. It has been shown<sup>5</sup> that for low pressure solar air heaters, the leaks do increase the efficiency although outlet air temperature decreases slightly.

Average boiler efficiency for the 12 day period in November is 68%. It looks good, considering that no retrofit measures been performed on auxiliary heating system. In Table VII the daily efficiency for November 1985 is presented.

The operational logic seems quite adequate. The huge mass of the building is used as thermal storage for the heat coming from the collectors and on sunny days this considerably reduces the auxiliary energy needs.

A comparison between March 83 energy use and March 85 energy<sup>6</sup> presented in Table VIII. For the two month period, there is over 45% reduction in oil consumption. Besides there is an increase in passive solar contribution, due to improved insulation of the building.

In conclusion the retrofit measures are adequately designed and with slight modifications the performance of the solar air heater can improve considerably. This will lead to a further reduction in oil consumption.

#### Acknowledgments

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6. The 1983 energy use was obtained from the daily field presently measured boiler efficiency. The UA value was calculated and then reduced by 34%. This percentage difference was obtained for the measured and calculated UA values after retrofit.

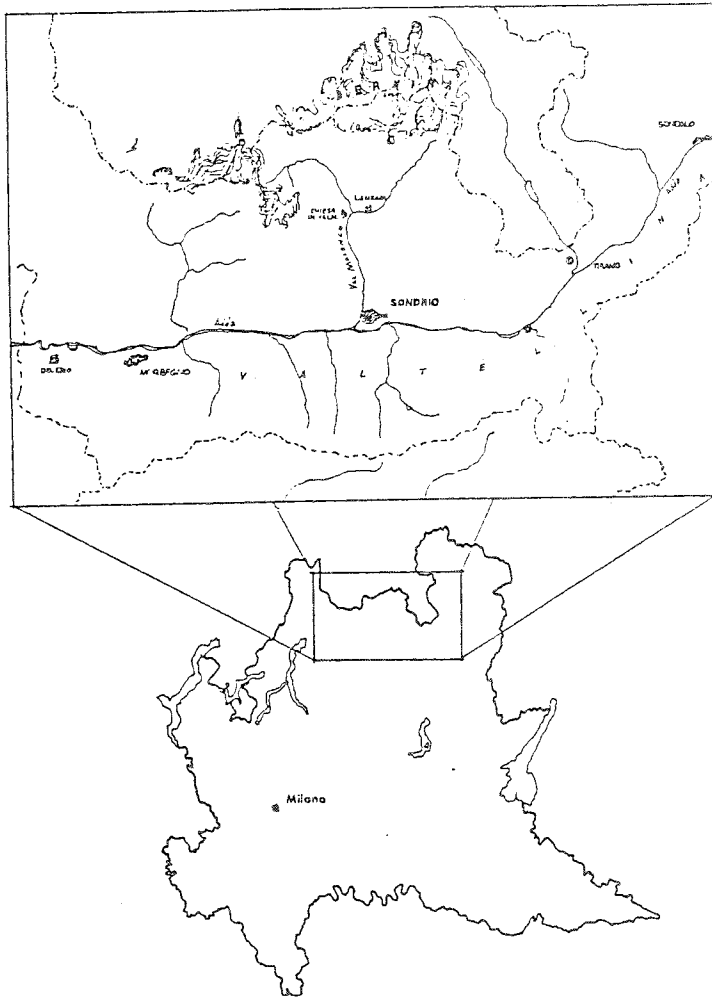


Figure 1. Site location map.

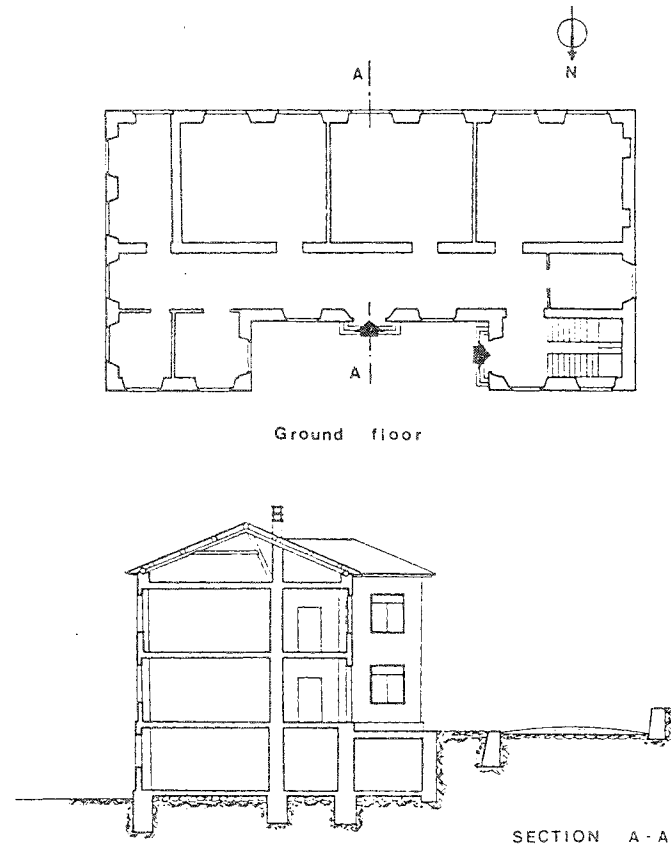


Figure 2. School building floor plan and a section.

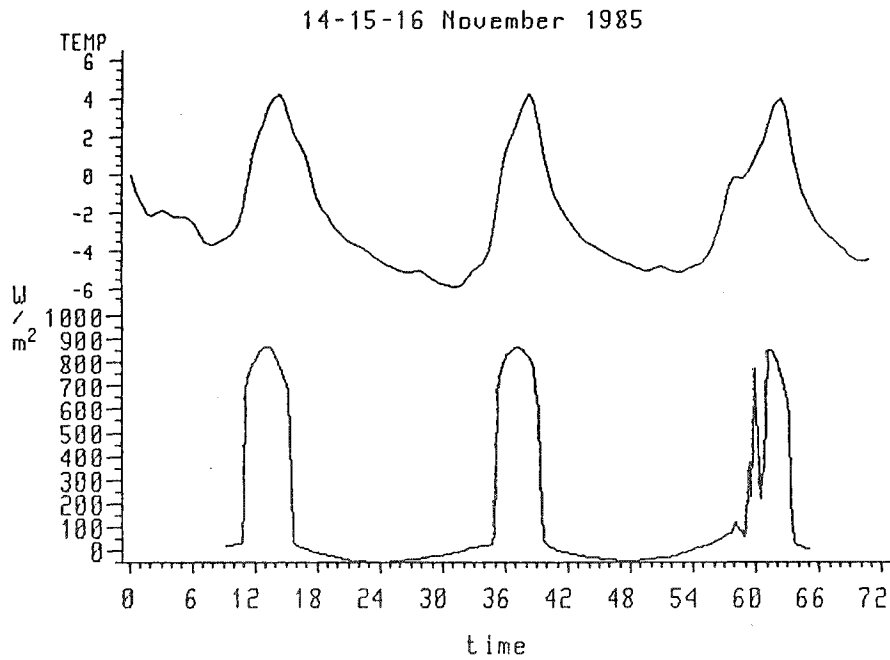


Figure 3. Solar radiation and ambient air temperature profiles for a three day period (Nov 14-16, 85).

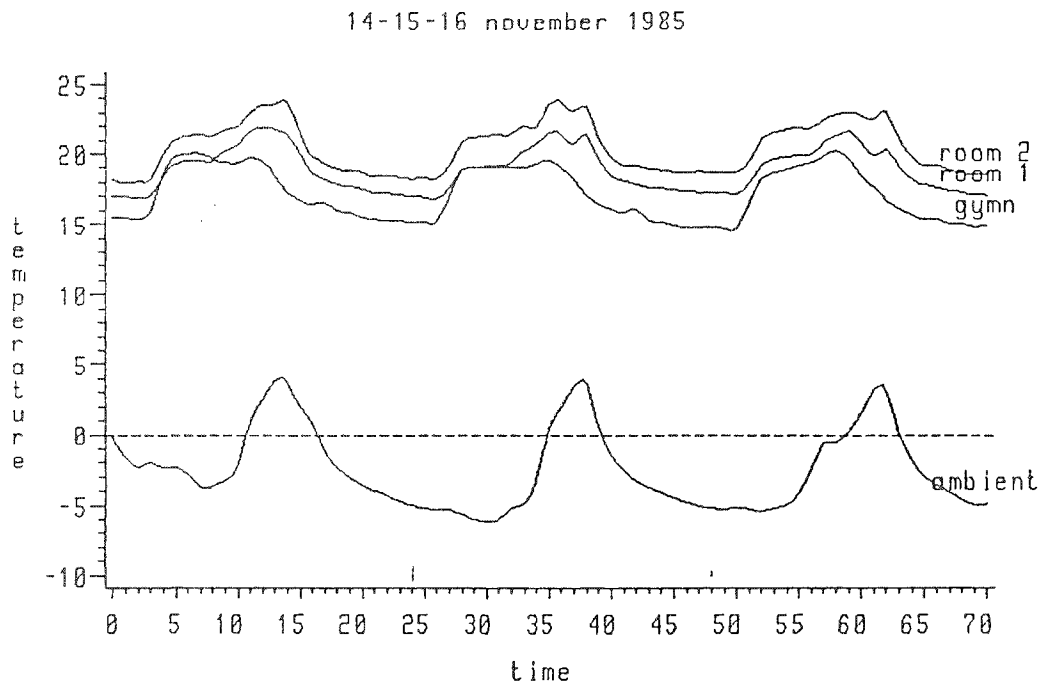


Figure 4. Indoor and ambient air temperature profiles for a three day period (Nov 14-16, 85).

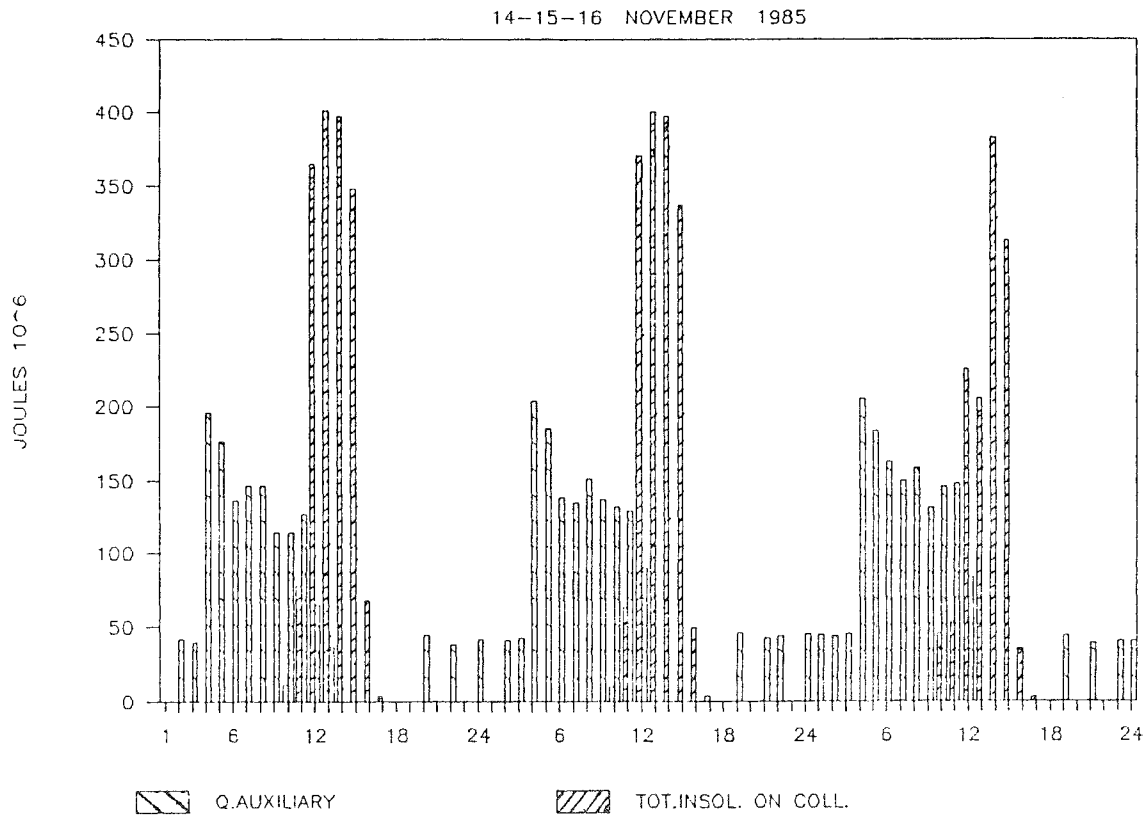


Figure 5. Auxiliary energy used and solar radiation incident on collector.

INTERNAL AVERAGE TEMPERATURE DISTRIBUTION (14 - 25 Nov. 1985)

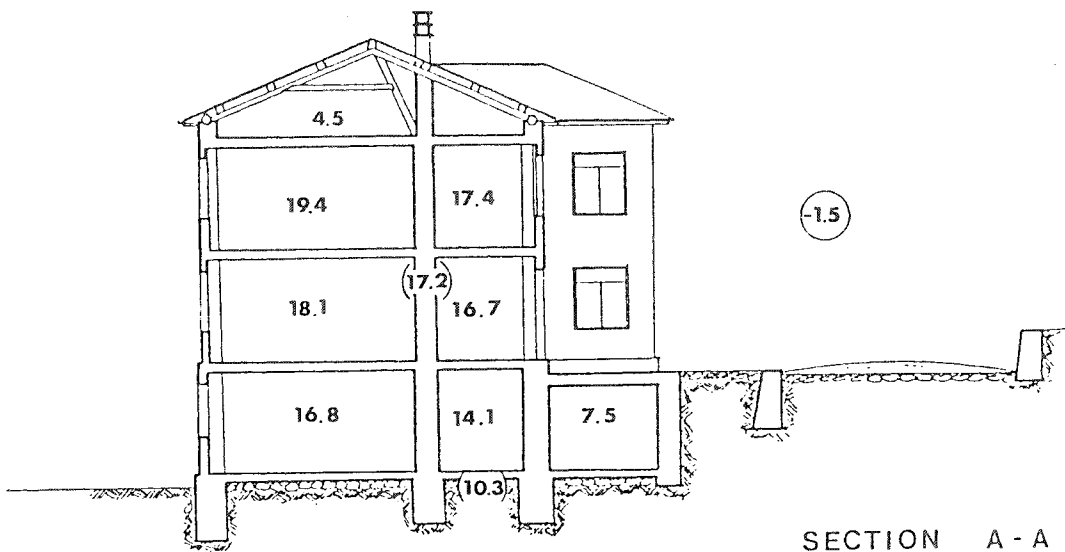


Figure 6. Average internal air temperatures.

Table I. Building parameters.

	VOLUME M <sup>3</sup>	FLOOR AREA M <sup>2</sup>	GLAZING M <sup>2</sup>
CLASSROOMS	894	271	48 (South)
CORRIDORS	720	218	15 (North), 6 (East), 6 (West)
GYMNASIUM	294	90	16 (South)
TOILETS	225	68	24 (East), 6 (North)
OTHERS	464	110	8 (South), 21 (North)

INSULATION ( After Retrofit )

NORTH FACADE	5 cm. Polystirene + Vapour Barrier
GLAZING	Double Pane Glass on North Side
ATTIC	5 cm. Polystirene

Table II. UA Values (W/C) of various part of building.

CALCULATED VALUES (ITALIAN UNI-DTI 7357)

	SURFACE M <sup>2</sup>	BEFORE W/C	AFTER W/C
WALLS	758	742	519
WINDOWS	194	880	701
DOORS	20	18	16
ROOF	270	316	153
GROUND	88	50	50
FLOOR	322	305	305
TOTALS	1652	2311	1744

MEASURED VALUES	NOV 18	1176	W/C
AFTER RETROFIT	NOV 19	1139	"
	NOV 20	1150	"
	NOV 21	1240	"
	NOV 22	1021	"
AVERAGE VALUE ASSUMED		1145	W/C

Table III. List of measured quantities.

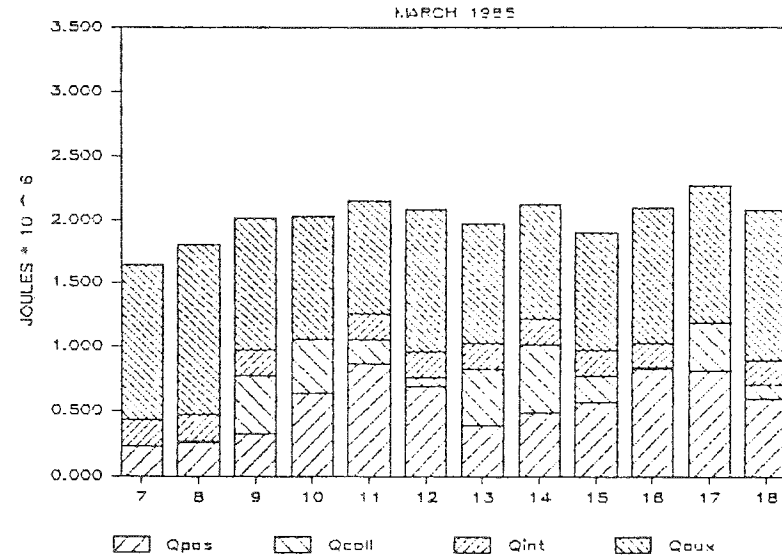
N. PROBE	DESCRIPTION	TIME SCAN	STATS ON TAPE
1	Air Temp. out of Collector	50 sec.	10 min.
2	Air Temp. Hole Second Floor	50 sec.	10 min.
3	Air Temp. Hole First Floor	50 sec.	10 min.
4	Air Temp. Inlet of Collector	50 sec.	10 min.
5	ON-OFF Furnace		
6	ON-OFF Water Pump		
7	ON-OFF Fan Low-Speed		
8	ON-OFF Fan High-Speed		
9	Auxiliary Water Flow Rate	90 sec.	90 sec.
10	Water Temp. OUT	90 sec.	90 sec.
11	Water Temp. IN	90 sec.	90 sec.
12	Solar Insol. on Collector Plane	50 sec.	10 min.
13	Solar Insol. on Horizontal Plane	50 sec.	10 min.
14	Wall Temperature	50 min.	50 min.
15	Corridor Temp. at Lower Level	50 min.	50 min.
16	Coal Deposit Temp.	50 min.	50 min.
17	Room Temp. Second Floor	50 min.	50 min.
18	Room Temp. First Floor	50 min.	50 min.
19	Gymnasium Temp.	50 min.	50 min.
20	Corridor Temp. Second Floor	50 min.	50 min.
21	Corridor Temp. First Floor	50 min.	50 min.
22	Attic Temp.	50 min.	50 min.
23	Ground Temp.	50 min.	50 min.
24	Ambient Temp.	50 min.	50 min.

Table IV. Infiltration rate measurement results.

AIR CHANGES PER HOUR

	OCCUPIED	UNOCCUPIED
CLASSROOMS	0.60	0.41
CORRIDORS	2.00	1.86

Table V. Energy use for the month of March 1985.



Lanzada Elementary School - MARCH 1985 [ JOULES \* 10<sup>6</sup> ]

DATE	Qloss	Qint	Qaux	Qsolar Coll.	Pass.	pas %	int %	sol %
Thu 7	1637.2	200.0	1205.8	4.5	226.9	14%	12%	0%
Fri 8	1802.0	200.0	1329.8	22.2	250.0	14%	11%	1%
Sat 9	2002.8	200.0	1029.7	448.7	324.4	16%	10%	22%
Sun 10	2021.4	0.0	959.1	424.9	637.5	32%	0%	21%
Mon 11	2148.8	200.0	895.0	192.3	861.4	40%	9%	9%
Tue 12	2081.4	200.0	1120.5	68.7	692.3	33%	10%	3%
Wed 13	1968.3	200.0	940.4	433.1	394.8	20%	10%	22%
Thu 14	2118.5	200.0	900.4	534.7	483.5	23%	9%	25%
Fri 15	1899.0	200.0	923.1	210.4	565.5	30%	11%	11%
Sat 16	2093.1	200.0	1059.1	6.0	828.0	40%	10%	0%
Sun 17	2262.0	0.0	1068.4	386.3	807.3	36%	0%	17%
Mon 18	2078.8	200.0	1180.4	111.0	587.4	28%	10%	5%
	24113.4	2000.0	12611.7	2842.8	6658.9	27%	8%	12%

Table VI. Energy use for the month of March 1985.

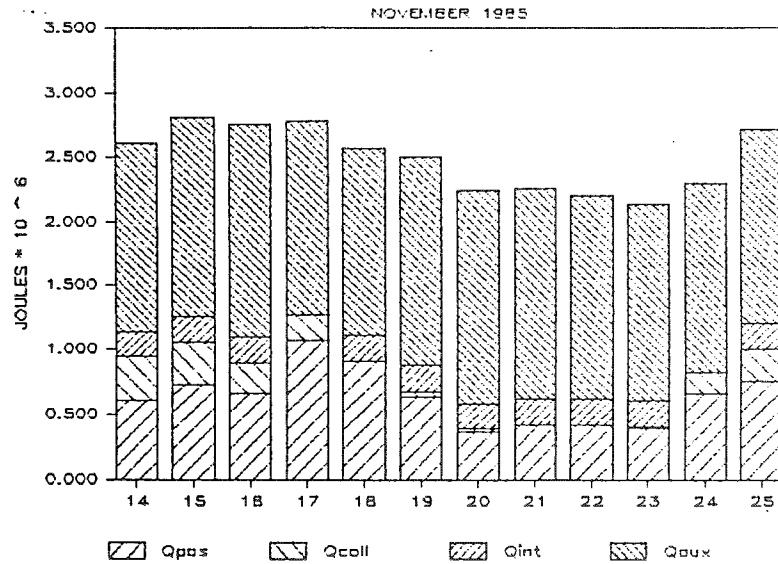


Table VII. Boiler efficiency.

DATE	FUEL BURNED [kWh]	Qaux TOTAL [kWh]	EFFICIENCY %
Thu 14	573	406	70.9%
Fri 15	602	433	72.0%
Sat 16	644	462	71.8%
Sun 17	617	417	67.5%
Mon 18	656	406	61.8%
Tue 19	682	453	66.3%
Wed 20	669	458	68.5%
Thu 21	678	454	67.0%
Fri 22	639	440	68.8%
Sat 23	622	425	68.4%
Sun 24	596	407	68.3%
Mon 25	615	420	68.3%
TOTALS	7593	5181	68.3%

Lanzada Elementary School - NOVEMBER 1985 [ JOULES \* 10^6 ]

DATE	Qloss	Qint	Qaux	Qsolar		pas int sol		
				Coll.	Pass.	%	%	%
Thu 14	2602.4	200.0	1461.8	337.3	603.2	23%	8%	13%
Fri 15	2814.4	200.0	1560.5	318.6	735.3	26%	7%	11%
Sat 16	2758.3	200.0	1664.5	237.9	656.0	24%	7%	9%
Sun 17	2781.0	0.0	1501.1	207.4	1072.5	39%	0%	7%
Mon 18	2567.6	200.0	1461.2	1.9	904.5	35%	8%	0%
Tue 19	2503.3	200.0	1629.2	36.8	637.3	25%	8%	1%
Wed 20	2234.6	200.0	1649.7	18.0	366.9	16%	9%	1%
Thu 21	2247.7	200.0	1533.1	0.0	414.7	18%	9%	0%
Fri 22	2204.6	200.0	1583.4	0.0	421.2	19%	9%	0%
Sat 23	2132.8	200.0	1530.4	11.6	390.8	18%	9%	1%
Sun 24	2293.7	0.0	1465.5	171.1	657.1	29%	0%	7%
Mon 25	2718.8	200.0	1511.8	250.6	756.3	28%	7%	9%
TOTALS	29859.2	2000.0	18652.0	1591.4	7615.8	25%	7%	5%

Table VIII. Performance comparison (before and after retrofit).

	Ti-Te	Qloss	Qint	Qaux	Qsolar	
					Coll	Pass
MARCH 83	413	76532	5167	54857	--	16508
MARCH 85	464	62293	5167	32580	7345	17202

Measures in JOULES \* 10^6