RBS Technology:
Task 3 Report

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RBS Technology: Task 3 Report

TABLE OF CONTENTS

CHAPTER 1

EXECUTIVE SUMMARY

The purpose of this report is to discuss the current state of attic radiant barrier system (RBS) technology. Concepts, research issues and experimental test results are presented and discussed.

The existing body of world research conclusively shows that attic RBS are an effective means of reducing summertime ceiling heat gains. They consistantly produce measured ceiling heat gain reductions of 30 to 50 percent in summer. Reported cooling energy savings range from 7 to 21 percent and energy paybacks are reported to be rapid.

A number of RBS issues have been raised by the research community and in the marketplace. They are summarized by the following questions.

- o How does insulation level affect performance?
- o Does location in the attic affect performance?
- o Will dust accumulation affect performance?
- o How does attic ventilation affect performance?

- o How do RBS affect roof and shingle temperatures?
- o Will RBS cause moisture problems in attics?
- o How is performance affected by climate?

Many of these issues are due to the unfamiliarity of RBS concepts and the fact that there are no standards for RBS. As one result, researchers have conducted and reported RBS tests differently from one another. As might be expected, this has lead to "apparent" conflicts in the test results and, in turn, to increased confusion about attic RBS. The marketplace often finds the technology confusing because RBS concepts are quite different from conductive insulation concepts and infrared radiation phenomena are sometimes counterintuitive.

This report attempts to provide the necessary logical explanations and suporting test data to clarify attic RBS concepts. Whenever possible, discussions are presented from a common sense perspective.

The principle finding of this report is that there is convincing scientific evidence to allow for the safe, effective and economic use of attic RBS in southern buildings. Their use has been shown to economically reduce both cooling energy consumption and peak electric demand.

Although the scientific evidence is compelling, the building community at large is not convinced because standards (from ASTM) and design guidance (from ASHRAE) are needed to confidently specify and use RBS in the field. Such standards and guidelines evolve through a somewhat contentious but deliberate consensus process. The membership of appropriate ASTM and ASHRAE committees need convincing amounts of high-quality research data before RBS guidlines and standards will be adopted.

This need has led to the formulation of a comprehensive research program. With assistance from the sponsors of this report, the Florida Solar Energy Center (FSEC) maintains a long-term research program emphasizing RBS performance and reliability measurement. This report also discribes this research effort.

Over the past two years this research program has accomplished the following:

- o Found that attic RBS block radiation transfer across the attic airspace equally, independent of location of the radiant barrier in the attic; whether glued to the roof decking (RBS facing down), draped over roof trusses (RBS facing down) or located on top of ceiling insulation when new (RBS facing up).

- o Established that there is relatively rapid dust accumulation on upward facing horizontal RBS surfaces in attics. Over time, this renders upward facing horizontal RBS surfaces ineffective. Field samples, however, indicate that dust collection on downward facing aluminum surfaces does not occur. Surface degradation of high purity aluminum (>99%) foil does not appear to occur except in very rare cases where severe environmental polution exists. Very dusty high emittance samples (0.36) revert to their original low emittance when cleaned (0.05).

- o Measured building cooling energy use and peak demand savings between 7 and 10 percent in small houses (1200 ft^2) with R-19 ceiling insulation. In larger houses (2500-3000 ft^2) where roof loads constitute a greater percentage of the air conditioning energy consumption, computer simulations indicate that RBS may save 15 percent or more in houses with R-19 ceiling insulation. If existing ceiling insulation levels are lower than R-19 (e.g. many retrofit applications) RBS cooling energy savings may increase to 20 or 25 percent, depending on insulation level and house size.

- o Developed detailed RBS computer models which can account for both the heat and moisture transfer effects in attics. Inclusion of attic moisture transfer effects dramatically improves agreement between predictions and measurements. A simplified, heat-balance model using ASHRAE methods has also been developed and used to identify system performance sensitivities.

- o Developed a dust accumulation and material degradation monitoring protocol and started field measurements in 12 houses using foil swatches in attics.

- Begun construction of a RBS test facility to evaluate the long-term performance of different RBS installation and their effects on roofing materials.

- Provided the technical basis for including RBS in the Florida Model Energy Code for new building construction.

- Maintained a technical information program that responds to over 5 thousand public inquiries per year. This service distributes general RBS literature and provides answers to specific questions by direct oral and written communication.

- Actively participated in ASHRAE, ASTM, DOE, and EPRI activities that relate to attic RBS.

CHAPTER 2

INTRODUCTION

A radiant barrier system is a building construct that consists of a low emissivity surface (usually aluminum foil) bounded by an open air space. The word "open" is quite important. The airspace condition is the major distinction between radiant barrier systems and reflective insulation systems, which use enclosed airspaces.

The intent of the enclosed airspaces is to limit convective heat transfer. In reflective insulation systems it is quite common to have multiple airspaces so that convective heat transfer is as restricted as possible. In this regard, reflective insulation systems are intended as an alternative to fibrous and foam insulations.

Radiant barrier systems are intended to complement fibrous and foam insulations. Like reflective insulation systems, RBS block heat transfer by radiation. But unlike them, RBS attempt to enhance convective heat transfer. A brief explanation of RBS concepts follows.

The external skin of a building is normally at a temperature that is significantly different from the ambient air temperature. During the day the external skin is hotter than the air because it absorbs solar radiation. On hot summer days this excess skin temperature causes increased heat gains to the building. At night the skin is cooler than the air because it loses energy through infrared radiation to the cold night sky. On cold winter nights this skin temperature reduction causes increased heat losses from the building.

If the exterior of the insulation envelope can be brought to the ambient air temperature during these times, then the thermal performance of the building will improve. Radiant barrier systems do this by shading the insulation from the skin. Two things are needed for an effective RBS -- a vented airspace between the skin and the insulation envelope and a means of blocking infrared radiation.

Attics of buildings are especially amenable to RBS. They normally contain a fairly large, vented air cavity and once radiation transfer across the attic airspace is blocked, ceiling insulation top-surface temperatures are reduced to a level that is very near the ambient air temperature (generally within 3-5 F). In a typical attic, a single sheet of high purity aluminum foil will reduce the normal radiation transfer across the attic airspace by 90 to 95 percent. This results in significantly reduced ceiling insulation top-surface temperatures. The experimental results show that this temperature decrease is so significant that heat gains through the ceiling are reduced by up to 50 percent on sunny summer days.

One thing should be emphasized -- in essence, an attic RBS is simply an infrared shade for the attic insulation. The restriction of convective heat transfer in the attic is not the intent of an attic RBS. In fact, vented attic RBS perform better than unvented attic RBS. Unlike reflective insulation systems, RBS have no requirement to limit convective heat transfer and multiple airspaces are not necessary. A single low-emissivity surface will reduce the radiation transfer across an attic airspace by 90 to 95 percent. In vented attics, the addition of a second, low-emissivity surface can only affect the remaining 5 to 10 percent.

2.1 BACKGROUND

The objective of this research project is to assess the performance and reliablity of attic radiant barrier systems.

The performance of RBS can be characterized in a number of ways. One method is to define the effect of the RBS on the building cooling and heating energy consumption. Building cooling and heating energy use is determined by a large number of interrelated parameters that include climate, insulation level, building size and geometry, occupancy pattern, orientation and many other even more complex factors. Thus, building energy savings from attic RBS may vary widely from building to building and are not well characterized by the performance of a single house type.

A more explicit and determinant method of characterizing attic RBS performance is to define the parameters that affect the ceiling heat transfer into and out of the conditioned space. Once this is accomplished, heat transfer models can be developed and verified, then RBS energy savings can be determined through parametric computer modeling where a wide variety of building parameters can be studied quickly.

A major long-term performance concern is the reliability of the radiant barrier surface. If, for any reason, surface emittance increases over time, then performance will degrade. Questions regarding dust collection and material degredation are valid research issues. Also, since RBS alter the thermal regiems of the attic, there are research questions regarding other roof and attic materials, specifically asphalt roof shingles.

In order for attic RBS to be accepted in the marketplace other issues must also be addressed. These issues concern interrelated factors like consumer acceptance, codes and standards and cost.

Marketplace issues are often less straightforward than research issues. For example, consumers are acustumed to equating energy savings with R-value. Radiant barrier systems do not have defined R-values. To complicate the matter, the Federal Trade Commission (FTC) requires that insulating products be tested and marketed in accordance with specific standards that are generally promulgated by the American Society for Testing and Materials (ASTM). To date, ASTM has adopted no standards for RBS. The lack of RBS standards, codes and regulations is a major obsticle to market acceptance of RBS.

FSEC works closely with national organizations like ASTM and the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) to develop standards and performance measures for attic RBS. ASTM Committee 16.21 on Reflective Insulation Systems now supports a task group (TG 101) whose charge is the development of test methods and material and use specifications for RBS.

ASTM does not support research. ASHRAE, however, does support research and works closely with ASTM. ASHRAE Technical Committee 4.9 (Building Envelop Systems) is currently soliciting research using steady-state laboratory tests to determine attic RBS performance. Results of this research may be incorporated in the ASHRAE Handbook and in ASTM standards.

Cost is an obvious market issue. Radiant barriers fair well in this regard because the materials can be purchased for $.10 to $.20 per square foot. Reasonable installation costs are more difficult to obtain because RBS concepts are not well accepted by the construction trades.

Labor savings are a major consideration in the construction industry. It is much more time efficient to attach radiant barriers to the underside of roof decking than to the bottom side of roof rafters or truss chords. In new construction, radiant barriers may be simply stapled to the roof decking on the ground before the plywood is lifted to the roof and fastened to the roof structure. This can significantly reduce installation time as compared to current practice. Recent RBS performance findings show that this application offers the same performance benifits as other, less time-efficient applications. Additional inovative, labor-saving RBS application methods are needed, especially for retrofit construction.

Product confidence is critical in the construction marketplace. Long-term performance is required to fully develop this confidence. RBS technology has been impeded in the marketplace partly because of the familiarity of fibrous insulation products. In the highly competitive construction industry consistency is preferred. New products are often avoided unless cost and performance benifits are obvious.

2.2 OVERVIEW

Over the past few years, RBS research has been conducted by a number of U.S. research laboratories and universities. They include FSEC, Oak Ridge National Laboratory (ORNL), Tennessee Valley Authority (TVA), University of Pennsylvania, Texas A&M University, Oklahoma University, University of Arizona, University of Mississippi and others. Attic RBS have also been studied in South Africa, New Zealand, and Australia. Without exception, the experiments have shown that attic RBS are a very effective method of reducing summer heat gains through ceilings. Results consistantly show that attic RBS reduce the summer heat gains through ceilings by 30-50 percent.

Some researchers have reported measured or calculated building cooling energy reductions due to RBS. Because buildings vary so widely, these results are not as consistant as the reported ceiling heat gain reductions. Cooling energy savings from 7 to 21 percent are reported by the researchers.

The proponderance of the evidence clearly demonstrates that attic radiant barrier systems offer significant cooling energy benefits, especially for buildings in hot climates. There is also reason to believe that attic RBS provide winter benifits as well. However, winter RBS benefits are less well defined and additional research is needed before definitive recommendations can be made for northern climates.

The research also shows that most of the issues associated with attic RBS are resolvable. Some of these issues involve more research but that research is not necessary before RBS can be safely, effectively and confidently used in the attics of buildings.

Unless improperly installed, RBS performance should not change significantly over time. Existing data indicate that high-purity aluminum foil will not degrade except in rare cases. Horizontal attic RBS, however, will collect dust on their upper surface and their performance will degrade to the extent that the upper surface is the operative radiant barrier surface.

There are no national standards for attic RBS. No laboratory test standard exists that will define the thermal performance of an attic RBS. Nevertheless, sufficient testing has been accomplished to assure that attic RBS are a cost effective method of reducing unwanted heat gains through the ceilings of buildings.

There are also no installation, use or material standards for RBS. This may not be consistent with the health, safety, and consumer protection standards to which the nation is accustomed. Until such time as national standards are adopted, it is recommended that local jurisdictions adopt reasonable health, safety and use standards to protect against unscrupulous and unknowledgeable RBS practitioners, who unfortunately do exist.

CHAPTER 3

RESEARCH ISSUES

It is important to point out that results from recent tests have stimulated a national discussion on RBS. As a result, a number of important RBS research issues have been raised by the research community and in the marketplace. The state of RBS technology is not well understood without a discussion of these issues. The primary RBS research issues are:

- o Effect of ceiling insulation level,
- o Roof versus floor mounting,
- o Dust accumulation and surface degradation,
- o Effect of attic ventilation methods,
- o Effect on roof and shingle temperatures,
- o Moisture flows in attics and
- o Effect of climates.

FSEC maintains an active involvement in the national effort to resolve RBS research issues. The principal investigator for this research serves as chairman of ASTM's C-16.21 task group on RBS, as research chairman of ASHRAE TC 4.4 (Thermal

Insulation and Moisture Retarders), as a member of ASHRAE TC 4.9 (Building Envelope Systems) and as a member of DOE's RBS Technical Panel. Thus, FSEC is very well acquainted with existing and planned research on RBS and is familiar with RBS field application and use issues.

The remainder of this chapter is devoted to a point-by-point discussion of these issues. To the degree possible, the discussions are presented from a common sense perspective. Simple mathmatical equations are often used to illustrate principles and, where available, experimental data are presented to support assumptions and logical arguements.

3.1 Effect Of Ceiling Insulation Level

The effect of ceiling insulation level on the performance of attic RBS is a common marketplace concern. One would like to have a ceiling insulation level that optimizes the effectiveness of the RBS and vise versa.

One might expect that the presence of the RBS could alter the actual thermal performance of the ceiling insulation. If this is the case, then either higher or lower levels of ceiling insulation will produce more thermally efficient RBS. In order for this to occur, the ceiling insulation level must have a direct bearing on RBS efficiency.

It should be possible to discern the presence of any such effect through analysis of a simple attic problem. Referring to Figure 3.1-1, let us assume the following steady-state conditions:

160 F = Tsol-air > Ts >> Td >> Ti => Tamb => Tc > Tr = 78 F

Now ask the following question: "If all radiant heat transfer across the attic airspace is eliminated (a 'perfect' radiant barrier), then what is the minimum insulation surface temperature (Ti) we can attain if attic ventilation is optimized?"

Because the attic is well vented, the maximum effect that the "perfect" radiant barrier system may achieve is to lower the upper surface temperature of the insulation to the ambient air temperature (Tamb). Thus, the answer to our

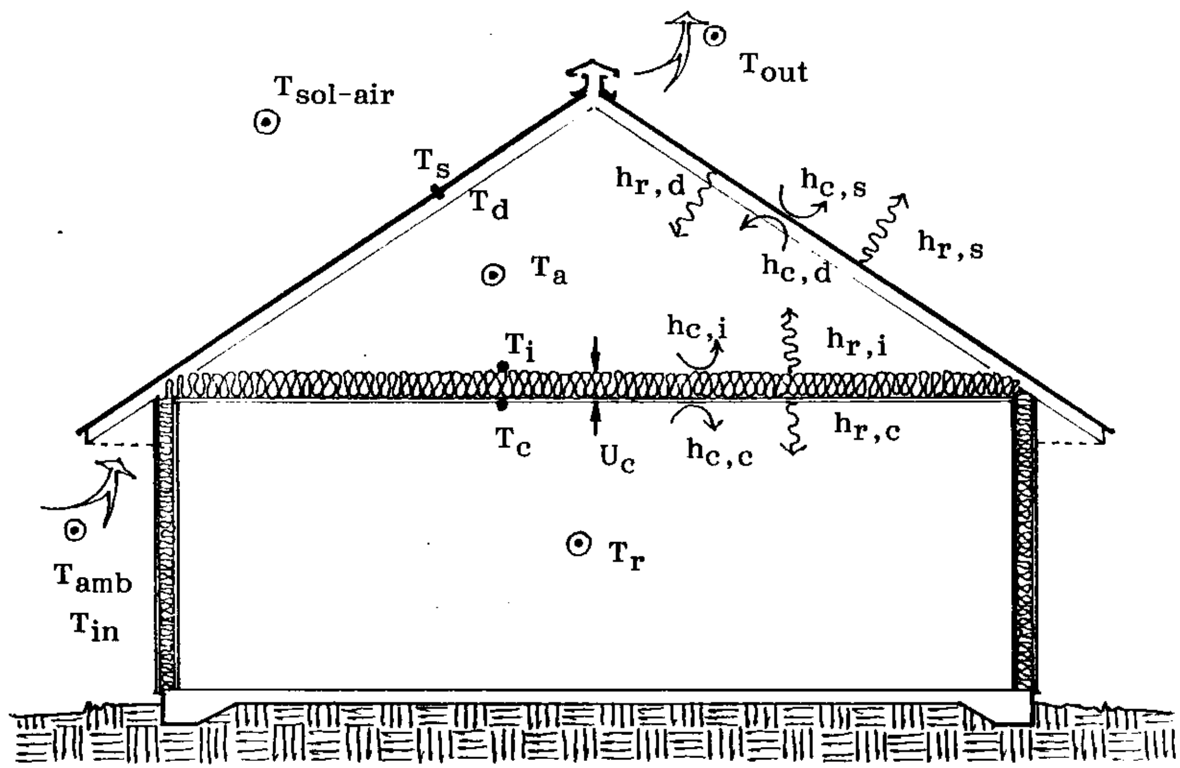

Figure 3.1-1 Schematic diagram of house showing temperatures and boundary conditions for simple attic RBS problem.

question is:

$$T_{i,rbs} = T_{amb}$$

Let us make two additional, substantiated assumptions. First, in a standard attic without a radiant barrier, the upper surface temperature of the ceiling insulation will be approximately 15 F higher than the ambient air temperature due to radiation from the hot roof decking (Td). Thus, without a radiant barrier

$$T_{i,std} = T_{amb} + 15 \text{ F}$$

Second, the temperature of the ceiling will be very close to the temperature of the room -- perhaps 2 F greater than the room temperature. Thus,

$$T_c = T_r + 2 \text{ F} = 80 \text{ F}$$

Because we have a steady-state problem, calculation of the ceiling heat flux per unit area is simply defined as

$$Q_c = U_c * (T_i - T_c) \quad (1)$$

Now let's compare the ceiling heat flux for cases with and without our "perfect" radiant barrier system by substituting our values for Ti and Tc into Equation 1.

$$Q_{c,rbs} = U_c * (T_{amb} - 80) \quad (2)$$

$$Q_{c,std} = U_c * ((T_{amb} + 15) - 80)$$
$$= U_c * (T_{amb} - 65) \quad (3)$$

We may also define the effectivness of the radiant barrier system as

$$\text{theta} = \frac{(Qc,std - Qc,rbs)}{Qc,std} \qquad (4)$$

and by substituting Equations 2 and 3 into Equation 4 we obtain

$$\text{theta} = \frac{Uc*(Tamb-65) - Uc*(Tamb-80)}{Uc*(Tamb-65)}$$

which reduces to

$$\text{theta} = \frac{15}{(Tamb-65)} \qquad (5)$$

Now we need only know the ambient temperature and we can determine the maximum possible effectiveness of a radiant barrier system under these conditions. For example, if the ambient temperature is 100 F, theta = 0.429, representing a 42.9% reduction in ceiling flux, and if ambient is 90 F, theta = 0.6, representing a 60% reduction. Obviously, if ambient is 80 F there will be no heat flow through the ceiling for our simplified example and the reduction in ceiling heat flux will be 100%.

At this point it is appropriate to point out that the ceiling conductance term, Uc, does not appear in the final form of Equation 5. This is because the surface temperature of the ceiling insulation will change by virtually the same amount irrespective of the ceiling insulation level. Therefore, for all practical purposes, the percentage reduction in ceiling heat transfer that is attributable to an attic radiant barrier system will not be a function of the ceiling insulation level.

One may argue that the example is too simplified to illustrate the point conclusivly. But Equation 5 can be recast in more general terms. Assume that the radiant barrier system causes a change in the ceiling temperatures (Tc) as well as the upper surface temperatures of the insulation (Ti). Further, assume that one has no knowledge of the upper surface temperatures of the insulation (Ti,std and Ti,rbs). Now on substituting the ceiling heat flux equations into Equation 4 one obtains

$$\text{theta} = \frac{Uc*(Ti,std-Tc,std) - Uc*(Ti,rbs-Tc,rbs)}{Uc*(Ti,std-Tc,std)}$$

which reduces to

$$\text{theta} = \frac{(Ti,std-Tc,std) - (Ti,rbs-Tc,rbs)}{(Ti,std-Tc,std)} \qquad (6)$$

Equation 6 is the general form of Equation 5. It clearly shows that the effectiveness of attic radiant barrier systems is not a first order function of the ceiling conductance (Uc). All other things being equal, the percentage reduction in ceiling heat transfer for attic radiant barrier systems as compared to standard attics should remain constant regardless of ceiling insulation level.

The reader is cautioned, however, not to equate a percentage reduction in ceiling heat transfer to a reduction in building cooling energy use. Simple logic will explain that as ceiling insulation levels are increased, the effect of the radiant barrier system on the building cooling energy use will be decreased. For example, a radiant barrier installed in an attic with no ceiling insulation will substantially reduce the cooling energy use but a radiant barrier installed in an attic with R-60 ceiling insulation may have no noticeable effect on cooling energy use -- 50% of a large number may be substantial but 50% of nothing is still nothing!

3.2 Roof Versus Floor Mounting

For all practical purposes, radiation transfer across a typical attic airspace is analogous to radaition transfer between two infinite parallel plates. Accepted radiation theory holds that the net radiation transfer (Qr,net) for infinite parallel plates is expressed by the following equation [Ozisik, 1985]:

$$Qr,net = \frac{s*(Th4-Tc4)}{\frac{1}{Eh} + \frac{1}{Ec} - 1} \qquad (1)$$

where:
- s = Stephan-Boltzmann constant
- Th = absolute temperature of hot surface
- Tc = absolute temperature of cold surface
- Eh = surface emittance of hot surface
- Ec = surface emittance of cold surface

The denominator of Equation 1 essentially defines the degree to which the radiation transfer will be inhibited by the surface properties (E) of the materials. It can be considered analogous to a heat transfer coeficient such that

$$Hr = \frac{1}{\frac{1}{Eh} + \frac{1}{Ec} - 1} \qquad (2)$$

and Equation 1 becomes

$$Qr,net = Hr*s*(Th4-Tc4) \qquad (3)$$

Equation 3 now looks similar to the equations for steady-state convective and conductive heat flux with the exception that the temperatures are raised to the 4th power.

The transfer coeficient, Hr, is our primary concern.

If both Eh and Ec are unity (perfect blackbodies), then Equation 2 evaluates to unity. If Ec and Eh are very small, say 0.05, then Equation 2 evaluates to 0.03 and the net radiant transfer between the two surfaces will be reduced by 97 percent. If the hot surface has a high surface emittance (Eh=0.9) and the cold surface has a low emittance (Ec=0.05) then Equation 2 evaluates to 0.05. If the emittances are switched, hot to cold and cold to hot, the answer is still 0.05.

If both surfaces have an emittance of 0.9, then Equation 2 evaluates to 0.81. And, all other things equal, if either surface in the system is changed to a low emittance (0.05), then the net radiation transfer will be reduced by about 94 percent. Thus, for all practical purposes, there should be no significant difference between the performance of an attic roof-mounted and an attic floor-mounted radiant barrier system.

One may observe that the temperatures of the surfaces (Th and Tc) will change if the emittance of one surface is substantially reduced. If the radiation transfer between the surfaces is essentially eliminated and the heat flux to the hot side of the system is held constant (as in attics), then the hot side temperature (Th) is increased and the cold side temperature (Tc) is reduced. How sensitive is the system to this probability with respect to radiation transfer?

By evaluating Equation 1 over a range of temperature differentials and emittances we should be able to answer this question. The results of such an evaluation are given in Figure 3.2-1. One realizes that if both surfaces have high emissivities, then the temperature differential between the surfaces and the mean temperature of the system can significantly alter the net radiation transfer. However, when just one surface emittance is reduced to 0.05 the system is quite insensitive to changes in either the mean temperature or the temperature differential.

This tells us that the temperature of the low emissivity surface has very little effect on the net radiation transfer in the system. Additionally, we are able to graphically understand the extraordinary influence of the denominator of Equation 1.

Translating this information to attic radiant barrier systems indicates that neither the temperature nor the placement (hot side or cold side of the airspace) of a radiant barrier in an attic will make any significant difference in the net radiation transfer across the attic airspace. Therefore, if all other heat transfer mechanisms of the attic are similar, then radiant barriers mounted at the roof and gable surfaces of the attic should perform almost identically to radiant barriers mounted at the floor of the attic on top of the ceiling insulation.

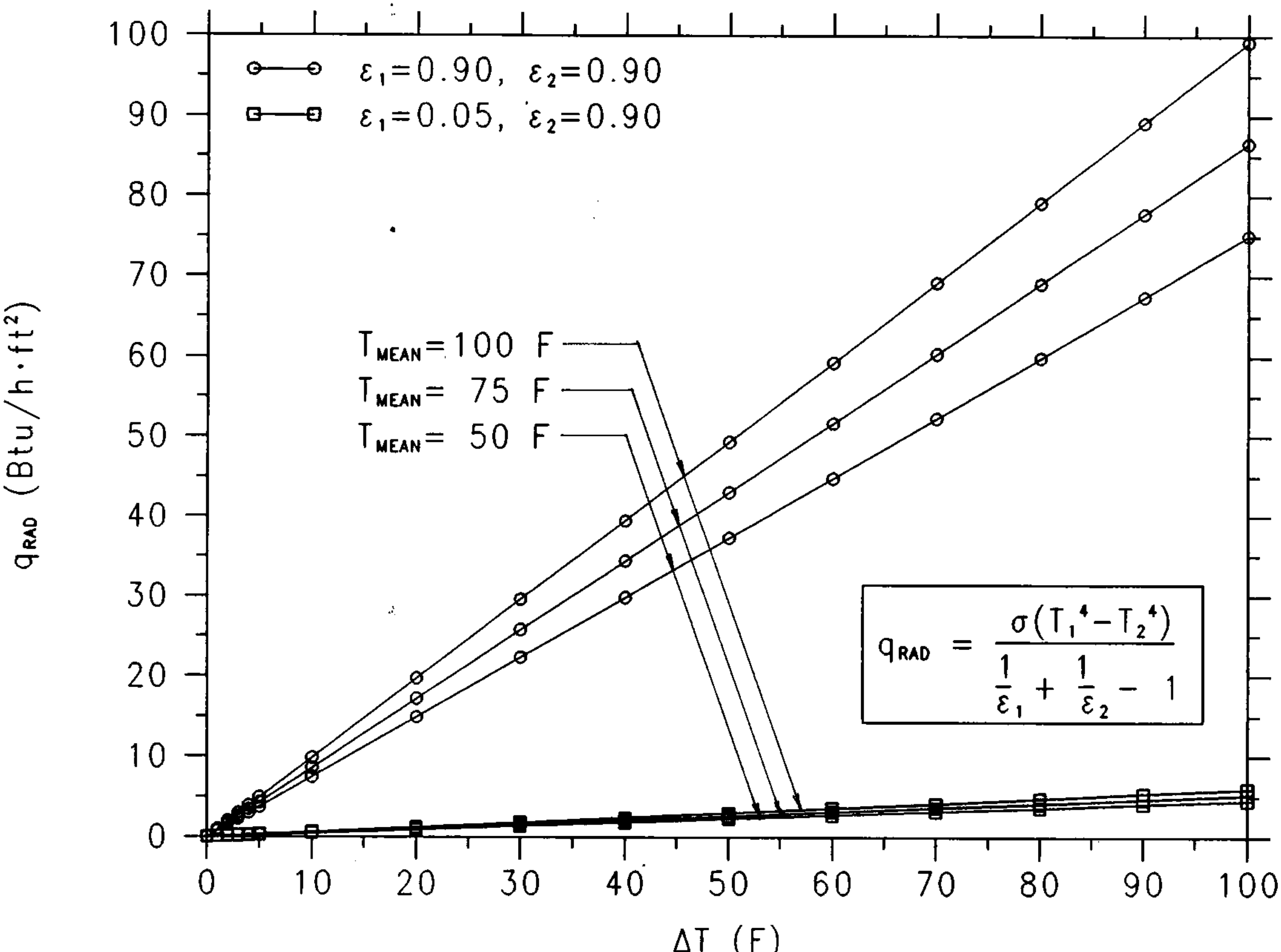

Figure 3.2-1 Effect of ΔT and mean temperature on net radiation transfer when one surface emittance is reduced from .90 to .05

Results from tests conducted at the FSEC Passive Cooling Laboratory support this hypothesis very well, showing no significant difference in ceiling heat flux regardless of the placement of the radiant barrier in the attic.

Figure 3.2-2 gives results from side-by-side tests of three identical attic spaces having three different mounting positions. In Cell 1 the radiant barrier is glued to the underside of the roof decking (RBS surface facing down); in Cell 2 it is mounted 3.5 inches below the roof decking (RBS surface facing down); and in Cell 3 it is mounted on top of the ceiling insulation at the attic floor (RBS surface facing up). All three attics were vented at a constant ventilation rate of approximately 2.5 air changes per hour during both sets of tests. There is no significant difference in the ceiling heat flux measurements.

It is important to point out that these tests were accomplished in a carefully constructed and controlled building and that ventilation airflows were parallel to the attic framing members. In field buildings RBS location may have an effect on the performance of the system. However, it is equally important to point out that these effects are rarely a result of infrared radiation phenomena. In gable roofs, however, radiation from unprotected gables can reduce the effectiveness of roof mounted systems slightly so gables should also have RBS.

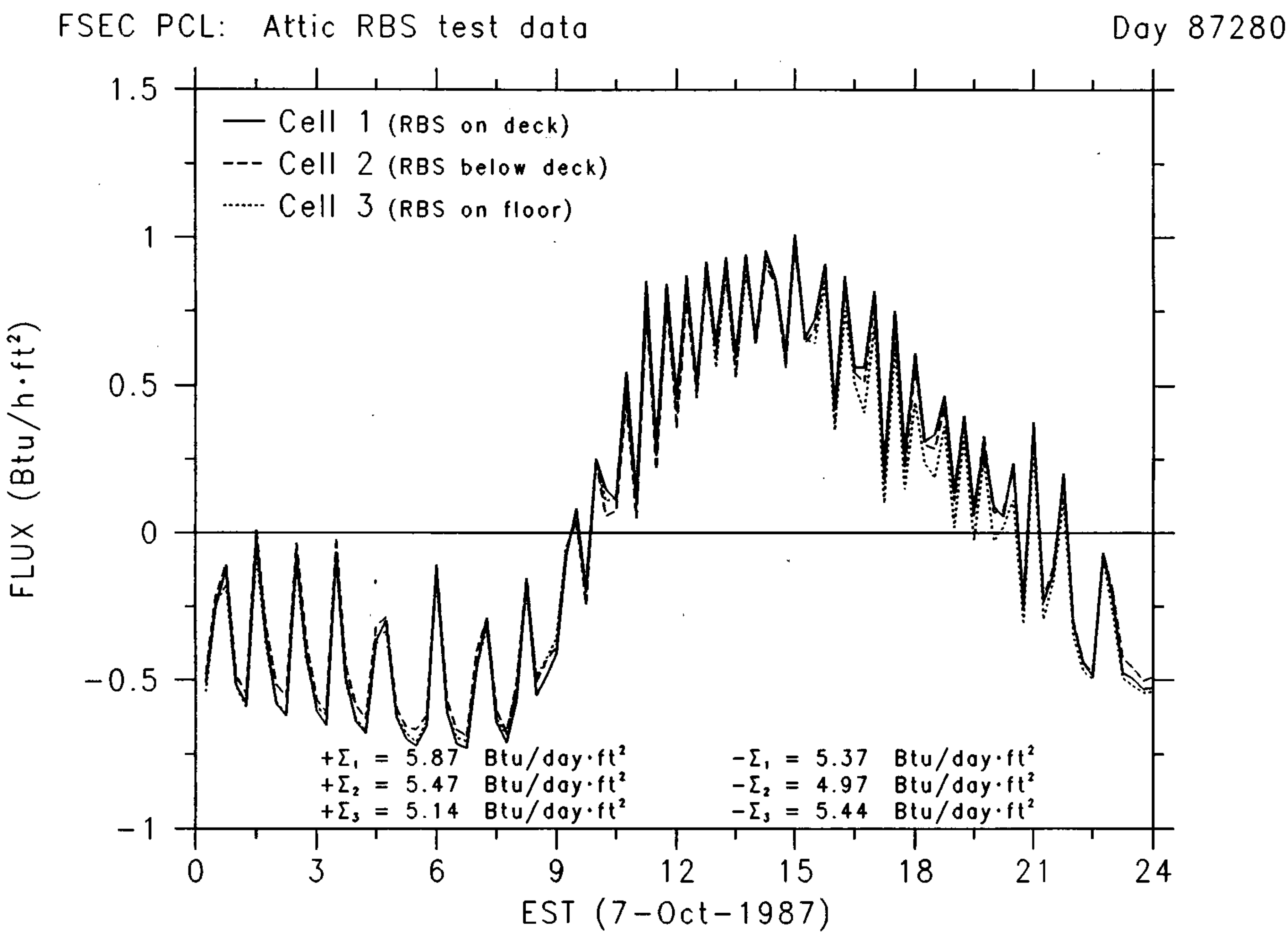

Figure 3.2-2 Comparison of normalized ceiling heat fluxes showing effects of RBS location in attics with R-19 ceilings.

If the location of the RBS significantly alters ventilation of the attic airspace, then location can affect performance. An example of this condition exists in most buildings with gable vents. If a RBS is attached to the bottom of the attic truss in a gable vented attic, then the vent outlet is located below the RBS surface. On the other hand, if the RBS is located on the attic floor the vent outlet will be above the RBS allowing bouancy to carry warm attic air toward the outlet.

Additionally, if the RBS installation is such that the main attic airspace is cut off from the ventilation appertures then performance will also be affected. An attic RBS located at the bottom of the trusses that is well sealed continuously from the soffit inlets to the roof peak is an example of such a system. In this case there would be no means for warm air within the main attic airspace to escape the attic and attic air temperatures would rise.

Another example of this condition can be found in attics that have outlet vent systems that are highly centralized like turbine vents, etc. With the RBS attached to the bottom of the trusses these vents are capable of venting only the space between one set of trusses and the main attic airspace is cut off from the outlet vent.

All three of these conditions are obviated if the RBS is attached directly to the roof decking.

Another apparent location effect of attic RBS can occur in attic floor mounted systems. This effect is also not attributable to radiation phenomena. In most houses the electrical wiring and plumbing stacks run through the top plate of the walls and into the attic.

Unless these penetrations are sealed, there is a high likelyhood that there will be a fair amount of air communication between the house and attic. This is especially true when air conditioning equipment is operating. The air handler unit for the air conditioner normally induces a low pressure at the return side of the system. Most residences now have central returns. This means that the space containing the air handler return (usually the largest space in the house) will be at a lower pressure than the attic space.

This pressure difference will induce an air flow from the attic to the house and can significantly increase air conditioning energy use. If an attic floor-mounted RBS is added to such a house, then it is likely that this air communication will be reduced. This obviously causes a reduction in building energy use that can be significant. This savings, however, can be accomplised by sealing the leakage areas between the attic and the house and is not the result of any attic radiation phenomenon. In new construction it is obviously preferable to thouroughly seal any penetrations between the house and the attic before interior finish materials are applied to the walls.

3.3 Dust Accumulation And Surface Degradation

Dust accumulation or any other radiant barrier surface emissivity increase wil have deleterious effects on the performance of an attic radiant barrier system. If the emittance of the radiant barrier surface increases for any reason, then its ability to block the transfer of radiation across its adjoining airspace will be significantly reduced.

The literature contains only a limited discussion of these effects. From the historical perspective, material surface degradation was investigated by Wilkes [1939] and dust accumulation was studied by Lotz [1964] and Van Stratten [1967] in South Africa. More recent investigations of the effects of dust accumulation have been performed by Yarbrough [1987] in the laboratory. Results of Yarbrough's tests are given in Figure 3.3-1. It is evident from the results that the effective surface emissivity of a radiant barrier material will be a strong function of the amount of dust on its surface. According to Yarbrough, a dust accumulation level of 1 mg/cm^2 constitutes a thin layer of visible dust as might be expected to elicit dusting if found on household furniture. Even at this level, the effective surface emittance of the material is raised from its original value of 0.02 to an emittance in excess of 0.4. There is no question that this increase will cause a decrease in the material's ability to block the transfer of radiation across an airspace. The data do not show any noticeable sensitivity to dust particle size.

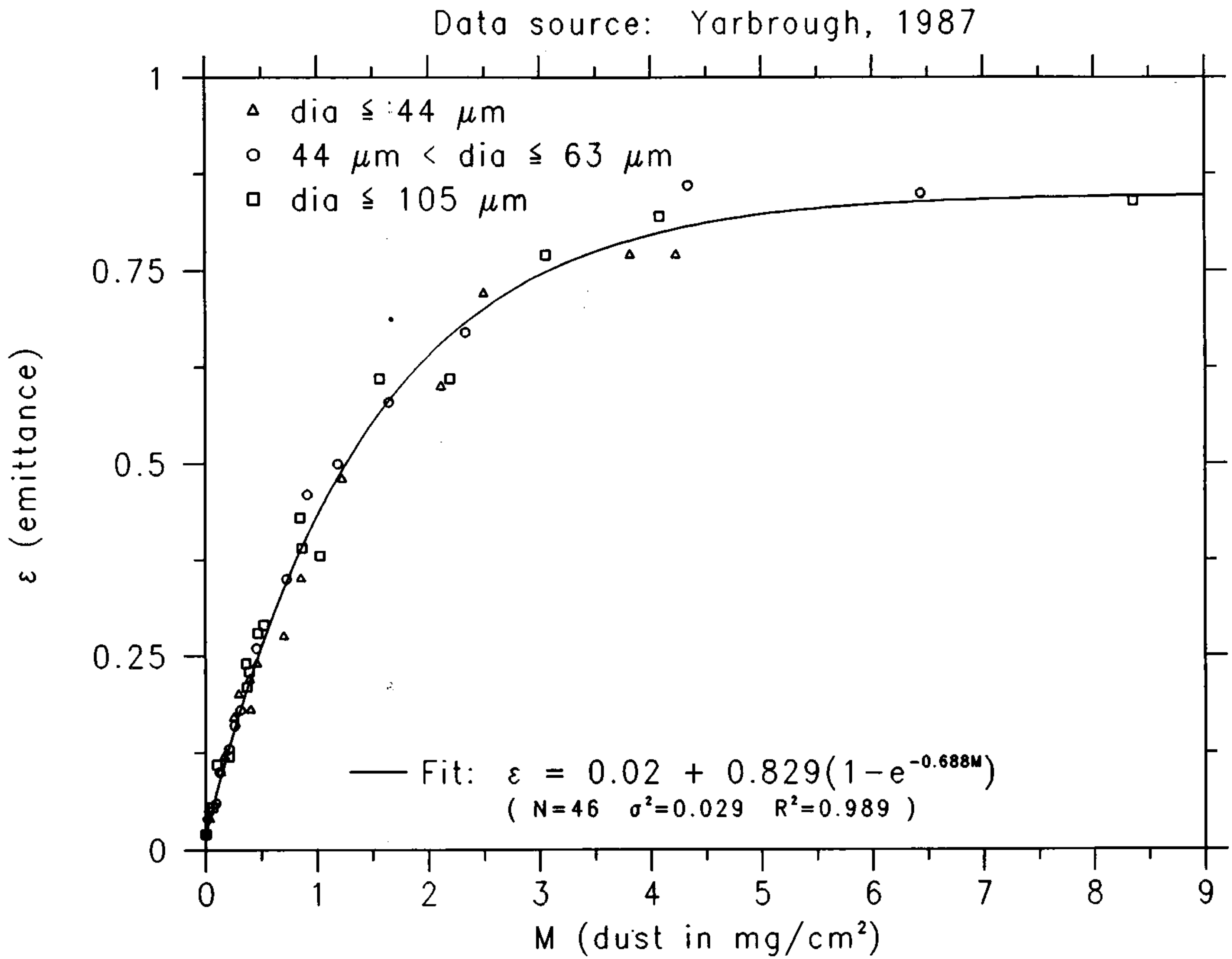

Figure 3.3-1 Relationship between dust accumulation and surface emittance for aluminum foil with an original surface emittance of 0.02

The work of Lotz [1964] and Van Stratten [1967] in South Africa was more extensive. Clear glass slides were placed in the attics of homes in suburbs near Pretoria and three samples slides were removed from each residence at monthly intervals. A dust particle count was taken from the slides using microscopy techniques. Their findings indicate an average dust collection rate of 28.6 percent area coverage per year (see Table 3.3-1) and an estimated full coverage in approximately 5 years.

Table 3.3-1
Rates of dust deposit per year in five houses

House No.	Age of house (years)	Weight of dust/yr ($lb/ft^2 \cdot yr$)	Corresponding area coverage (%)
1	2	3.5 e-4	7.2
2	1	11.5 e-4	23.2%
3	43	14.1 e-4	28.5%
4	38	16.6 e-4	33.5%
5	1	14.3 e-4	29.0%
Mean (2 to 5)		14.1 e-4	28.6%

Source: Lotz, 1964

One of the attics involved in their tests (house #1) was sealed to preclude the entry of outside air. Even for this attic the dust accumulation rate was 7 percent area coverage per year. Neither Lotz nor Van Stratten report any measured emissivities with accumulated dust. They do, however, report a measured performance degradation for attic radiant barriers versus area coverage by dust. Figure 3.3-2 presents a graphic analysis of their findings. Note that the shape of their performance curve is qualitatively

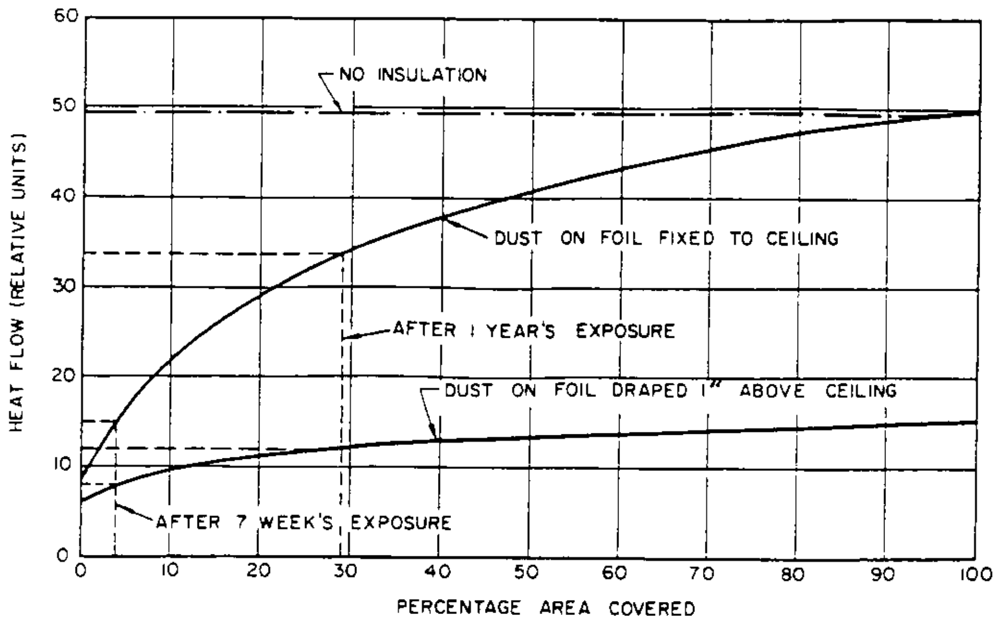

Figure 3.3-2. Increase in rate of heat flow through ceiling in relation to percentage area of reflective insulation covered with dust.

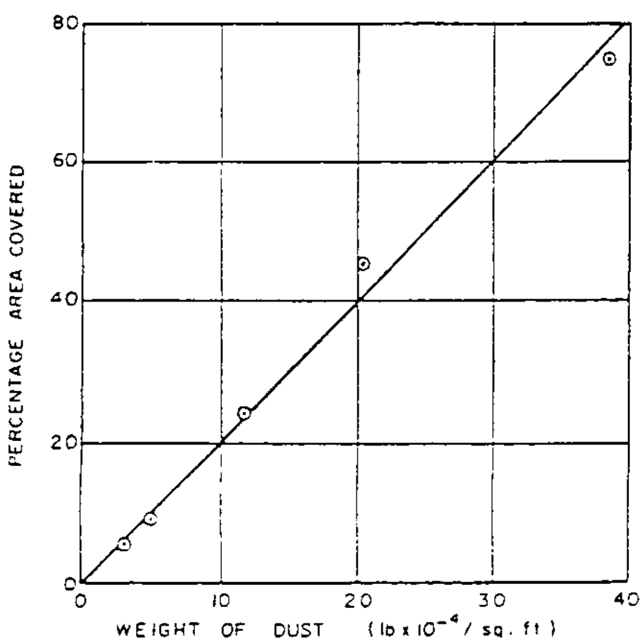

Figure 3.3-3. Relationship between weight of dust per unit area and percentage area covered.

analogous to Yarbrough's laboratory data.

Additionally, a relationship between percent area coverage and dust weight was developed by the South Africans (see Figure 3.3-3). This relationship would allow the South African dust accumulation data to be compared to Yarbrough's findings.

Surface degradation is a slightly different question than dust accumulation. Wilkes [1939] has reported his observations and the observations of others that he felt to be authentic dating to 1927. Many of the earlier observations were limited to visible inspection of the foil and reported in terms of the foil's "brightness" but some of the reported data included emissivity measurements. Wilkes reported no cases of significant degradation -- one personal observation Wilkes reports reads as follows:

> "Aluminum foil after two-year exposure to salt spray and moisture on underside of roof of log boat house in Newington, N.H. The foil was spotted with salt that had been left on the foil by evaporation of the salt spray. The emissivity was found to be 0.10."

3.4 Effect Of Attic Ventilation Methods

Attic ventilation phenomena are probably the least understood and most difficult to resolve of the radiant barrier system issues. It is widely acknowledged that surface convection phenomena are not amenable to simple analytical techniques. In most problems associated with convection, simplifying assumptions must be made before a solution is forthcoming. Most scientist and researchers agree that only the simplest of convection problems lead to direct, easily confirmed solutions. Convection in attic spaces exposed to natural environmental conditions definitely does not qualify as a simple problem. Nonetheless, a great deal of understanding of attic convection phenomena can be attained without exact, quantitative solutions.

The attic of a building is a container into and out of which a fluid flows. In this regard it is analogous to a solar hot water storage tank. There are a few basic principles of solar hot water storage tanks that are equally applicable to attics. First, if there is no flow through the tank the fluid will stratify with the hottest water at the top of the tank and the coolest at the bottom. Second, if there is flow to and from the tank there are proper and improper places for that flow to enter and leave the tank. For example, no reputable solar engineer would design a solar hot water storage tank with the cold water inlet at the top of the tank. Nor would the tank be designed with the hot water outlet at the bottom of the tank. This seems rather obvious but let us ask why this is so. One good reason that the cold water inlet should enter the bottom of the tank is because the natural stratification of the tank is more easily preserved when this is the case. Thus, the collector operates more efficiently, the water delivered to the load is hotter and more useful energy is stored by the system.

What does this have to do with an attic? Attics are also containers with an influx and outflux of fluid. If we wish to remove the greatest amount of energy from an attic, then we should follow the example of the solar hot water engineer and bring the cold fluid into the bottom of the attic and exhaust the hot fluid from the top. Furthermore, if our concern is to minimize heat flow downward through the ceiling of the building we wish to maintain the greatest possible degree of natural stratification in the attic airspace. Thus, the optimum solution would disperse the entering fluid across as wide an inlet area as possible. We do not want a jet of air entering at a very high velocity through a small inlet. Such an air jet would entrain large amounts of attic air, increasing air turbulence in the attic airspace and destroying the stratification we would like to preserve.

It is obvious that attics are far more complex than the example indicates. But the principles and ultimate objectives are valid -- we wish to exhaust the hottest air in the attic and keep the coolest air next to the attic floor (ceiling insulation surface). To accomplish this we wish to maintain the highest degree of thermal stratification possible. We already know from the preceeding example that high velocity inlet jets are less advantageous than dispersed inlet flows. Now let us examine some of the other parameters that might affect attic airflows and, as a result, the thermal stratification in attic airspaces.

Unlike hot water storage tanks, attics normally do not have smooth internal surfaces. Most conventional attics are of truss construction. This means that a significant number and variety of flow obstructions exist in attics. Therefore, the manner in which attics are vented may have a profound effect on the degree of air turbulence in the attic airspace. When ventilation air must travel perpendicular to the direction of the attic trusses the attic air is likely to be much more "well mixed" than otherwise. As a result it is likely that the attic air will "destratify" somewhat, bringing the hot air near the roof decking down toward the attic floor. This may result in a higher insulation surface temperature and greater downward heat flow through the ceiling insulation.

Conversely, if attic ventilation airflow runs parallel to the direction of the attic trusses and the inlet and outlet flow aperatures are dispersed, and if inlets are located low in the attics and outlets are at the attic peaks we would expect that thermal stratification would be optimized. This type of ventilation would likely result in laminar airflows that act in concert with natural thermal buoyancy forces in the attic. Ventilation now removes hotter air from the attic and, thereby, more energy per unit of airflow than would be removed by perpendicular airflows. Ceiling insulation surface temperatures remain closer to inlet vent air temperatures and downward heat flow through the ceiling is reduced.

Even though the arguments presented so far appear logical, the scientific literature does not contain much information on the effect of attic ventilation on radiant barrier systems. One directly applicable experimental steady-state study of radiant barrier systems under the influence of ventilation has been reported by Joy [1958]. His work supports the preceding logical arguments.

Joy constructed a steady-state attic test facility in which the roof surface temperature and the room air temperature could be carefully controlled. Two test sections were evaluated -- one flat roof attic with airflow parallel to the attic structure and one pitched roof attic with airflow perpendicular to the attic structure. Result from the tests showed that attic radiant barrier systems appear significantly more effective when airflow is parallel to the structure. Figure 3.4-1 compares Joy's reported results for the two test sections. It is quite clear from the figure that the radiant barrier system is significantly more effective when ventilation airflow is parallel to the attic

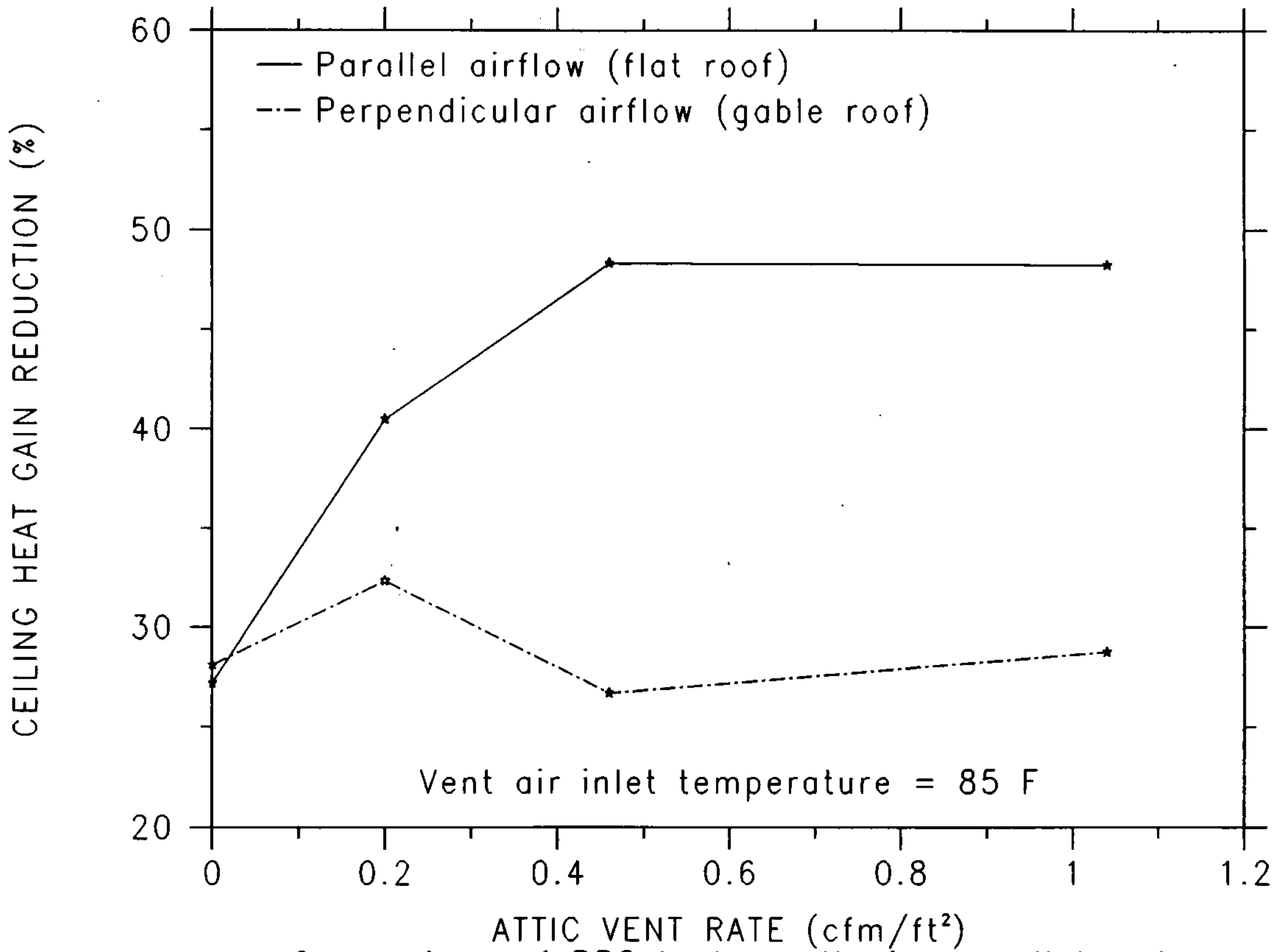

Figure 3.4-1 Comparison of RBS test results for parallel and perpendicular ventilation airflows as reported by Joy

structure.

Joy explains the source of the differences as follows:

> "With the flat roof the effective resistance of the attic rises sharply with 85 F ventilation, especially when the breather is aluminum foil. This appears to be due to laminar flow of the ventilating air with a high degree of stratification in the attic space....I believe that nearly as good results could be obtained under a gable roof if it is feasible to provide a similar air path." [Joy, 1958]

The provision of parallel airflow in pitched roofs is not only feasible but is quite common in conventional construction. Continuous sofit and ridge venting will provide the proper airflow direction, will provide for disperse airflow inlets and outlets and will bring cool air in at the base of the attic and exhaust hot air at the peak. Thus, we should be able to meet all our previous criteria for maintaining good thermal stratification within the attic.

Again, no specific data on thermal stratification in vented attics is available in the literature. Measurements of attic air temperature distributions in the FSEC passive cooling laboratory do confirm the validity of these hypotheses for parallel airflows. To our knowledge, however, there is no corresponding data for attics with perpendicular ventilation airflows.

Figures 3.4-2 and 3.4-3 from tests conducted during the summer of 1987 clearly indicate the existence of thermal stratification in the test attic. It is very clear that when a radiant barrier system is added to the attic the stratification increases. Of particular interest is the fact that this degree of stratification exists in the standard attic in spite of the fact that the insulation surface temperature is hotter than all the air in the attic, even the air directly adjacent to the roof. This is indicative of the fact that thermal buoyancy forces are quite strong in attics, especially when radiation is blocked.

Let us try to examine the relationship between thermally driven and wind driven ventilation using available analytical calculations with the intent of finding the correspondance between the magnitudes of the two forces in common attics. Referring to Figure 3.4-4 we start with some simple assumptions about the attic. First, we have ventilation apertures at both eaves and at the peak of the roof ridge. This situation is quite common. Assume also that we are concerned about peak conditions when the stack effects are most significant. We now need a few equations that define the various ventilation pressure gradients across the attic space.

Pressure gradient across the attic due to bouyancy:

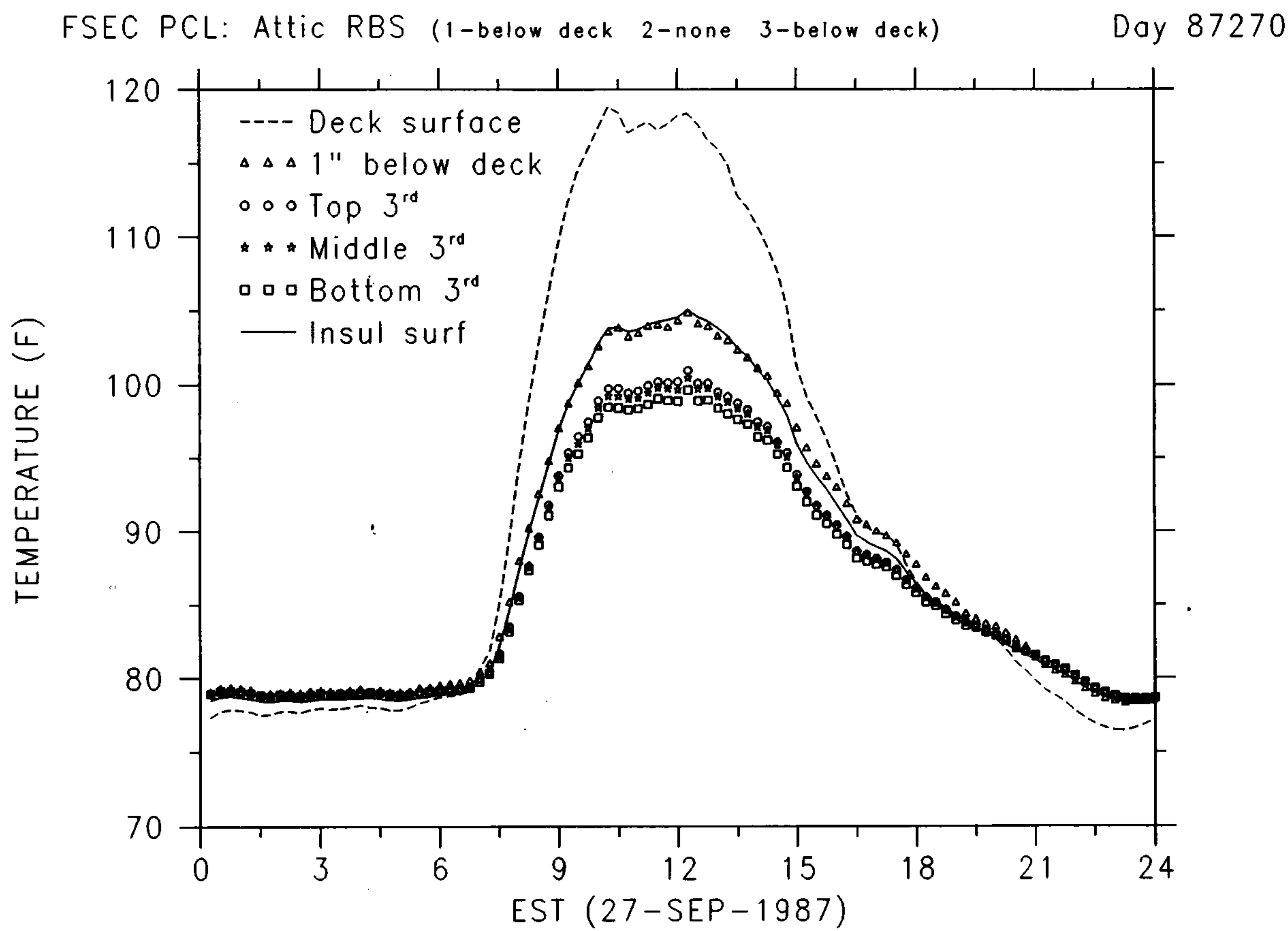

Figure 3.4-2 Cell 2 air temperature stratification at attic middle.

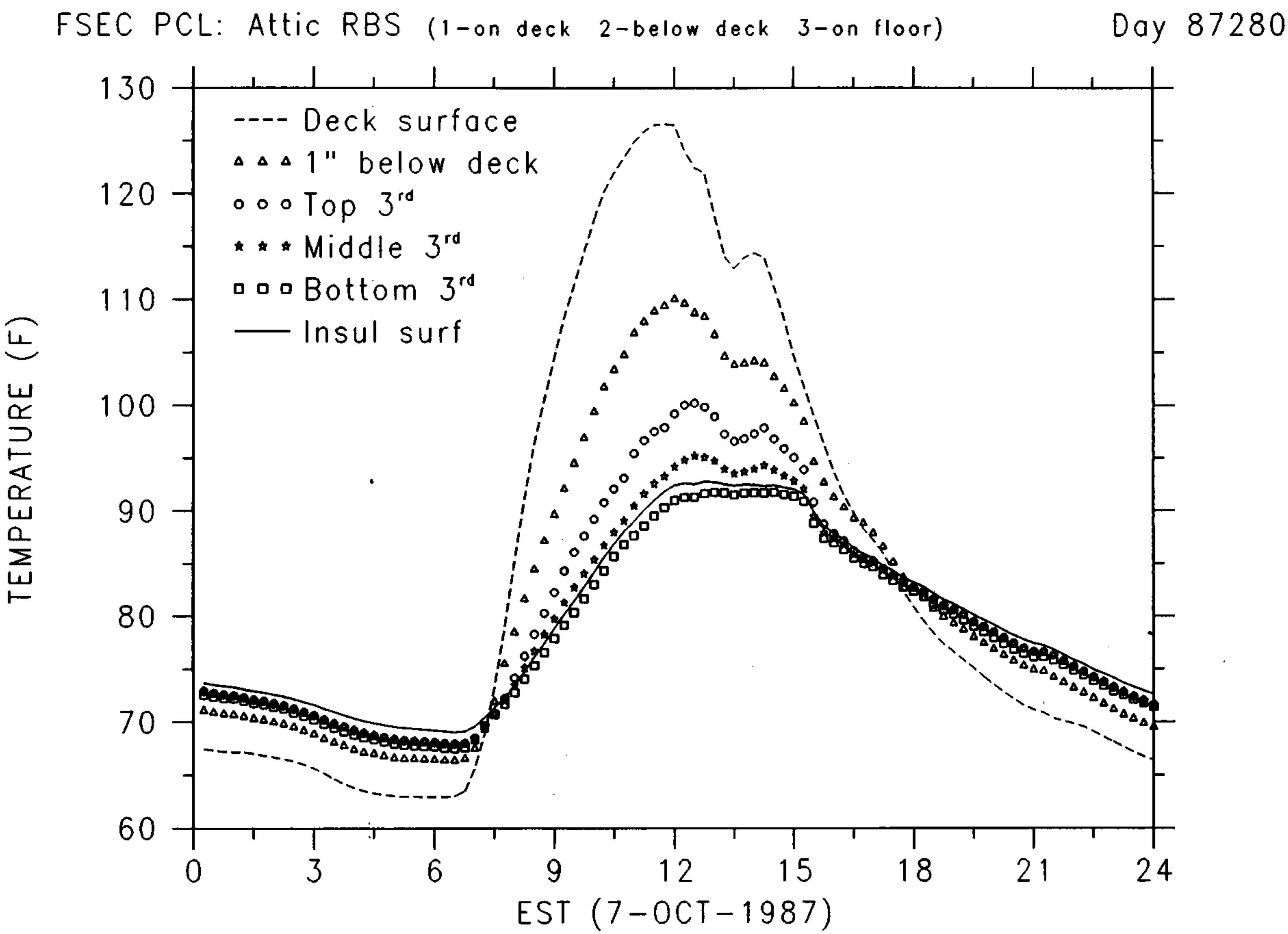

Figure 3.4-3 Cell 2 air temperature stratification at attic middle.

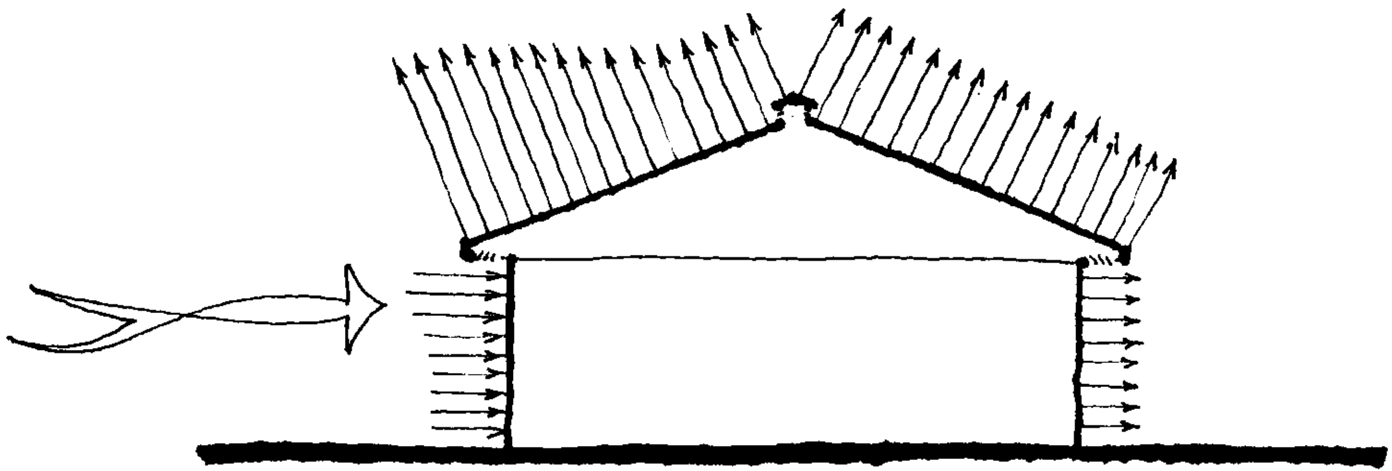

Figure 3.4-4   Typical pressure distribution for residence in the natural wind.

$$\Delta Pt = \frac{(po-pi)\cdot g\cdot h}{gc} \quad (4\text{-}1)$$

where

ΔPt = thermally driven pressure gradient
po = density of outside air
pi = density of attic air
g = acceleration due to gravity
h = height of attic
gc = universal gravitational constant

Pressure gradient across the attic due to wind:

$$\Delta Pw = (Cpi-Cpo)\cdot \frac{\frac{1}{2}\cdot p\cdot Vref^2}{gc} \quad (4\text{-}2)$$

where

ΔPw = wind driven pressure gradient
Cpi = relative pressure coefficient at inlet
Cpo = relative pressure coefficient at outlet
p = density of the air
Vref = reference wind velocity
gc = universal gravitational constant

But we have three apertures and we need some method of determining which are inlets and which are outlets. In order to do this we need an overall or effective pressure coefficient for the inside of the attic. Fortunately an expression for multiple inlet airflows is available (Vickery, 1983).

$$Qi = Cdi\cdot Ai\cdot Vref\cdot \frac{(Cpi-CpI)}{|Cpi-CpI|^{\wedge}(\frac{1}{2})} \quad (4\text{-}3)$$

where

Qi = flow through the ith aperture (ft^3/s)

Cdi = discharge coefficient for ith aperture
Ai = area of ith aperture (ft^2)
Vref = reference velocity (ft/s)
Cpi = pressure coefficient for ith aperture
CpI = internal pressure coefficient (unknown)

Note: the solution is iterative (see Swami and Chandra, 1988)

Using Equation 4-3 and typical pressure coefficients at building surfaces it is possible to determine a pressure coefficient for the attic interior. Assume that the wind is normal to one of the eave sides of the building (see Figure 3.4-4). The windward eave vent is subjected to a positive pressure coefficient of about +0.5 and the leeward eave vent is subjected to a negative pressure coeficient of about -0.3. The ridge of the roof is under a suction pressure and will be subject to a pressure coeficient of about -0.6 (see Dick, 1950). On solving Equation, 4-3 a value for CpI of -0.322 is obtained for the effective pressure coefficient of the internal attic space.

We can now examine the correspondance between thermally induced stack ventilation and wind driven ventilation in the attic by setting the right hand sides of Equations 4-1 and 4-2 equal to each other (i.e., $\Delta Pw = \Delta Pt$) and solving for the wind velocity that is required to match a given set of thermal stack conditions.

$$(Cpi-Cpo) \cdot \frac{\frac{1}{2} \cdot p \cdot Vref^2}{gc} = \frac{(po-pi) \cdot g \cdot h}{gc}$$

and rearrangement yields

$$Vref = \sqrt{\frac{2 \cdot g \cdot h \cdot (po-pi)}{p \cdot (Cpi-Cpo)}} \qquad (4-4)$$

Assuming a stack height and attic and outside temperatures allows us to calculate the reference wind velocity that would yield an equivalant ventilation potential to the thermal stack effect under those conditions. Let us assume an attic height of 6 feet and temperatures of 80 F and 120 F for the ambient and attic air, respectively. On calculating the respective air densities (0.0734231 lb/ft^3 and 0.0683595 lb/ft^3) and solving Equation 4-4 we find that a reference wind velocity of 9.79 ft/sec or 6.67 mph exerts an equal pressure on the attic system as the assumed thermal stack conditions.

The example, although highly simplified, illustrates the point that thermal stack forces can be significant in attics and on calm days may provide for the majority of the attic ventilation. It is also fair to say that for the given example the wind driven and thermally driven attic ventilation forces compliment each other, both driving the vent flow from the eaves to the ridge of the attic. If the example were constructed using gable vents rather than a ridge vent then the stack forces would drive the warm air to the top of the attic and the wind forces would drive the air from one end of the attic to the other. This flow would be perpendicular to the attic structure causing increased turbulance in the airflow stream. The likely result of this is that the bulk attic air would be less thermally stratified causing warmer air temperatures near the ceiling insulation (see Joy, 1958).

Additionally, the wind direction will play a much more critical role when gable vents are present. Since gable vents are on the face of the building rather than the roof ridge their pressure coefficients are much more dependent on wind direction fluxuations than the ridge vent. It is entirely possible to have rapid ocillations in the wind direction that cause the gable to rapidly switch back and forth from an inlet to an outlet. This situation can result in a "slug" of air that is virtually pushed one way and then the other in the center of the attic space. This also should cause greater air turbulence and work to destratify the attic air.

3.5 Effect On Roof Temperatures

The application of attic radiant barrier systems has led to pertinent questions regarding the resultant temperatures of roof materials. Specifically, there is a concern on the part of asphalt-based shingle manufacturers that temperatures may rise to levels at which their products may degrade more rapidly. Roof surface temperature increases due to attic radiant barrier systems that are reported in the literature range from highs of 10 F [Levins and Karnitz, 1986] and 8 F [Hall, 1986] to lows of 2 F [Fairey, 1982]. These data, however, have been reported without benefit of control test normalization. In other words, we do not know whether the reported differences are caused by the attic radiant barrier system or whether they are differences in weather [Hall, 1986] or actual differences in the test structures [Levins and Karnitz, 1986 (and) Fairey, 1982].

For the most part, tests conducted at the FSEC Passive Cooling Laboratory indicate the lesser temperature increases. Tests conducted in the summer 1985 [Fairey, 1985] using medium brown shingles show an increase in the shingle top surface temperature of only 1.1 F at peak. Figure 3.5-1 gives the coincident shingle surface temperature differences between the two attics used for the analysis. The abscissa of the graph is the shingle surface temperature of the control test cell (i.e., the test cell which remained the same during both tests). The ordinate of the graph gives the temperature difference between the

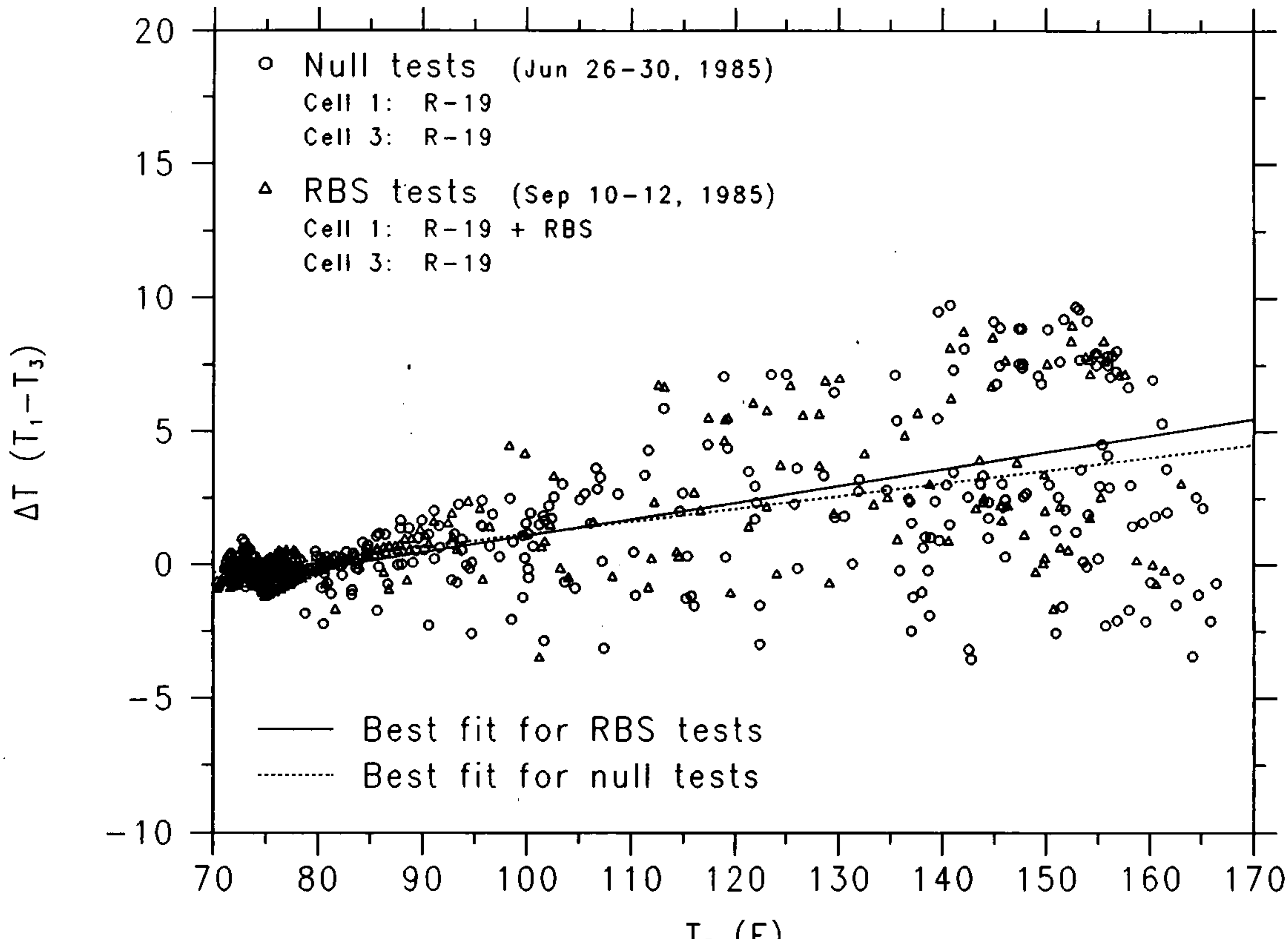

Figure 3.5-1 Coincident shingle surface temperature differences between cell 1 and cell 3 during null test and RBS test

shingles of the alternate test cell (cell 1) and the control test cell (Cell 3).

Two points are clear from the data. First, there is a real difference between the two test cells when they are configured alike (null test data), and second the data scatter is significantly greater than any statistical temperature difference between the two alternatives (radiant barrier vs. no radiant barrier). Differences between temperatures during null tests are probably due to slight differences in shingle color. As with most shingles, there are differences in the shade of the shingles so as to give an aesthetic mottled appearance to the roof. The scatter in the data is due to slight differences in the environmental influences on the roofs. Even though the two measurements are within 10 feet of one another, passing clouds, changing wind patterns and other ambient influences can cause rapid and significant changes in surface temperatures. During the daytime it is possible for the surface temperature to change as much as 10-15 F within a few seconds due to a passing cloud.

Figure 3.5-2 shows the same analysis using the top surface temperature of the plywood roof decking. These data can also be taken to represent the bottom-side shingle temperature. One notes that the temperature difference between the null test and radiant barrier system test conditions has increased from 1.1 F at peak to about 5.1 F at peak. The peak temperature, however, has dropped from

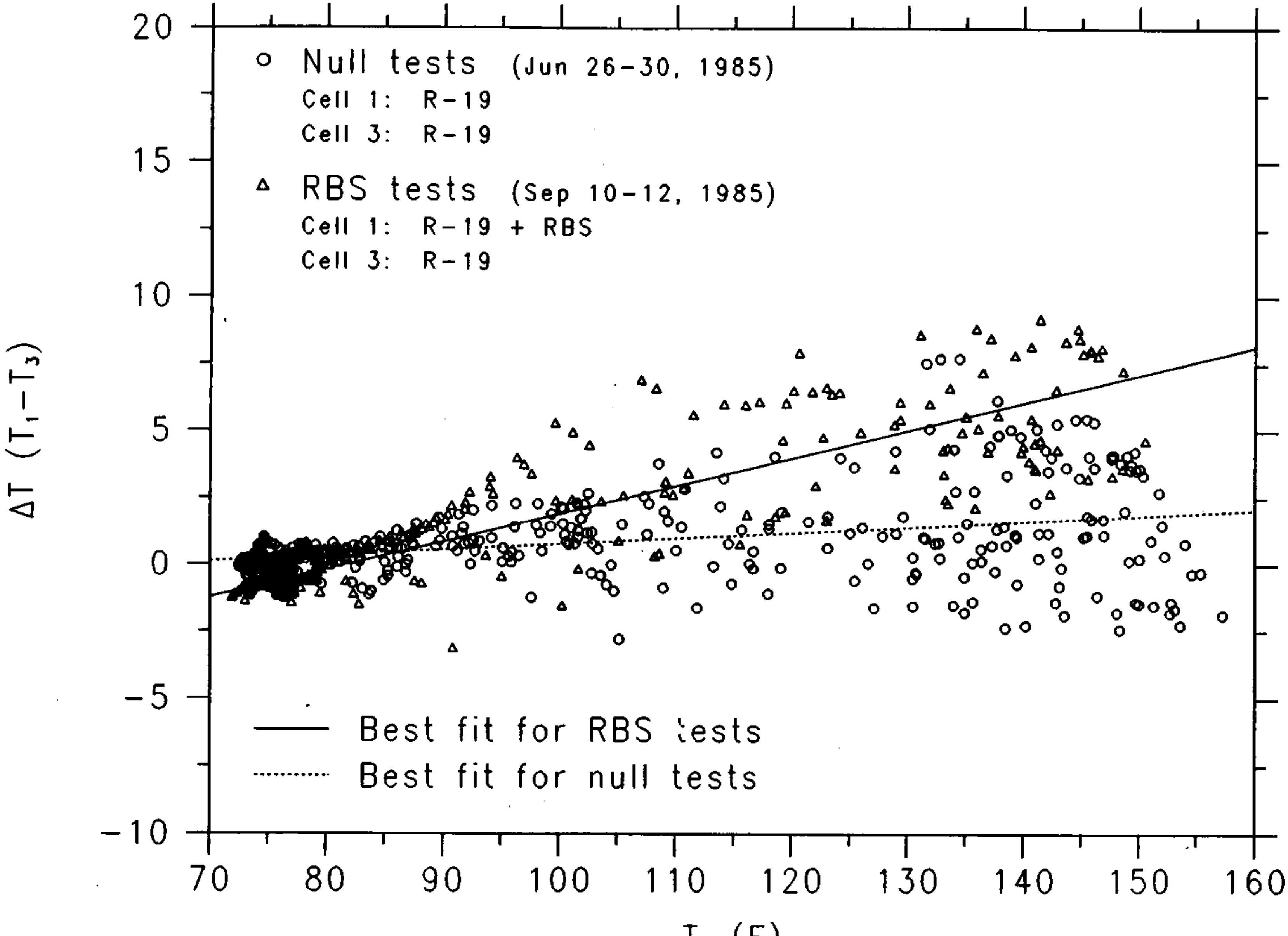

Figure 3.5-2 Coincident outside decking surface temperature differences between cell 1 and cell 3 during null test and RBS test

about 168 F to about 158 F, so these temperatures should have less effect on shingle durability than the upper surface temperature.

Carrying the analysis one step further and looking at the bottom-surface temperature of the roof plywood, one sees that the difference between null test and RBS test has increased to about 12 F (see Figure 3.5-3).

Finally, Figure 3.5-4 repeats the analysis for the ceiling insulation top-surface temperatures. Here the differences between null test and radiant barrier system tests are in the opposite direction. This figure vividly illustrates the great benefit to be derived from radiant barrier systems during summer when cooling is required. Even though the peak temperatures are only 118 F, the radiant barrier system is able to reduce insulation surface temperatures by over 20 F.

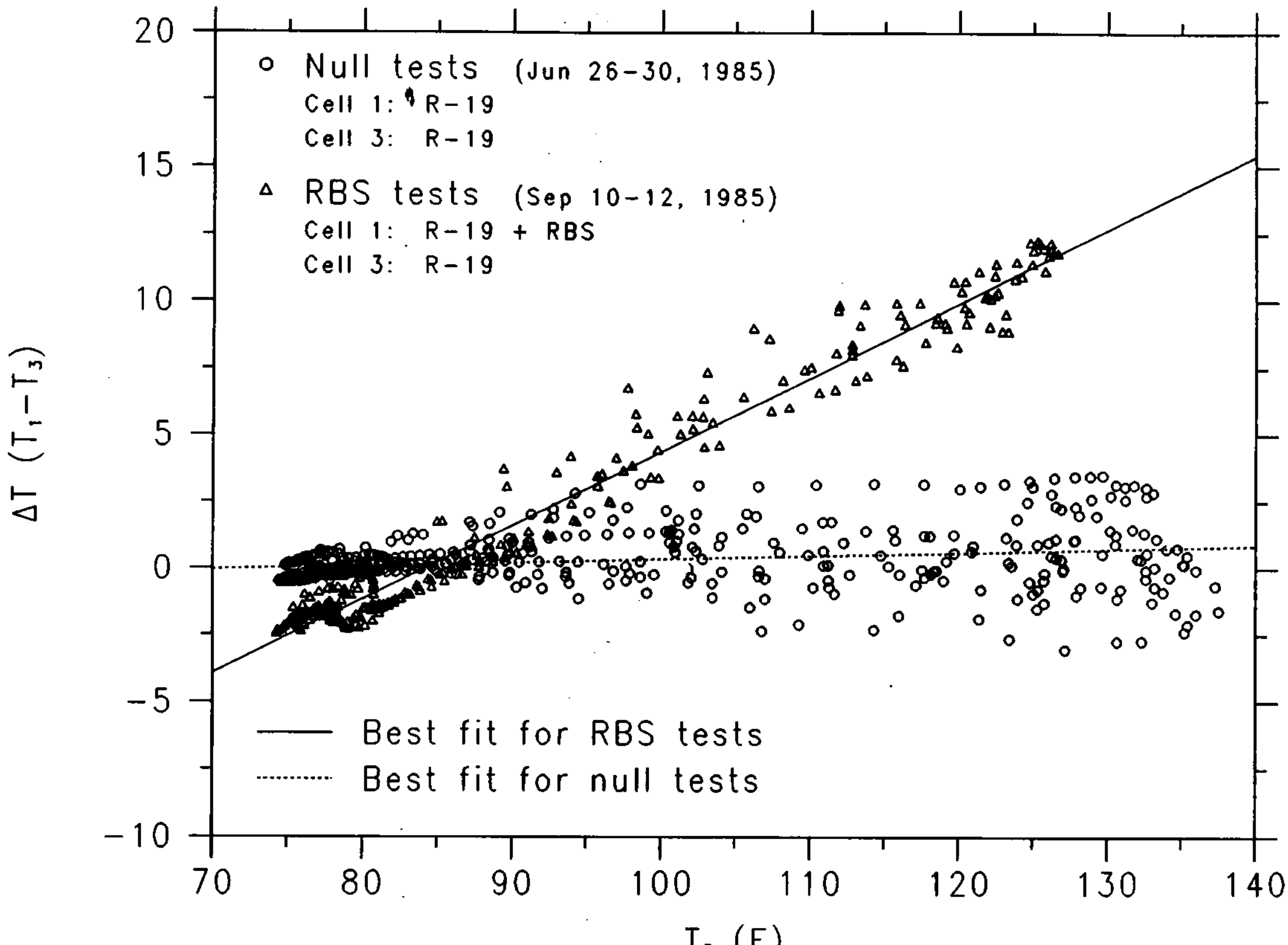

Figure 3.5-3 Coincident inside decking surface temperature differences between cell 1 and cell 3 during null test and RBS test

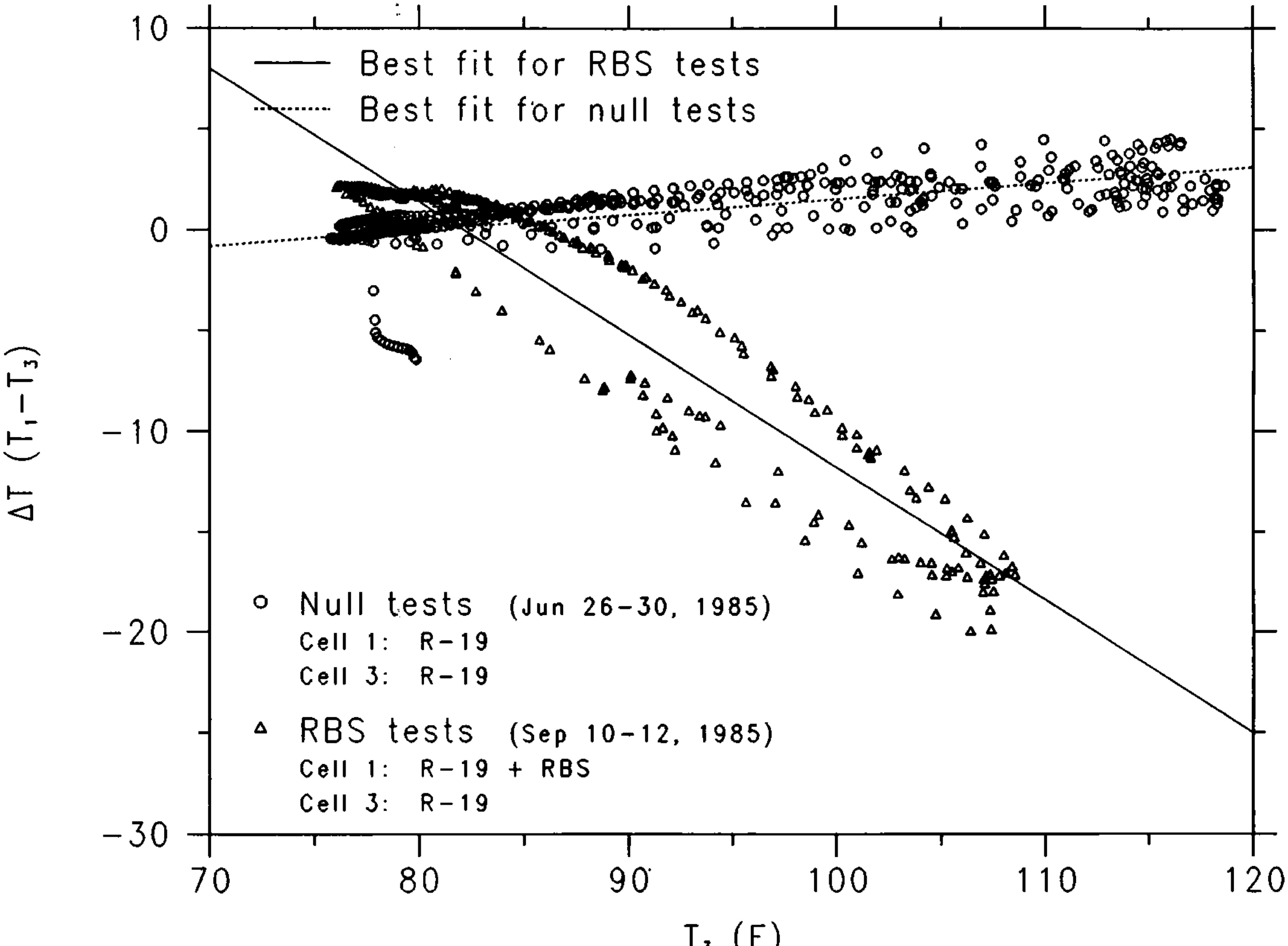

Figure 3.5-4 Coincident ceiling insulation top surface temperature differences between cell 1 and cell 3 during null test and RBS test

3.6 Moisture Flows In Attics

The attics of buildings are subject to substantial moisture transport. The predominant attic material is wood and wood is capable of holding surprising amounts of moisture. During the day when the roof absorbs large amounts of solar radiation the consequential heat transfer through the roof decking moves moisture out of the decking and into the attic air. At night, when the roof is radiating energy to the night sky, the roof is cool and adsorbs moisture from the attic air. This results in a rather substantial cyclic transfer of moisture into and out of the attic materials.

Figure 3.6-1 illustrates this phenomena. The inlet and outlet dewpoint temperatures for the three PCL attic test cells show a substantial change in the attic air moisture content over the course of the day. This moisture either went into or came out of the attic materials. The daily cycle is apparent in the figure.

A few points are worth noting. The inside surface of the roof plywood in Cell 1 is covered with an impermeable radiant barrier glued to the plywood. This causes the outlet dewpoint in Cell 1 to be closer to the inlet dewpoint during most of the day. Only the plywood is covered so the remaining attic materials condinue to adsorb and desorb moisture. There is a distinct cycle in the process. The outlet dewpoint is lower than the inlet dewpoint until the sun rises. However, while the roof is being heated by solar

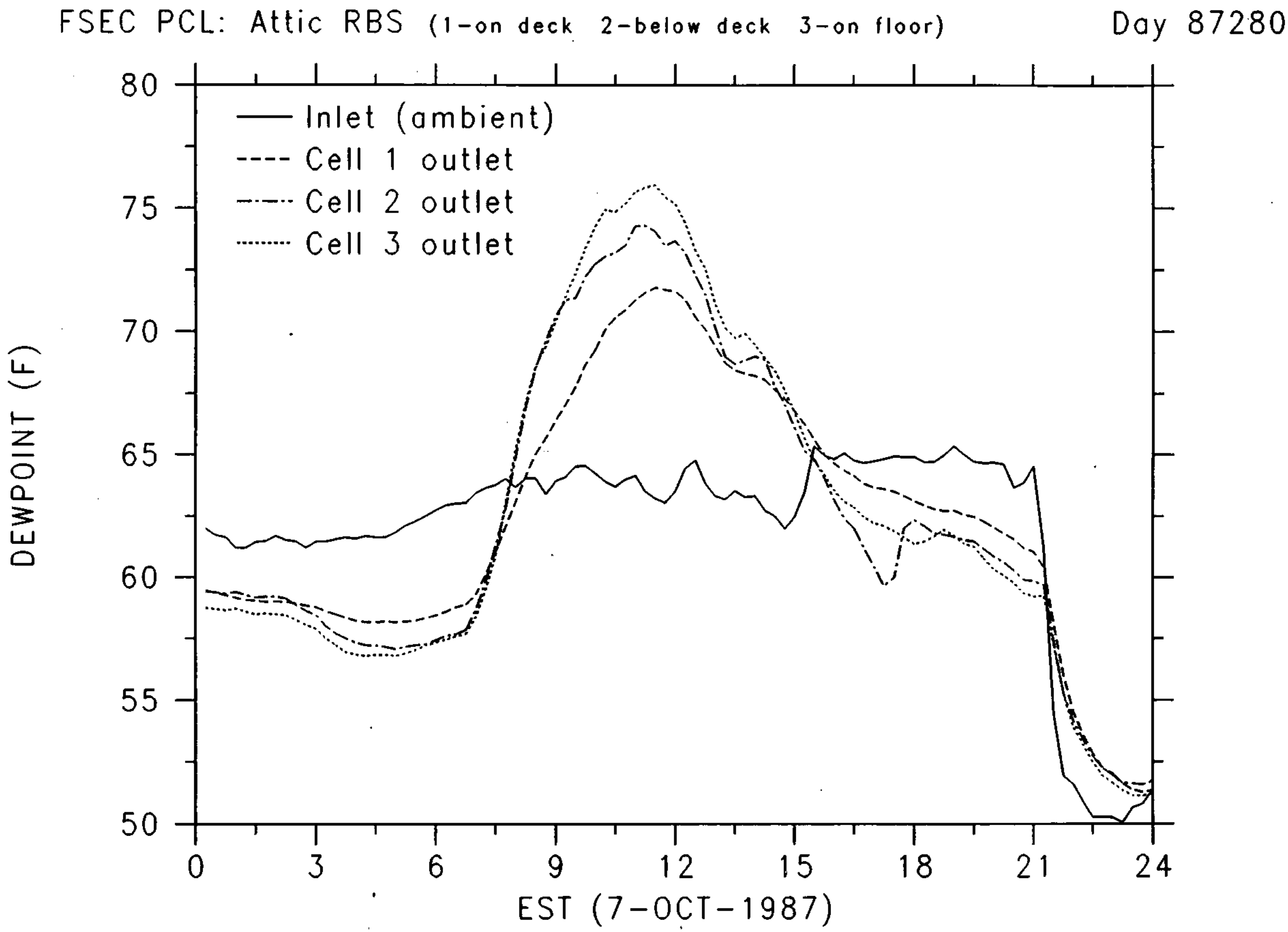

Figure 3.6-1 Inlet and outlet dewpoint temperatures for attic test cells.

radiation, moisture is being driven from the attic materials into the ventilation airstream and the outlet dewpoint is significantly higher than the inlet dewpoint, carrying moisture out of the attic.

There is also a rapid 15 F drop in the inlet air dewpoint at about 9:00 pm EST. This results in a shift in the respective dewpoint temperatures. After begining to adsorb moisture at around 3:30 pm, the attics begin to desorb moisture as a result of the 9:00 pm dewpoint drop.

The effect of this reversal is illustrated by figure 3.6-2. This figure plots the energy removed from attic Cell 2 by the vent airstream. Note that the thermal energy removal from the attic is always positive while the moisture removal rate is negative until the sun rises and is positive until it sets. The change in ambient air conditions at 9:00 pm. is vivid, causing a reversal in the moisture energy flow as well as the total energy removed by the attic vent airstream. It is also important to note that the moisture energy flow (mass flux times the heat of vaporization for water) into and out of the attic materials is almost equal to the thermal energy transfer during peak conditions.

Other researchers have observed identical phenomena in attics [Cleary, 1985]. These measurements point to the possibility that most of the moisture in attic materials probably comes from the vent airstream as a result of the daily thermal cycles of the attic and is probably not the

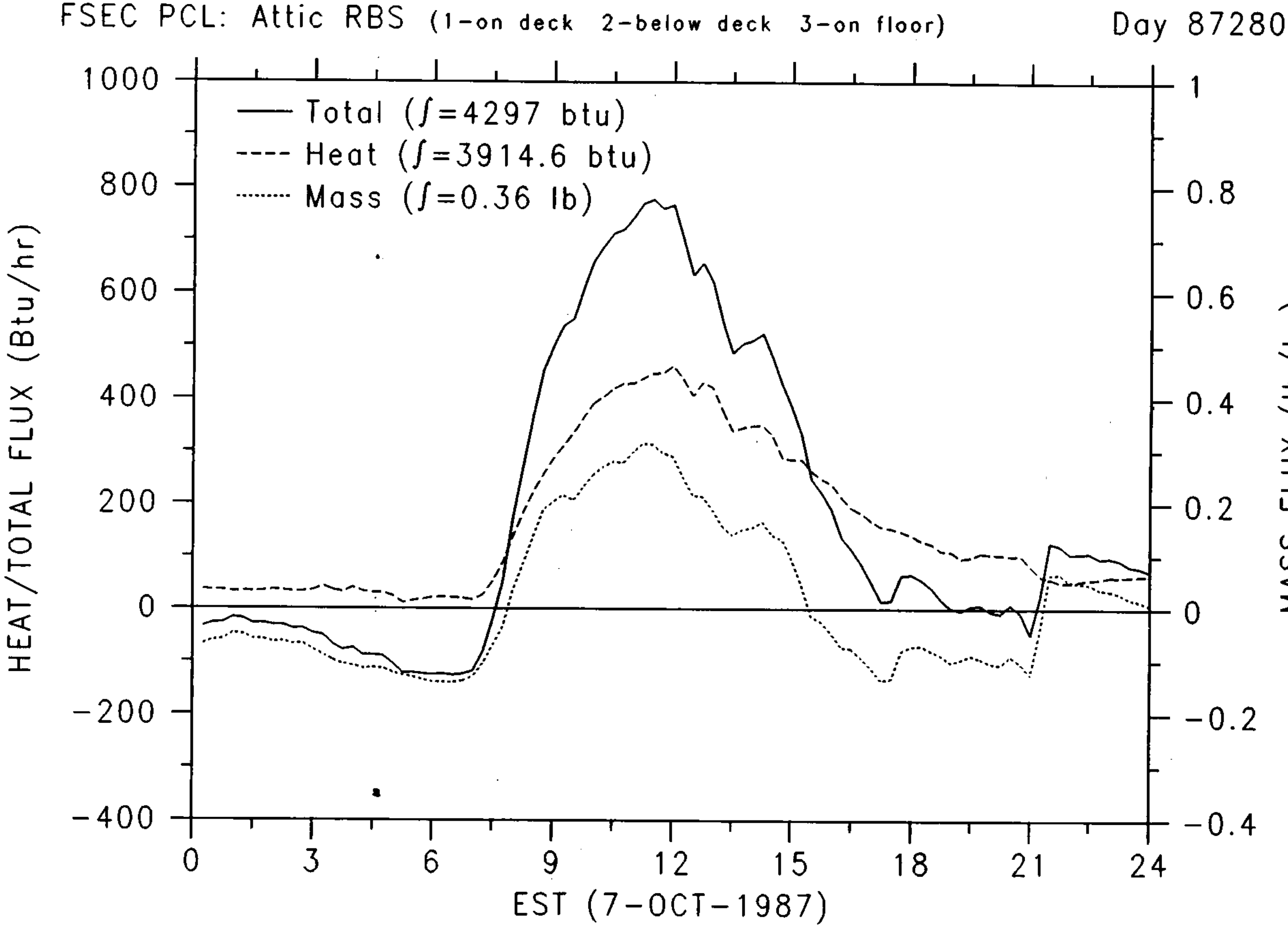

Figure 3.6-2 Cell 2 vent airstream heat and mass removal rates.

result of moisture diffusion from the house to the attic through the ceiling materials.

The major moisture concerns with respect to attic RBS are applications where the radiant barrier is laid directly on top of the ceiling insulation. It is quite possible that such applications will trap moisture inside the ceiling insulation if the radiant barrier is not permeable to water vapor. This may be especially true in very cold climates where large amounts of ceiling insulation are common. Under these conditions, the radiant barrier can function as a moisture "dam". This will be especially true if air communication paths between the house and attic are not sealed.

It is clear that moisture flows in attics are substantial. It is not clear whether or not impermeable coverings on top of ceiling insulations will cause moisture damage in ceilings. As long as the posibility of moisture damage exists, however, impermeable membranes placed directly on top of the ceiling insulation should be avoided.

This may also be true for radiant barriers attached directly to roof decking materials. If they are not permeable, the roof decking may not be able to dry sufficiently to avoid moisture damage, especially if there are roof leaks. A large number of radiant barrier manufacturers produce permeable products. If a radiant barrier is used in direct contact with attic materials it is recommended that it be permeable. Products with tested water vapor transmission rates of 15 perms or higher should not cause moisture problems.

3.7 Effect Of Climates

Attic RBS are primarily a summertime heat gain control stategy. Thus, their use is more appropriate and beneficial in the sunbelt than the north. There are winter benefits for attic RBS but the magnitude of the savings (ceiling heat flow reductions) are less in winter than in summer. There are two reasons that this is true. The first is related to the potential for radiation to occur across the attic airspace and the second is related to the behavior of convective heat transfer in attics.

The effectiveness of an attic RBS is primarily driven by the difference in temperature between the attic ventilation air and the roof surface temperature. If the roof surface temperature is the same as the ambient air temperature there will be no significant radiation transfer between the roof and the ceiling insulation in well vented attics. This is a fairly important point because it helps explain part of the reason why attic RBS are less efficient in winter than in summer.

In summer, the temperature of the roof during the middle of the day is likely to be significantly warmer than the ambient air because of solar radiation. It is not uncommon for roof surface temperatures to be as much as 80 to 90 F hotter than air temperatures under these conditions. There is a large potential for radiation transfer from the roof to the ceiling insulation under such conditions.

On cold winter nights, the roof is usually colder than the ambient air so there is a potential to transfer radiant energy from the ceiling insulation surface to the cooler roof. At night, however, this potential is significantly less than during the day because roof temperatures are only 10 to 25 F below ambient air temperatures [see Clark,1981].

A second and very important reason that attic RBS are less effecient in winter than summer stems from the nature of convective heat transfer. Natural convection is a bouyancy dirven phenomon. Thus, in the absence of external forces, convection will always be in the upward direction. This means that natural convection in attics will always work to cool the upper surface of the ceiling insulation -- summer and winter.

In summer, this upward convection is beneficial in protecting against unwanted ceiling heat gains. In winter, however, this upward convection increases heat losses from the upper surface of the ceiling insulation, resulting in greater heating energy use by the building. It is important to remember that an attic RBS blocks only the radiation transfer. If most of the total energy transfer across the attic airspace is by radiation (summer condition), then the RBS will have a significant effect on the ceiling heat flow. However, if a large portion of the total heat transfer across the attic airspace is by convection (winter condition), then the attic RBS will have a less significant effect on the ceiling heat flow.

It is quite important to point out that reductions in ceiling heat transfer caused by attic RBS are well matched to normal building loads, during both summer and winter [see Fairey, et.al., 1986]. Wintertime heating energy use in buildings is significantly higher at night. During this time of the day, attic RBS perform well, significantly reducing ceiling heat loss. During summer, the opposite is true and the greatest cooling load occurs during the day when both the attic RBS and the upward convection from the ceiling insulation are working in parallel to reduce heat gains into the building. There is limited field data supporting these hypotheses, however, more high quality experimental data from cold climates is needed to quantify these effects in detail.

The reader should remember, however, that an attic RBS will block daytime heat transfer across the attic airspace on winter days as well as on summer days. This daytime ceiling heat gain may be benefical in winter and attic RBS may not be warranted on steeply sloped, south facing roofs in cold climates.

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CHAPTER 4

RESEARCH APPROACH AND RESULTS

The Florida Solar Energy Center (FSEC) has been conducting RBS research since 1981. Although this report covers the most recent research work, it is predicated upon significant previous experience and research on the subject.

In October, 1986 a comprehensive cooling research program that is cooperatively supported by the U.S. Department of Energy (DOE), Florida Power and Light Company (FPL) and the Gas Research Institute (GRI) was initiated at FSEC. One of the five major research tasks of this project is radiant barrier systems research. The RBS research program was designed to be broad based and address three major research topics.

- o Material reliability
- o Performance measures, and
- o Analytical modeling.

Both experimental and analytical research are required. Experimental efforts are needed to examine the performance issues and to provide detailed, high-quality data for model development. Analytical research is needed to identify performance sensitivities and to develop RBS economic performance criteria across a wide range of climates.

The FSEC Passive Cooling Laboratory (PCL) is being used to study and measure the detailed, short-term performance of RBS alternatives so that system alternatives can be better understood and analytical models can be developed and verified.

To examine dust collection and material degradation potentials, field tests using RBS material swatches placed in the attics of 12 local residences were begun in September, 1987.

During the summer of 1987, whole-building energy performance was studied under subcontract with the University of Florida at two residences located at the Energy Research and Development Park in Gainesville, FL. The intent of these studies was to study RBS electrical demand reduction.

A new facility to study the long-term performance of installed RBS has been designed, critically reviewed, and is under construction at FSEC's new auxiliary test site in Cocoa, FL. This facility will be operational in the summer of 1988.

4.1 Detailed PCL Measurements

The FSEC PCL is a heavily instrumented, residential-scale building that allows for detailed, side-by-side study of building systems and components (Fairey, 1982). The data quality is such that results can be used for development and verification of mathmatical models.

Three test cells have been created in the east facing attic of the PCL to study the performance of RBS alternatives in detail (Fairey, 1985). The three attic cells are directly over a single conditioned space having a special air distribution system designed to maintains the same room conditions underneath each attic test cell.

The attic test cells are heavily instrumented to measure temperature regiems, air moisture regiems, heat fluxes, air velocities and ventilation air flow rates (see Appendix A). Ambient solar radiation, air temperature, air moisture content and wind speed and direction are also measured. The attic ventilation rates are controlled by a damper and blower arrangement that allows both control and measurement of the attic vent airflow rates.

These experiments have been very productive. Important questions pertaining to radiant barrier placement in the attic and attic ventilation rate have been answered in this facility. Before comparitive testing is attempted in the PCL, null tests are performed. Null tests are experiments that are used to assure that all three attic test cells are responding alike when they are configured identically. There is usually a small difference in performance between the test cells.

This difference is accounted for by normalizing the data with respect to a reference test cell. For the tests reported here cell 2 was used as the reference cell. Figures 4.1-1 and 4.1-2 show the results of the normalization analysis for two days during the null test period. On the figure, the number of data points considered by the regression analysis is denoted by 'N', the residual standard deviation of the regression error is denoted by 's^2' and the coefficient of correlation for the regression is denoted by 'R^2'.

After normalization coefficients are determined they are used to adjust the results so that equivalence between the test cells is achieved. Figures 4.1-3 gives normalized ceiling heat fluxes from these days using this technique.

The reported RBS configurations are illustrated in Figure 4.1-4. Note that 1.5 inches of attic framing is left exposed in each case and that only the roof decking or attic ceiling insulation is fully protected by the radiant barrier. The side and end walls of the attics are constructed using low emittance surfaces so that the only significant radiation is between the roof decking and the attic floor (insulation surface), simulating infinite parallel planes.

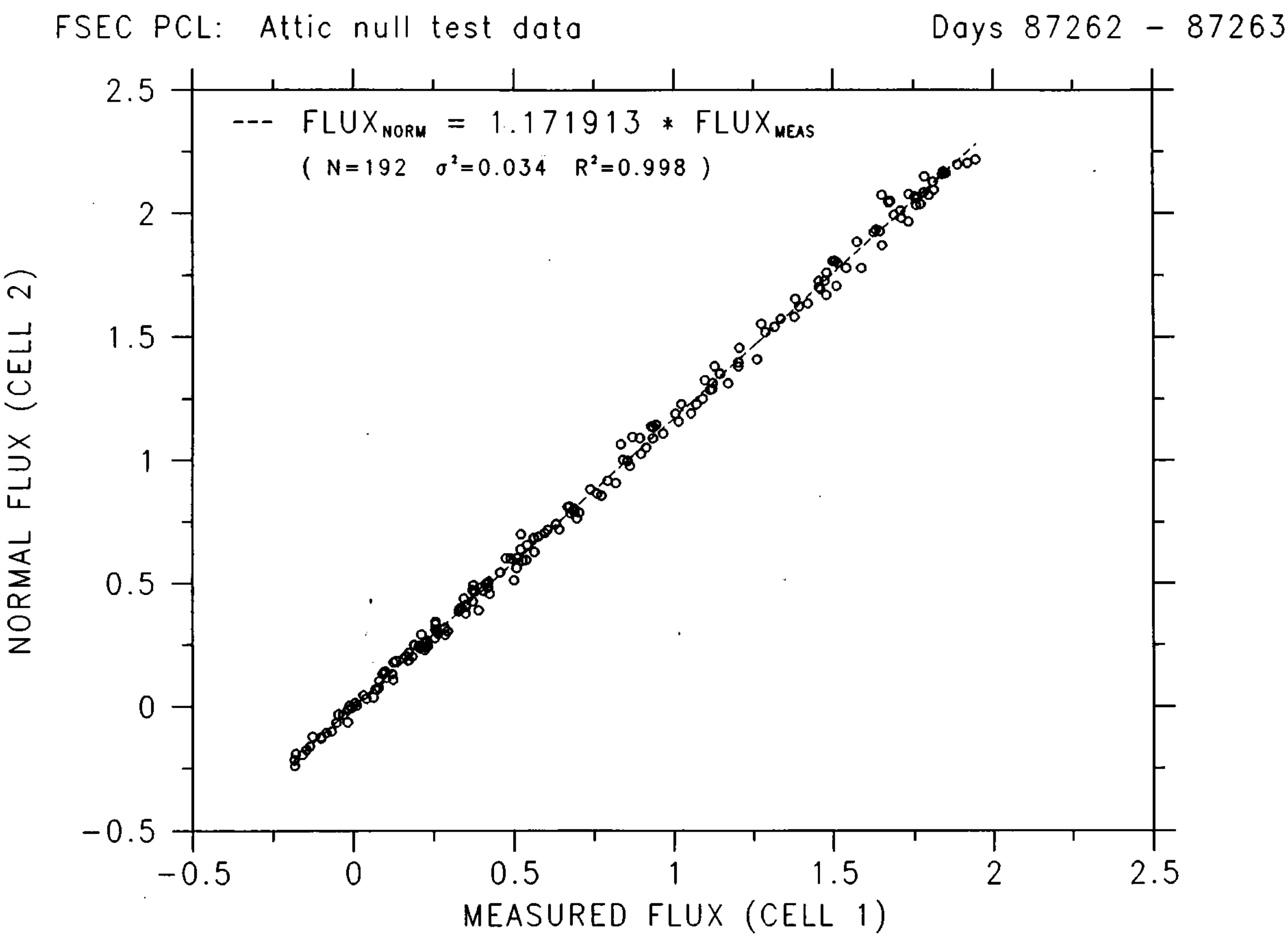


Figure 4.1-1 Normalization coefficient for cell 1 ceiling heat flux with respect to cell 2 ceiling heat flux.

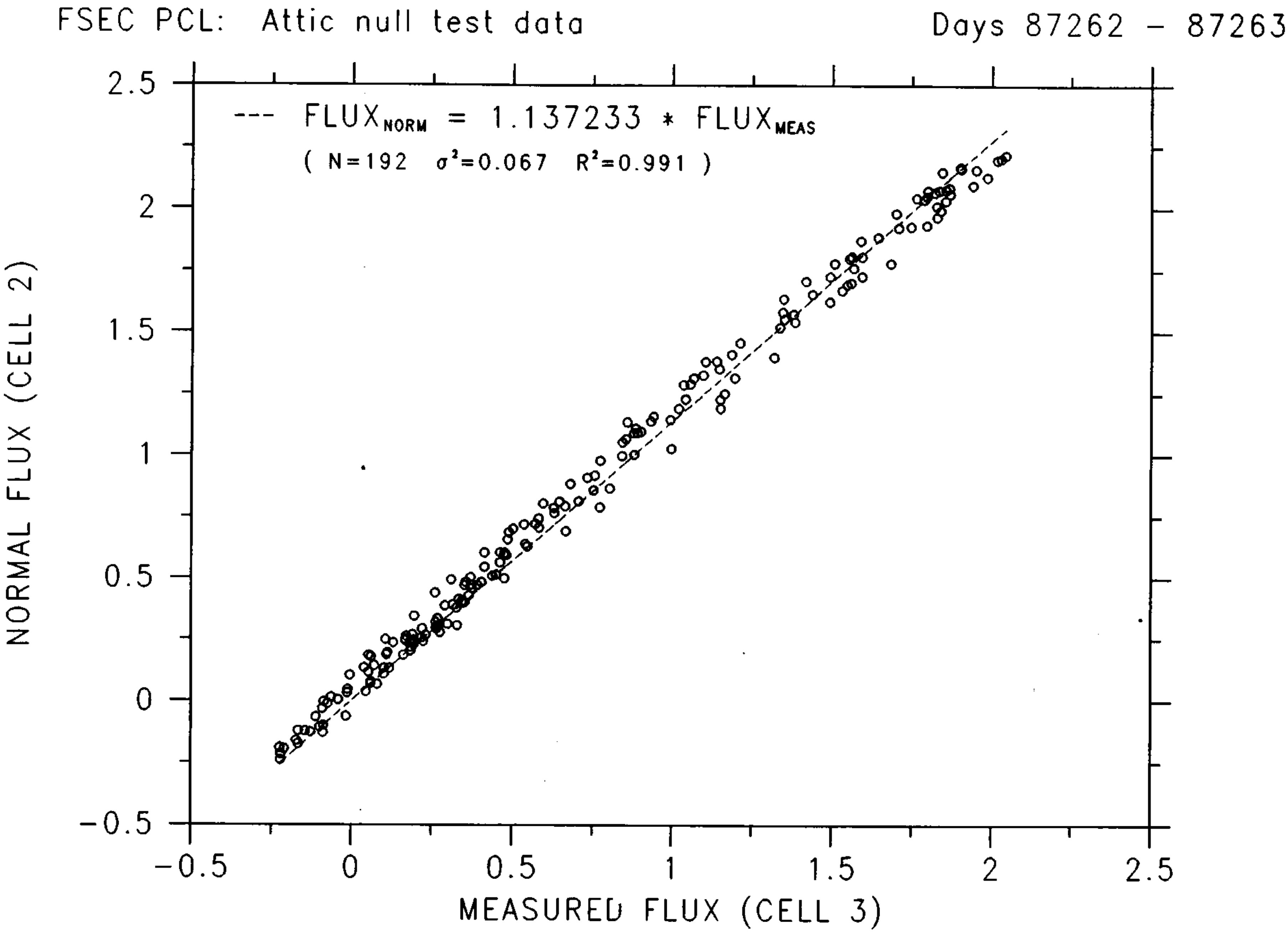


Figure 4.1-2 Normalization coefficient for cell 3 ceiling heat flux with respect to cell 2 ceiling heat flux.

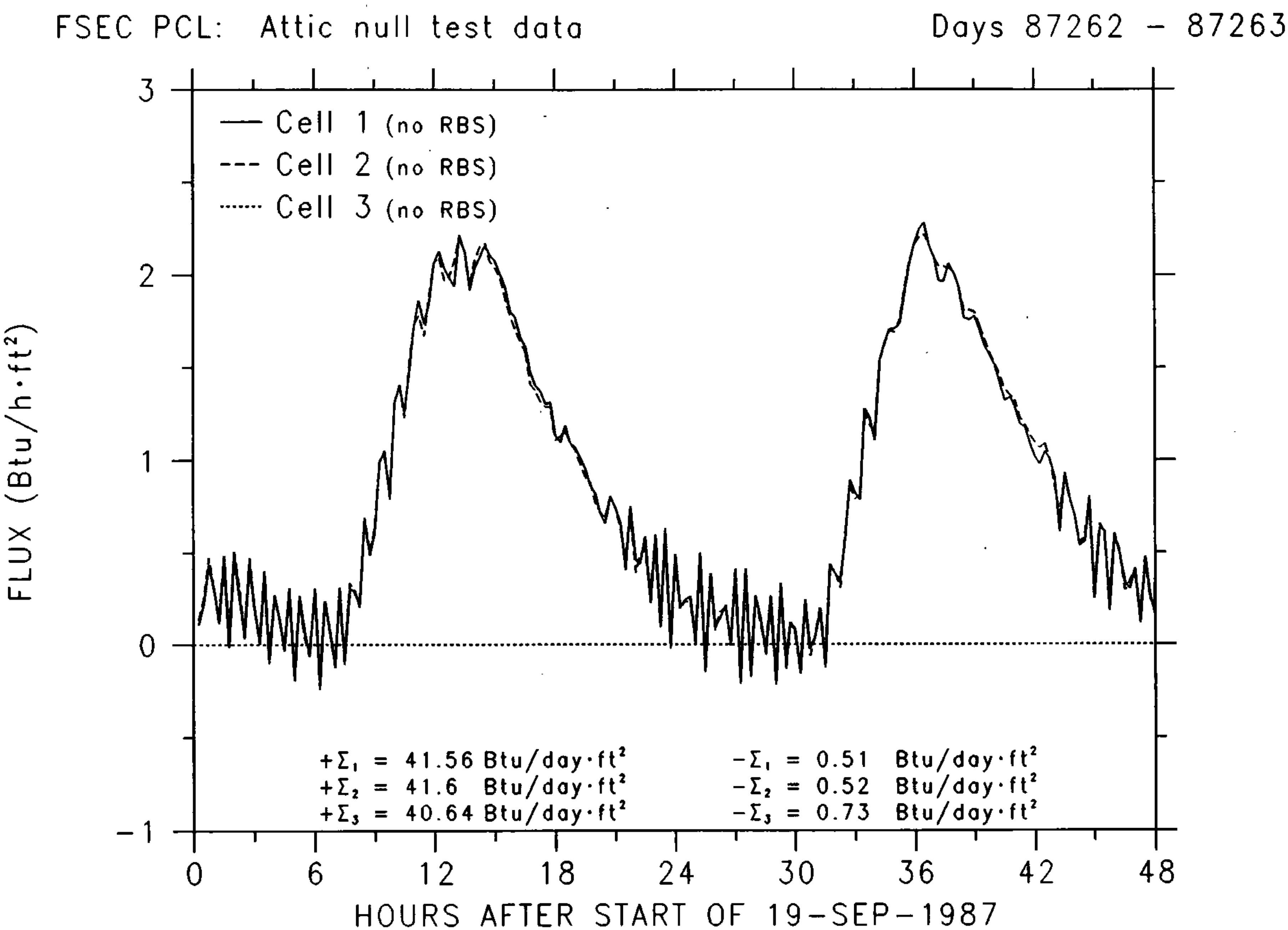


Figure 4.1-3 Comparison of normalized ceiling heat fluxes showing null test results in attics with R-19 ceilings.

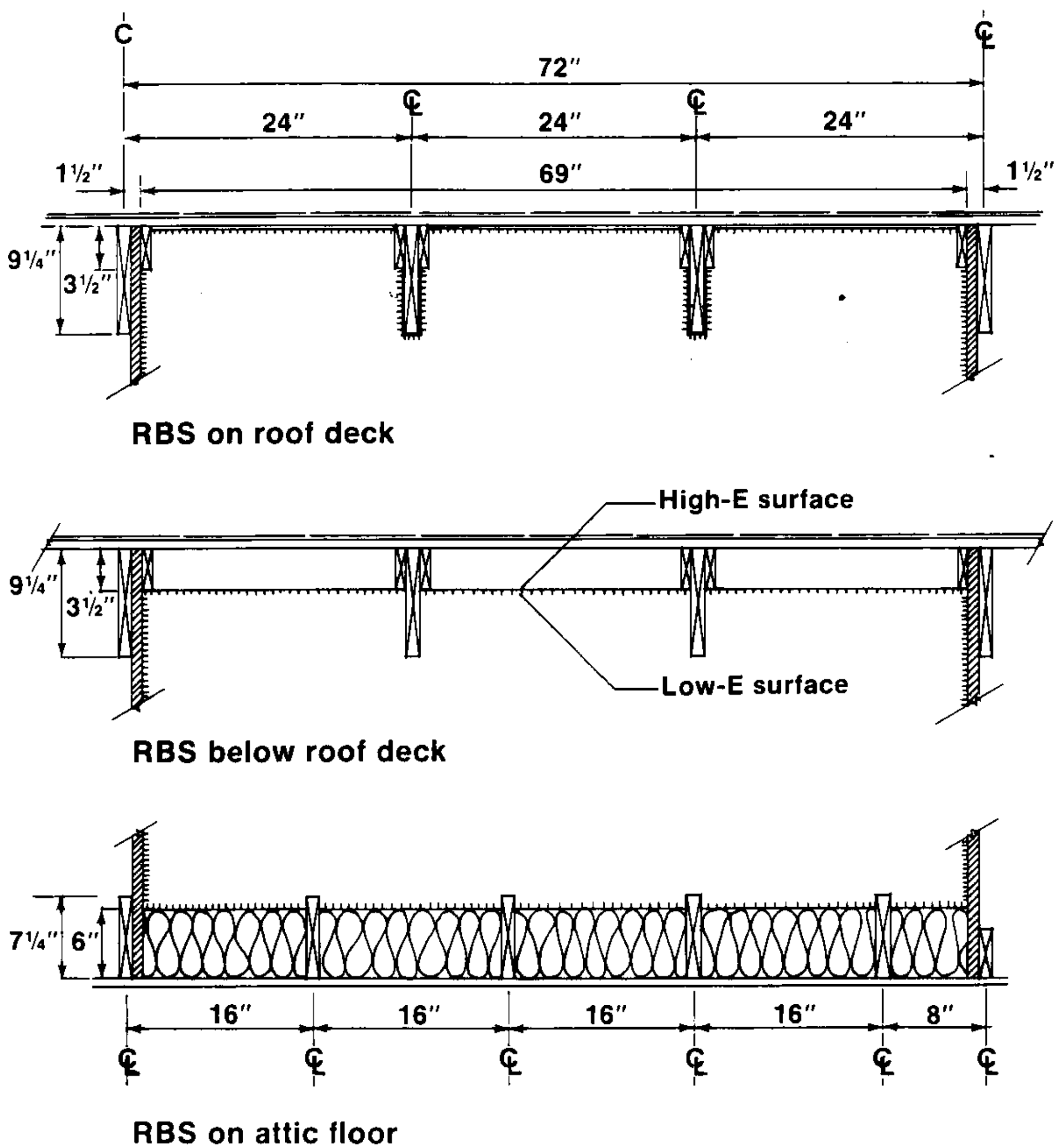


Figure 4.1-4 Location of RBS surfaces for PCL Attic tests during 1987.

Figure 4.1-5 gives results from the initial set of RBS tests. It clearly indicates that attic RBS are effective. The RBS in cell 1 is glued to the plywood roof decking and the RBS in cell 3 is placed 3.5 inches below the roof decking so as to have a vented airspace above it. There is no significant difference between the performance of the two RBS test cells. As compared to cell 2, the RBS in cells 1 and 3 reduced heat gains (sum of the positive ceiling fluxes) through the ceilings by 47.9 and 50.8 percent, respectively. The total daily heat fluxes through the ceiling (gains plus losses) were reduced by 37.3 and 40.3 percent, respectively.

In order to see if the agreement between cells 1 and 3 could be repeated using cells 1 and 2, a third test was conducted. Cell 2 was fitted with a radiant barrier 3.5 inches below the roof deck and a radiant barrier was placed between the ceiling joists directly on top of the ceiling insulation in cell 3. This afforded an opportunity to answer two questions. First, does cell 2 behave as much like cell 1 with the RBS 3.5 inches below the decking as cell 3 did? And second, how does a floor mounted RBS perform relative to the other two locations?

Results of this test are presented in Figure 4.1-6. It is apparent that performance for the three RBS locations is virtually identical. Perhaps more important it was possible to move the RBS that was 3.5 inches below the deck from cell 3 to cell 2 without seeing a significant difference in

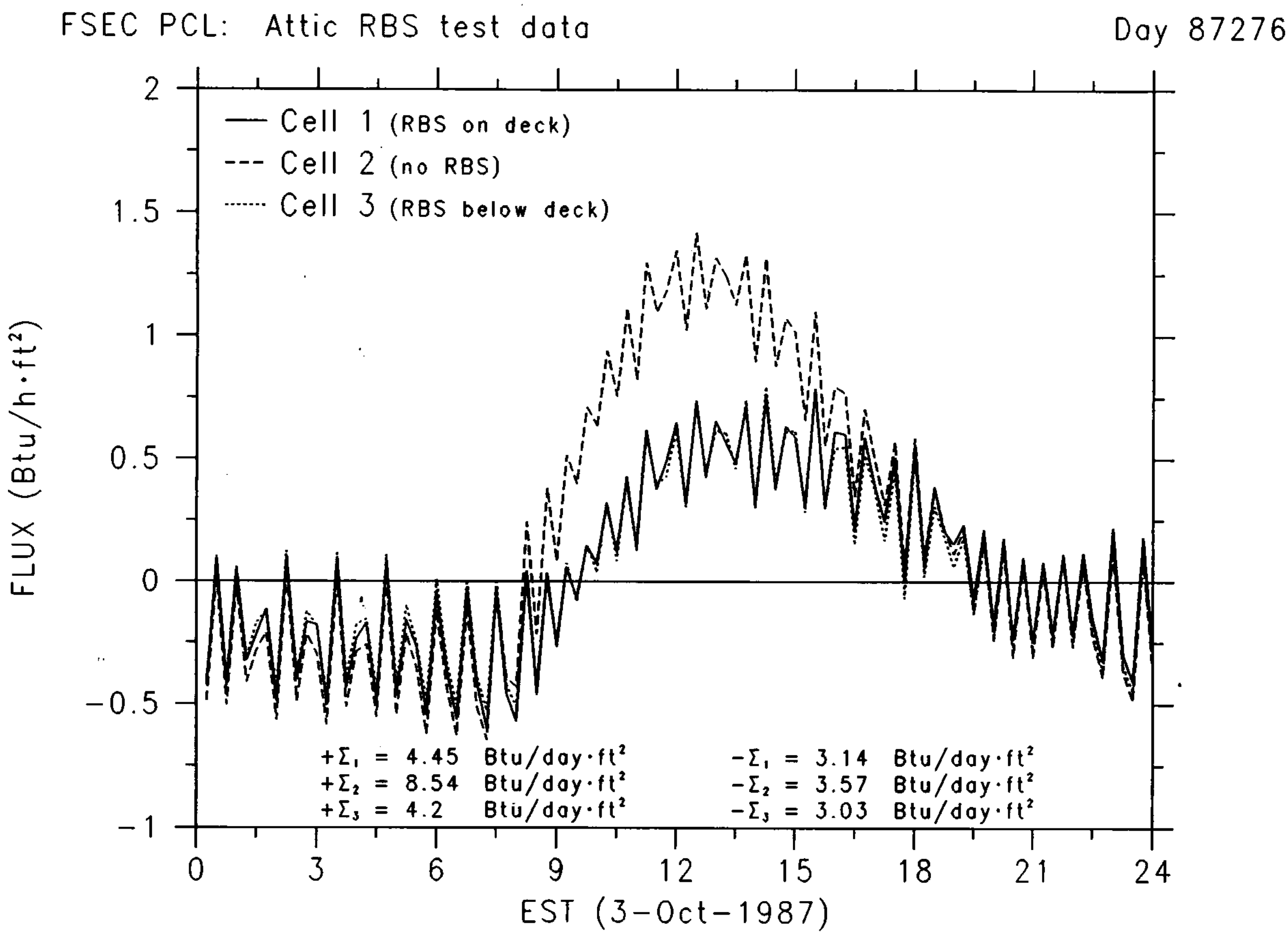


Figure 4.1-5 Comparison of normalized ceiling heat fluxes showing effects of RBS in attics with R−19 ceilings.

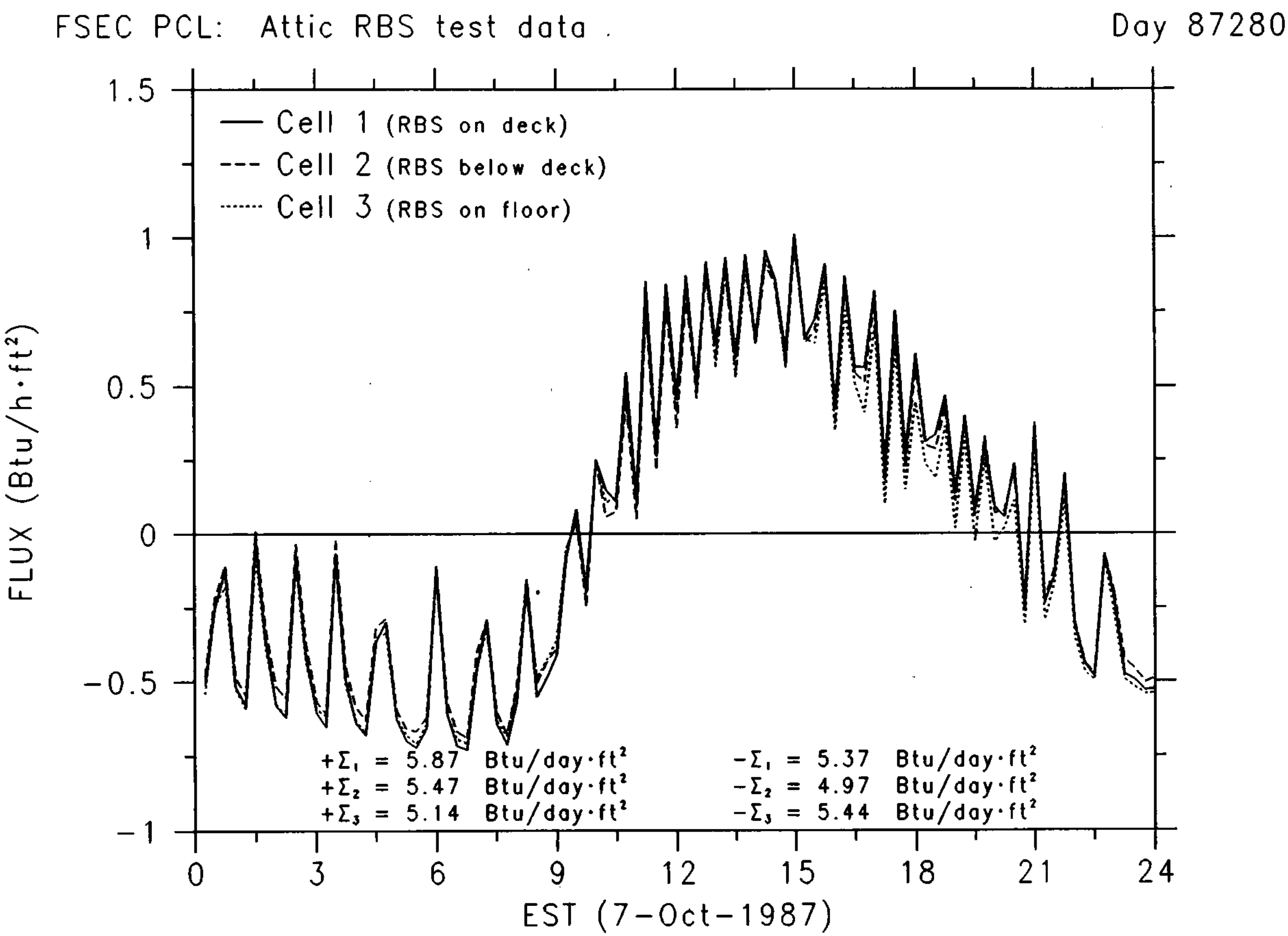


Figure 4.1-6 Comparison of normalized ceiling heat fluxes showing effects of RBS location in attics with R-19 ceilings.

performance with respect to the glued RBS in cell 1. This indicates that the three attic test cells are well matched.

In all cases single-sided radiant barriers were used. The emittance of the foil side was 0.03 and the emittance of the non-foil side was 0.9. Their low emissivity surface always faced the main attic airspace and the attics were force vented at at a constant rate of 2.5 air changes per hour (ach). In the case where the radiant barrier was located 3.5 inches below the roof decking both the main attic airspace and the airspace between the radiant barrier and the decking were vented but the total attic air change rate was held at 2.5 ach in each case. A full compliment of test data for the three test days used in this analysis is given in the Appendix of this report.

In previous tests (Fairey, 1985) these attics have been used to study attic ventilation strategies, single-sided versus double-sided RBS and roof versus floor mounted RBS. Summary results from these tests are presented in Table 4.1-A.

4.2 RBS Mathmatical Model Development

Data from PCL experiments have also been successfully used to develop and verify a detailed finite element model. The model predicts attic behavior with significant accuracy. In addition to the detailed model a simple heat balance model using ASHRAE heat transfer algorithms was developed and exercized to study the sensitivity of the main parameters

TABLE 4.1-A

Summary of Results from PCL Attic Tests for Summer 1985

TEST CONDITION	Base Strategy	Alternative Strategey	Period of Analysis	Flux Ratio (alt/base)	% Difference from Base
NULL TESTS	No insulation (cell 3), sealed	no insulation (cell 1), sealed	Jun 18-Jun 23 (169-174)	1.04	-4%
	R-19 standard (cell 3), sealed	R-19 standard (cell 1), sealed	Jun 26-Jun30 (177-181)	1.12	-12%
VENT TESTS	R-19 standard (cell 1), sealed	R-19 standard (cell 3), nat 2.5 ach	July 13-July 14 (194-195)	0.63	37%
	R-19 standard (cell 1), sealed	R-19 standard (cell 2),force=15 ach	July 13-July 14 (194-195)	0.62	38%
	R-19 standard (cell 3),nat 2.5 ach	R-19 standard (cell 2),force-15 ach	July 18-July 14 (194-195)	0.98	2%
RBS TESTS (SEALED)	R-19 standard (cell 3), sealed	R-19 + FRBS (SS DN) (cell 1)	Aug 11-Aug 12 (223-224)	0.99	1%
	R-19 standard (cell 3), sealed	R-19 + FRBS (SS UP) (cell 1)	Aug 17-Aug 18 (229-230)	0.82	18%
	R-19 standard (cell 3), sealed	R-19 + RRBS (SS DN) (cell 1)	Aug 24-Aug 26 (236-238)	0.81	19%
RBS TESTS (VENTED)	R-19 standard (cell 3), 5 ach	R-19 + RRBS (SS DN) (cell 1), 5 ach	Sept 2-Sept 5 (245-248)	0.57	43%
	R-19 standard (cell 3), 5 ach	R-19 + RRBS (DS) (cell 1), 5 ach	Sept 10-Sept 12 (253-255)	0.57	43%
	R-30 conserve (cell 3), 5 ach	R-19 + RRBS (DS) (cell 1), 5 ach	Sept 23-Sept 26 (266-269)	0.68	32%
	R-30 conserve (cell 3), 5 ach	R-11 + RRBS (DS) (cell 1), 5 ach	Sept 30-Oct 1 (273-274)	0.99	1%

that effect RBS performance.

Attics are extremely complex systems involving simultaneous heat, mass and momentum transport. The degree to which these phenomena may be studied depend on the nature of the problem, the desired result and the available resources. With these constraints, two RBS modeling studies were conducted.

- o A detailed finite element model was used to study combined heat and mass transfer in attics, and
- o a simplified, heat-balance model was used to rapidly study the major parameters of attic RBS systems.

4.2.1 Detailed finite element model

As part of the effort, FSEC has developed detailed analytical capabilities to model combined heat and mass transfer phenomena in attics. The effort includes archiving the available moisture property data and development of accurate combined heat and mass algorithms based on available theories. An in-house software, FEMALP, capable of modeling simultaneous heat, mass and momentum transport is the result of this effort. Complete details of the various theories of combined heat and mass transport, algorithms developed based on the theories and moisture property data are catalogued in Kerestecioglu et.al. [1988].

Detailed modeling consisted of two studies: 1) thermal only simulation of the attic and 2) coupled heat and mass transport simulation of the attic. In both cases the finite element approach was used to solve the governing equations for the solid components of the attic and a lumped approach was used to model the attic air. The two domains (solid and air) were coupled at the boundaries using appropriate coupling coefficients. The Navier-Stokes equations were not solved for the air domain. The model used for moisture transport comes from evaporation-condensation theory. No discussion of the physics of moisture transport is presented here. A full discussion on this subject may be found in Kerestecioglu et.al. [1988].

The geometry simulated (attic Cell 2 of the FSEC PCL) is illustrated by Figure 4.2-1. Detailed measurements of temperatures, airflows, dew points and heat fluxes were obtained at 15 minute intervals. A more complete discussion of the instrumentation and the nature of the experiments is contained in the appendix to this report.

The attic air space is divided into seven lumped zones with ventilation air entering zone 1 at C'-I' and leaving the seventh zone at C-I. The seven zones are coupled by interzone air flow. That is, all air entering a zone leaves to the next zone until it exits from zone seven. The dashed lines in the figure indicate the zone partitions assumed for the purposes of simulation. No re-circulation of air between zones was considered. Although a single temperature

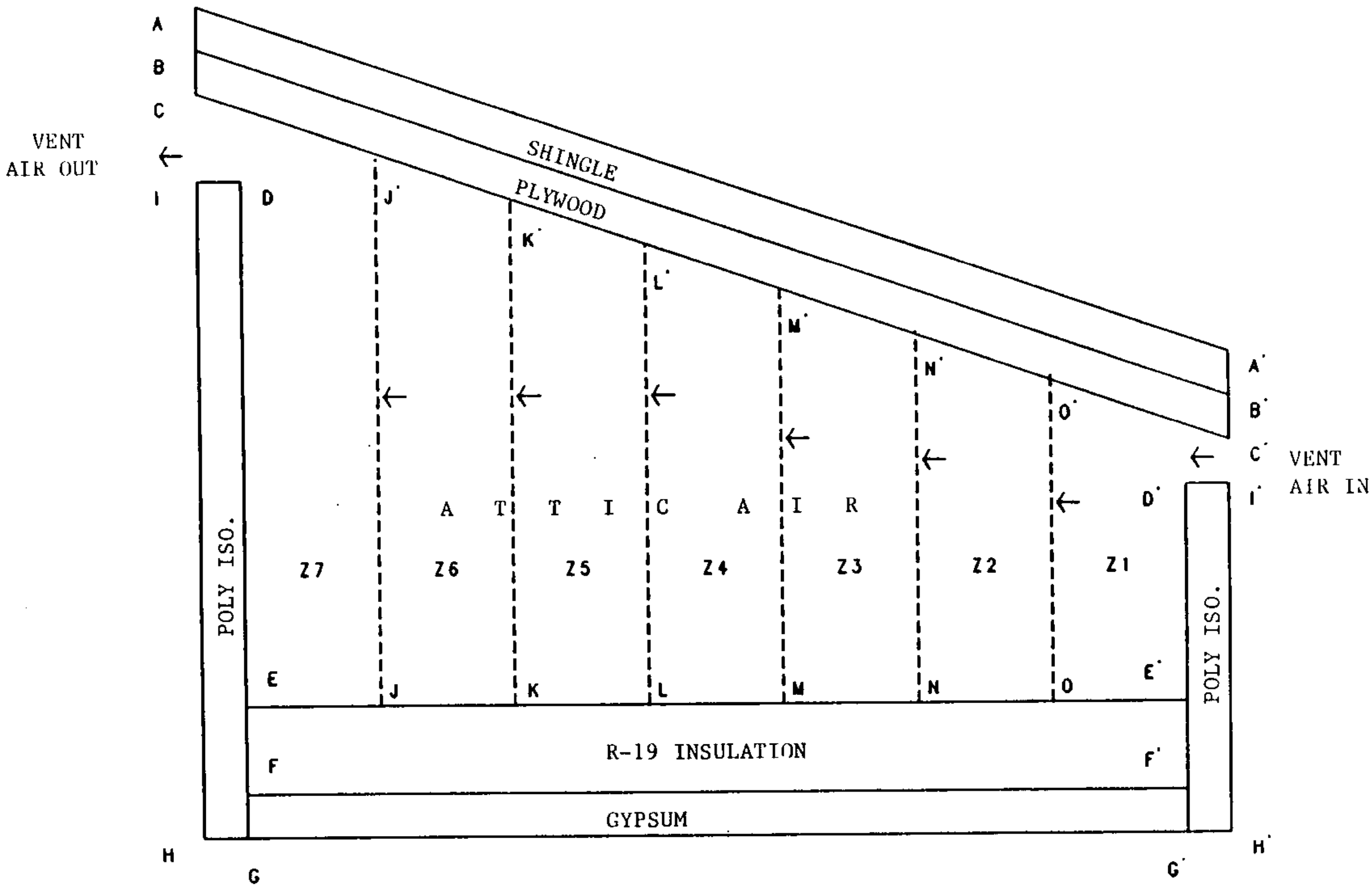


Figure 4.2-1 Layout of PCL attic cell 2.

defines the thermal state of a given zone, the multi-zone model allows the air conditions to vary from one zone to another. A seven zone model was chosen because this was the division used in the PCL measurements. Figure 4.2-2 shows a section of the finite element descretization.

Measured thermal data were used as boundary conditions at the bottom of the gypsum board (H-H') and the top of the plywood decking (B-B'). Figure 4.2-3 shows the center-line temperature history of the attic components for the simulation. The temperature for gypsum bottom and deck top are used as thermal boundary conditions in the model. Coupling coefficients between the attic air and solid surfaces were taken from ASHRAE [1985]. These coefficients were temperature and orientation dependent. Thermal radiation among viewing surfaces was modeled in detail using the Script-F concept.

Figures 4.2-4 and 4.2-5 give the meterological data for the day simulated. Although these data are not directly used in the simulation, they are presented to give an idea of the climatic conditions. The attic ventilation rate was maintained between 5.0 and 6.0 ach. Figure 4.2-6 gives the air flow history at two attic locations and in the vent outlet duct during the experiment. The measured airflow in the outlet duct served as input for the simulation.

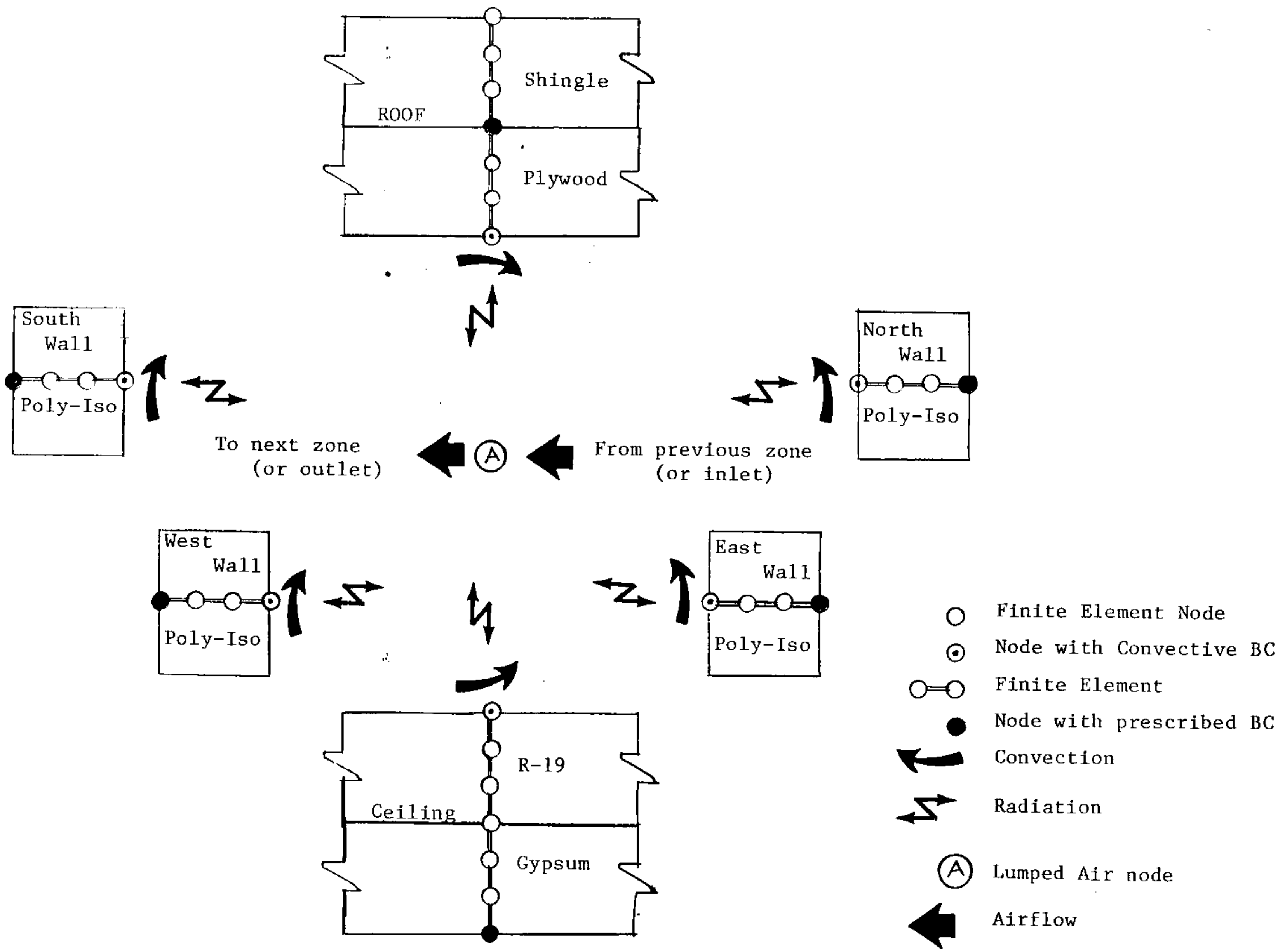

Shingle
ROOF
Plywood
South
Wall
Poly-Iso
North
Wall
Poly-Iso
To next zone
(or outlet)
From previous zone
(or inlet)
West
Wall
Poly-Iso
East
Wall
Poly-Iso
R-19
Ceiling
Gypsum
Finite Element Node
Node with Convective BC
Finite Element
Node with prescribed BC
Convection
Radiation
Lumped Air node
Airflow

Figure 4.2-2

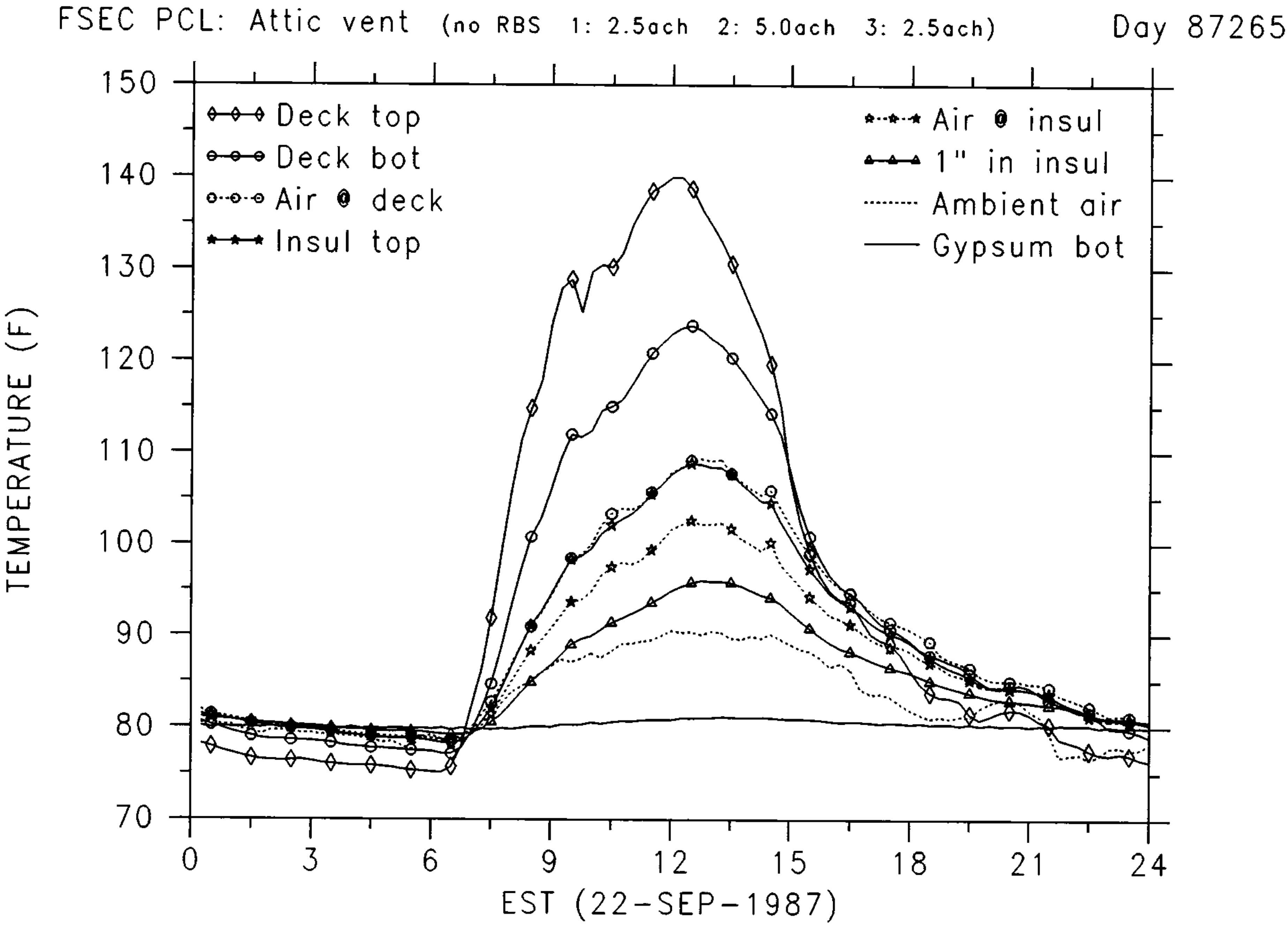


Figure 4.2-3 Distribution of cell 2 attic component temperatures.

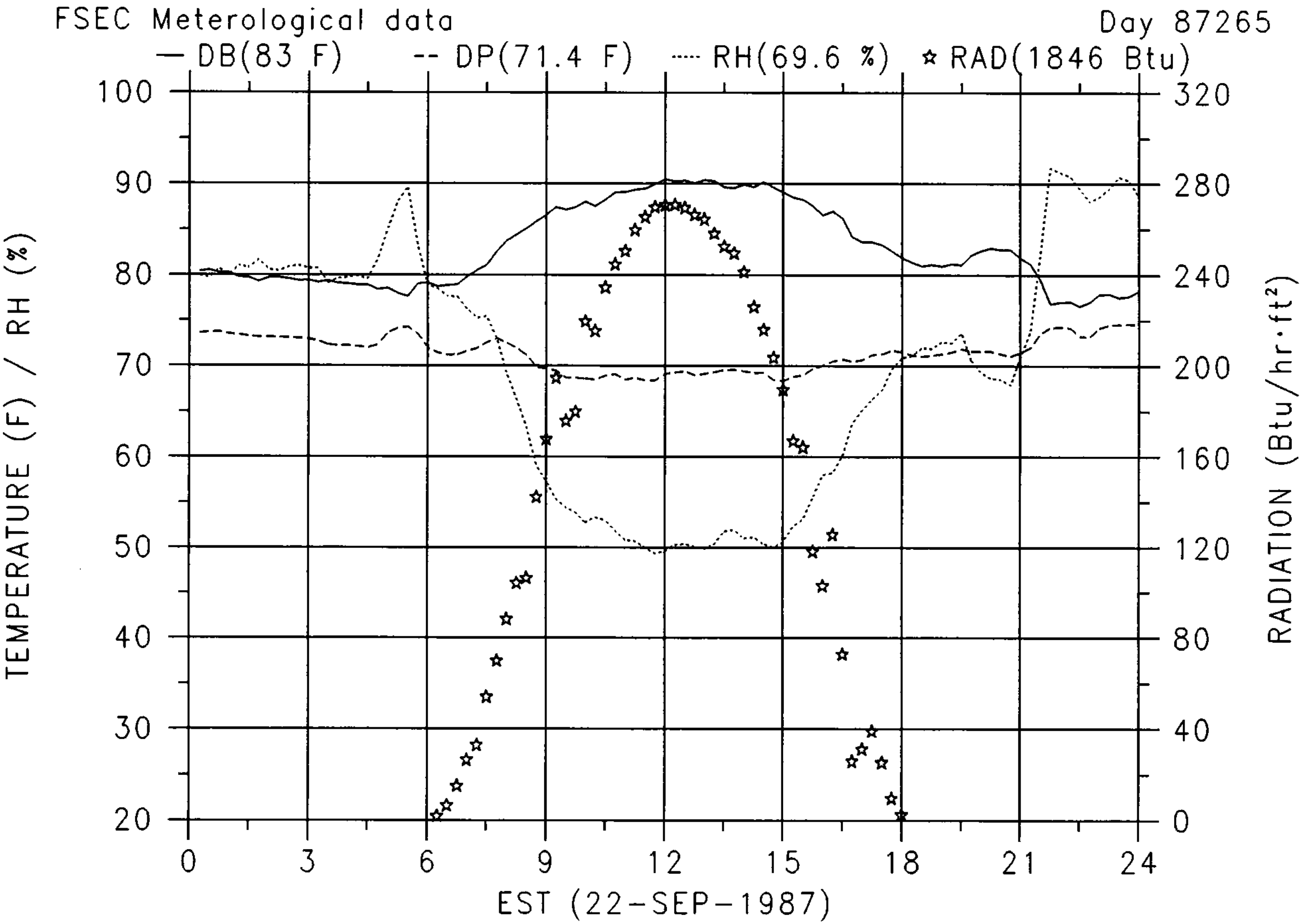


Figure 4.2-4 Ambient air conditions and horizontal solar radiation.

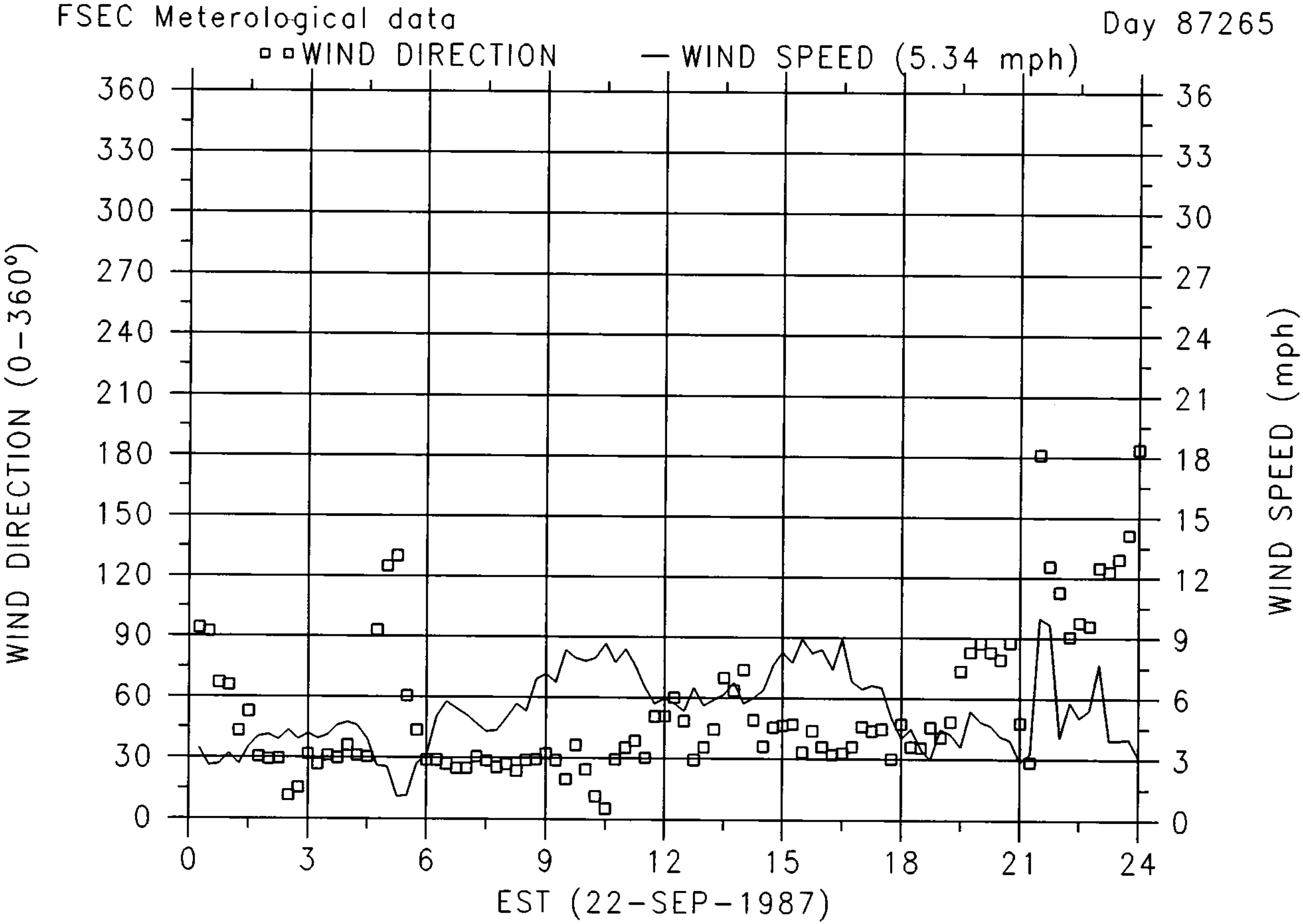


Figure 4.2-5 Local 10 meter wind measurements.

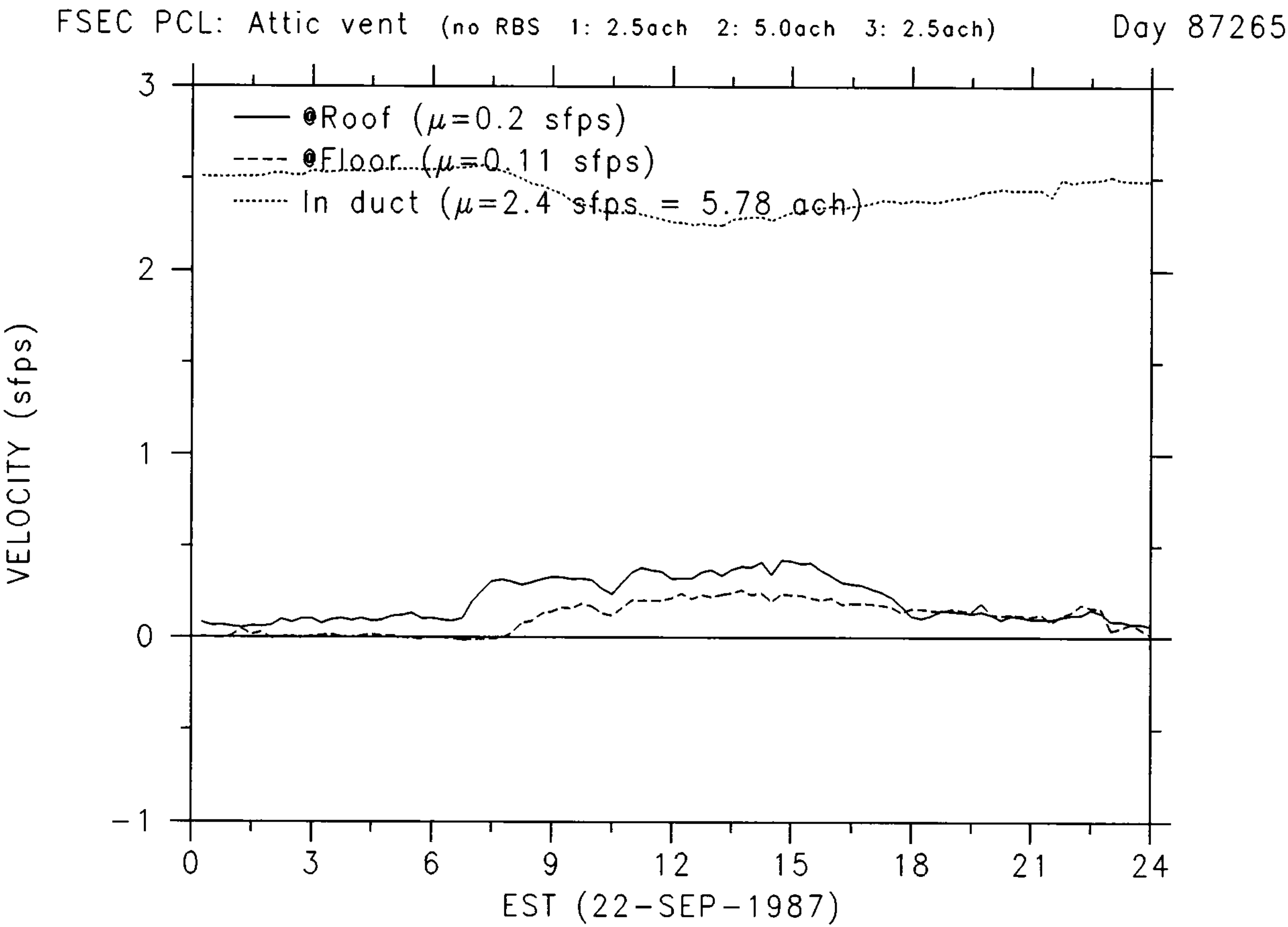


Figure 4.2-6 Cell 2 attic velocity profiles at three locations.

Values for the thermal properties, of conductivity, density and specific heat were taken from ASHRAE [1985]. Moisture properties were taken from Kerestecioglu et.al. [1988]. Properties of porosity, tortuosity and equilibrium moisture content are tabulated in Appendix D of this reference above.

For the first simulation, only the thermal transport was simulated. Figure 4.2-7 compares measured heat fluxes at the ceiling with results from the simulation. Although moisture effects were not modeled, the measured data match reasonably well with the results of the simulation.

Figure 4.2-8 compares the measured and simulated temperatures at the top surface of the ceiling insulation. Disparities between measured and predicted temperatures are expected when the effects of moisture are ignored. It is evident from the figure that the model under-predicts during the cooling period (nighttime) and over-predicts during the heating period (daytime). This is typical of the effects of moisture. During nighttime when moisture is adsorbed, the heat of adsorption causes higher surface temperatures. The reverse is true during daytime when desorption occurs. A large part of disparities observed in the figure may, therefore, due to be the effects of moisture.

This hypothesis is strengthened by data given in Figure 4.2-9. The temperature prediction error is plotted with the measured vent air moisture removal rate. The thermal prediction error is qualitatively analogous to the measured

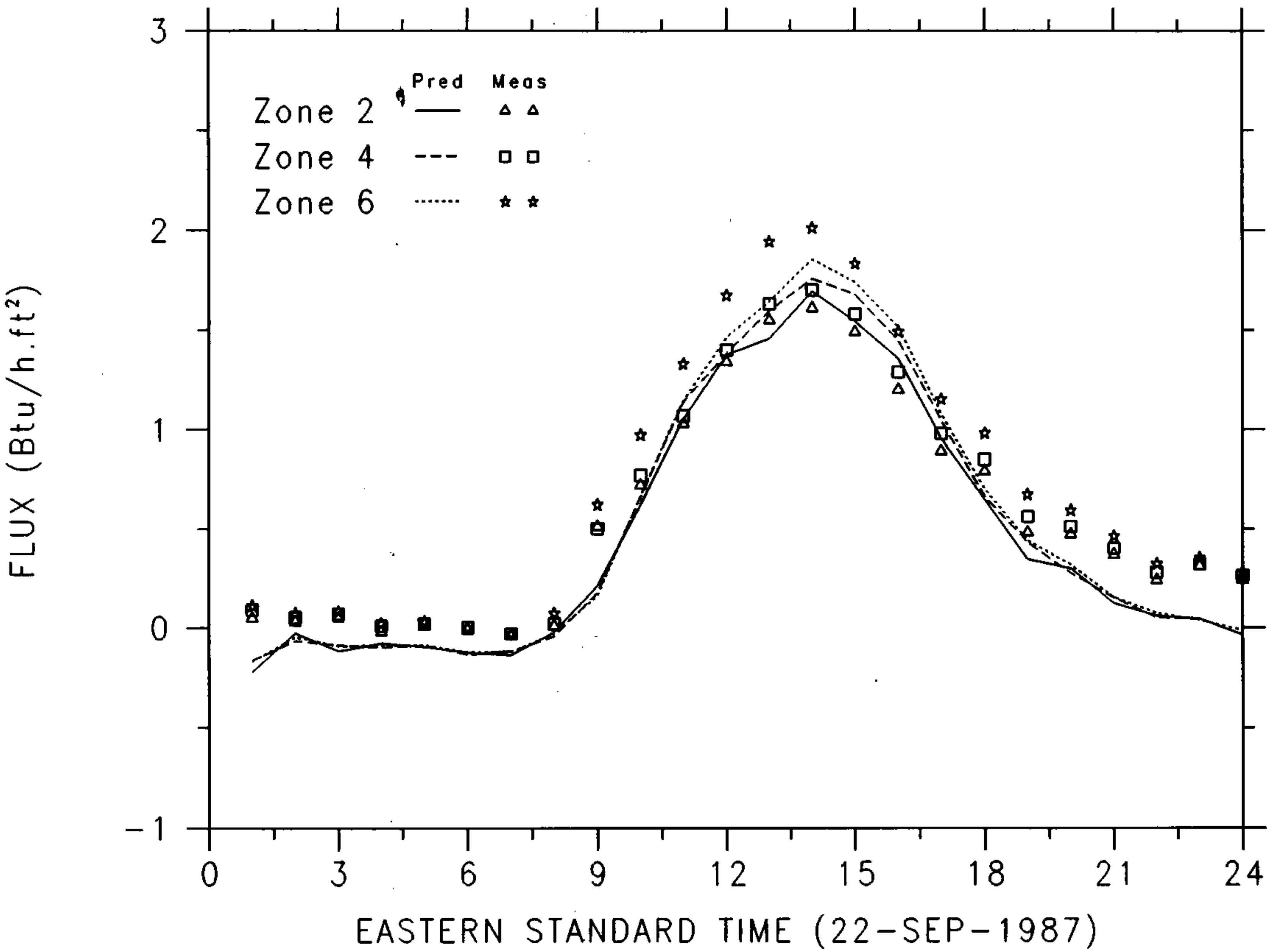


Figure 4.2-7 Comparison of predicted and measured ceiling heat fluxes without including moisture effects

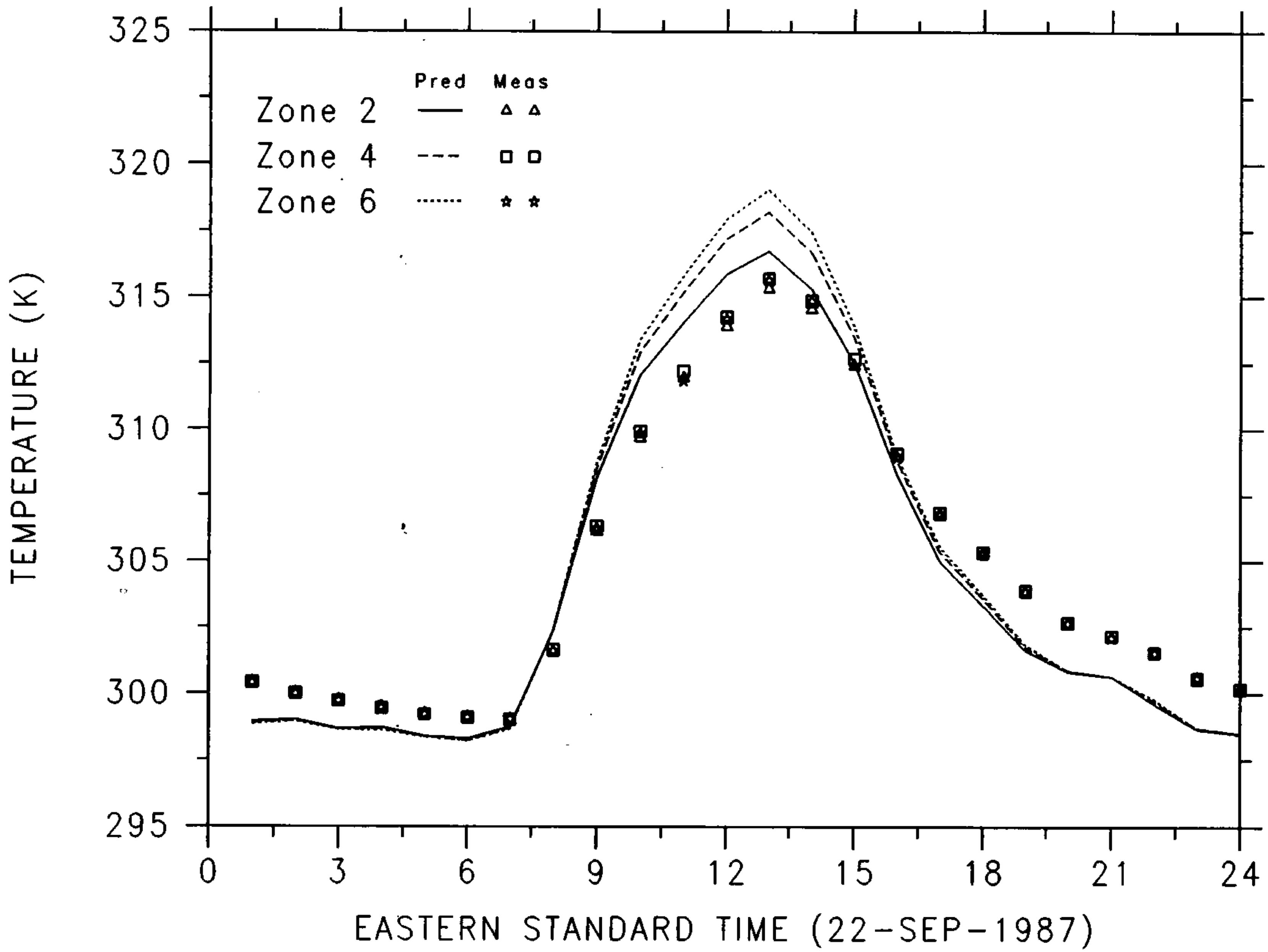


Figure 4.2-8 Comparison of predicted and measured temperatures at insulation top without including moisture effects.

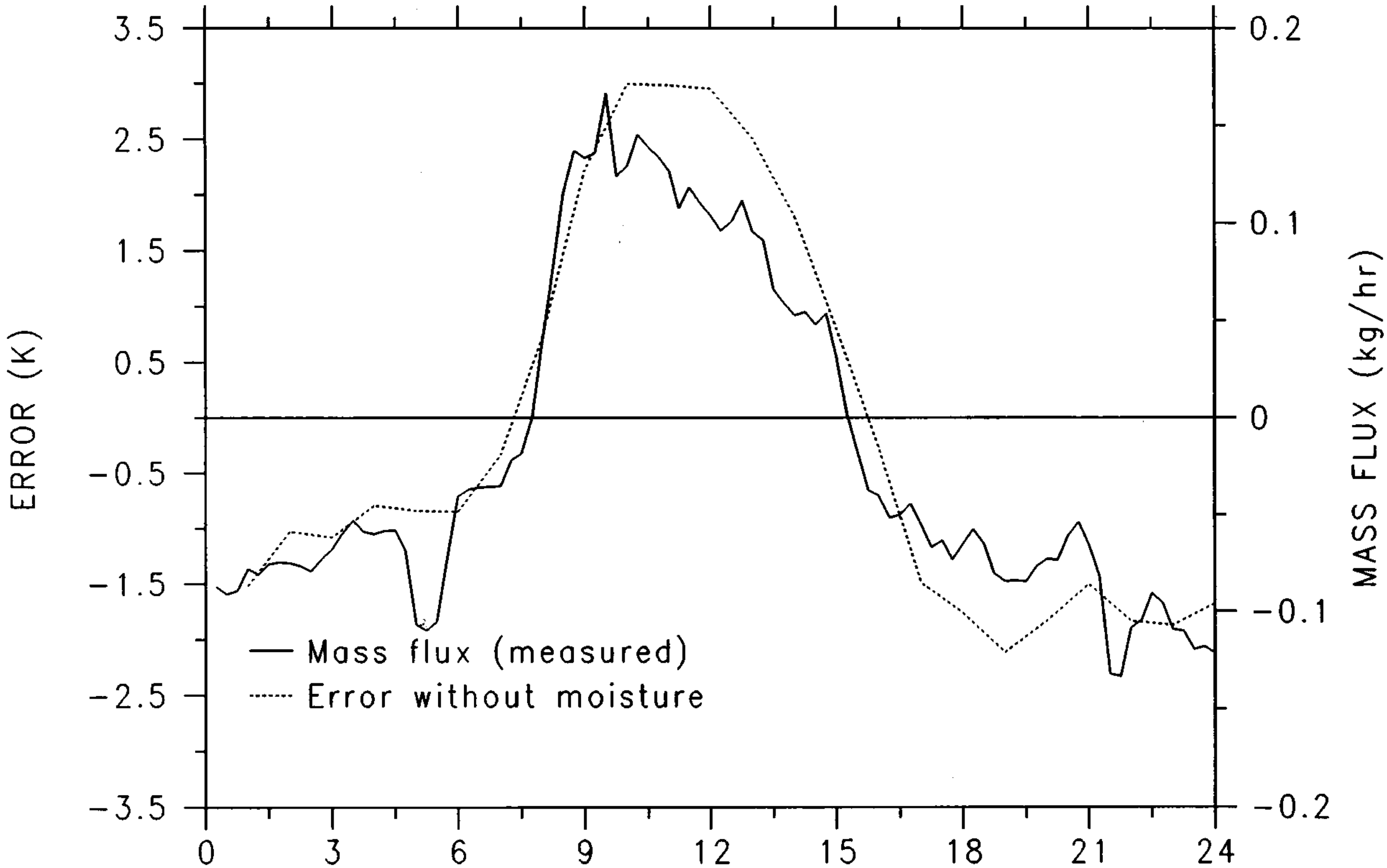


Figure 4.2-9 Comparison of insulation top temperature prediction errors and measured vent air moisture removal rate.

vent air moisture removal from the attic.

The coupled thermal and moisture transport in the attic was also simulated. Only inlet and outlet vent air moisture contents are measured so measured material moisture contents are not available for boundary condition data. Therefore, the simulation was run for a ten day period to allow initial material moisture conditions to decay beyond any significance.

Figure 4.2-10 shows the predicted and measured insulation surface temperatures after moisture transport is included in the simulation. The predictions are much closer to the measured values than for the previous simulation. (Figure 4.2-8). The measured data show a smaller temperature gradient between air zones 2 and 6 than the model. This is probably due to re-circulation and buoyancy effects occurring in the attic air.

Figure 4.2-11 compares the thermal prediction errors with and without the effects of moisture included in the model. The prediction error has considerably dampened when moisture effects are simulated. The maximum prediction error when moisture is ignored is about 3 K compared to 0.5 K when moisture effects are included.

Figure 4.2-12 compares predicted and measured humidity ratios at the outlet of the attic. While a similarity in trend has been established an exact match was not obtained. It is clear, however, that the inclusion of moisture

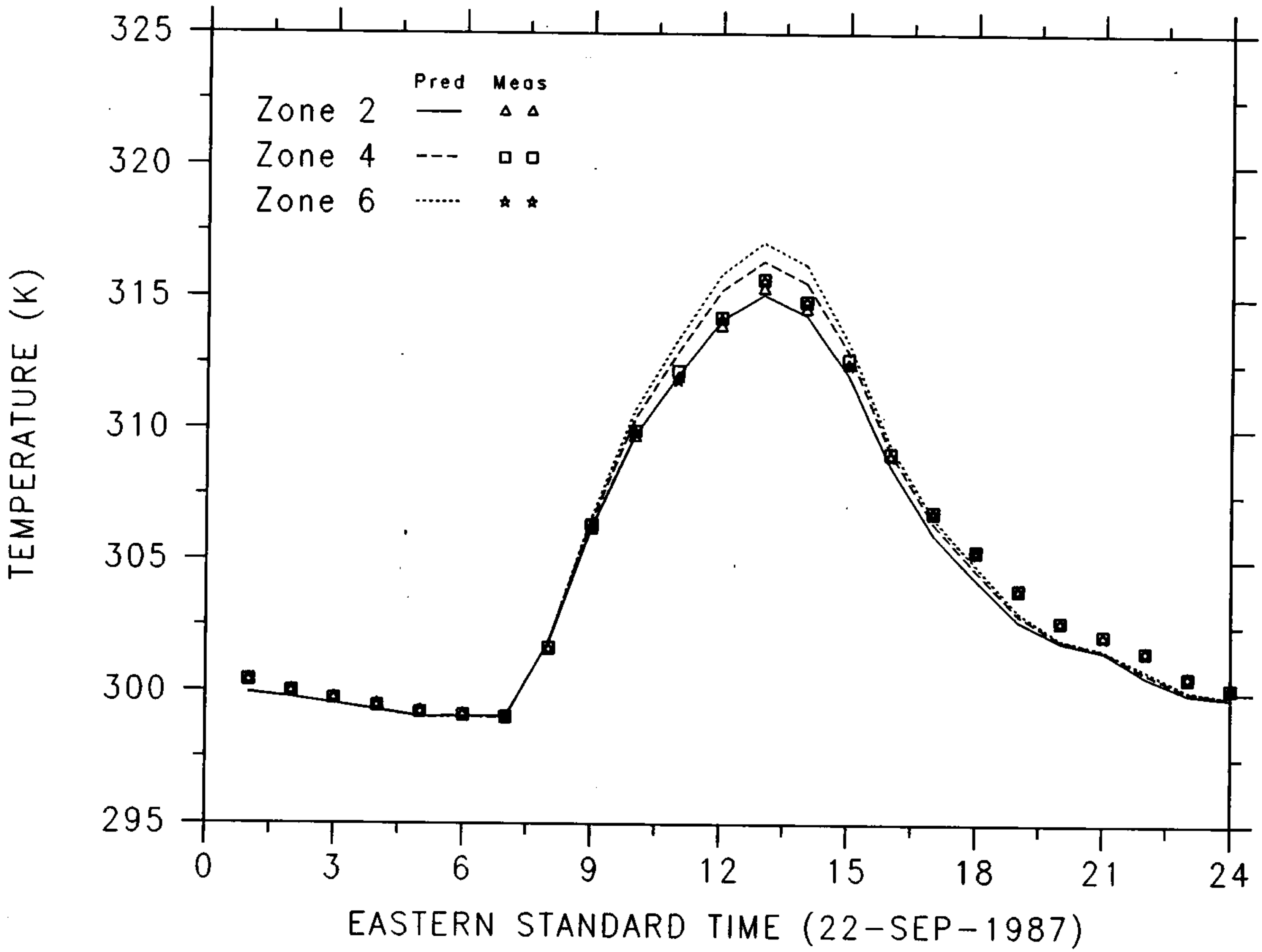


Figure 4.2-10 Comparison of predicted and measured temperatures at insulation top including moisture effects.

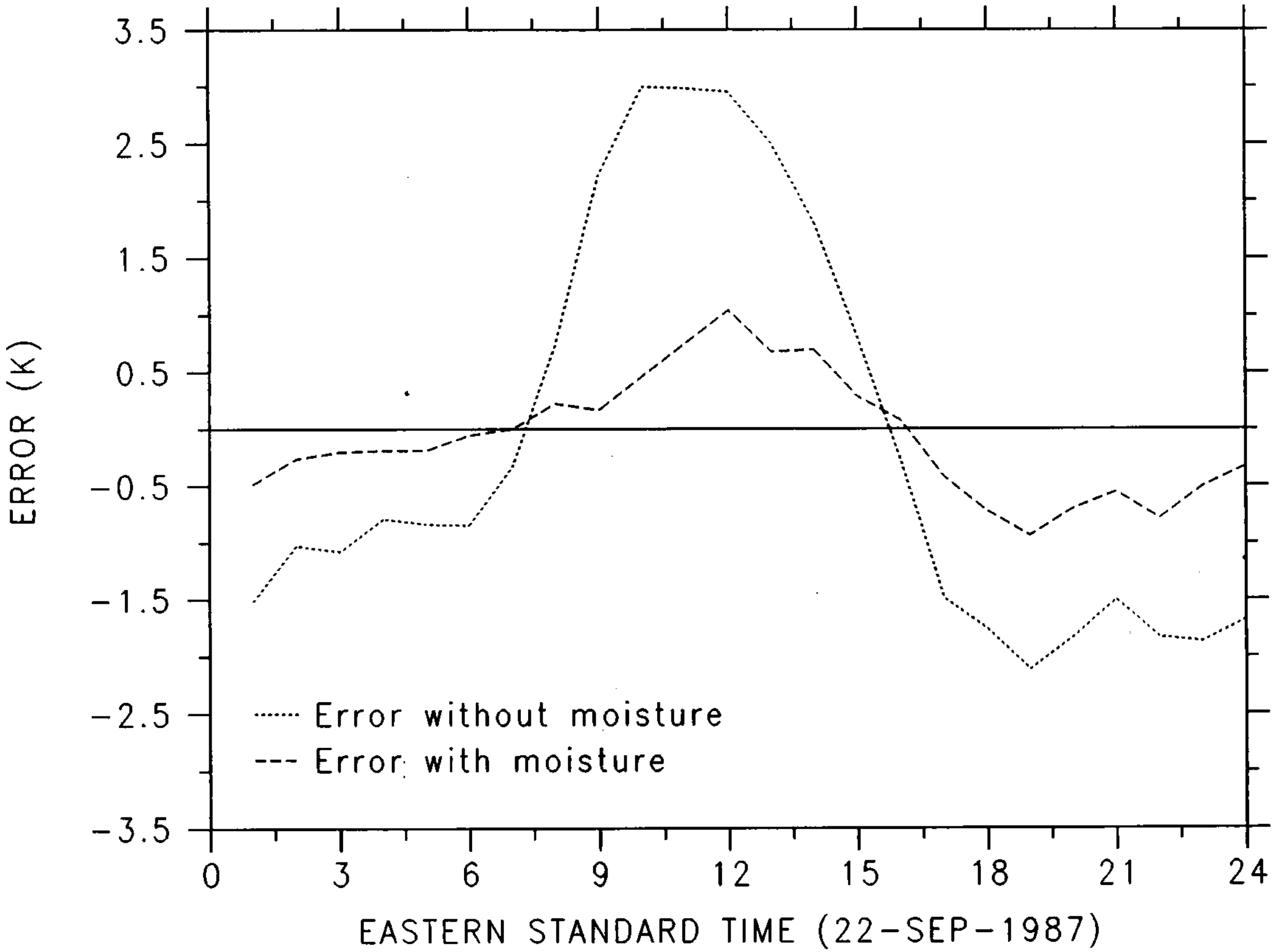


Figure 4.2-11 Comparison of insulation top temperature prediction errors

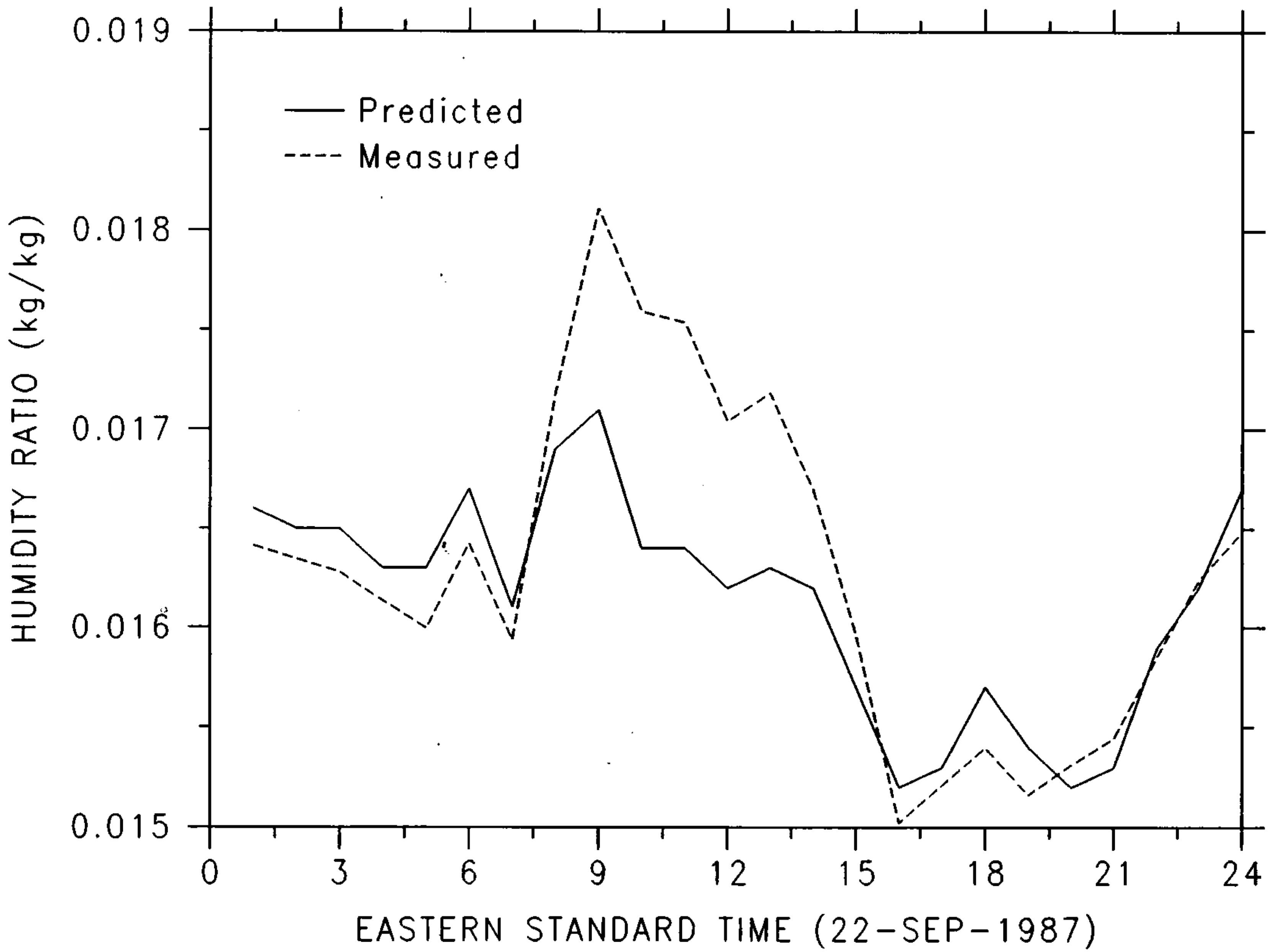


Figure 4.2-12 Comparison of predicted and measured outlet humidity ratios.

transport has substantially reduced discrepancies between predicted and measured data. Uncertainties in moisture material property data and attic airflow pattern are believed to cause the major disparities still existing between measurement and prediction. This stresses the need for extensive research on moisture properties for commonly used building materials.

4.2.2 Simple Heat Balance Model

A simple, steady-state, heat-balance model has also been developed. Figure 4.2-13 graphically illustrates the model. The model uses temperature and direction dependent flat-plate convection coefficients (ASHRAE) as boundary conditions for the solid domains of the problem. Radiation is modelled using infinite parallel plate assumptions. The major simplifying assumption used in the model is that airflow between the floor of the attic and the roof of the attic is driven by bouancy. No bouyancy calculations are performed but the energy flow between the air adjacent to the ceiling insulation (Ta) and the air adjacent to the roof (To) is assumed to occur by convective mass flow at the prescribed attic ventilation airflow rate (Vflow).

The model was compared to parallel airflow experimental results obtained by Joy [1958] with favorable results (see Figure 4.2-14). The model is not capable of modeling attics with airflows perpendicular to the attic structure. It is important to remember that the simplicity of the model

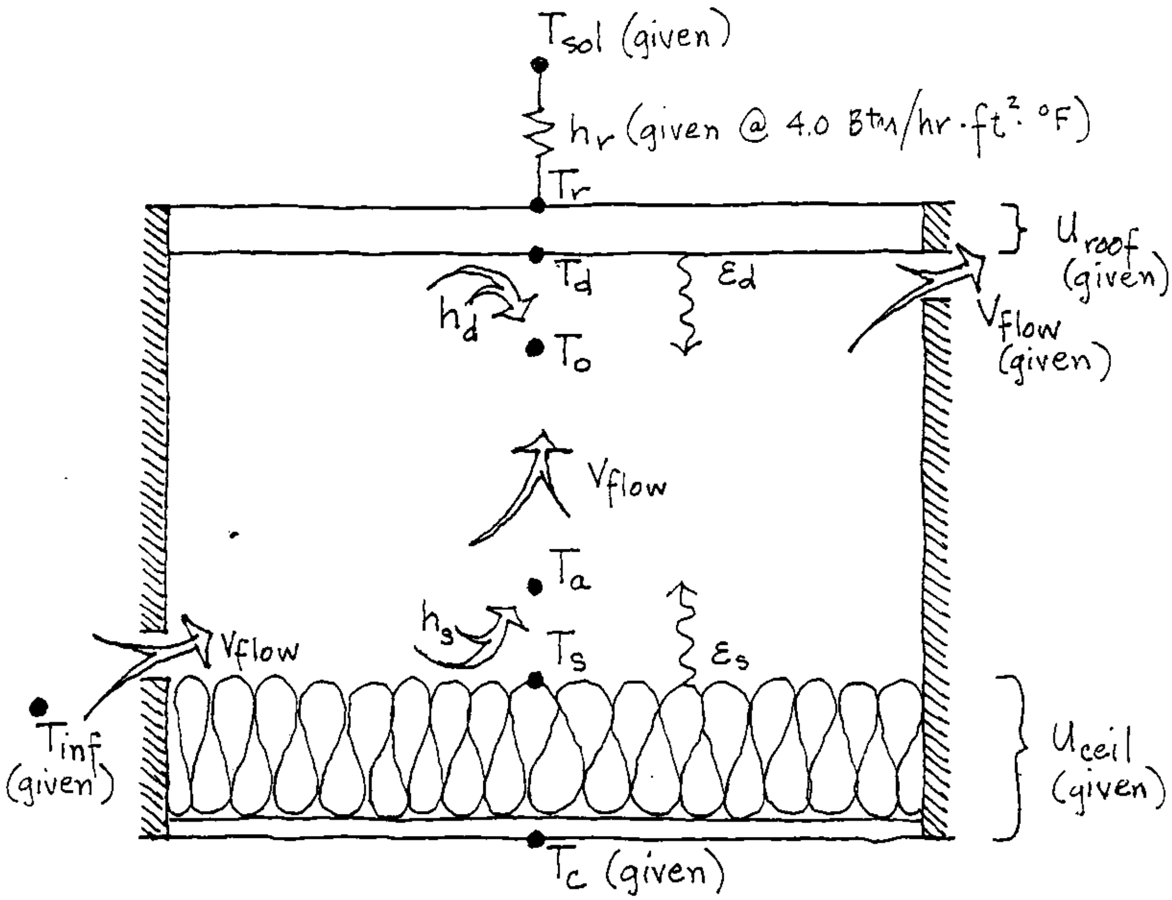


Figure 4.2-13 Schematic diagram of SIMPLE model

Energy balance equations:

$$@\ T_r:\quad h_r(T_r - T_{sol}) + U_r(T_r - T_d) = 0$$

$$@\ T_d:\quad h_d(T_d - T_o) + U_r(T_d - T_r) + E\,(T_d^4 - T_s^4) = 0$$

$$@\ T_o:\quad h_d(T_o - T_d) + V_f(T_o - T_a) = 0$$

$$@\ T_a:\quad h_s(T_a - T_s) + V_f(T_a - T_{inf}) = 0$$

$$@\ T_s:\quad h_s(T_s - T_a) + U_c(T_s - T_c) + E\,(T_s^4 - T_d^4) = 0$$

where

$$h_d = 0.12(T_d - T_o)^{0.25}$$

$$h_s = 0.27(T_s - T_a)^{0.25}$$

$$V_f = \rho V C_p$$

$$E = \frac{\sigma}{\frac{1}{\varepsilon_d} + \frac{1}{\varepsilon_s} - 1}$$

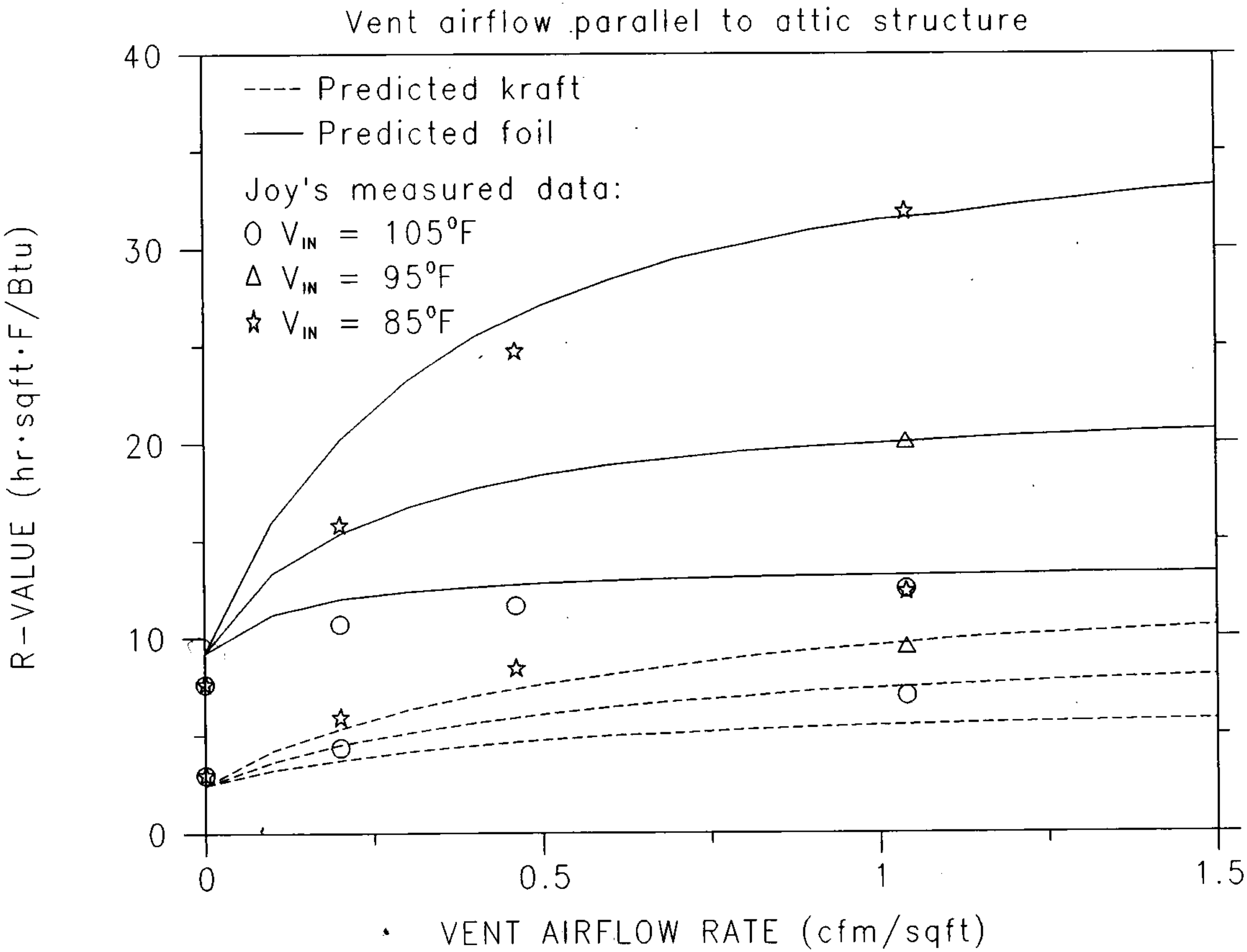


Figure 4.2-14 Joy's R-values versus predictions by XRBS model

requires that its results be interpreted only in a general sense. The model can show trends and parameter sensitivities but cannot fully describe the complex, dynamic phenomena that occur in real attics.

This simple model was used to examine the sensitivity of attic RBS to the following parameters:

- Ventilation air temperature
- Sol-air roof temperature
- Ceiling insulation level
- Radiant barrier emittance
- Room thermostat setting, and
- Radiant barrier location

Each of these parameters was examined at a range of attic ventilation rates and the results are given as a percent reduction in ceiling heat transfer with respect to the same attic system without a radiant barrier surface.

Results from the analysis show that ventilation air temperature and radiant barrier surface emittance are the prime parameters of attic RBS. Attic RBS effectiveness is most sensitive to surface emittance. Figure 4.2-15 clearly illustrates the effect of surface emittance changes on the performance of attic RBS. Figure 4.2-16 gives the effect of vent air temperature on attic RBS effectiveness. This figure also shows the effect of RBS location in the attic. While the effectiveness of the RBS is a fairly strong

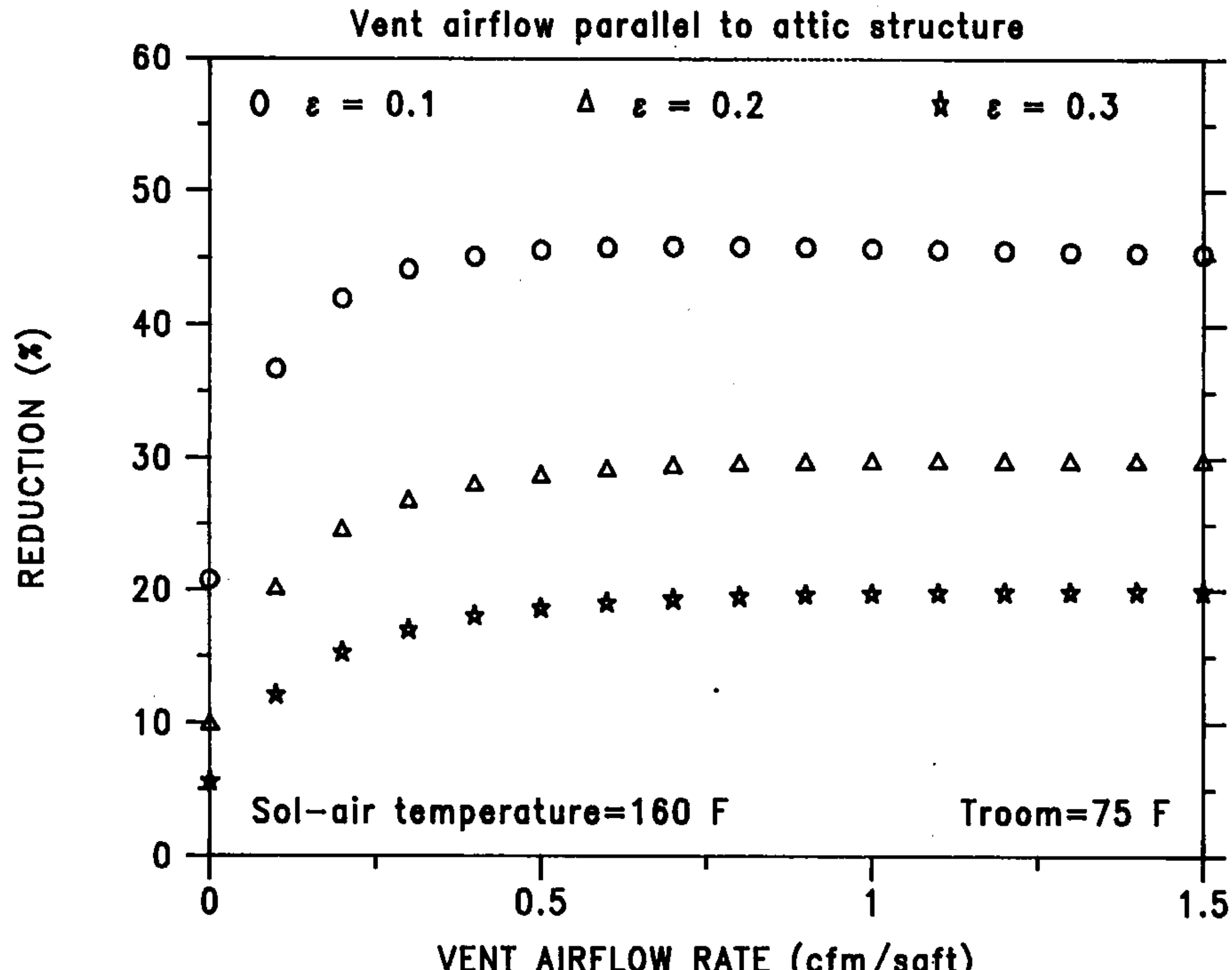


Figure 4.2-15 Comparison of effects of low-ε surface emittance for attics with R-19 ceiling insulation and vent air inlet=85 F

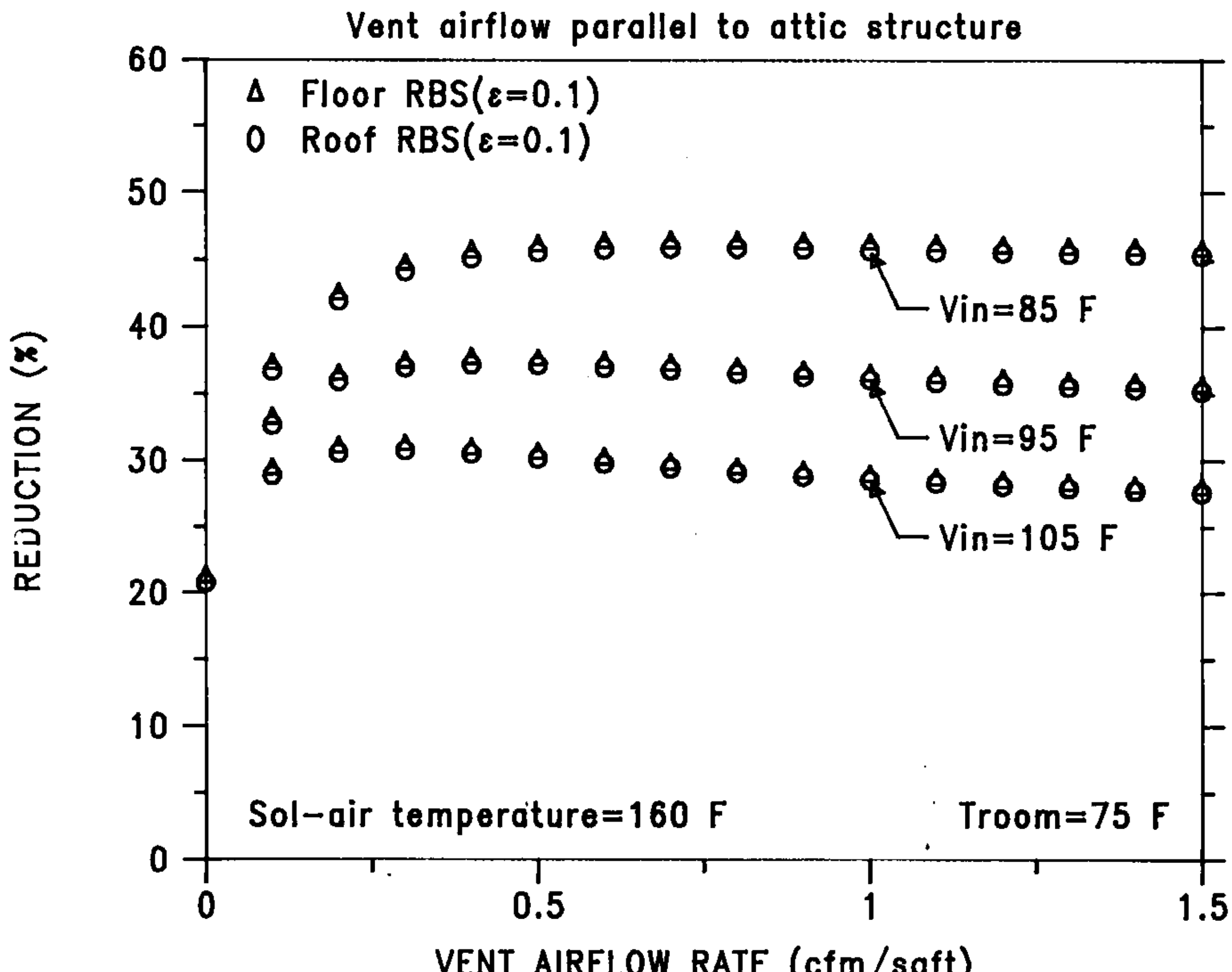


Figure 4.2-16 Comparison of SIMPLE predictions for attic roof and attic floor RBS for R-19 attics at 3 vent inlet temperatures

function of the vent air temperature, there appears to be no sensitivity in the model to the location of the radiant barrier (roof versus attic floor).

The remaining parameters show less sensitivity. Performance is somewhat sensitive to both the sol-air temperature (Figure 4.2-17) and the conditioned space temperature (Figure 4.2-18), but ceiling insulation level appears to have virtually no effect on the effectiveness of the attic RBS (Figure 4.2-19).

Thus, it appears that the major parameters affecting RBS performance are the emittance of the radiant barrier surface and the temperature of the attic ventilation air (ambient). It should be possible to combine the effects of the sol-air temperature and the vent air temperature by subtracting one from the other and developing an effectiveness based on the result. The ventilation airflow rate also affects performance but this effect appears to asymptotically approach the expected attic ventilation rates of naturally vented field attics (0.25 cfm/ft^2).

4.3 Field Swatch Tests

The field swatch tests are long-term field tests designed to record the effects of dust accumulation, chemical degradation and mechanical failure on two generic types of RBS, a vapor deposition product and a foil laminate product. A test protocol (Fairey and Beal, 1987) has been developed

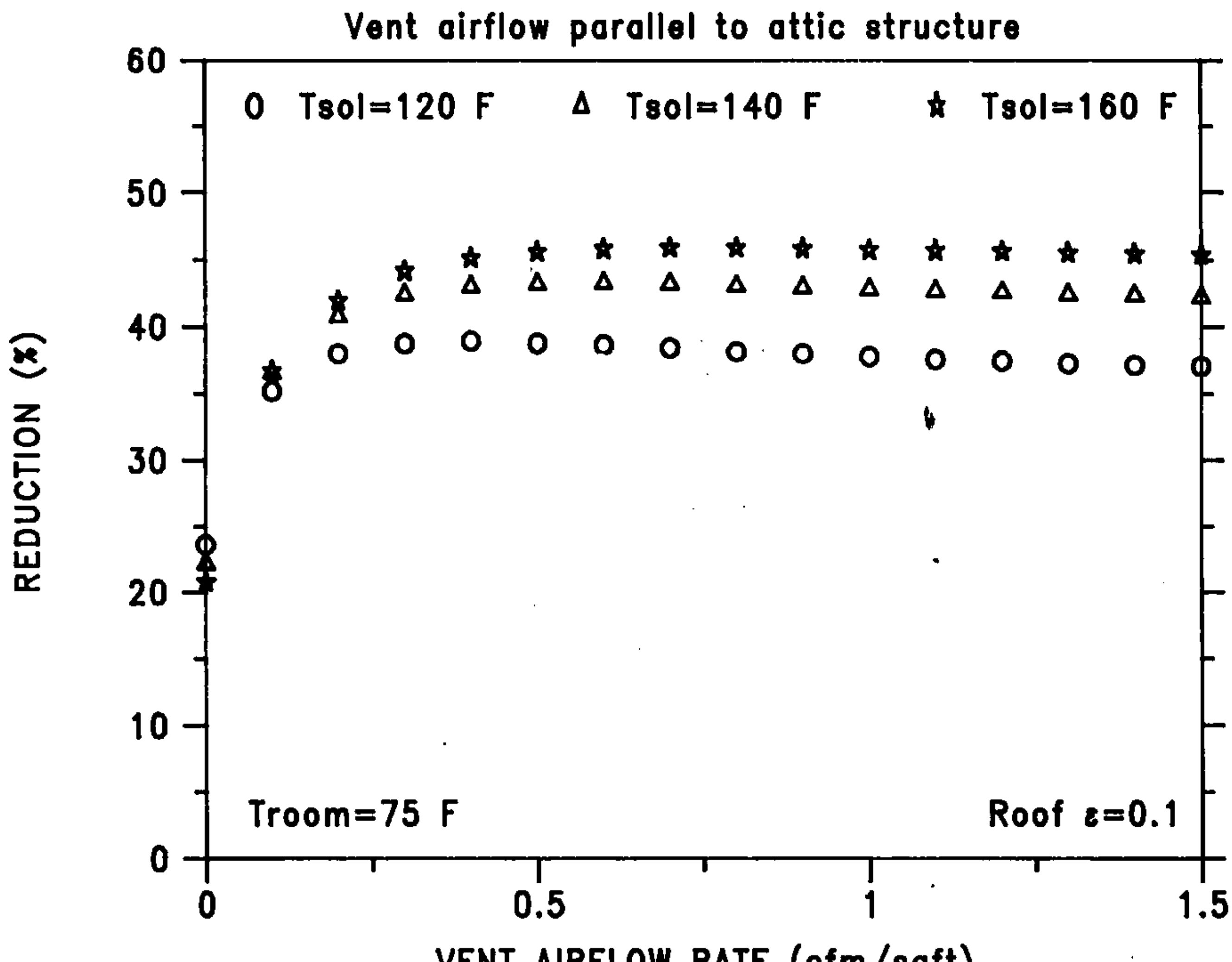


Figure 4.2-17 Comparison of effects of sol-air temperatures for attics with R-19 ceiling insulation and vent air inlet=85 F

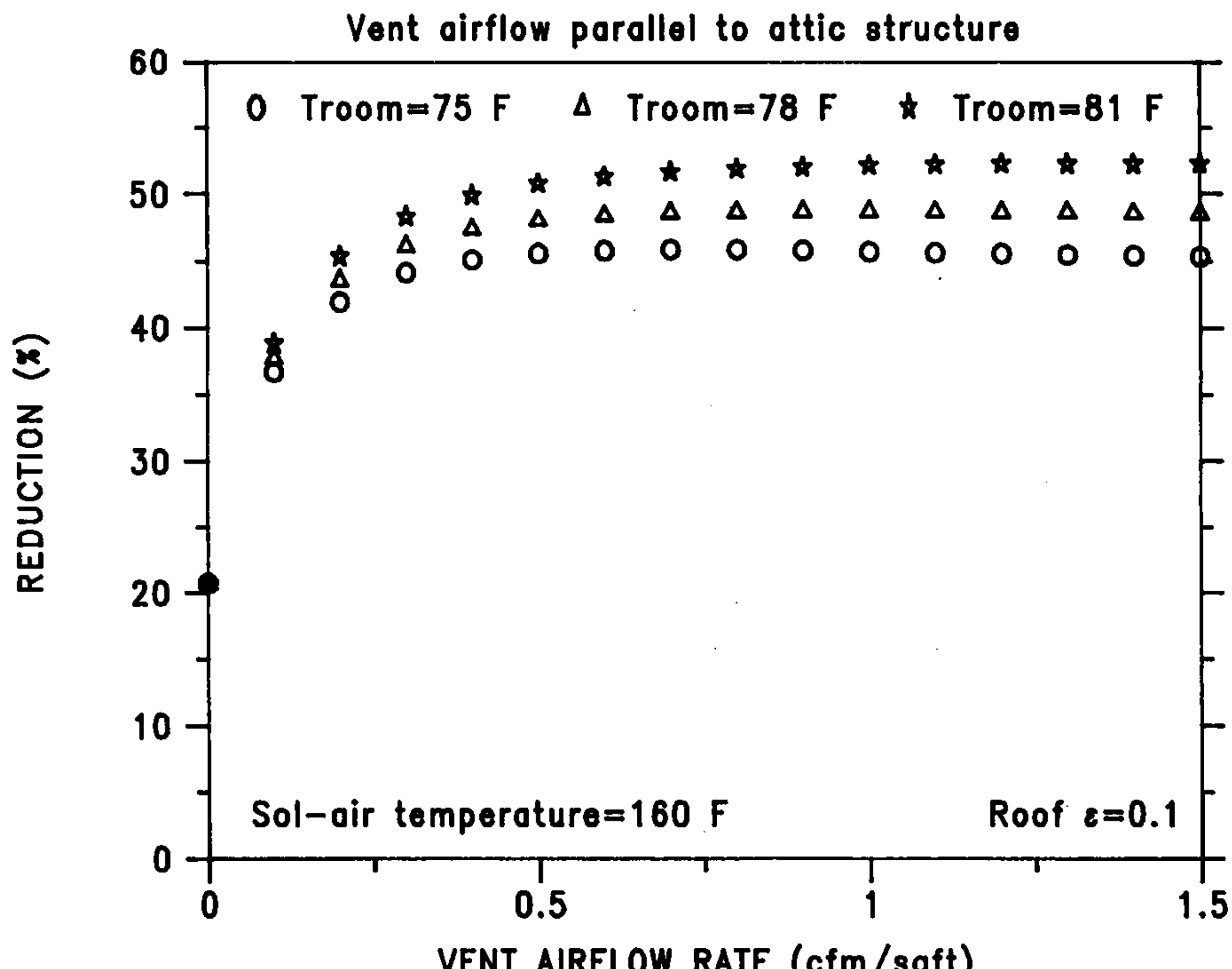


Figure 4.2-18 **Comparison of effects of room thermostat setting for attics with R-19 ceiling insulation and vent air inlet=85 F**

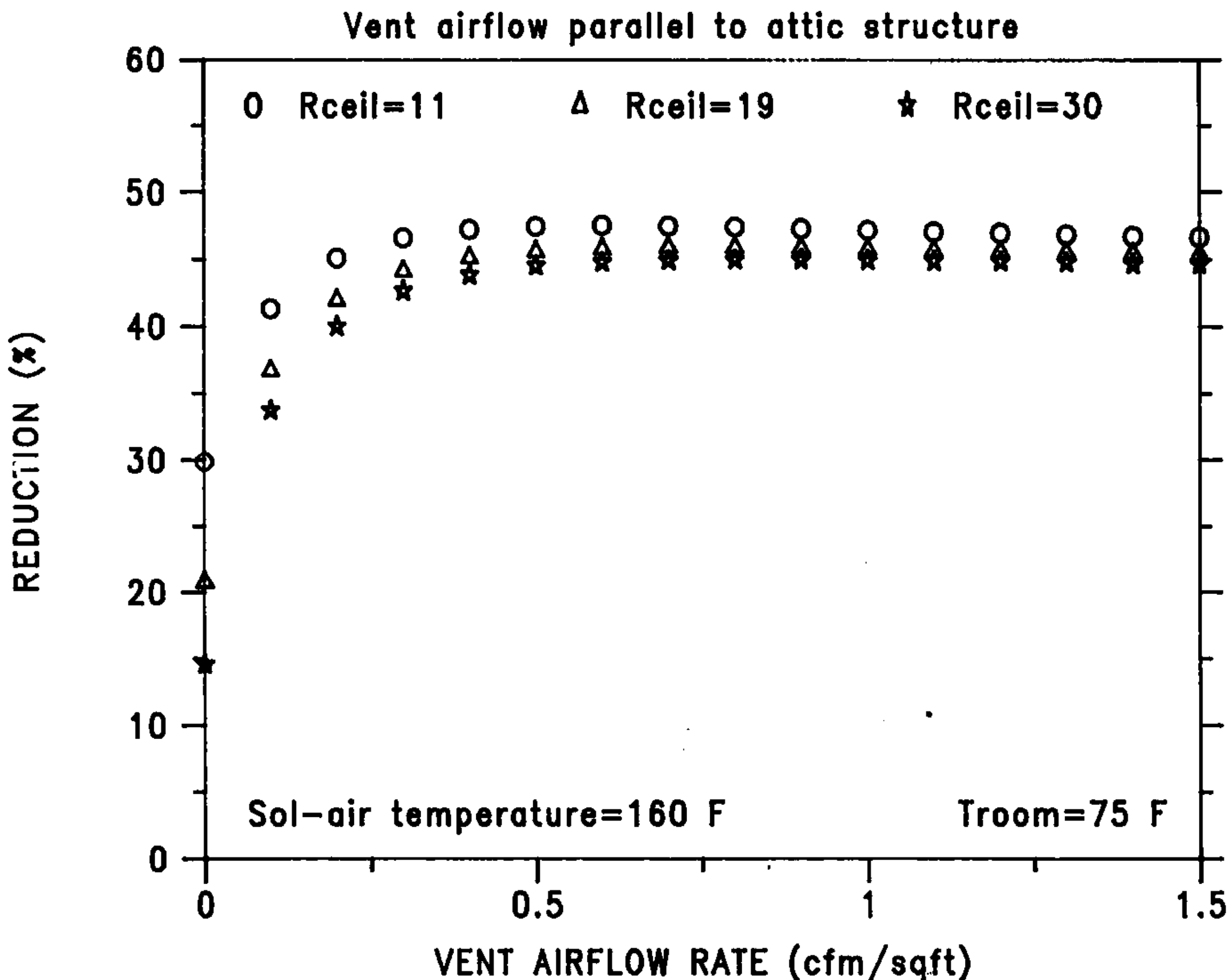


Figure 4.2-19 Comparison of effects of base ceiling insulation R-value with vent inlet air=85 F and ε=0.1 at attic roof

and samples have been placed in the attics of 12 local residences. On a periodic basis samples are removed from each residence and brought back to the lab for analysis.

Only preliminary data are available but it appears that dust collection occurs on horizontal surfaces at a fairly rapid rate in vented attics. As yet, no material surface degredation has been observed in these tests.

Sixteen samples of each type of RBS have been placed in a dozen houses. The samples are 4" by 8" swatches of material placed in a 5"x9"x 1/2" lidded PVC box. With each sample is a microscope slide. The samples and slides are coded with a simple binary code to indicate the house, the kind of RBS and the individual sample. The coding is implemented with a hole punch on the sample and an indelible marker on the slide.

Samples are to be collected from the field houses over a five year period. The samples were placed in the field houses during the week of September 14 - 18, 1987. Table 4.3-A gives the time schedule for the sample pickups.

Houses with a variety of attic environments have been selected; houses in rural and residential areas, houses on dirt roads and houses on paved roads are included. Their surroundings vary from water front to wood lot. Unfortunately, none of the houses is in a truly polluted air environment.

TABLE 4.3-A

Sample table for 5 year dust collection tests

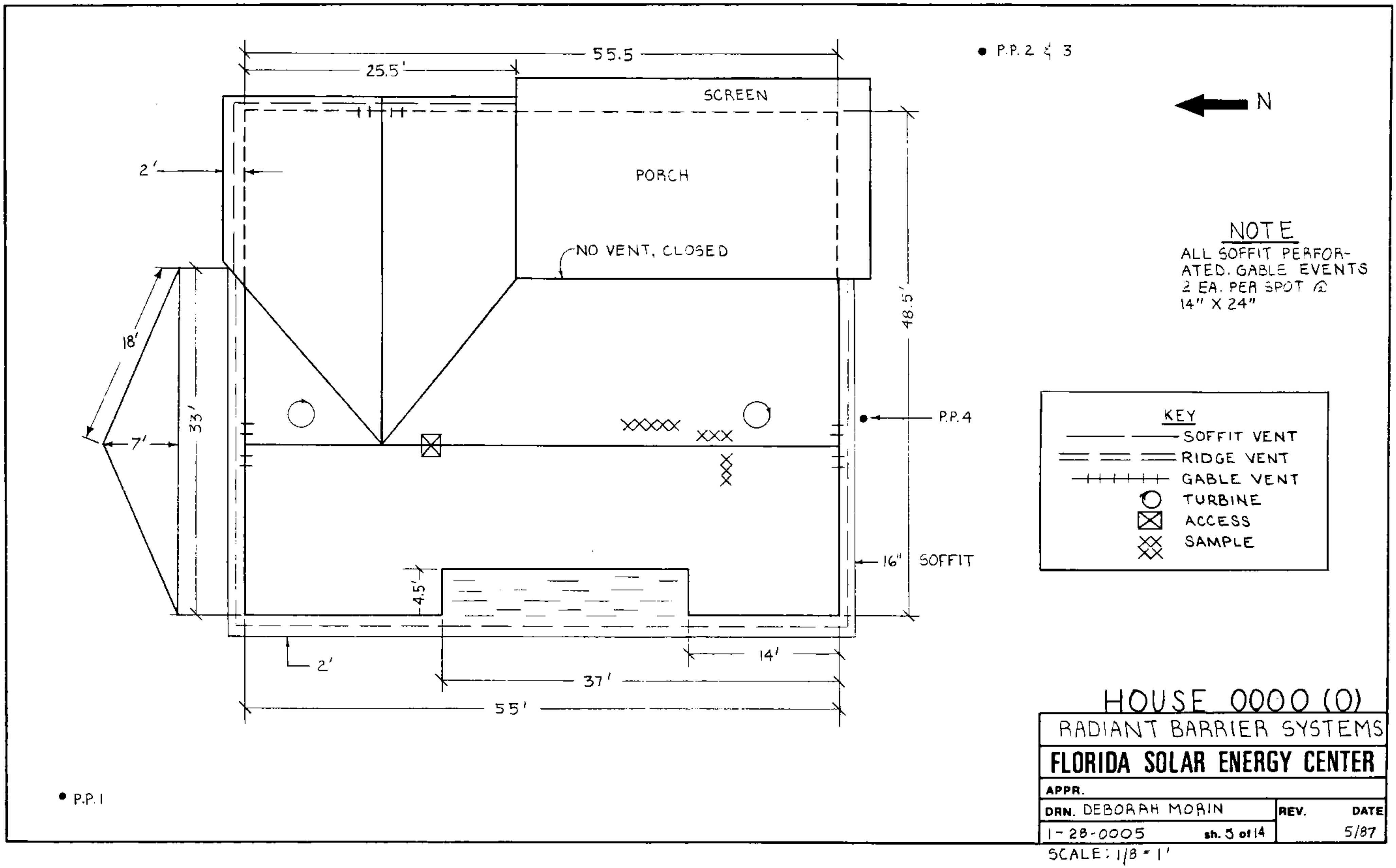
sample	#	1	=	37	days	delta	=	37	days
sample	#	2	=	80	days	delta	=	43	days
sample	#	3	=	130	days	delta	=	50	days
sample	#	4	=	187	days	delta	=	57	days
sample	#	5	=	253	days	delta	=	66	days
sample	#	6	=	329	days	delta	=	76	days
sample	#	7	=	417	days	delta	=	88	days
sample	#	8	=	519	days	delta	=	112	days
sample	#	9	=	635	days	delta	=	116	days
sample	#	10	=	770	days	delta	=	135	days
sample	#	11	=	926	days	delta	=	156	days
sample	#	12	=	1105	days	delta	=	179	days
sample	#	13	=	1312	days	delta	=	207	days
sample	#	14	=	1550	days	delta	=	238	days
sample	#	15	=	1825	days	delta	=	275	days

A detailed site plan, along with a written description and photographs, was made of each attic. Of special importance were the roof type and area; the attic venting and vent area; the attic floor space, area, and construction; and the kind of insulation. An example of the documentation is included in Figure 4.3-1.

As of February 23, 1988 two sample pickups had been made. One sample pickup was missed in December because the initial pickup had not been processed. The processing difficulties have been overcome and all future pickups can be made in a timely manner.

Initial emissivity measurements were taken on 256 samples of each of the two generic RBS types. The measurements by type were all within $\pm$1%. The foil laminate samples had average measured emittances of about 0.03 and the vapor deposition samples had measurements that averaged about 0.05.

The field samples are returned to FSEC for analysis. FSEC is equipped with a microscope that is capable of transmitted and reflected, bright field and dark field work. Visual magnifications of 50 and 100 power and photographic magnifications of 12.5 and 25 power are available. The camara is equipped with a data back that imprints an alpha numeric code on the negative. The binary code on the sample is represented by the middle two numbers. The type of RBS (foil or vapor deposition) is represented by the leading letter and the magnification of the picture (12 or 25) is



55.5
25.5'
SCREEN
PORCH
NO VENT, CLOSED
2'
18'
7'
33'
4.5'
14'
37'
55'
48.5'
16" SOFFIT
P.P. 1
P.P. 2 & 3
P.P. 4
N
NOTE
ALL SOFFIT PERFORATED. GABLE EVENTS 2 EA. PER SPOT @ 14" X 24"
KEY
SOFFIT VENT
RIDGE VENT
GABLE VENT
TURBINE
ACCESS
SAMPLE
HOUSE 0000 (0)
RADIANT BARRIER SYSTEMS
FLORIDA SOLAR ENERGY CENTER
APPR.
DRN. DEBORAH MORIN
REV.
DATE
5/87
1-28-0005
sh. 5 of 14
SCALE: 1/8 = 1'

Figure 4.3-1

represented by the trailing number. An example photograph of the dust collection over a 29 day period in one attic is included at Figure 4.3-2.

Emissivity increases measured from the collected field samples are shown in Figures 4.3-3 and 4.3-4. The graphs show the increase in emissivity from that originally recorded for the samples as a function of their exposure time in the field. The characters represent the house numbers (0 through 9 and A and B).

To get an accurate indication of the percentage dust accumulation and dust particle size the microscope image is digitized. A Charge Coupled Device (CCD) camera that mounts on the microscope and interfaces with an IBM XT and existing software is used. This method bypasses photography and takes a direct digital image of the slide. The software will allow use of the XT as a monitor, the making of hard copies via a laser printer and the calculation of dust coverage by percent area coverage. Examples of laser printer images of dust accumulation in the worst and best attics are given in Figures 4.3-5 and 4.3-6.

Dust accumulation data are then correlated to emittance measurements taken from the material samples. Results from this correlation are shown in Figure 4.3-7. The graph gives the increase in emissivity from that originally recorded for the samples as a function of the percent area dust coverage. Although the data are preliminary, a clear relationship

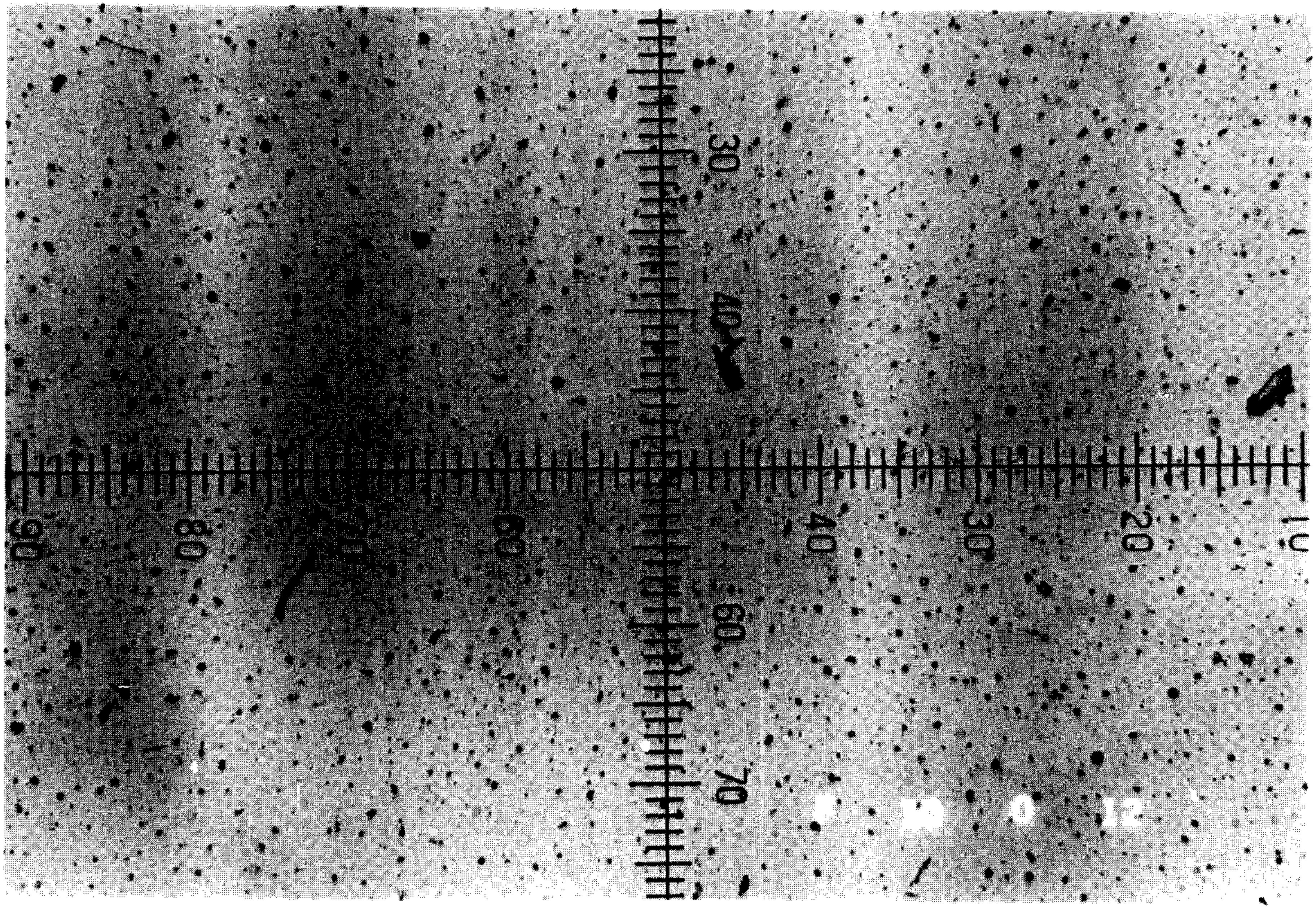


Figure 4.3-2 Photomicrograph of dust collection over 29 day period. (30 divisions equal 1 mm)

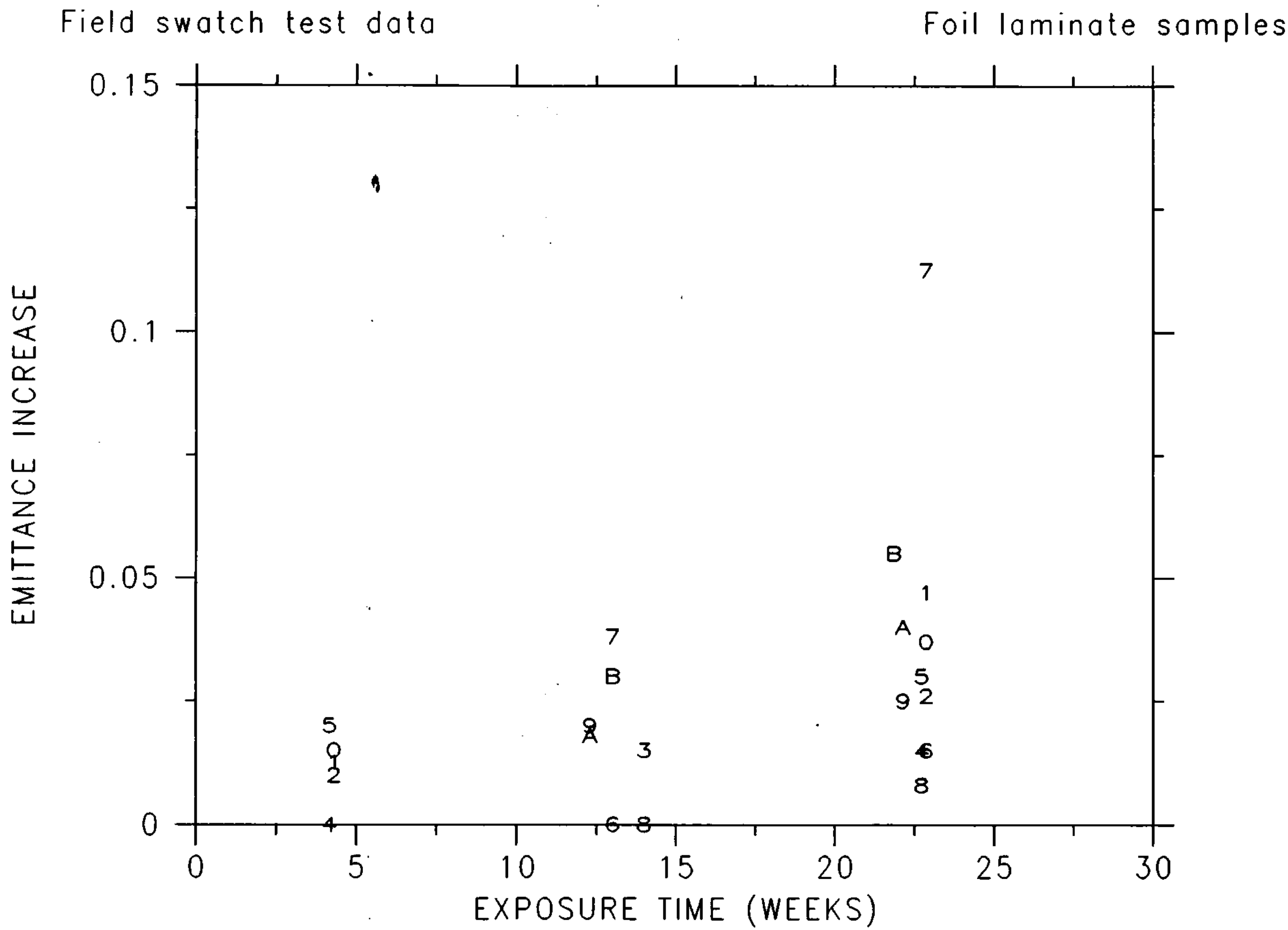


Figure 4.3-3 Change in measured surface emittance due to dust collection for foil laminate samples removed from attics over time.

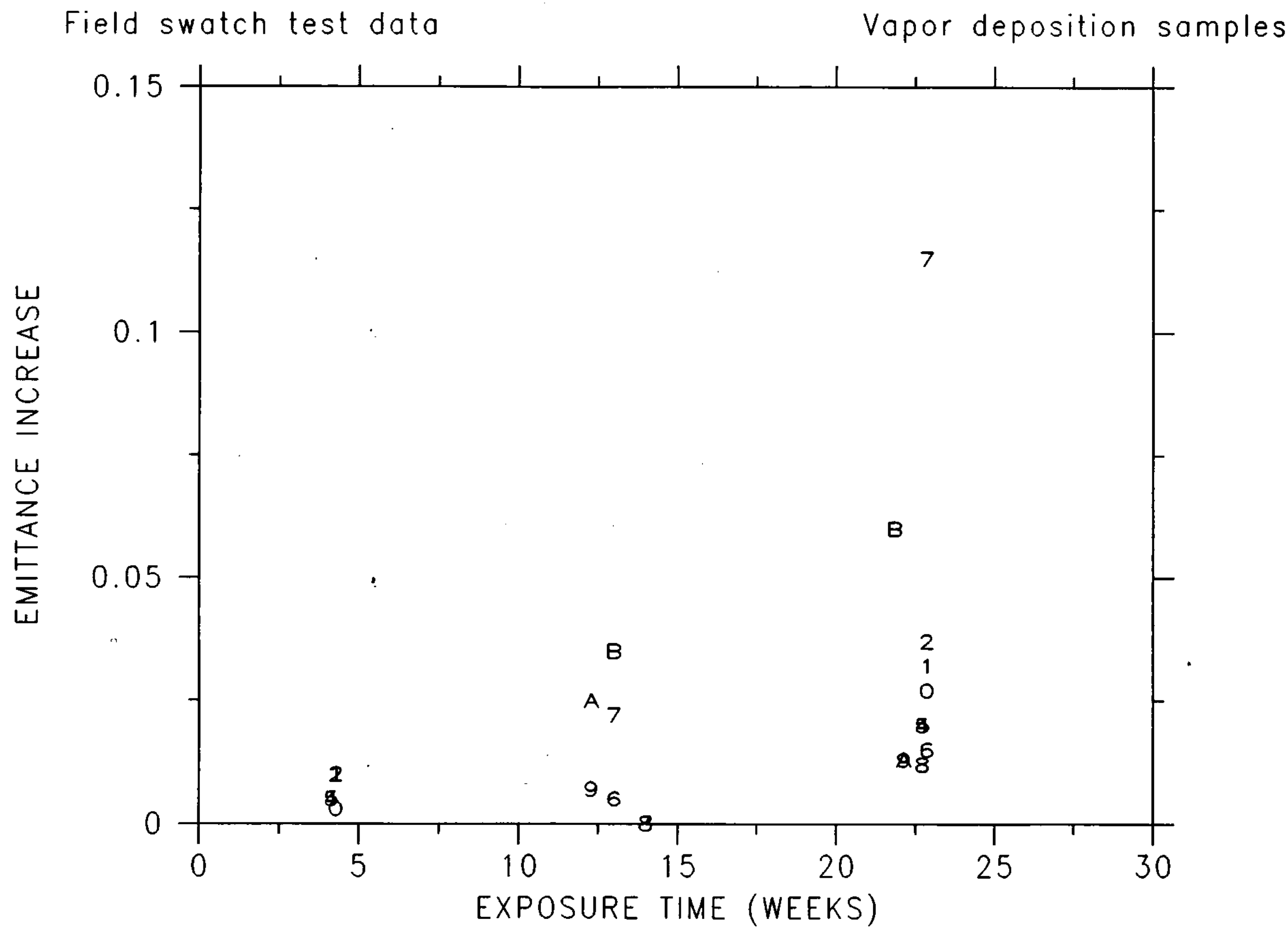


Figure 4.3-4 Change in measured surface emittance due to dust collection for vapor deposition samples removed from attics over time.

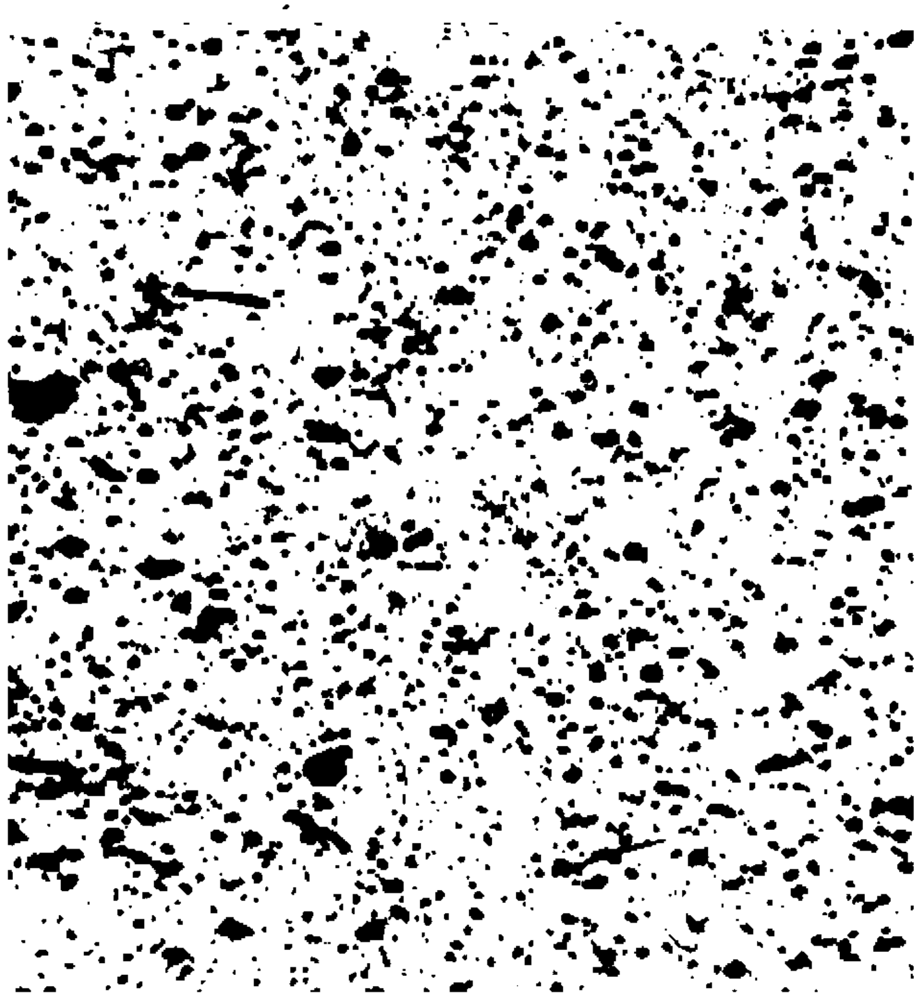


Figure 4.3-5 F0111 0001 160 DAYS 17.5%

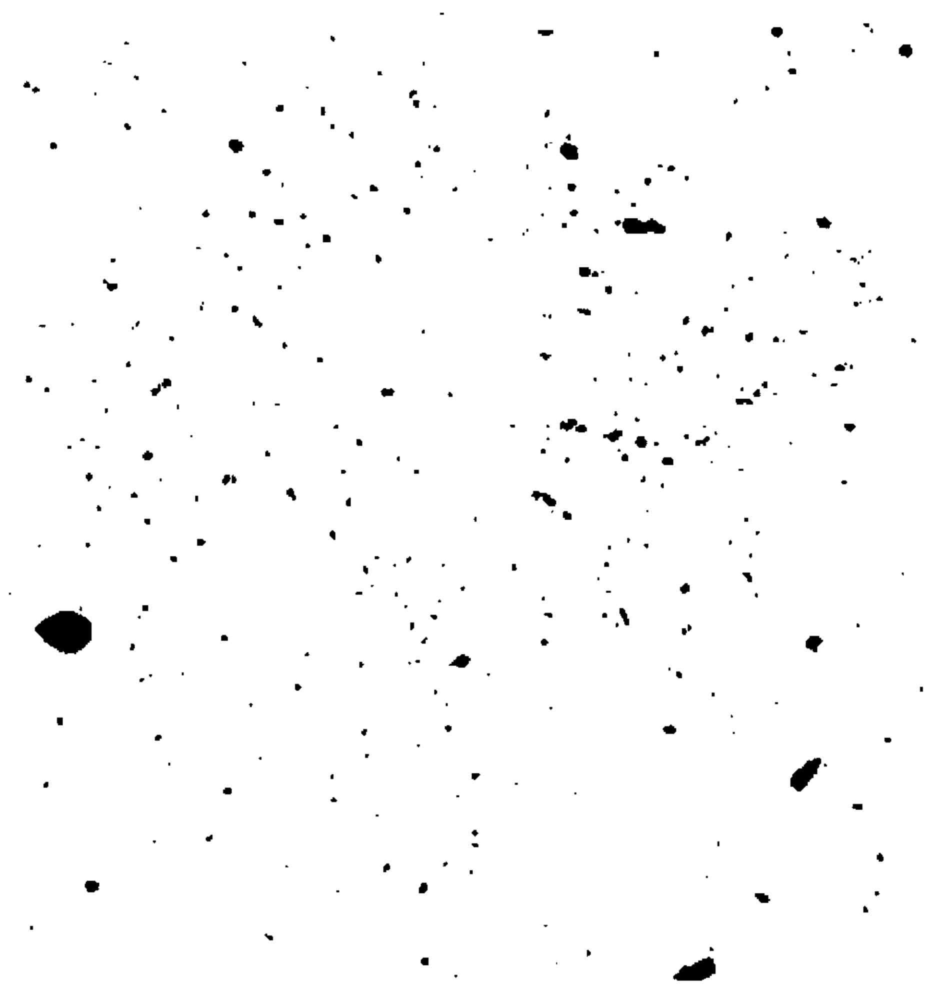


Figure 4.3-6 **F0100 0001** **159 DAYS** **1.2%**

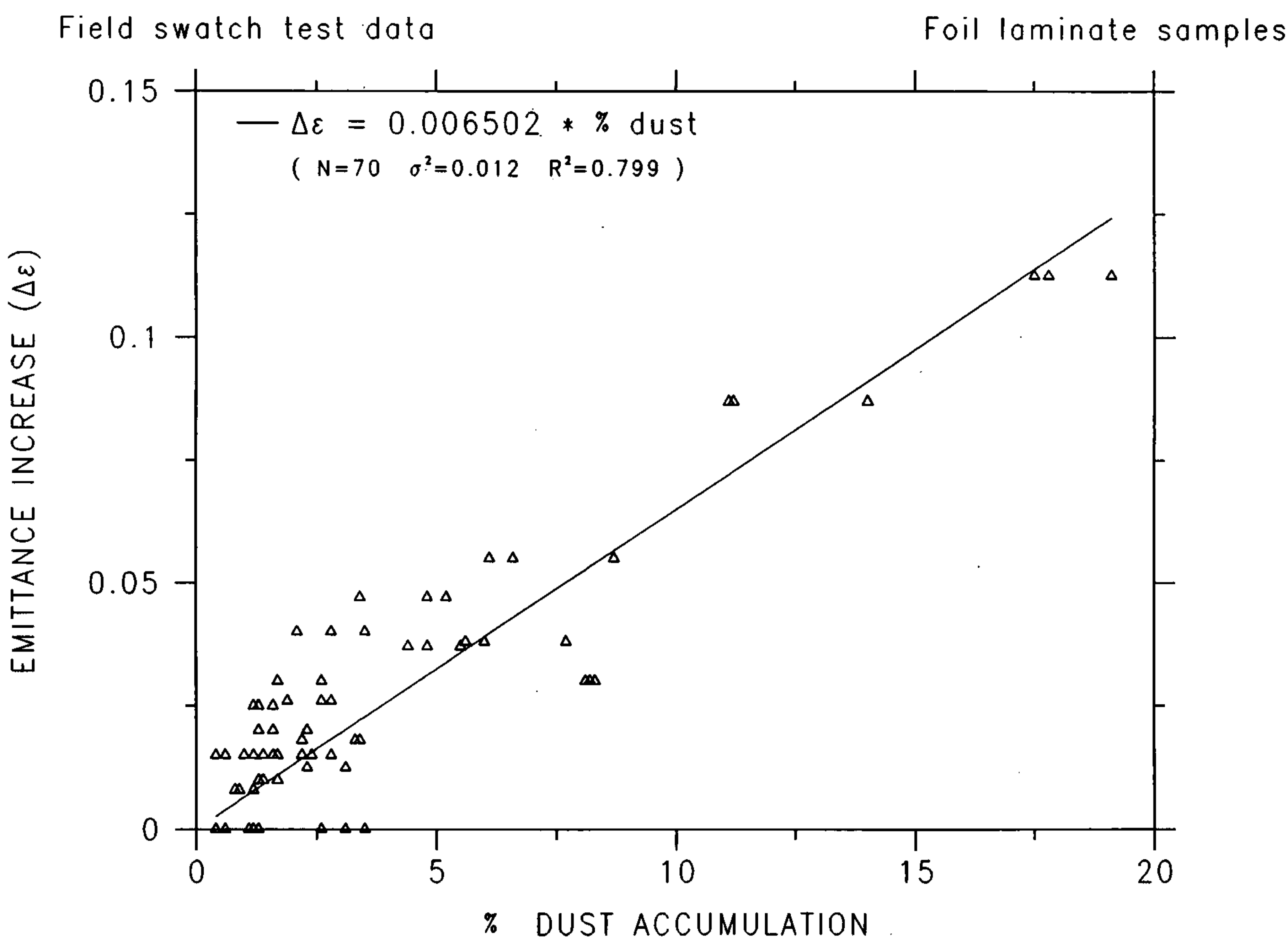


Figure 4.3-7 Change in surface emittance versus dust acculation

between dust coverage and emmisivity degradation is apperant. A liner fit of the data predicts an emmisivity increase of .65 when there is 100% dust coverage. It is not expected that this relationship will continue to be liner. Clearly the emmisivity will become that of the dust, setting an asymptotic limit for the emmisivity. Yarbrough's data (see Section 3.3) shows an emittance asymptote of 0.85 for dust used in his laboratory experiments.

Any visible surface degradation, other than dust accumulation, will be photographed and scanned as needed. The effect on emissivity can be deduced by cleaning of the sample and comparison to samples with similar dust accumulations. If severe material surface degredation is observed an effort will be made to determine its cause through chemical analysis of the sample.

Already attrition is striking the field houses. One of the attics was bombed for vermin, ruining all samples. Air conditioning repairmen disturbed samples in another and a curious raccoon played with the slides in one house. The last two intrusions did not significantly effect the samples.

4.4 UF Whole-house Tests

During summer 1987, RBS energy consumption and demand tests were performed by the University of Central Florida under subcontract with FSEC. The tests were performed at the

Energy Research and Development Park (ERDP) in Gainesville, FL in two similar residences having approximately 1200 ft^2 of conditioned floor space (see Lear, 1987). One house was of concrete block construction and one was wood frame construction. Both houses were subjected to internally generated loads of approximately 12.5 kWh per day and both were equipped with moisture generators to simulate normal internal moisture loads on houses. The air conditioning units in both houses were replaced at the start of the tests to provide matched units and both houses were tightened to similar infiltration levels through blower door techniques.

Because the houses are of different construction and slightly different in size it was necessary to perform a battery of RBS experiments that included the full compliment of possibilities. In the order of performance the tests were as follows:

- Both attics standard
- Frame attic standard and block attic RBS
- Both attics RBS
- Frame attic RBS and block attic standard

Both residences had R-19 ceiling insulation for all tests. For RBS test periods roof mounted RBS using single-sided radiant barriers facing the attic airspace were added. Each test condition was maintained for approximately 21 days before proceeding to the next test. The intent of the test series was to provide sufficient data so that performance could be normalized with respect to the two test conditions with the same configuration (i.e., both standard or both RBS). In this way both the differences between the houses and the differences in weather can be normalized to a common base.

As in most experiments, there were initially some problems and missed data. During the initial test period a significant amount of the electrical data was lost. Additionally, when the data were analyzed the measured house temperatures were found to be different during this test. The block house temperature was 0.4 F warmer than the frame house for the first test period but for the remaining three test periods the frame house temperature was 0.4 F warmer than the block house. Thus, only the last three test periods provide sufficient data and similar enough test conditions for analysis. The third test period (both RBS) provides normalization data for the other two test periods.

As previously stated, the intent of the tests was to study the electrical demand reduction resulting from the use of the attic RBS. Figure 4.4-1 compairs the coincident air conditioning electical demand for the two residences when they are configured alike.

It is important to note that the coincident air conditioning demand of the two residences is significantly different, even during the null tests. The regression shows a block house hourly demand of about 0.2 kW when there is no demand

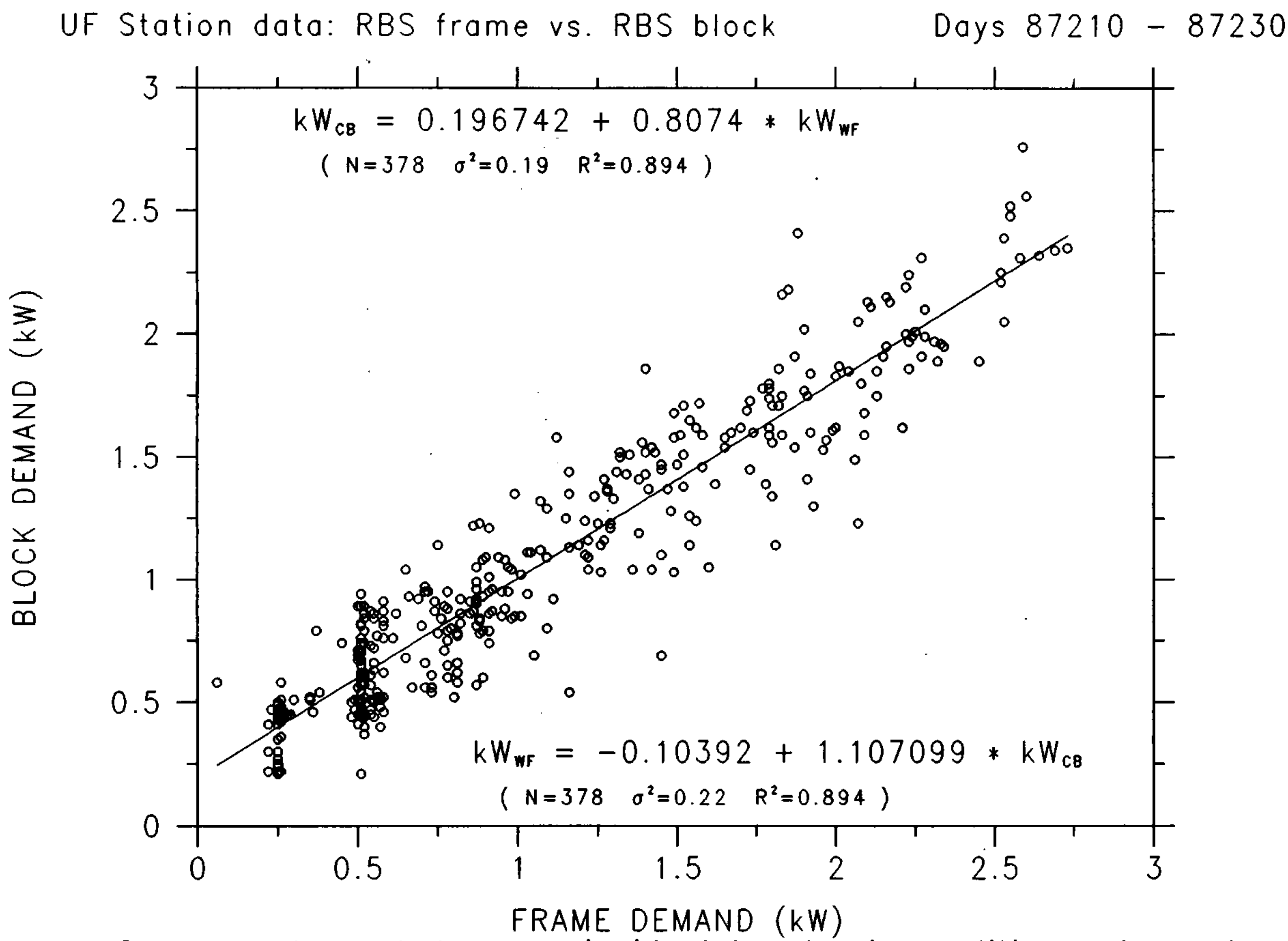


Figure 4.4-1 Correspondance between coincident hourly air conditioner demand for Gainesville, FL test houses

for the frame house. But at peak the frame house demand is almost 10 percent higher than the block house demand. This results in roughly equivalant total air conditioning consumption for the residences even though their demands are significantly different. Because the houses are different and the weather cannot be held constant from test to test, it is quite important that the analysis consider these demand differences. In order to do this the regression analysis given in Figure 4.4-1 is used to normalize the data from the other two test periods.

Figures 4.4-2 and 4.4-3 give the coincident air conditioning demands and regression analyses for the remaining test periods. The analysis is accomplished by comparing the regression from Figure 4.4-1 with each of the other regressions in the following manner:

For the frame(wf) house using the block(cb) house as the reference(ref):

```
   STD wf vs RBS cb:   kWwf  = -0.16506 + 1.239023*kWref
 - RBS wf vs RBS cb:   kWwf  = -0.10392 + 1.107099*kWref
 ------------------------------------------------------
   STD wf - RBS wf :   kWdif = -0.06114 + 0.131924*kWref
```

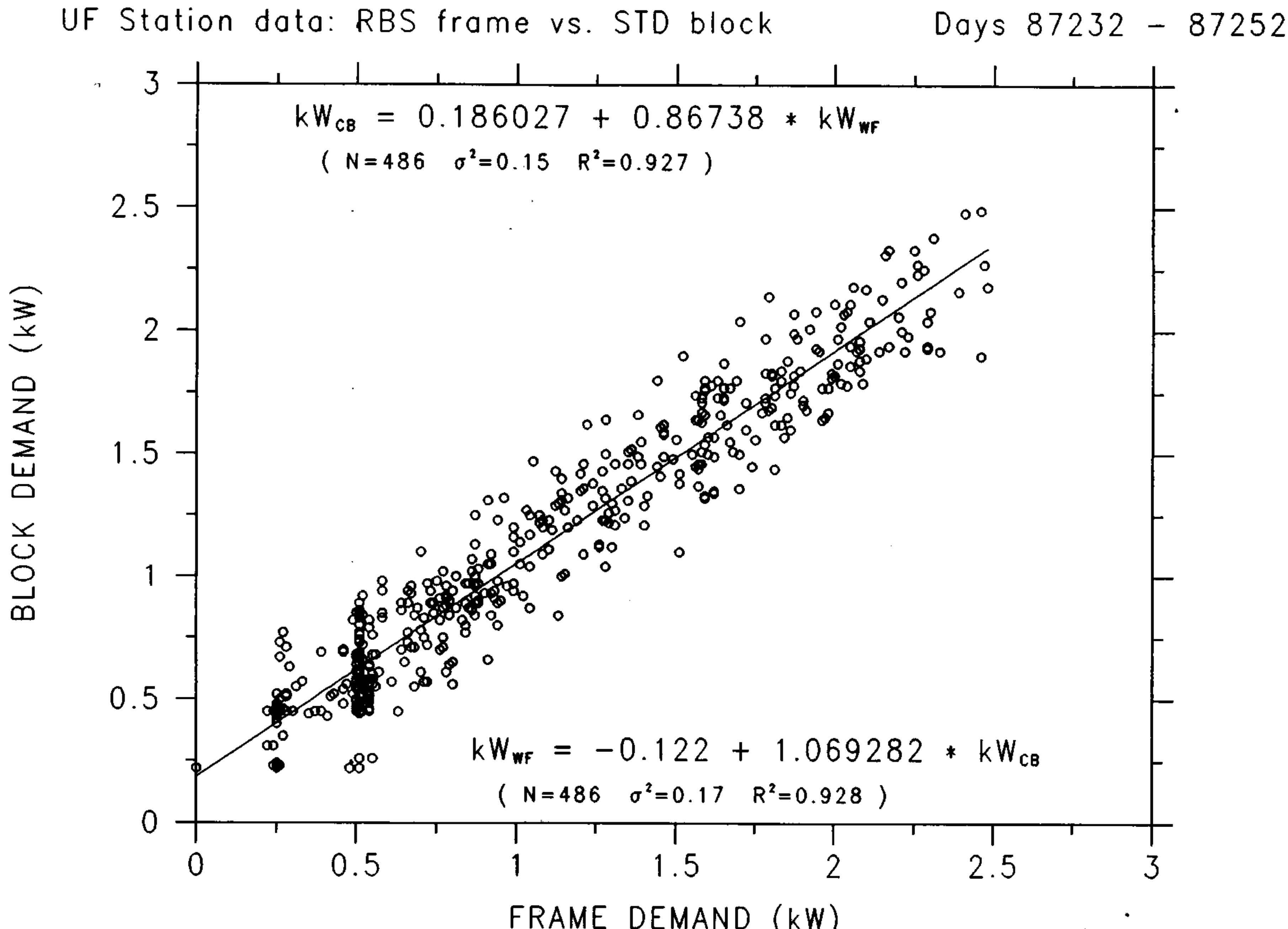


Figure 4.4-2 Correspondance between coincident hourly air conditioner demand for Gainesville, FL test houses

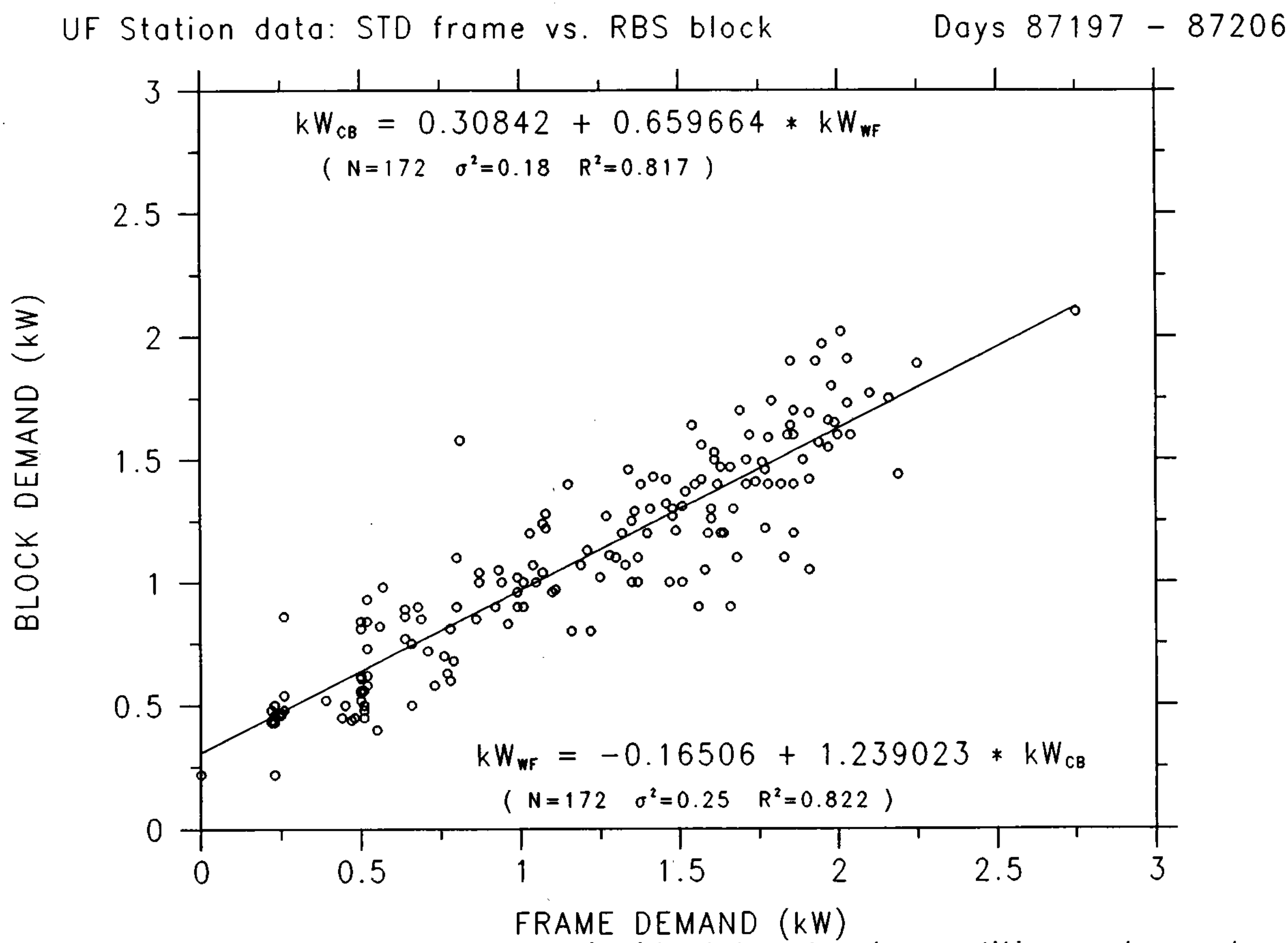


Figure 4.4-3 Correspondance between coincident hourly air conditioner demand for Gainesville, FL test houses

For the block(cb) house using the frame(wf) house as the reference(ref):

```
   STD cb vs RBS wf:   kWcb  =  0.186027 + 0.86738*kWref
 - RBS cb vs RBS wf:   kWcb  =  0.196742 + 0.80740*kWref
 ------------------------------------------------------
   STD cb - RBS cb :   kWdif =  0.010615 + 0.05998*kWref
```

The fact that the block house serves as the reference for the frame house and vise versa is significant only because the reference does not change between tests. Once the difference equation is obtained, any condition can be used as the reference. In other words, if the demand for the frame RBS house is known the demand for the frame STD house can be calculated from the frame house difference equation. A similar approach is used for the block house where the block house difference equation is used.

The results of the above analysis are presented graphically in Figure 4.4-4. It is interesting to note that the demand reductions are quite different for the two houses. The frame house RBS produces a significantly higher peak demand reduction than the block house. This is partly due to the fact that the frame house has significantly less thermal capacitance and partly due to the fact that it is operated at a higher thermostat setting making the RBS more effective at the peak condition.

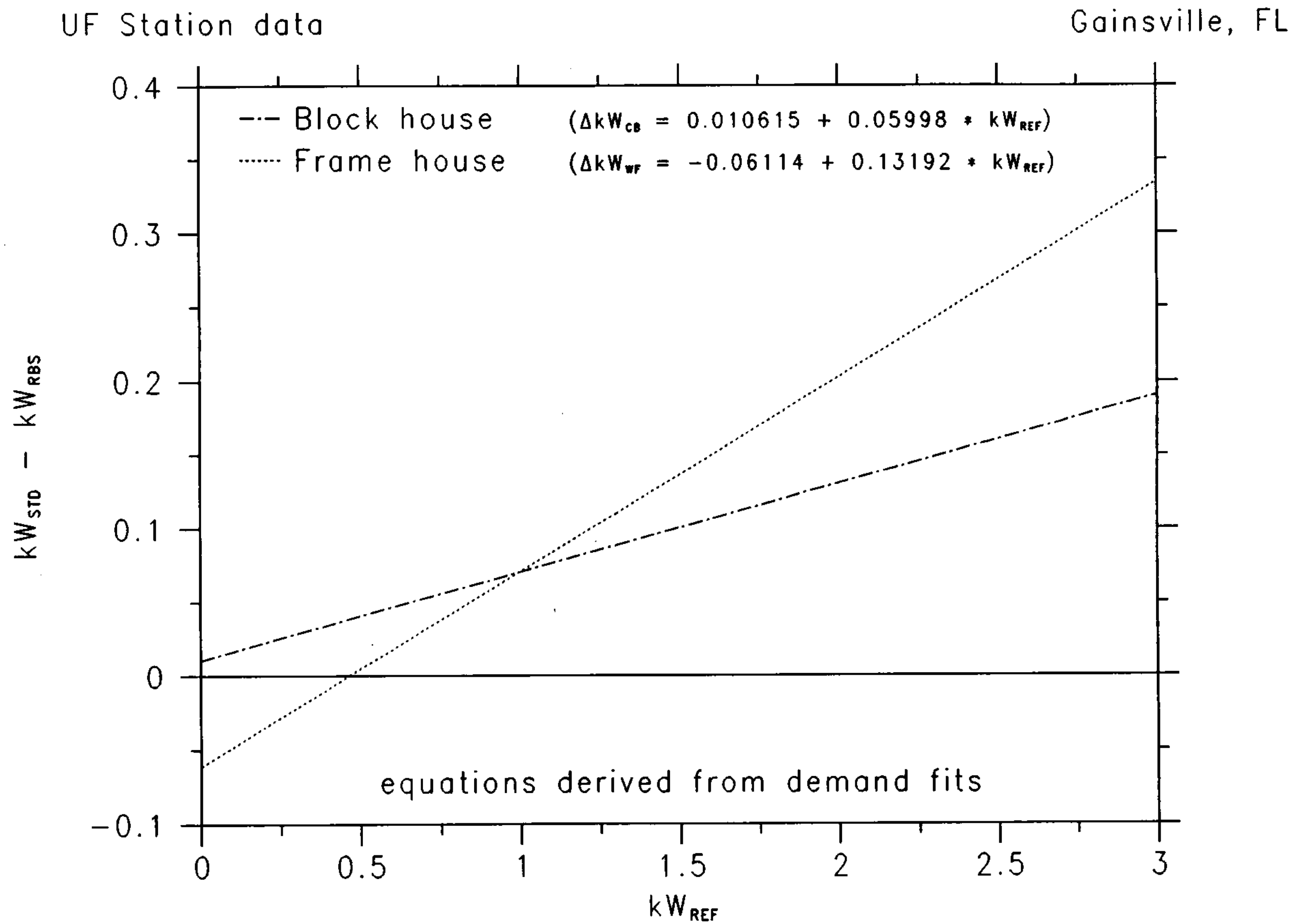


Figure 4.4-4 Difference in air conditioning demand between standard and RBS attics with respect to reference test demand

Demand curves comparing the standard and RBS attics are obtained by applying the respective difference equations to the measured demand. Figures 4.4-5 and 4.4-6 present the average hourly air conditioning demand for the two houses with and without RBS over a 16 day test period. As expected, the houses respond somewhat differently in time but both the average peak demand and the average daily consumption savings are apparent. For the block and frame house RBS the average peak demand reductions are 6.8 percent and 10.2 percent and the average daily consumption savings are 7 percent and 7.6 percent, respectively.

These building energy consumption savings are consistant with previous computer analysis performed by FSEC (Chandra, et.al., 1984). The computer analysis was conducted using a 1500 ft^2 frame residence and showed RBS cooling season savings between 8.6 and 10.5 percent for Florida locations. Additional computer analysis conducted by FSEC has shown that the energy savings for attic RBS in single story buildings increase with increasing floor area. Since the the University of Florida test houses are only 1200 ft^2 instead of 1500 ft^2 their measured RBS energy savings compare favorably with the computer predictions.

4.5 RBS Long-term Test Facility

The RBS long-term test facility is a residential-scale building, specifically designed to study the long-term performance of installed radiant barrier systems. Three

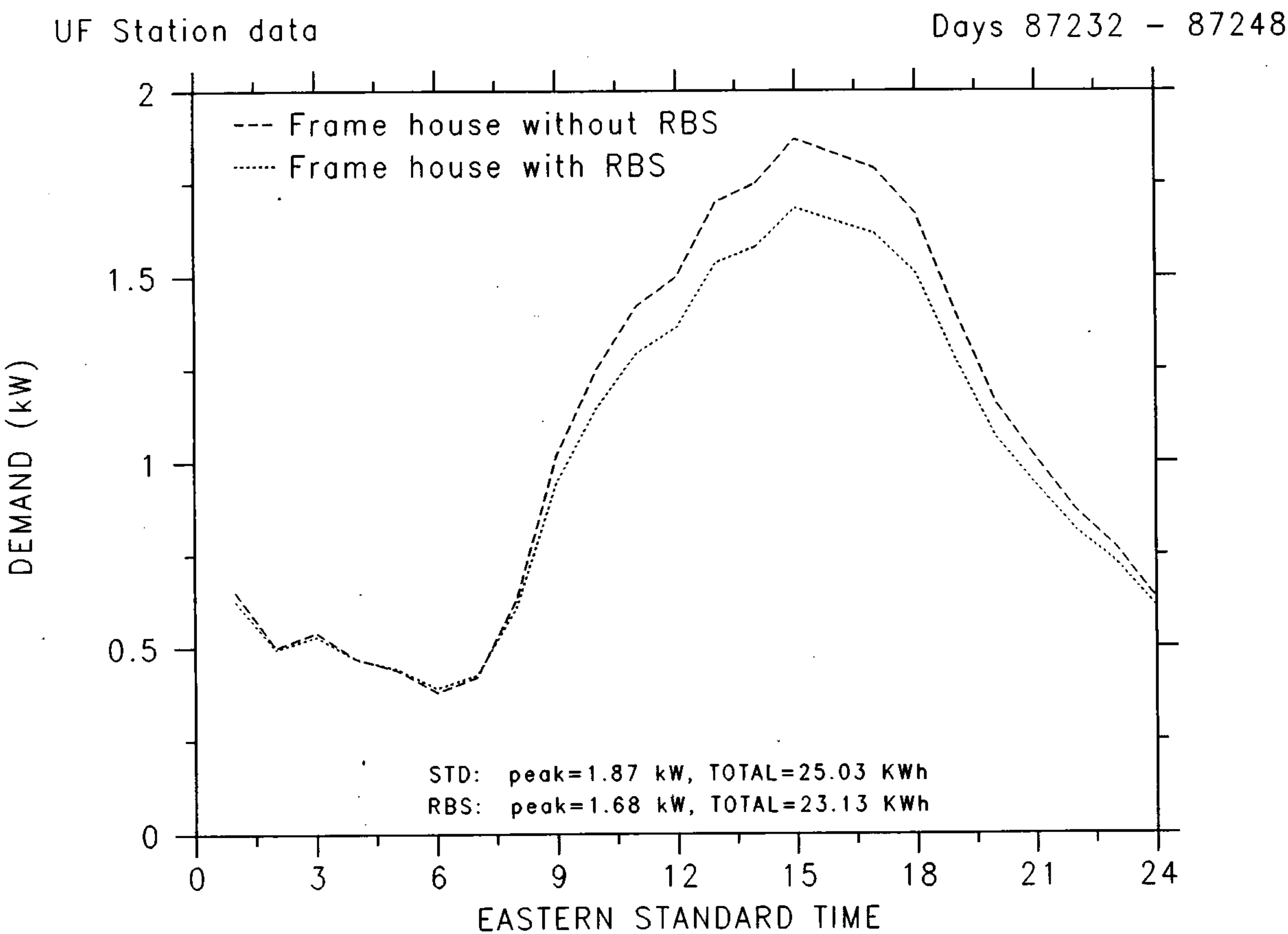


Figure 4.4-5 Average hourly air conditioning demand for frame house in Gainsville, FL, with and without attic RBS.

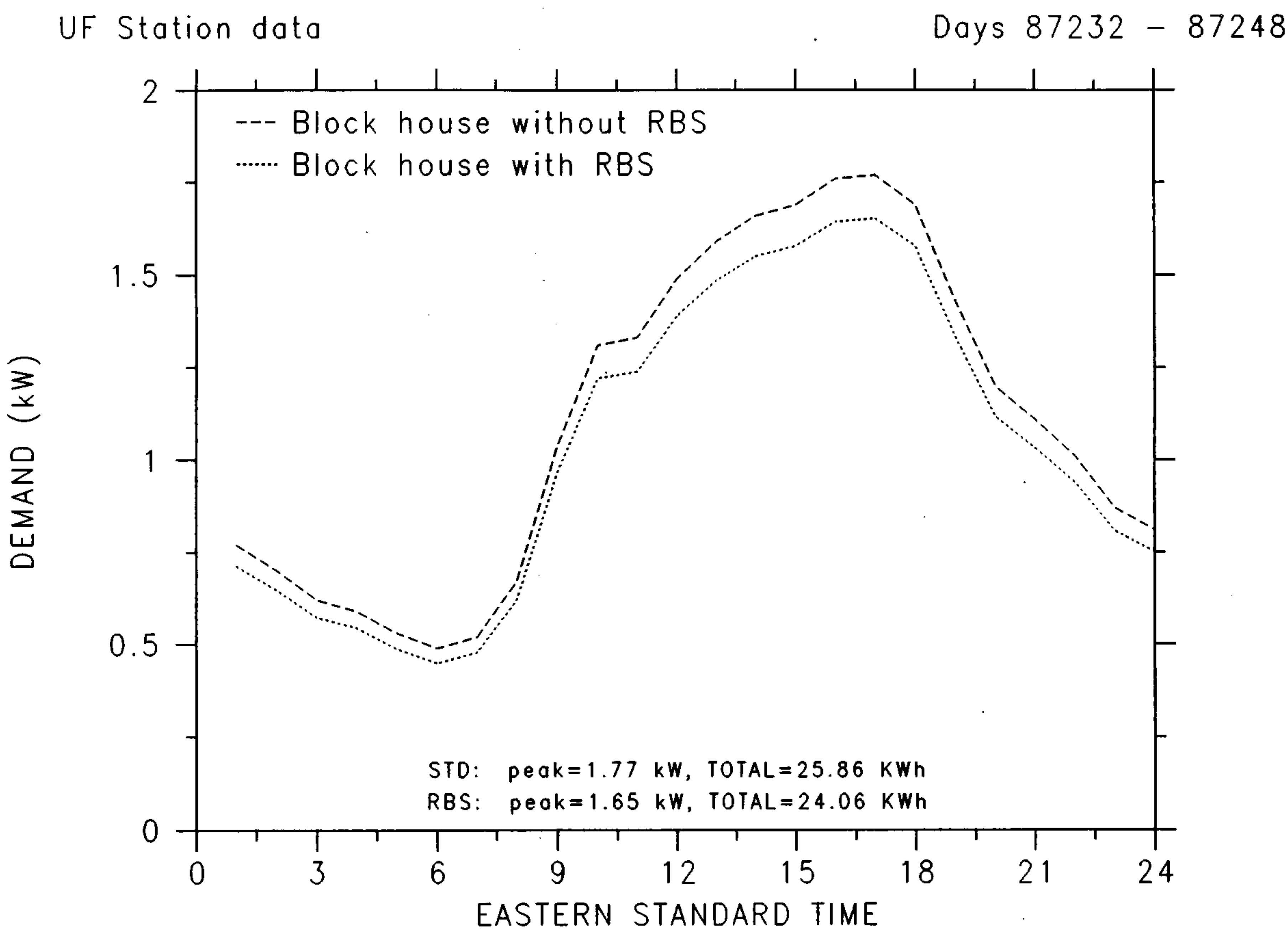


Figure 4.4-6 Average hourly air conditioning demand for block house in Gainsville, FL, with and without attic RBS.

expected to be operational in summer 1988. Construction drawings are given in the appendix to this report.

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CHAPTER 5

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Yarbrough, D.W., and Sang G. Kim, "Thermal Resistance of Reflective Insulations Installed in a Simulated Wall Cavity," presented at the ASHRAE/DOE Conference on Thermal Performance of the Exterior Envelopes of Buildings II, Las Vegas, NV, Dec. 1982.

Yarbrough, D.W., "Assessment of Reflective Insulations for Residential And Commercial Applications," ORNL/TM-8891, Oak Ridge National Laboratory, October 1983.

APPENDIX A

DETAILED PCL DATA

The PCL is a heavily instrumented experimental facility located on FSEC grounds in Cape Canaveral FL. Figure A-1 illustrates the measurement locations for the data reported in this appendix. A full compliment of test data for the three PCL attics on three test days is included in this appendix. The test days are the same days used to illustrate points in the main text of the report. For the most part the data are self explainatory.

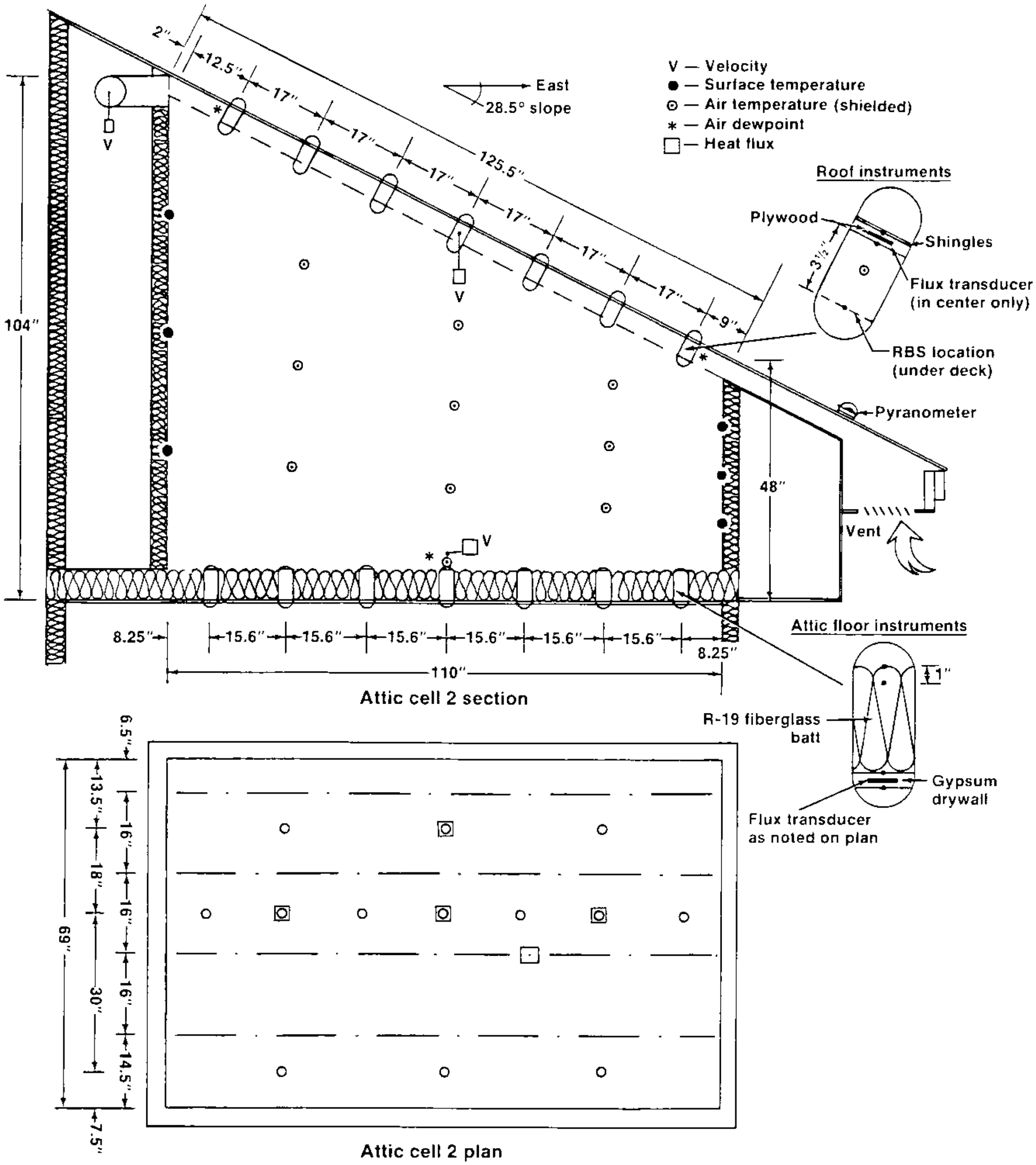
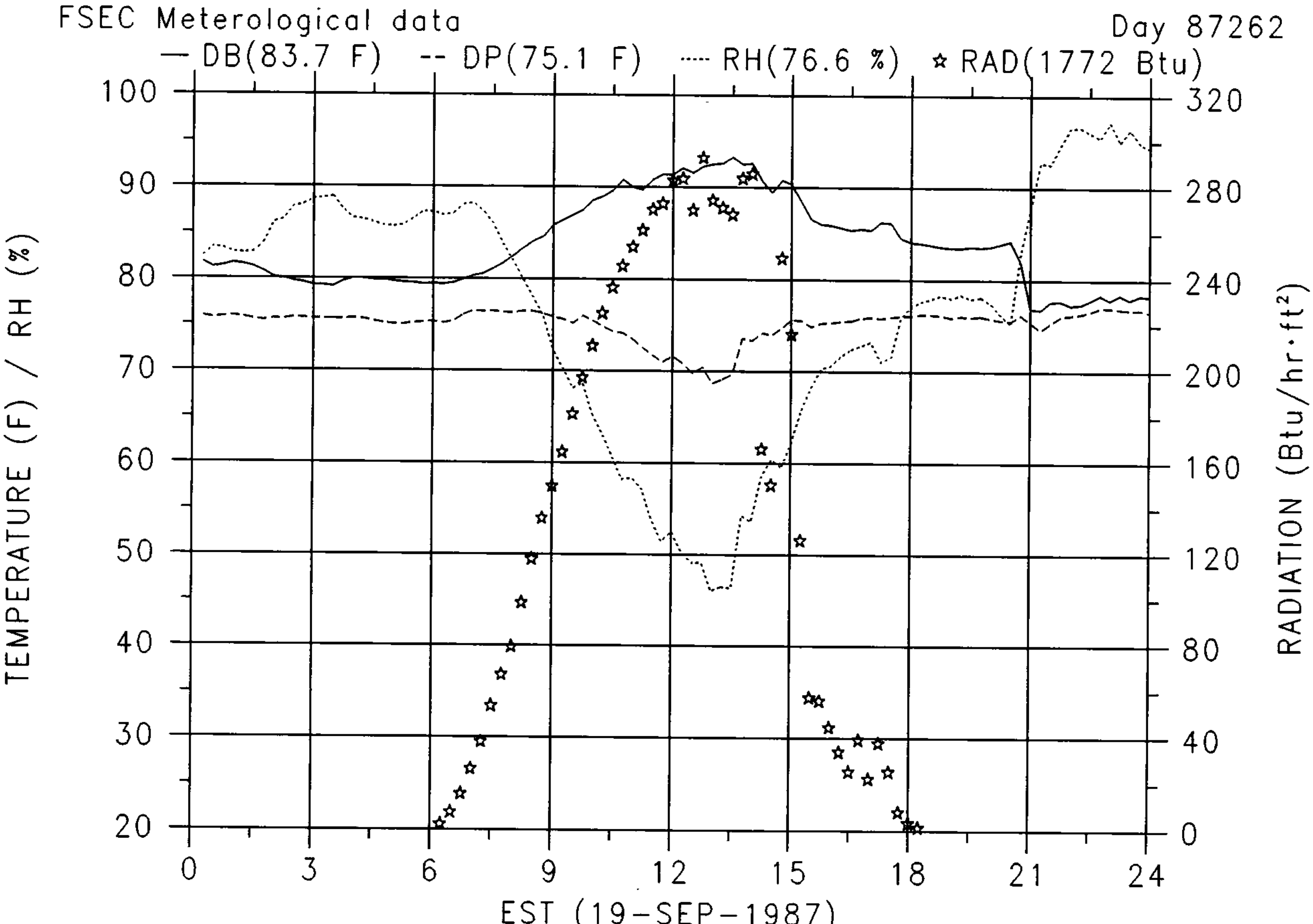
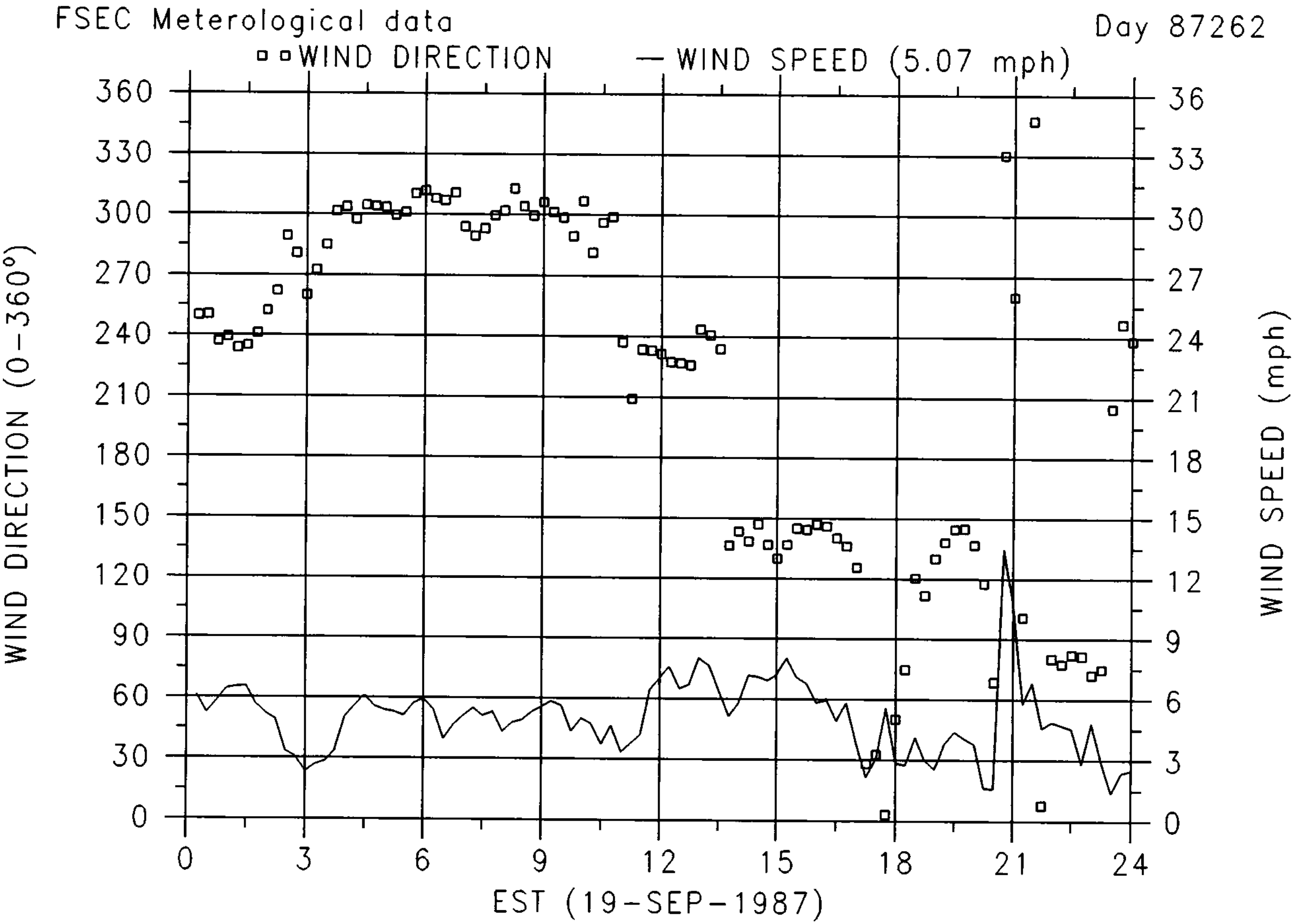


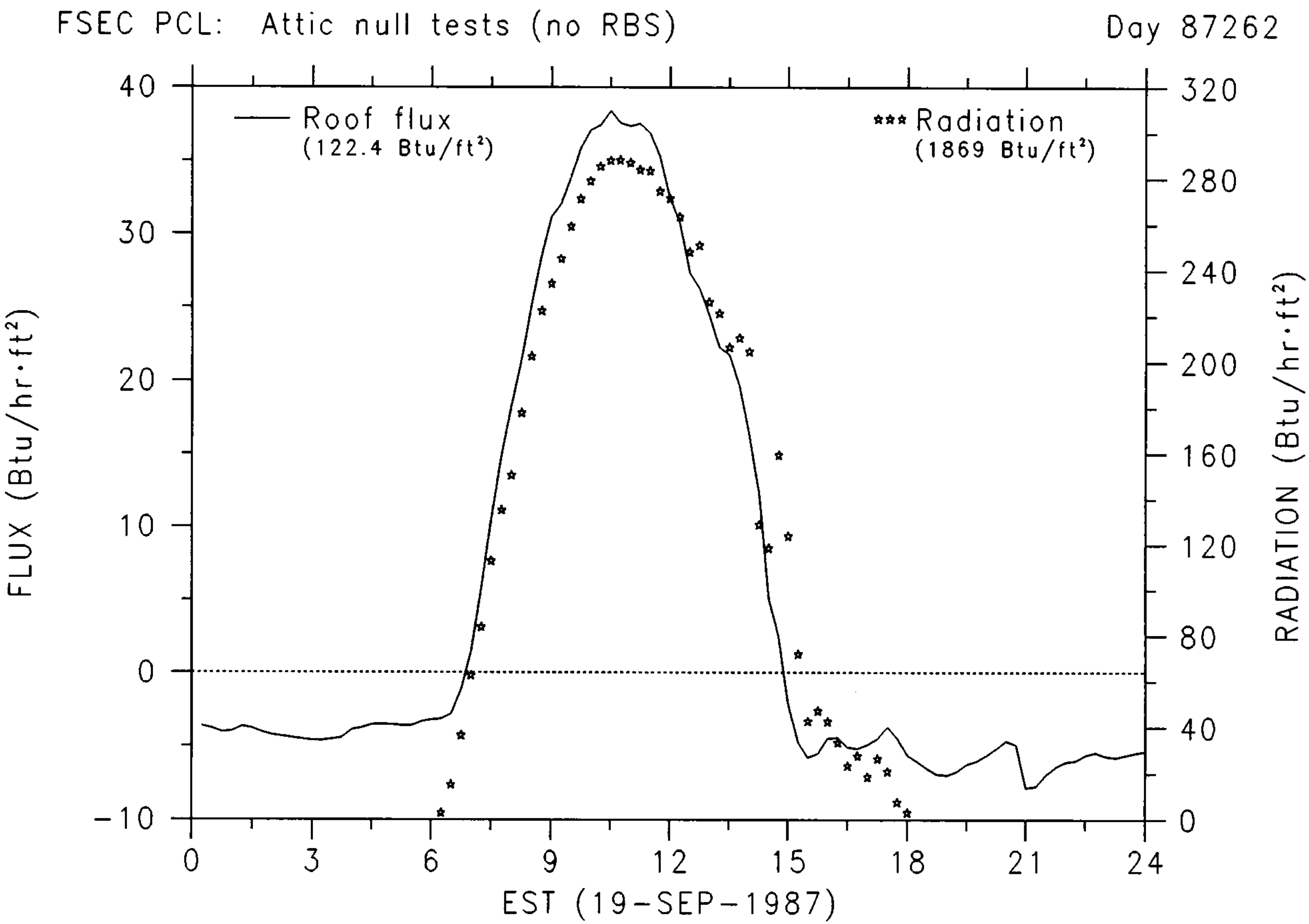
Figure A-1 Geometry and measurement points for PCL attics during 1987 Attic RBS tests.



Ambient air conditions and horizontal solar radiation.

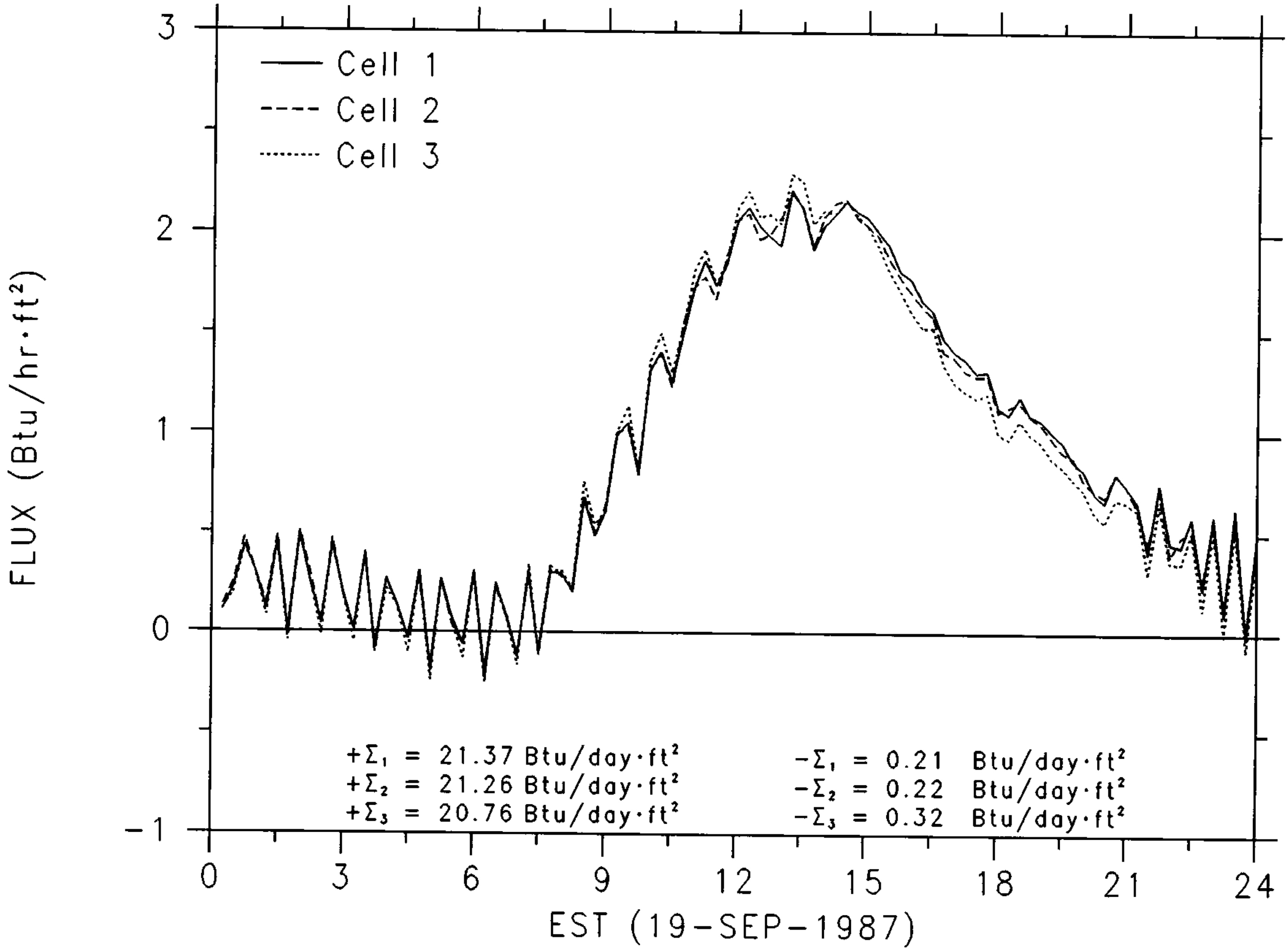


Local 10 meter wind measurements.

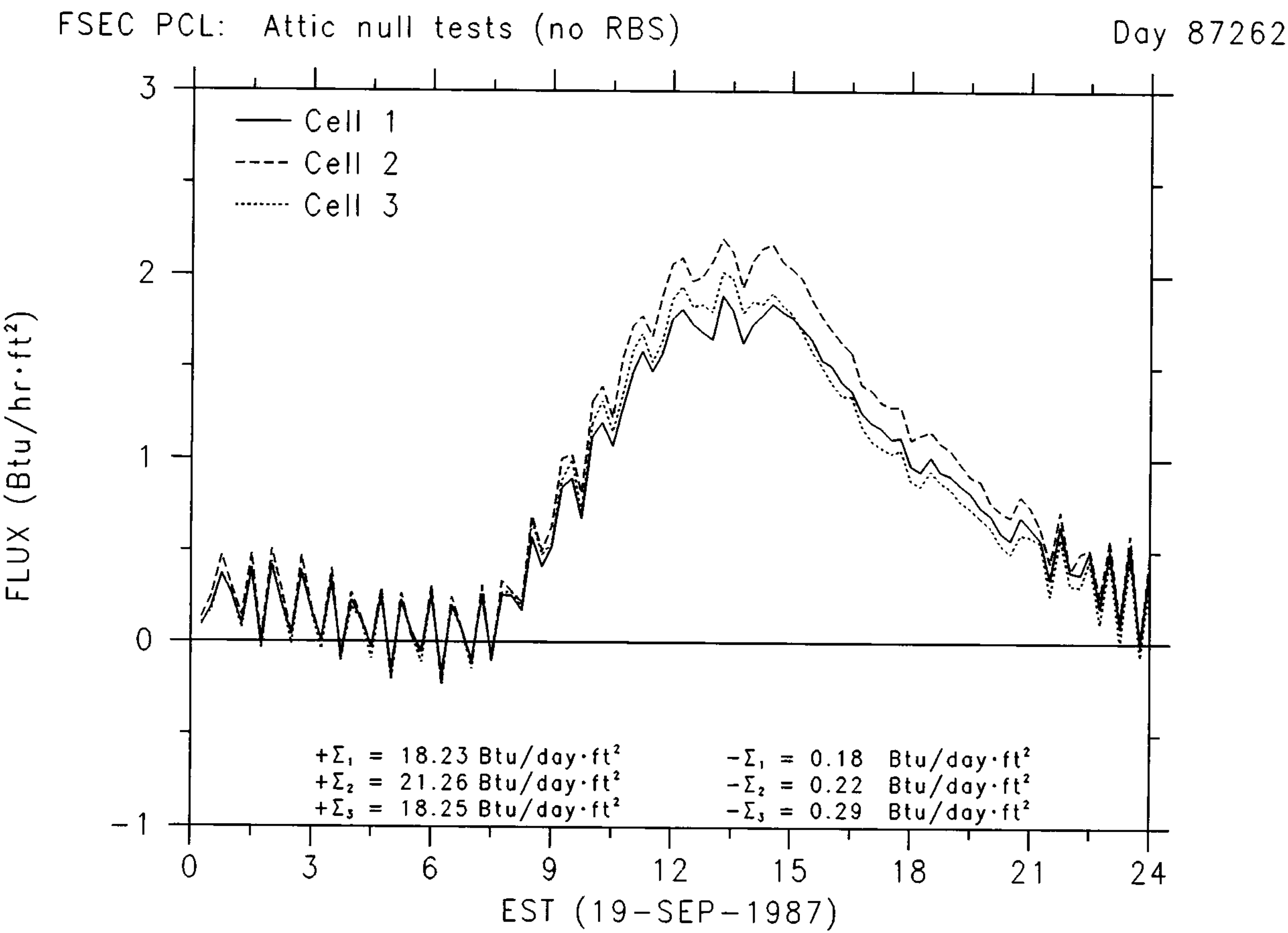


Cell 2 roof flux and incident solar radiation measurements.

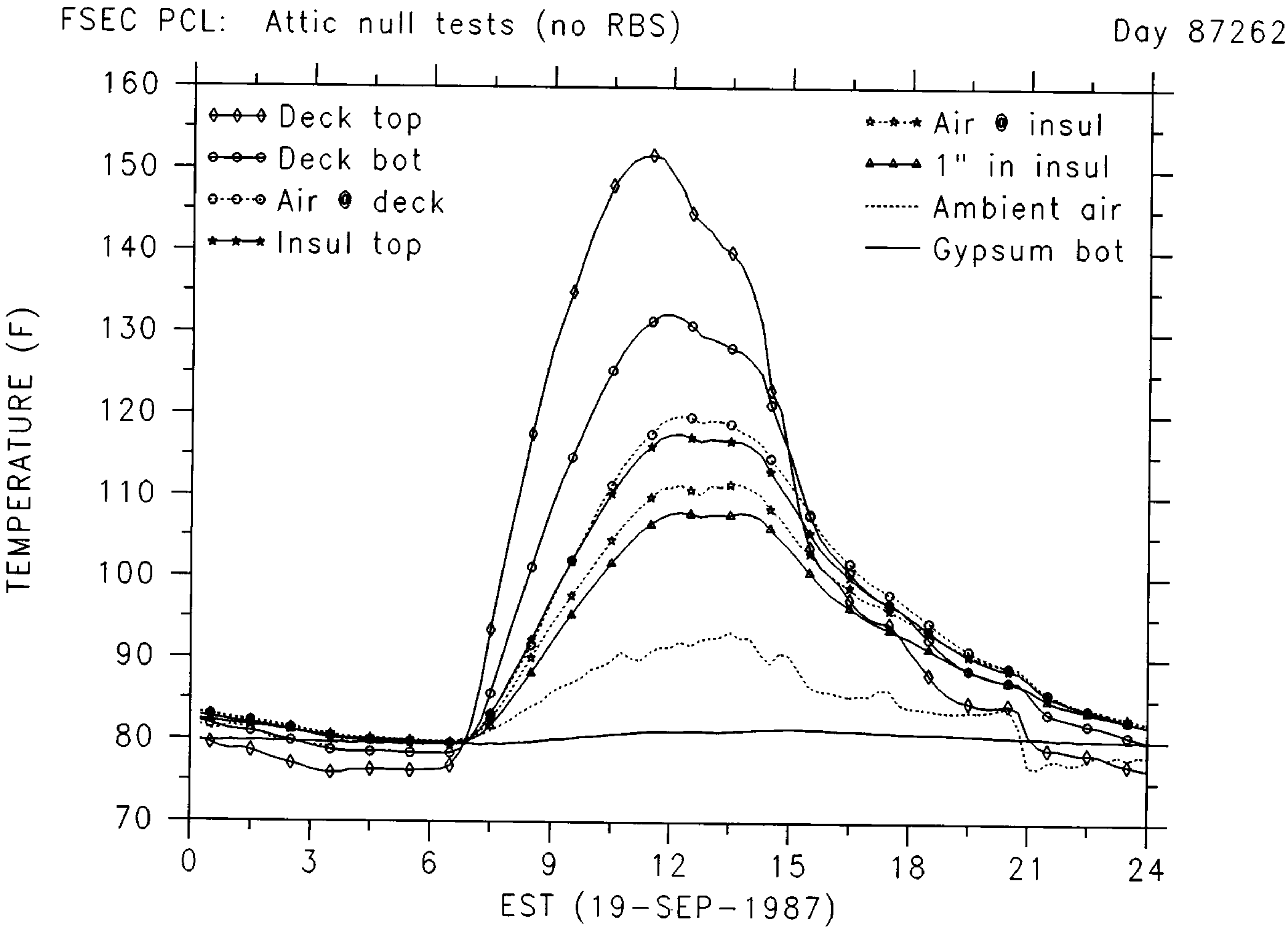
FSEC PCL: Attic null tests (no RBS) Day 87262



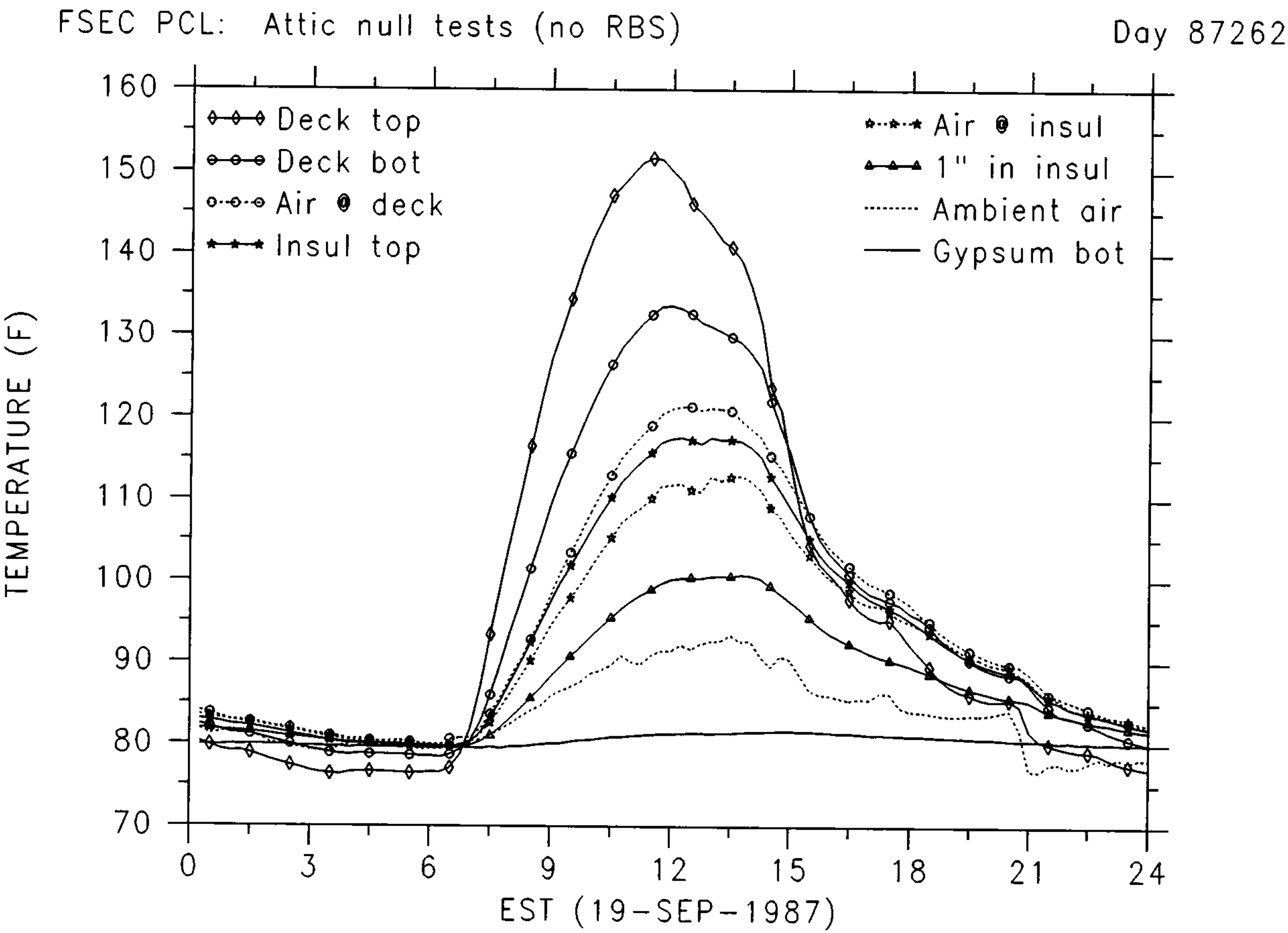
Normalized central ceiling heat fluxes for test attics.



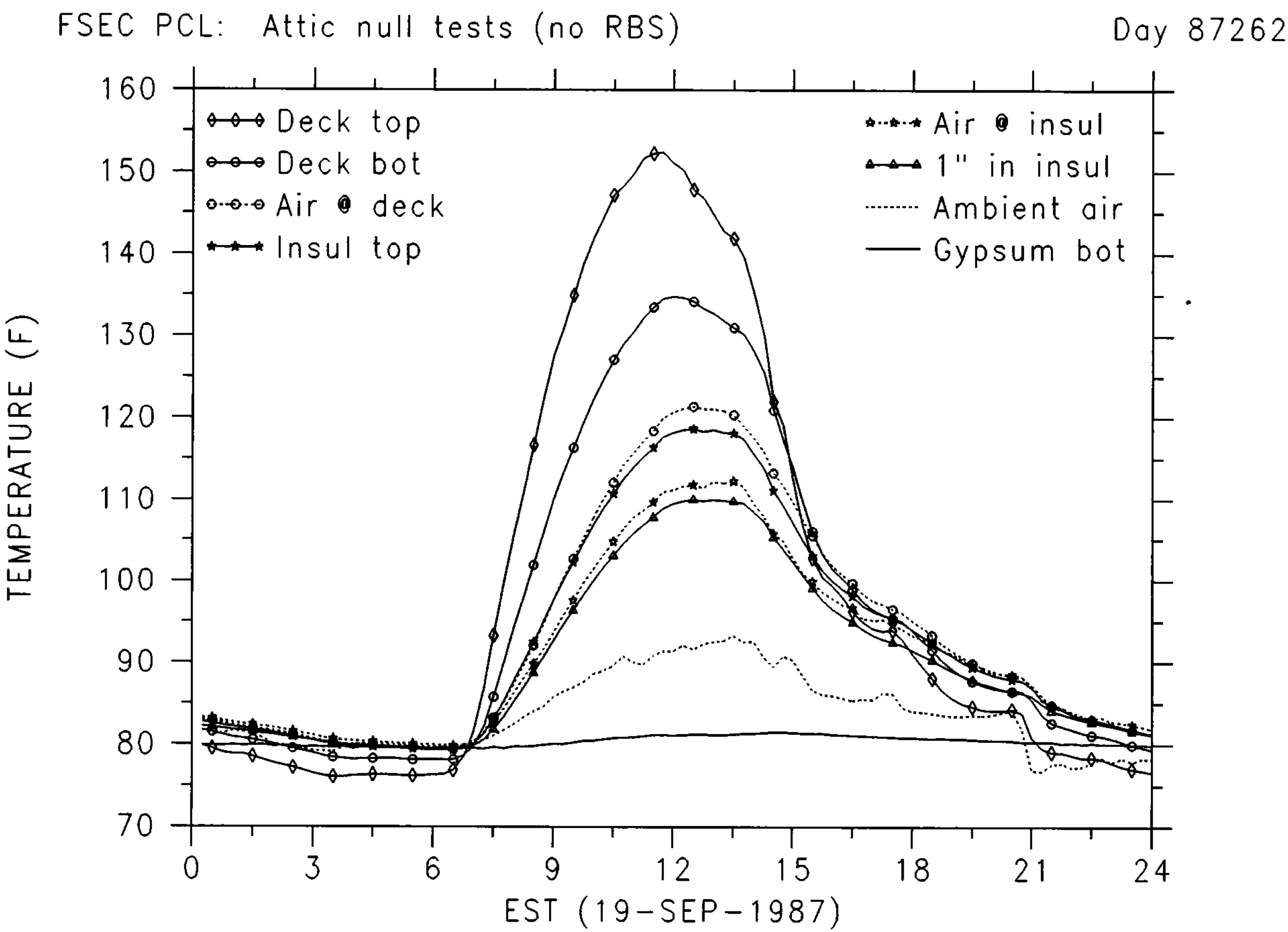
Measured central ceiling heat fluxes for test attics.



Distribution of cell 1 attic component temperatures.

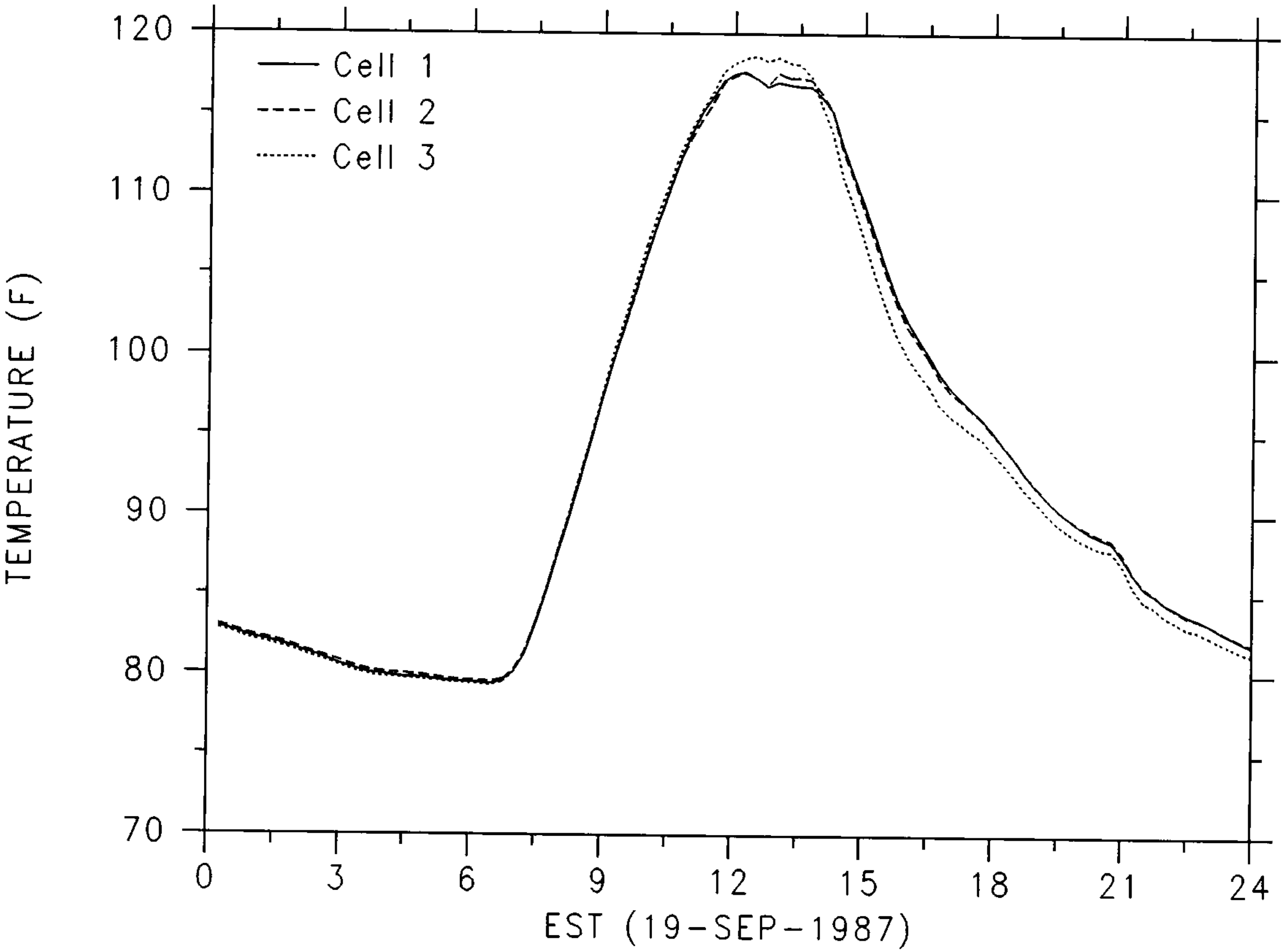


Distribution of cell 2 attic component temperatures.



Distribution of cell 3 attic component temperatures.

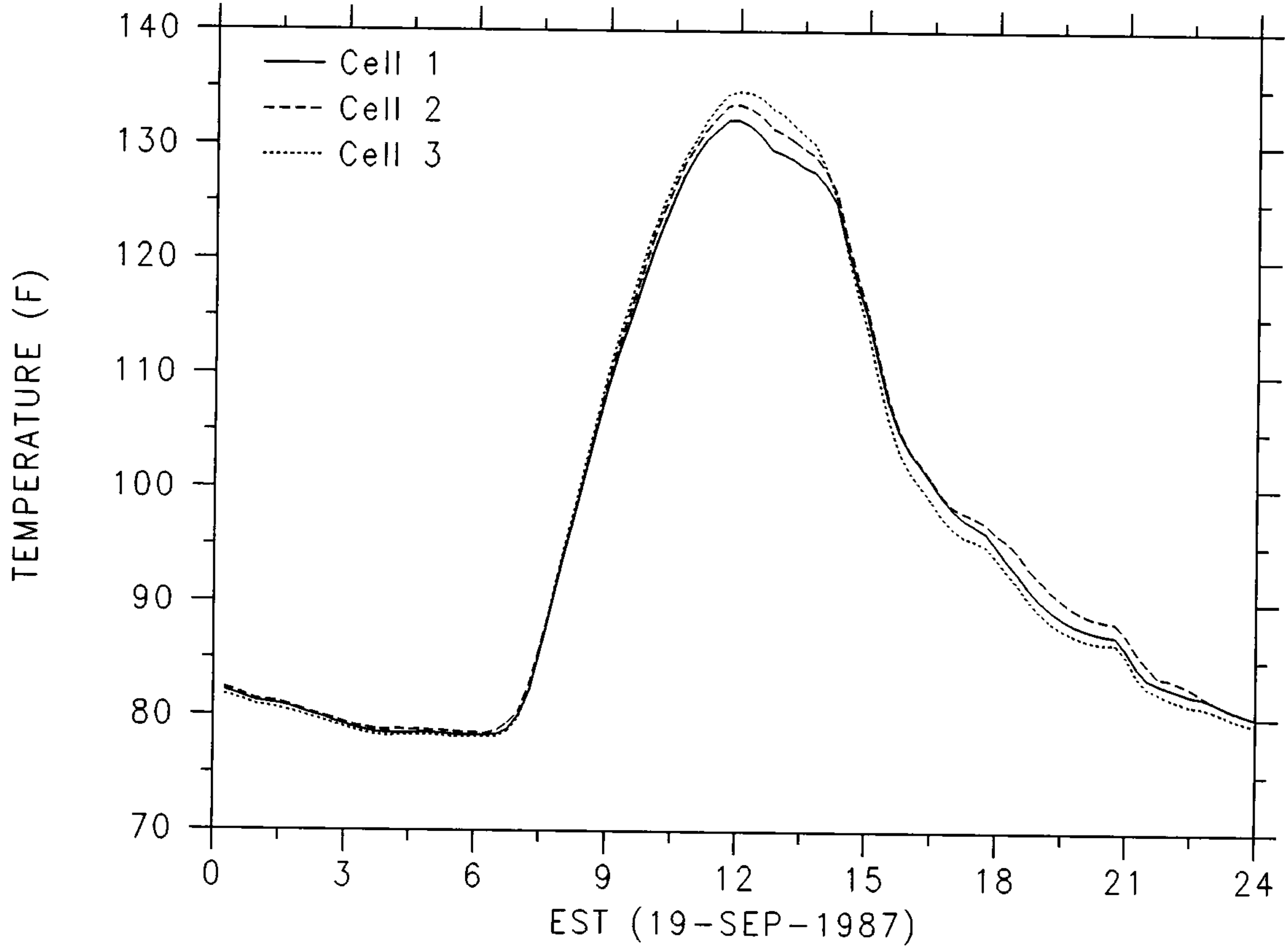
FSEC PCL: Attic null tests (no RBS) Day 87262



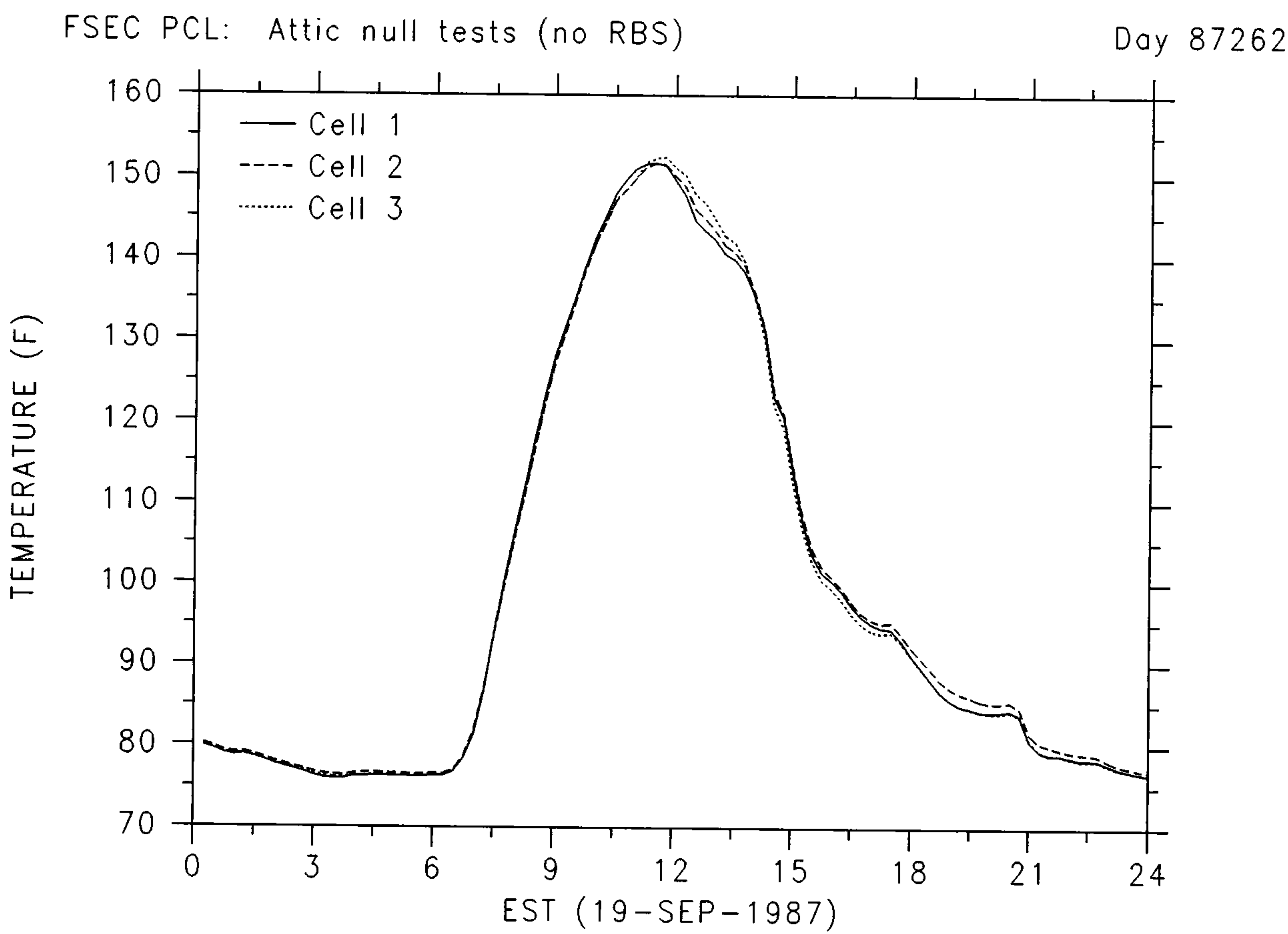
Insulation top surface temperatures in attic test cells.

FSEC PCL: Attic null tests (no RBS)

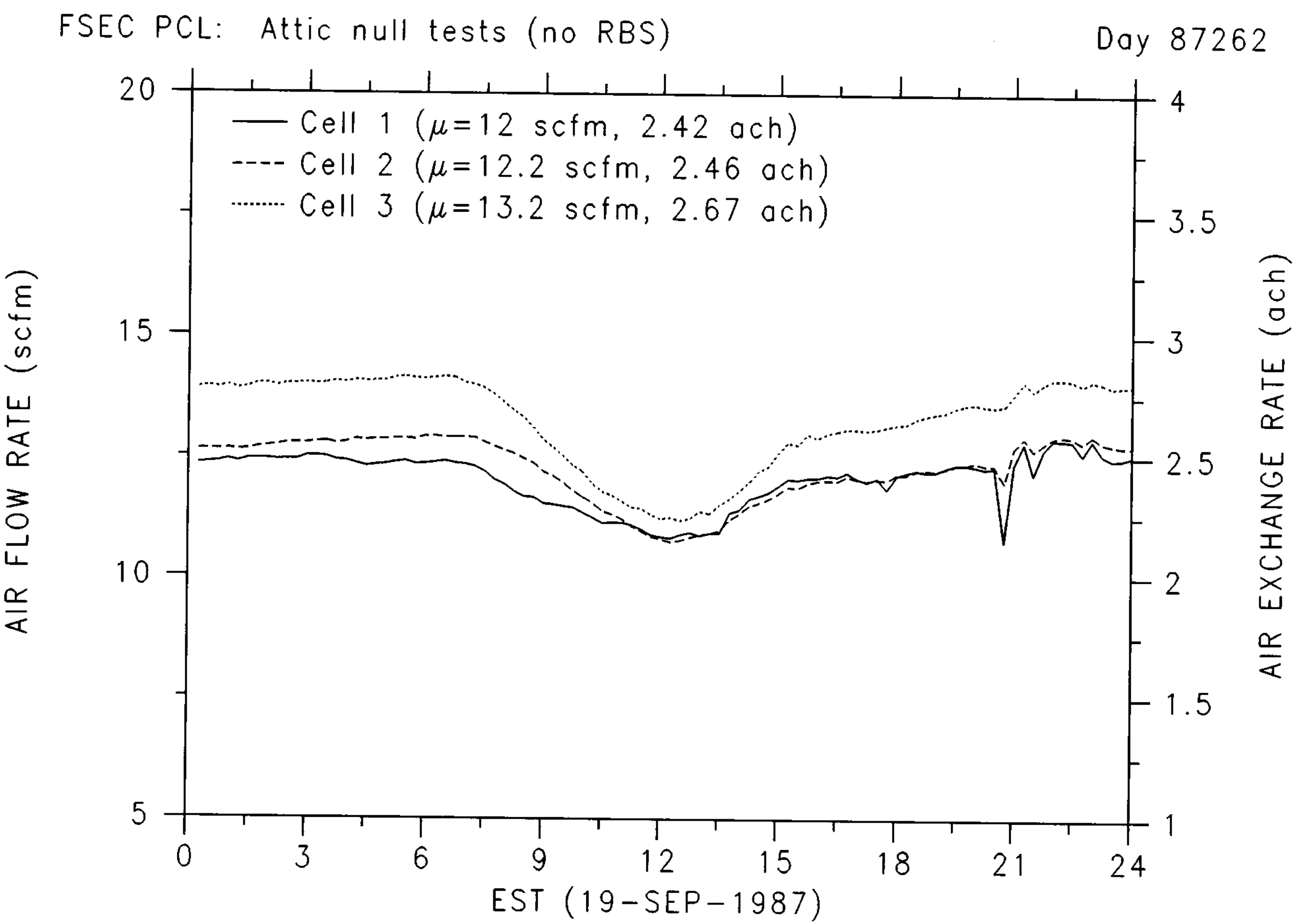
Day 87262



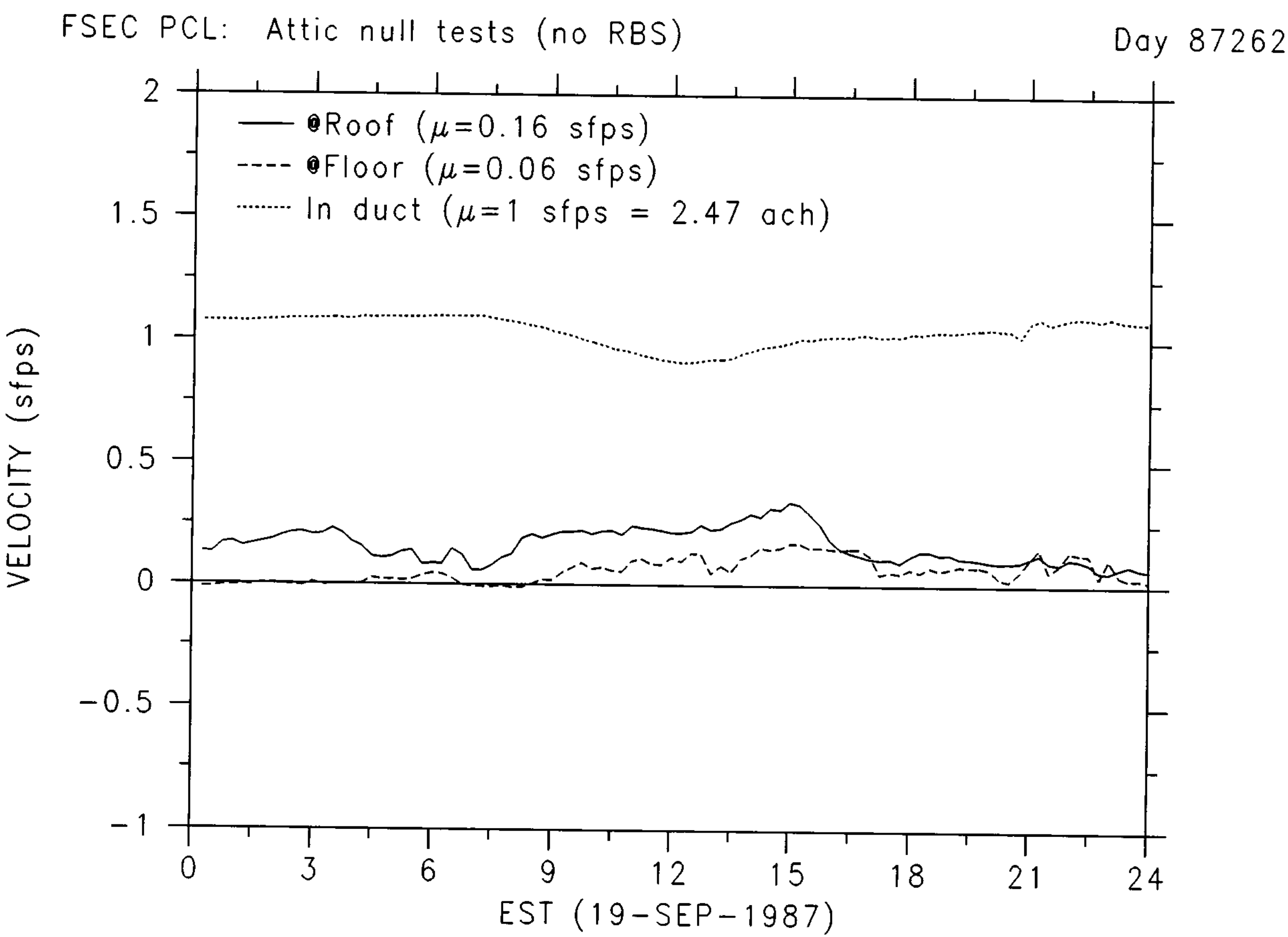
Inside roof decking temperatures in attic test cells.



Outside roof decking temperatures in attic test cells.

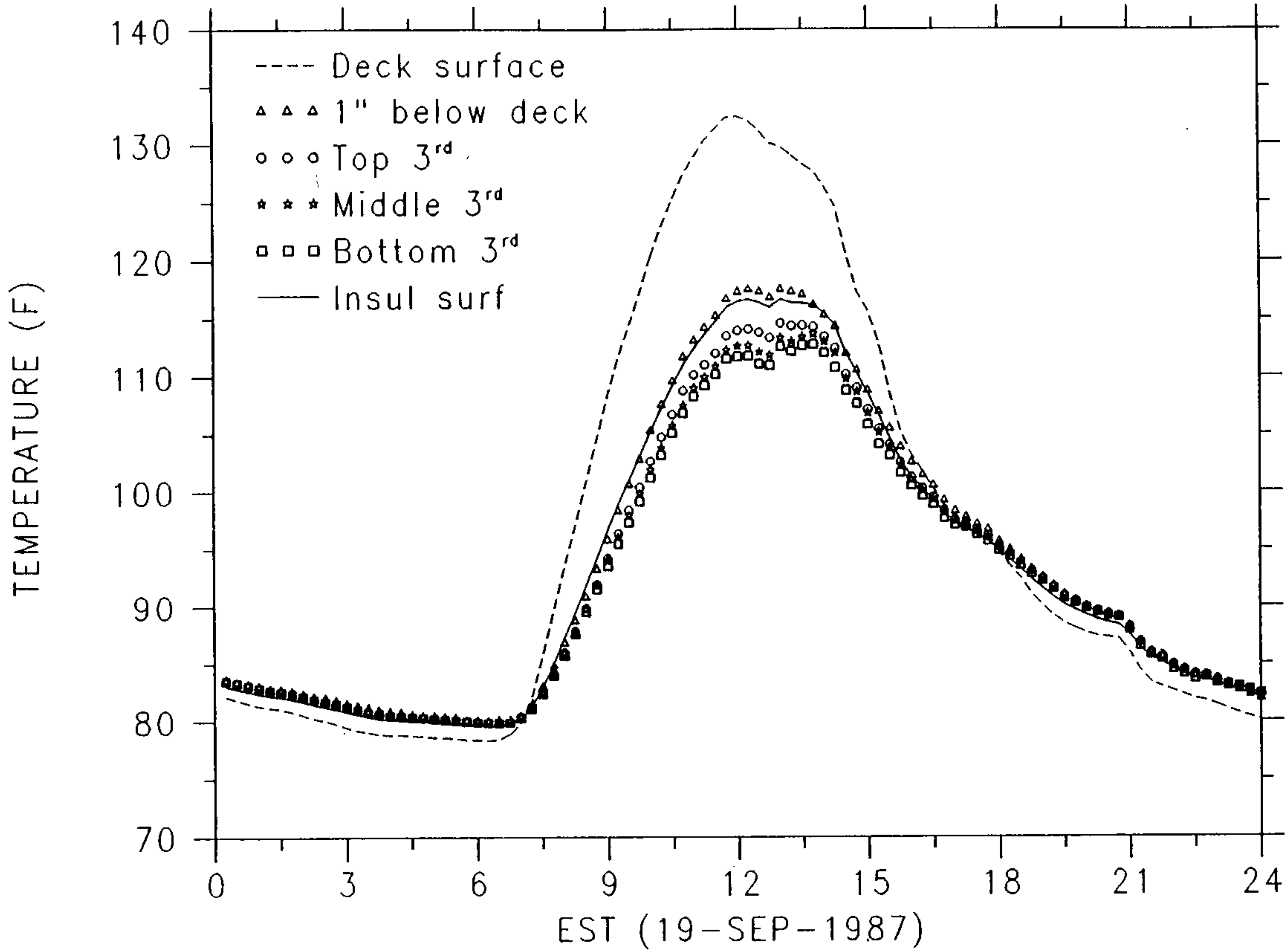


Attic bulk air ventilation rates for attic test cells.

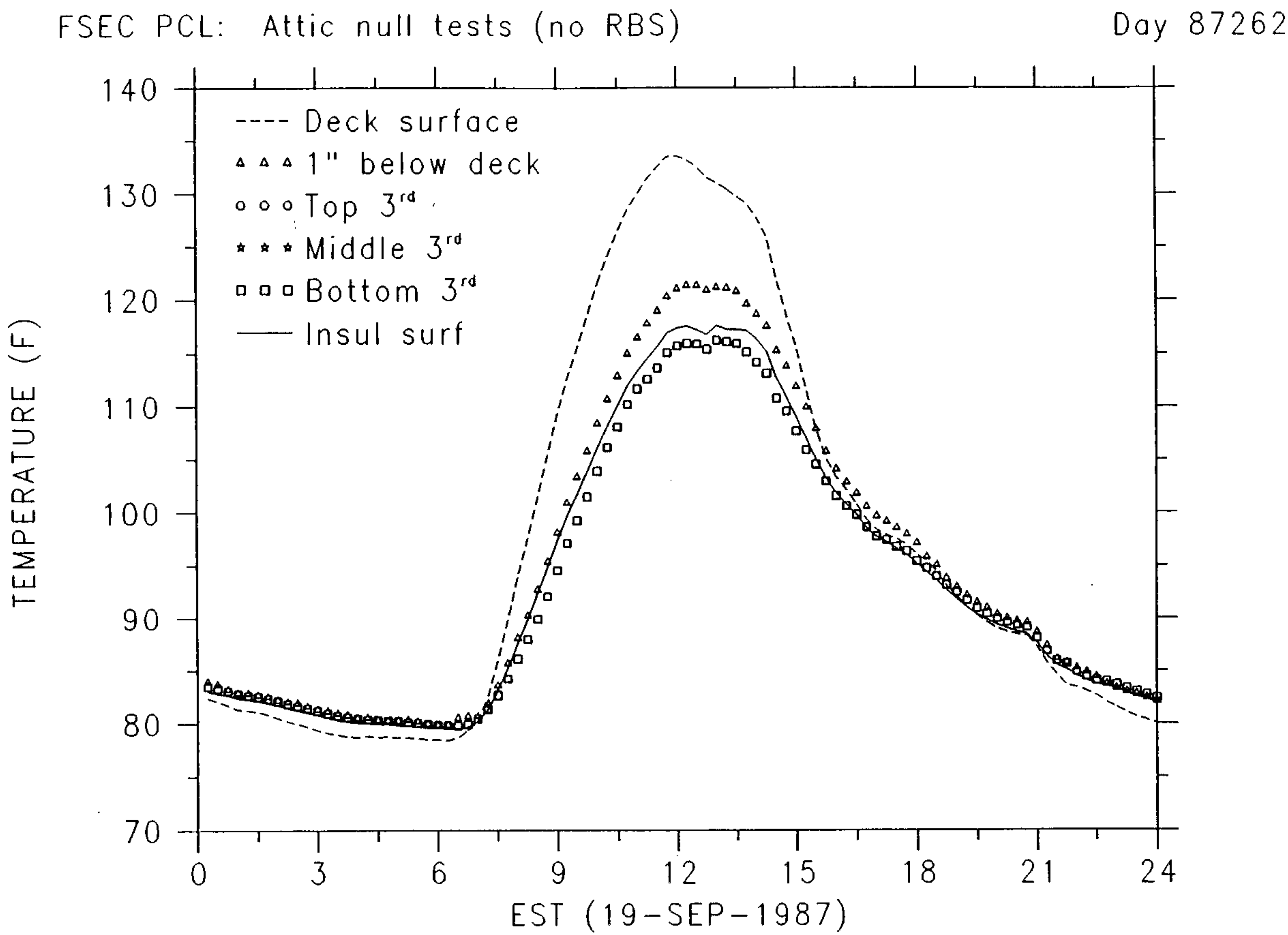


Cell 2 attic velocity profiles at three locations.

FSEC PCL: Attic null tests (no RBS) Day 87262

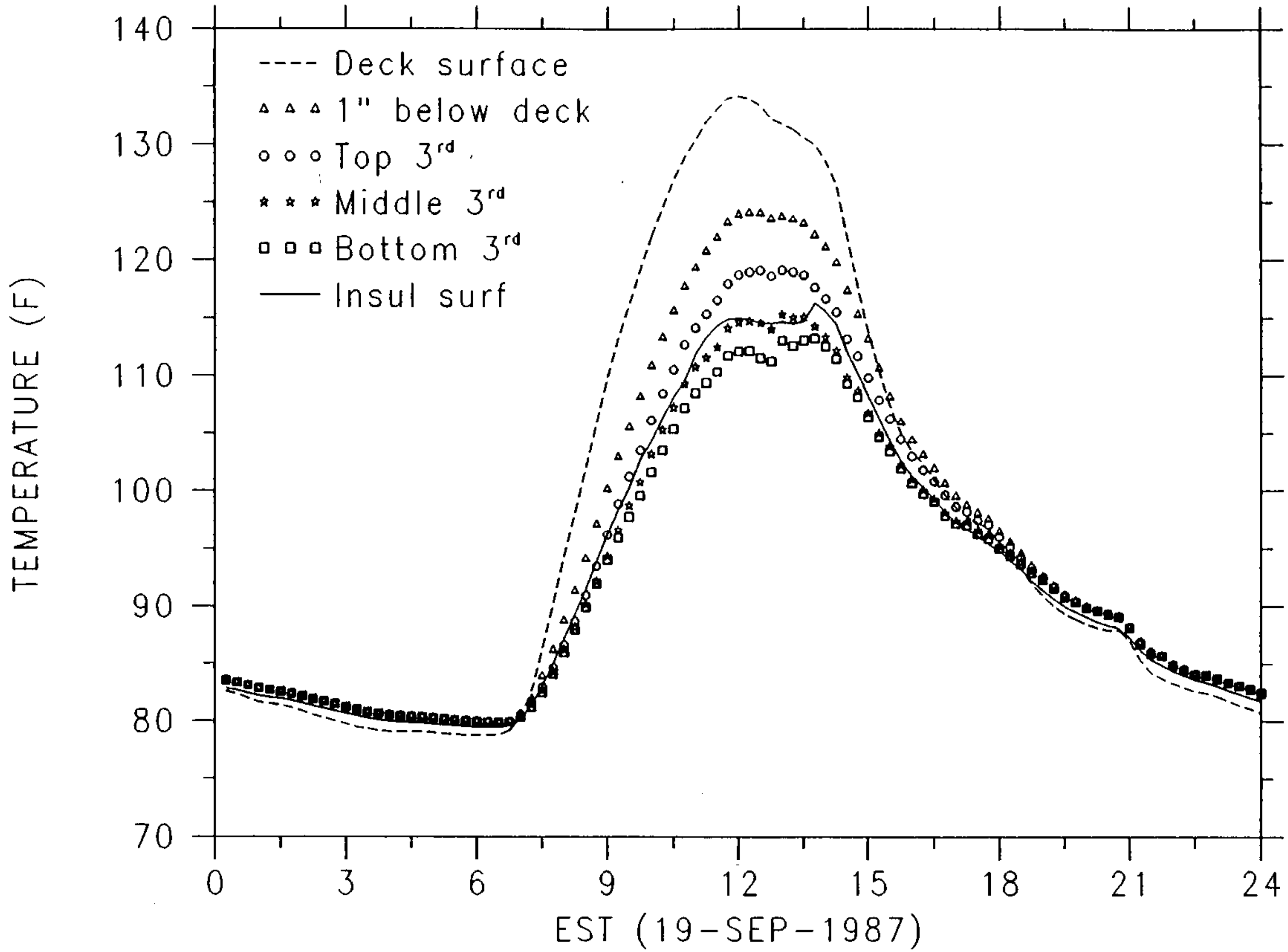


Cell 2 air temperature stratification at inlet end of attic.

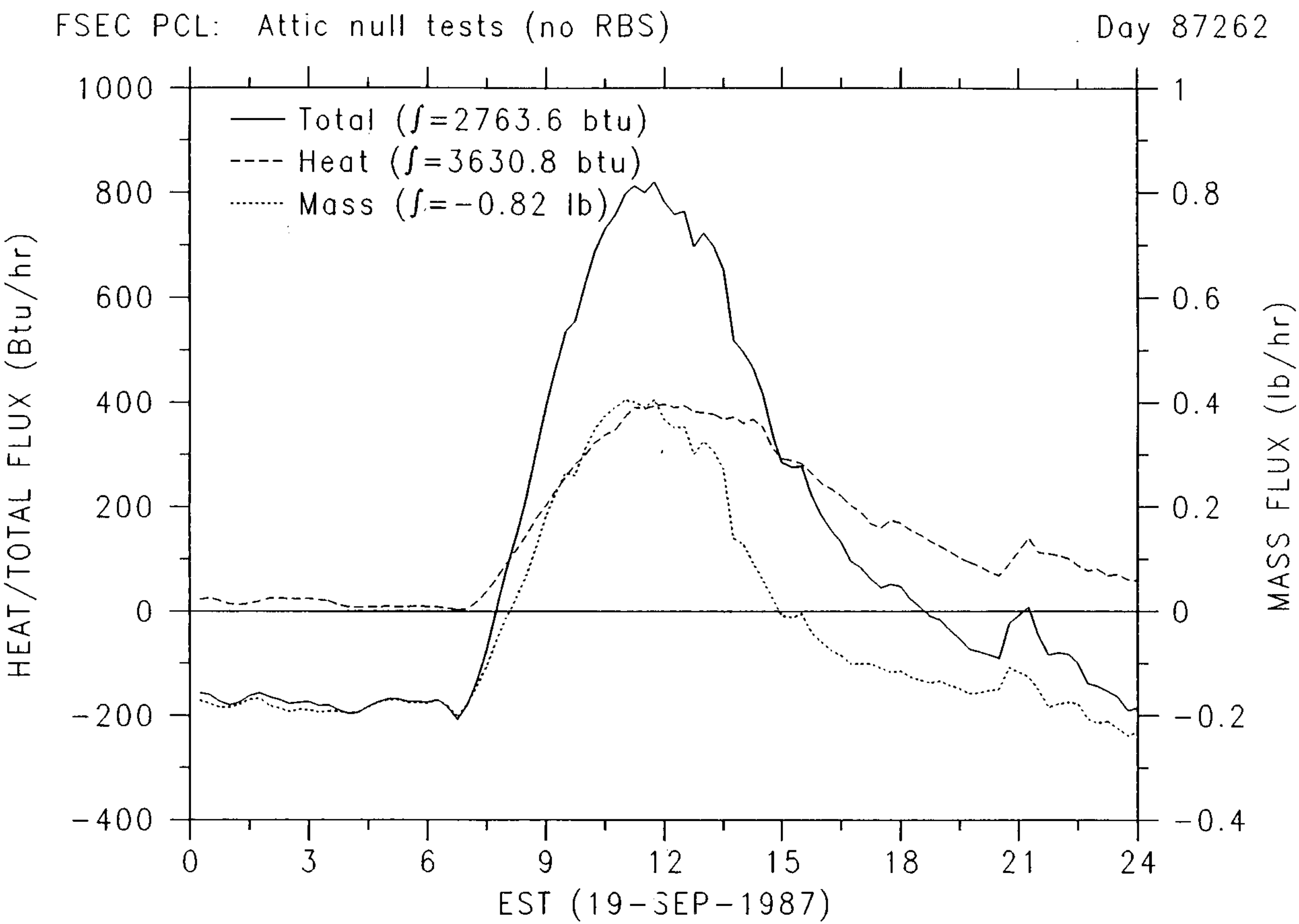


Cell 2 air temperature stratification at attic middle.

FSEC PCL: Attic null tests (no RBS) Day 87262

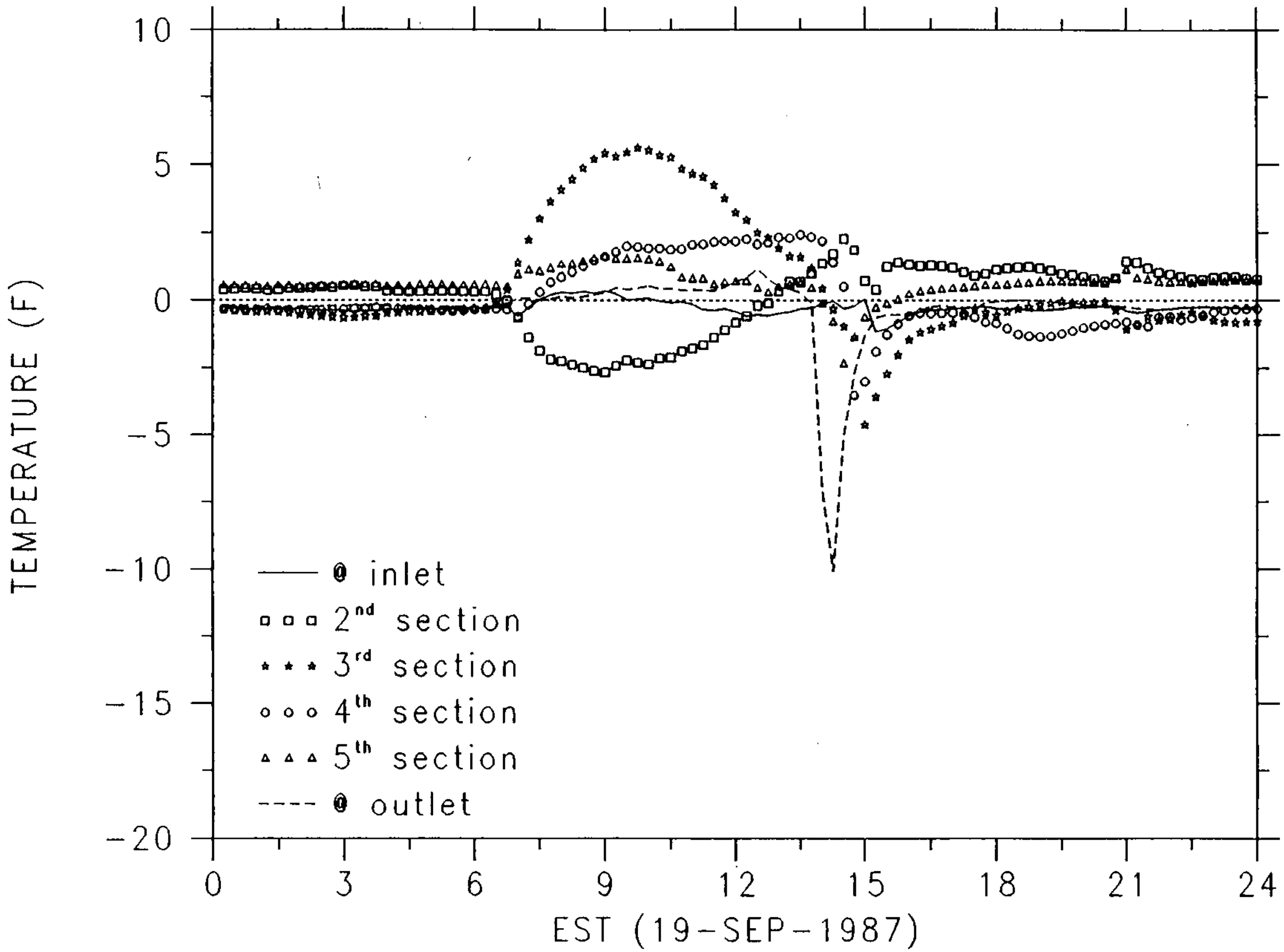


Cell 2 air temperature stratification at outlet end of attic.

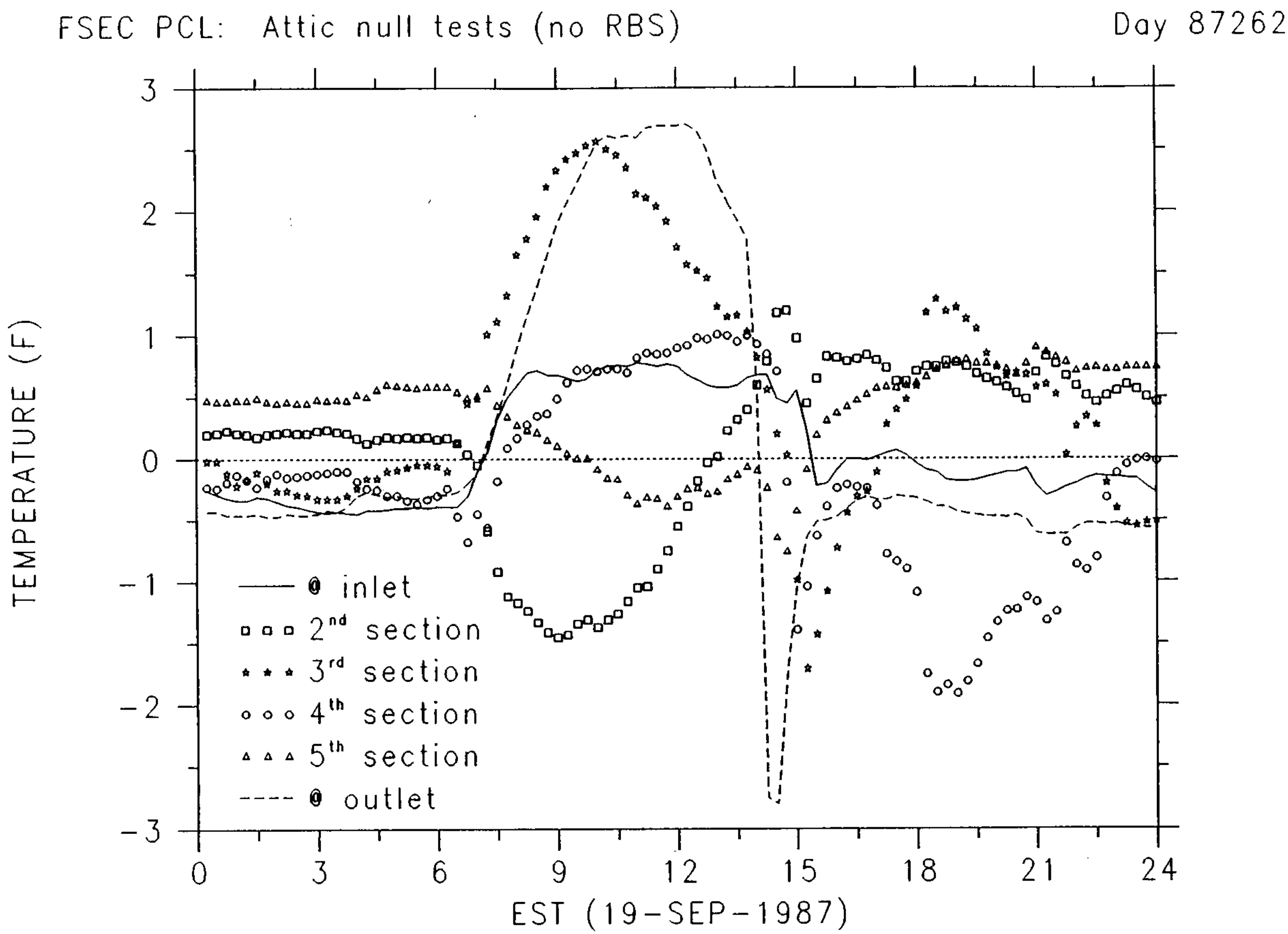


Cell 2 vent airstream heat and mass removal rates.

FSEC PCL: Attic null tests (no RBS) Day 87262

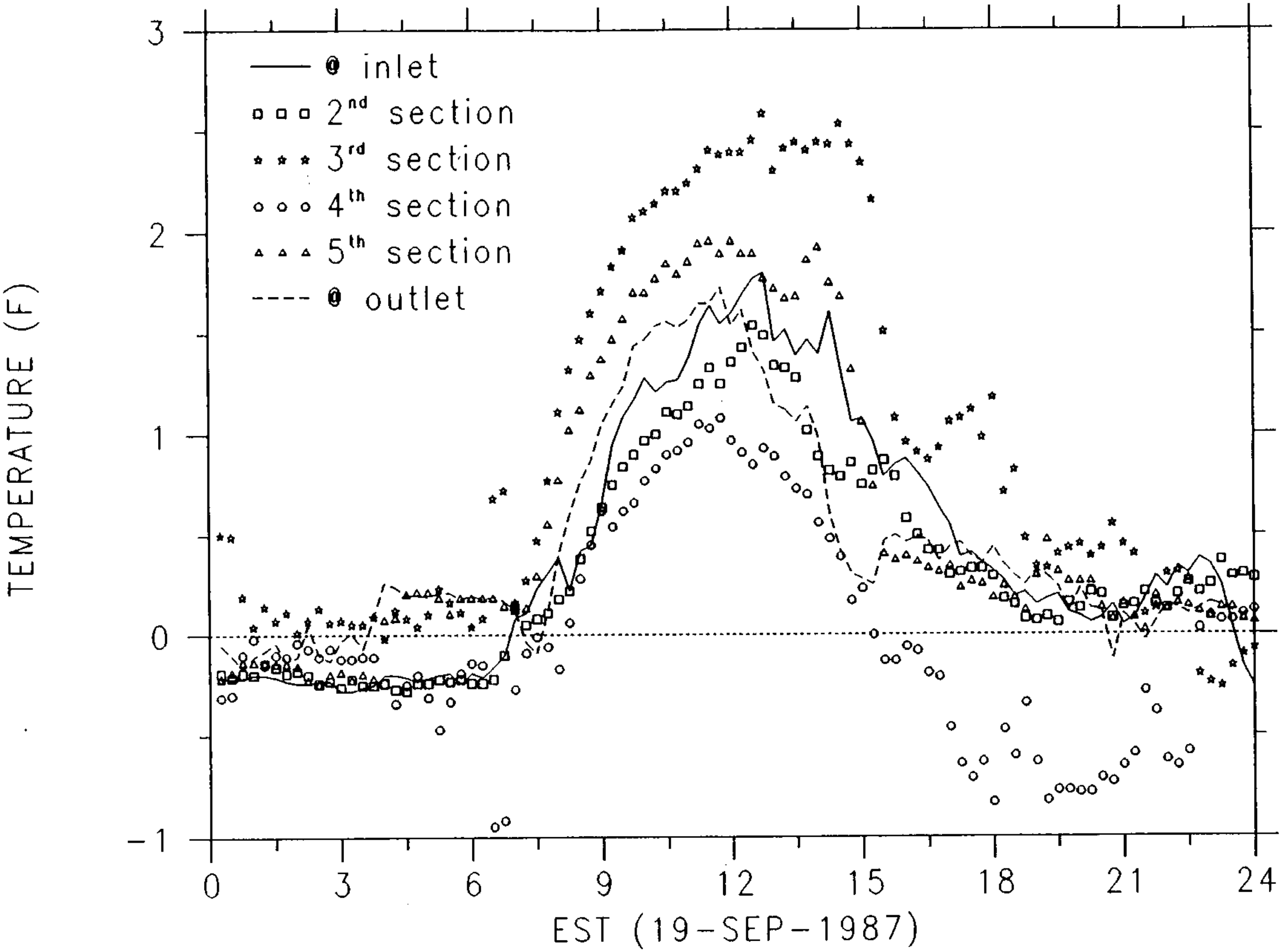


Temperature gradients between measurements at outside decking.



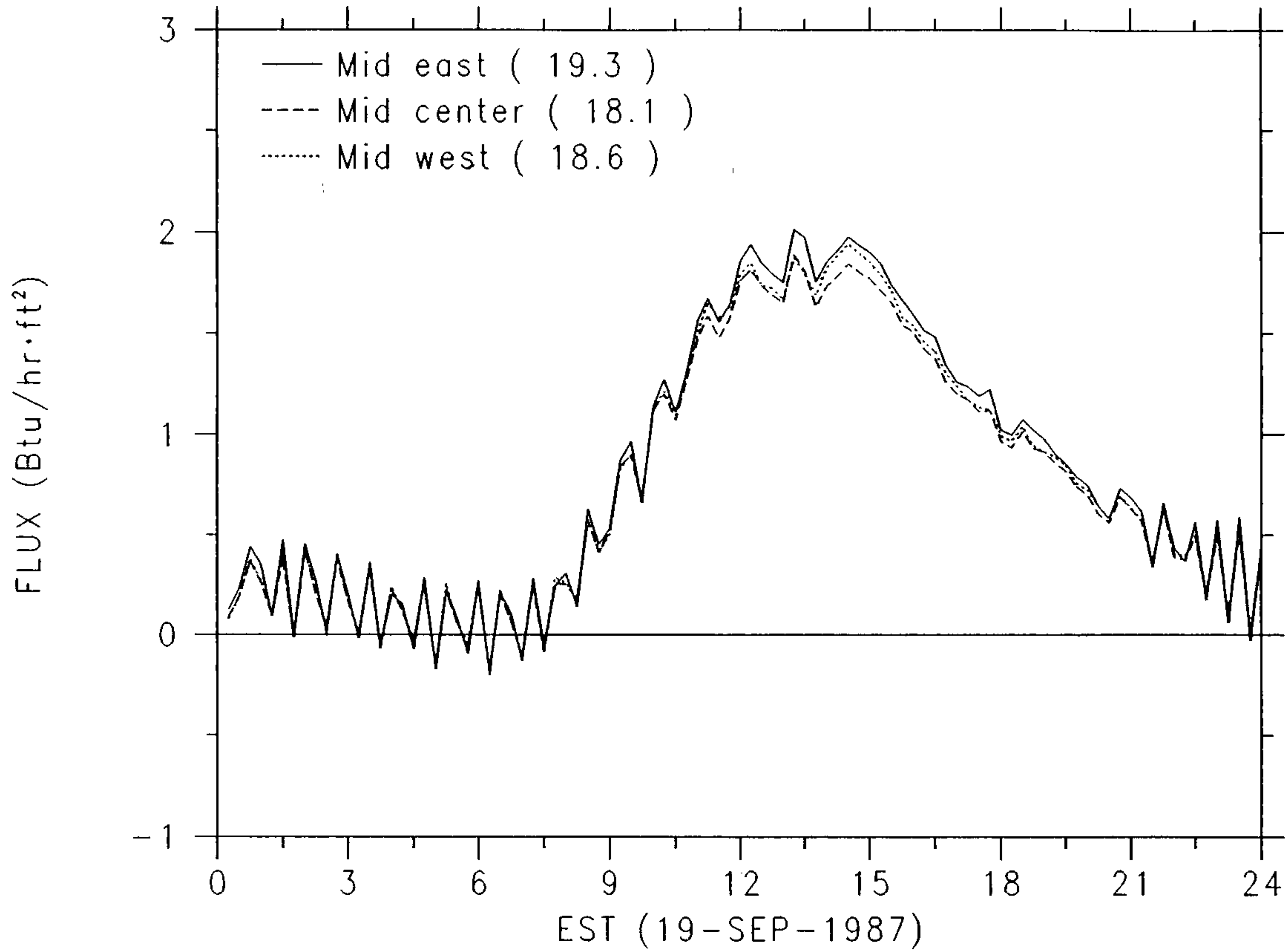
Temperature gradients between measurements at inside decking.

FSEC PCL: Attic null tests (no RBS) Day 87262

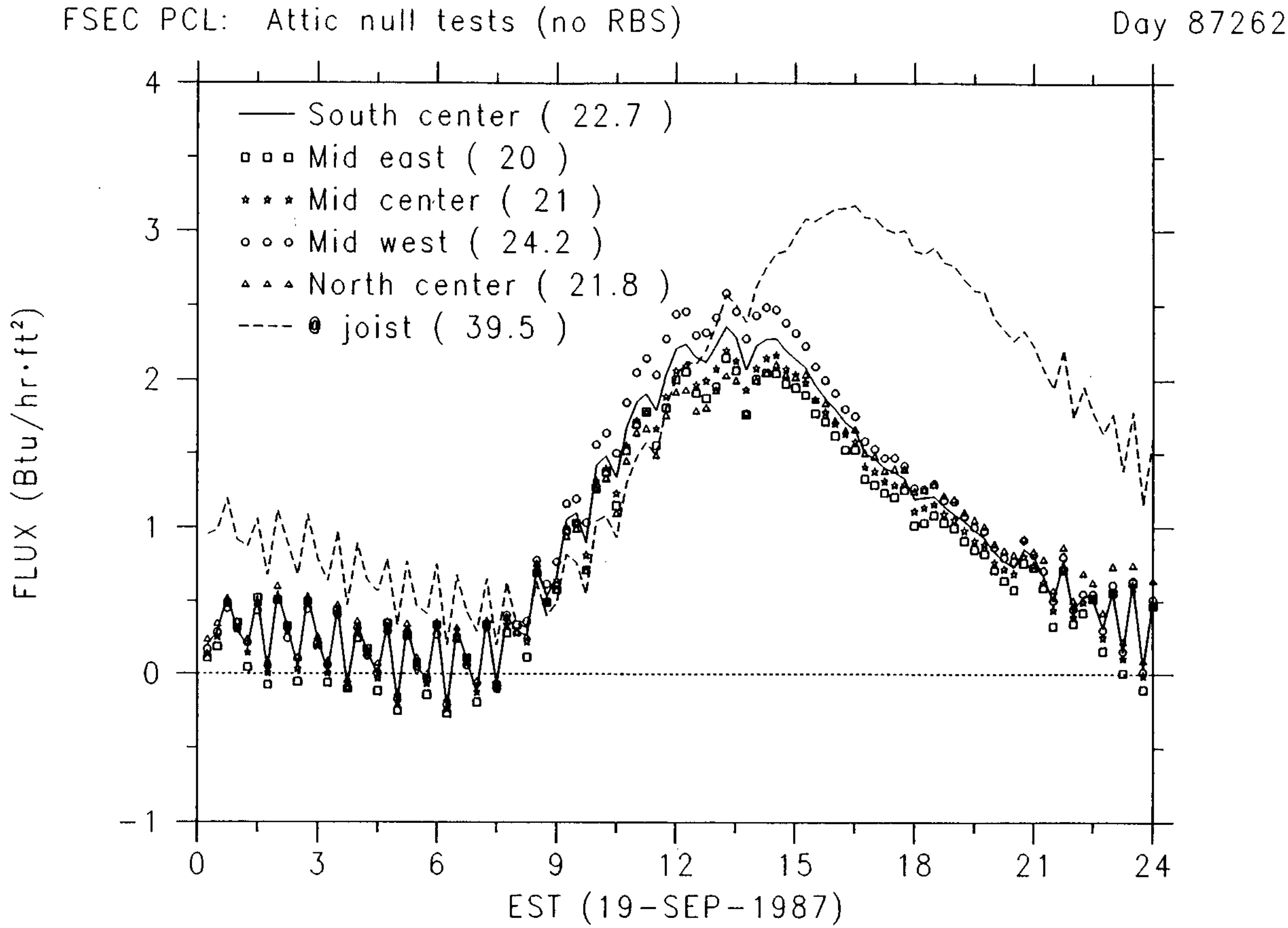


Temperature gradients between measurements in vent air.

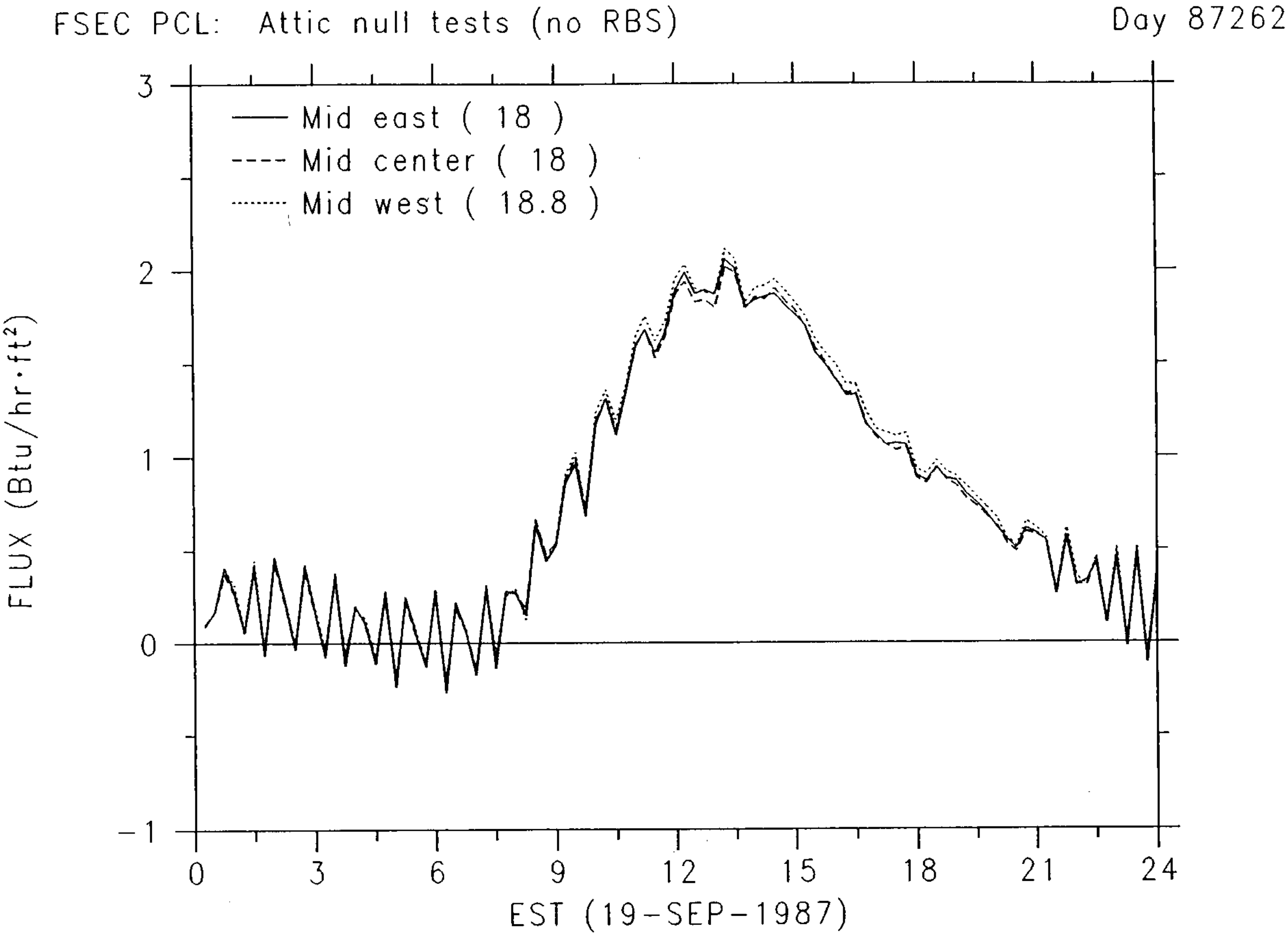
FSEC PCL: Attic null tests (no RBS) Day 87262



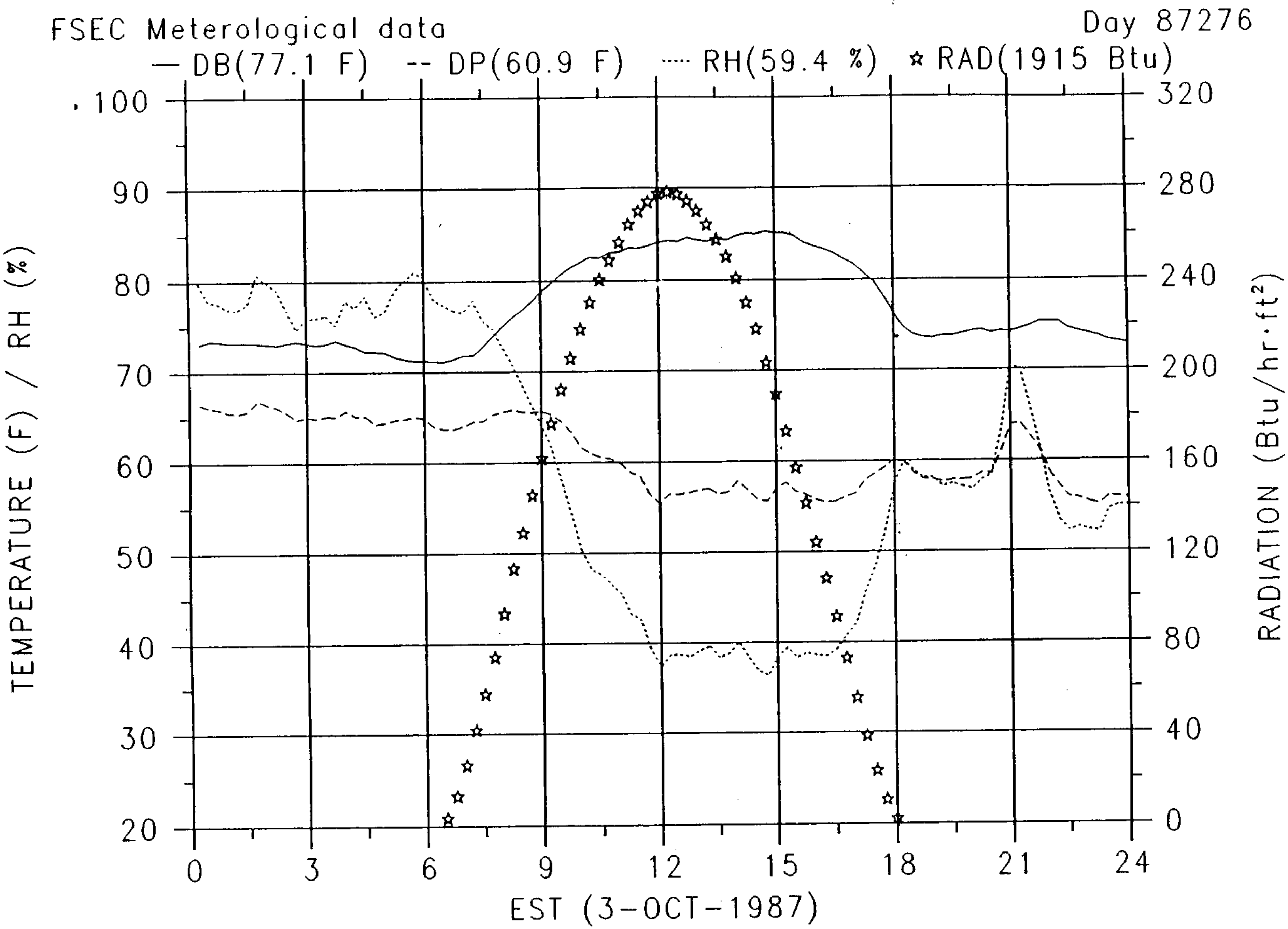
Cell 1 ceiling flux measurements at three locations.



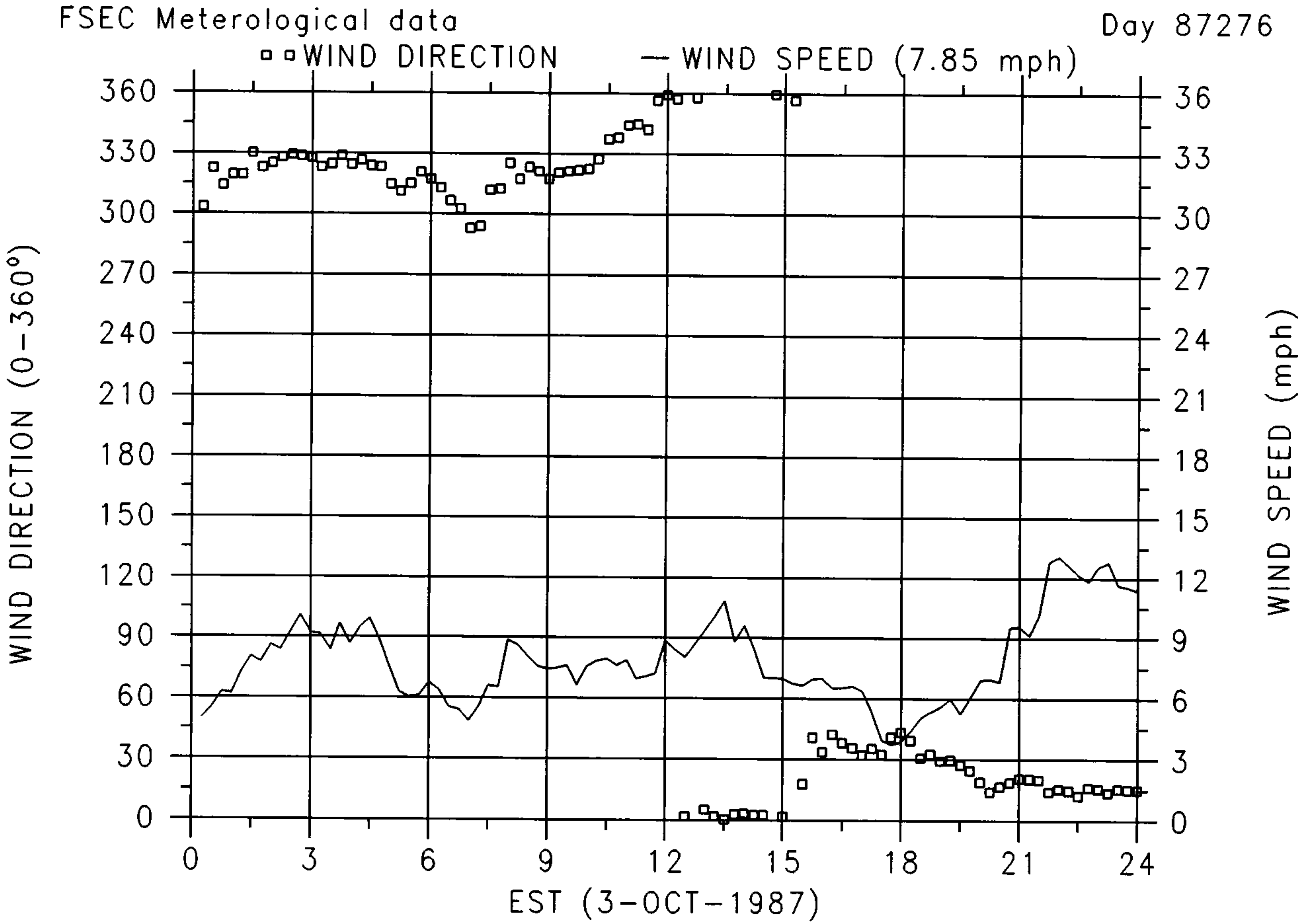
Cell 2 ceiling flux measurements at six ceiling locations.



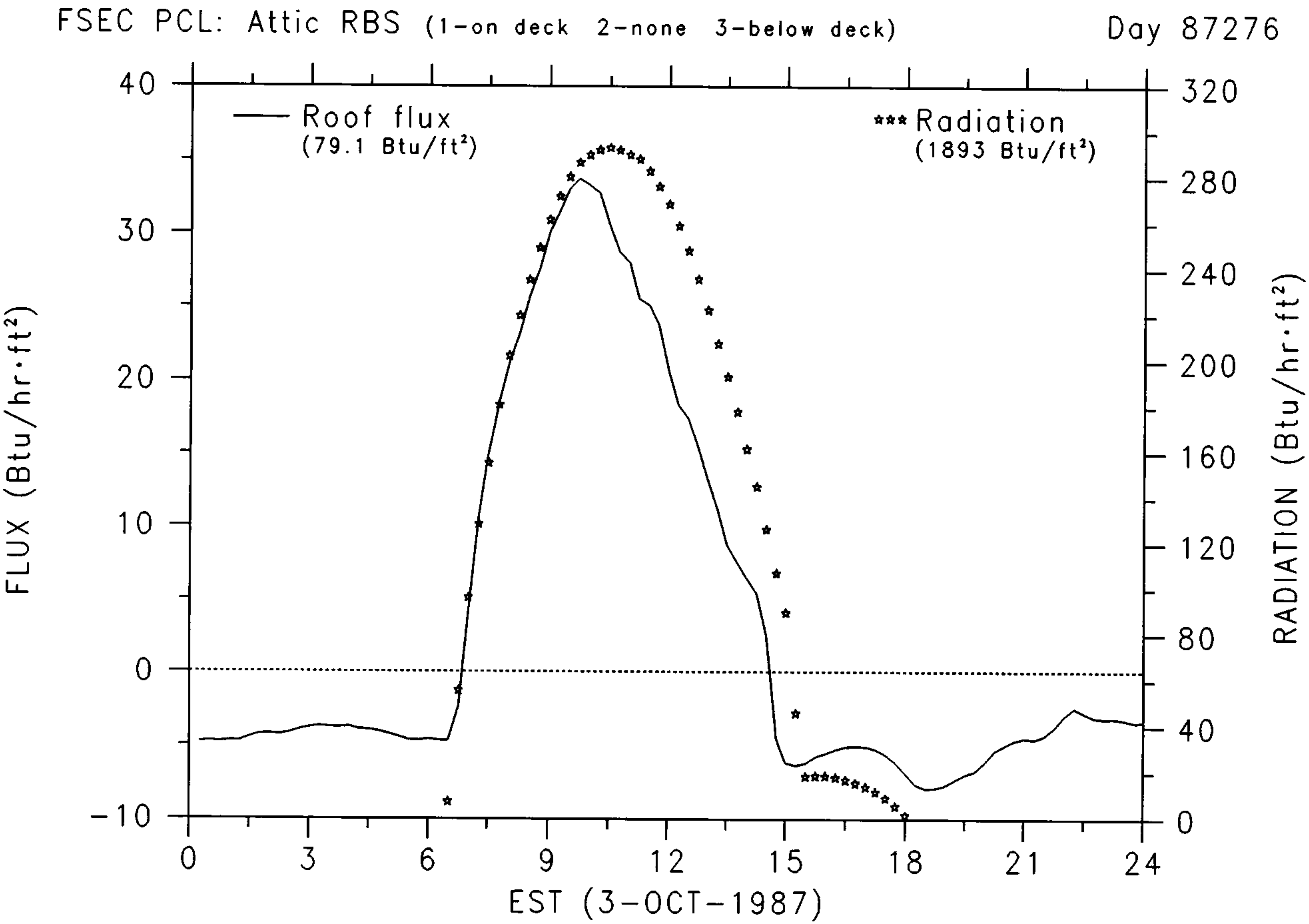
Cell 3 ceiling flux measurements at three locations.



Ambient air conditions and horizontal solar radiation.

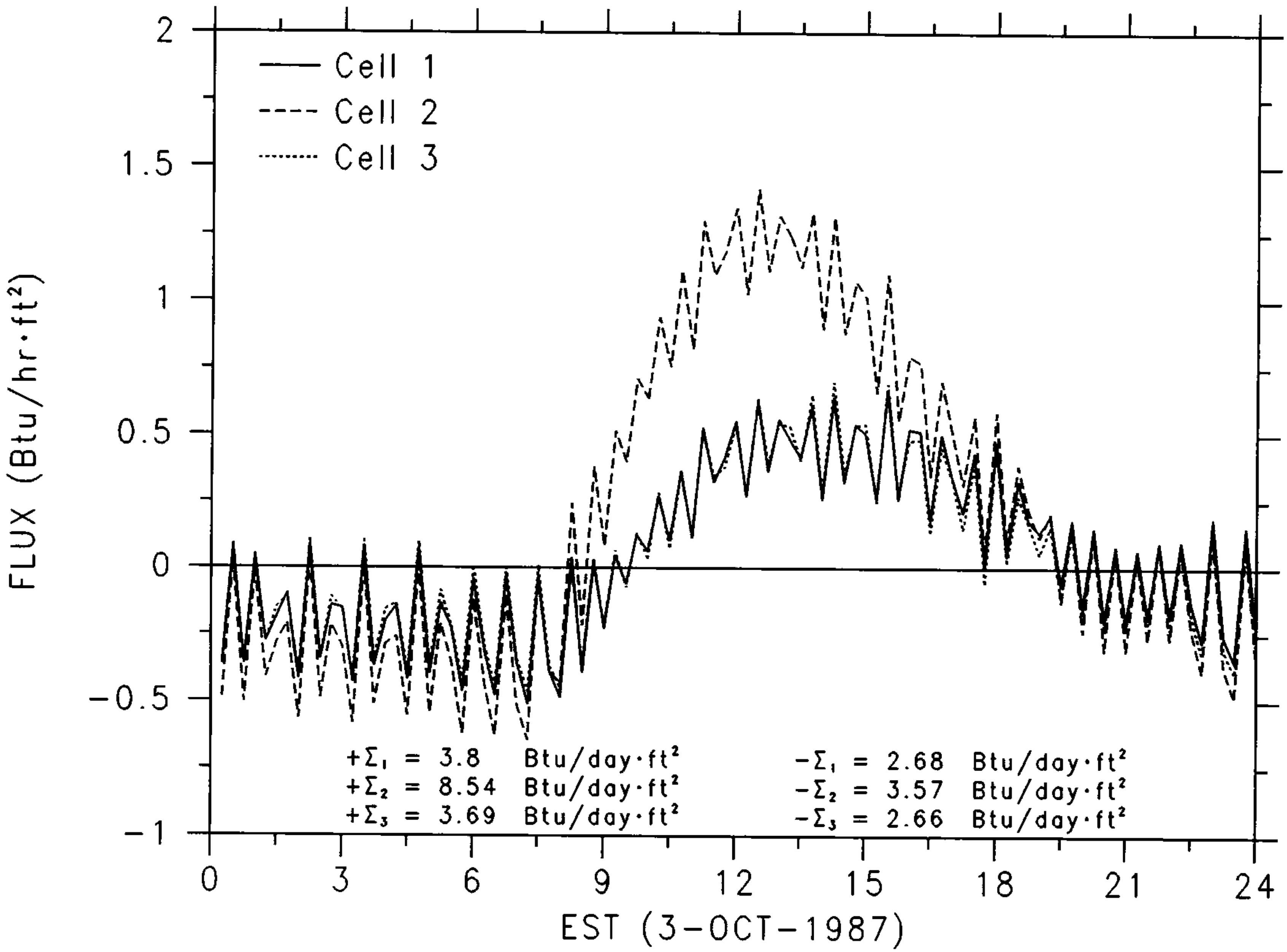


Local 10 meter wind measurements.

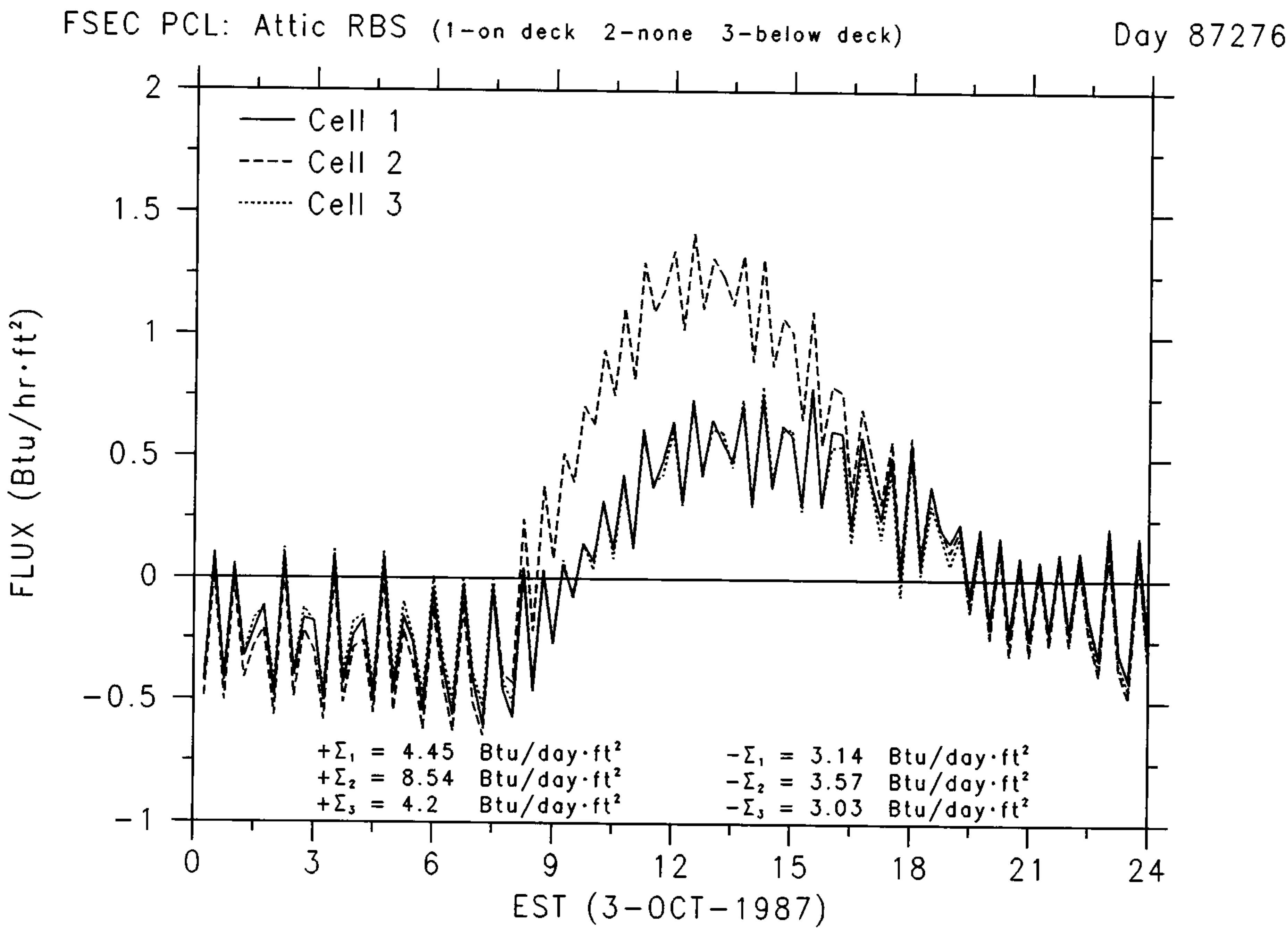


Cell 2 roof flux and incident solar radiation measurements.

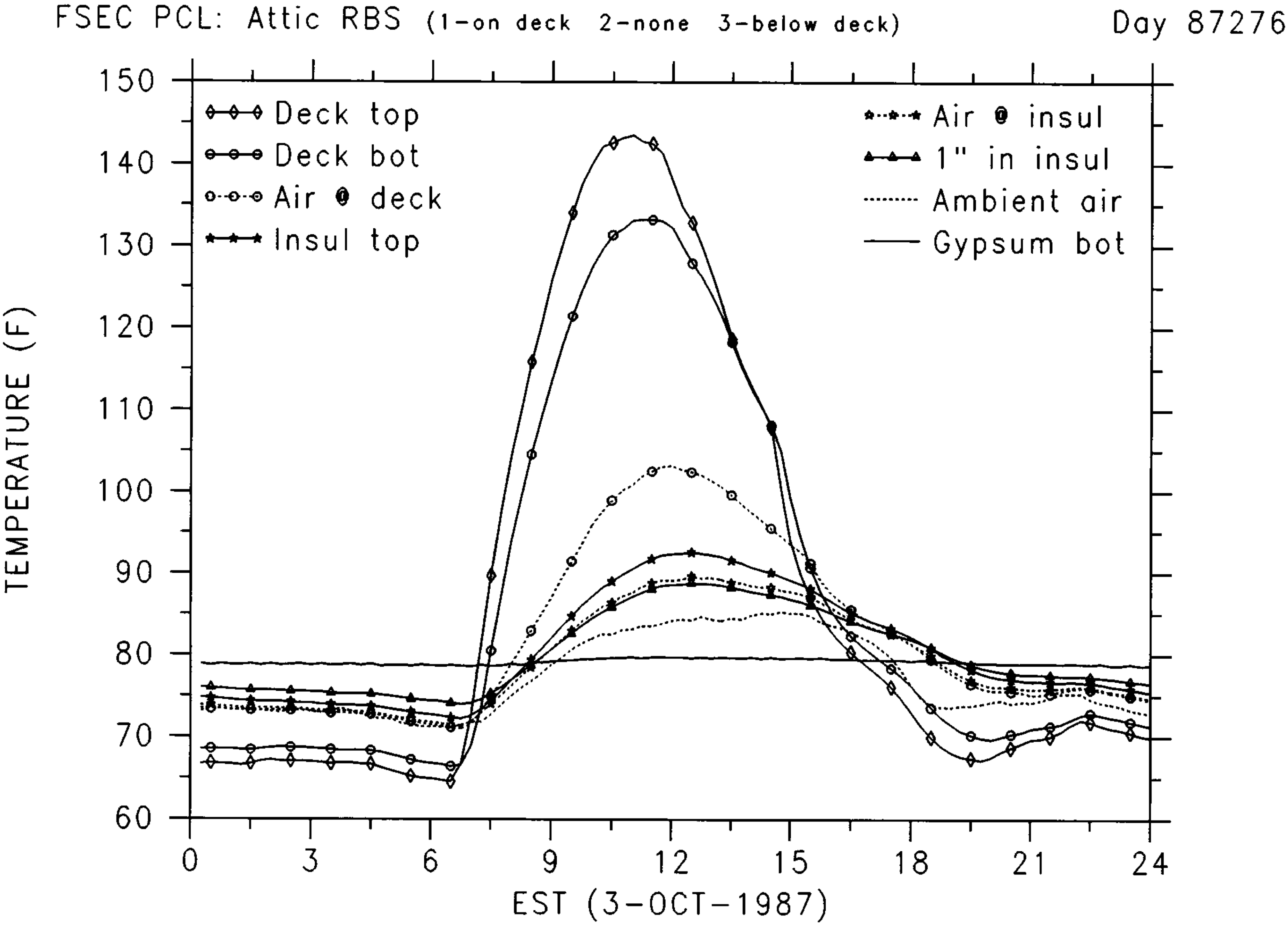
FSEC PCL: Attic RBS (1-on deck 2-none 3-below deck) Day 87276



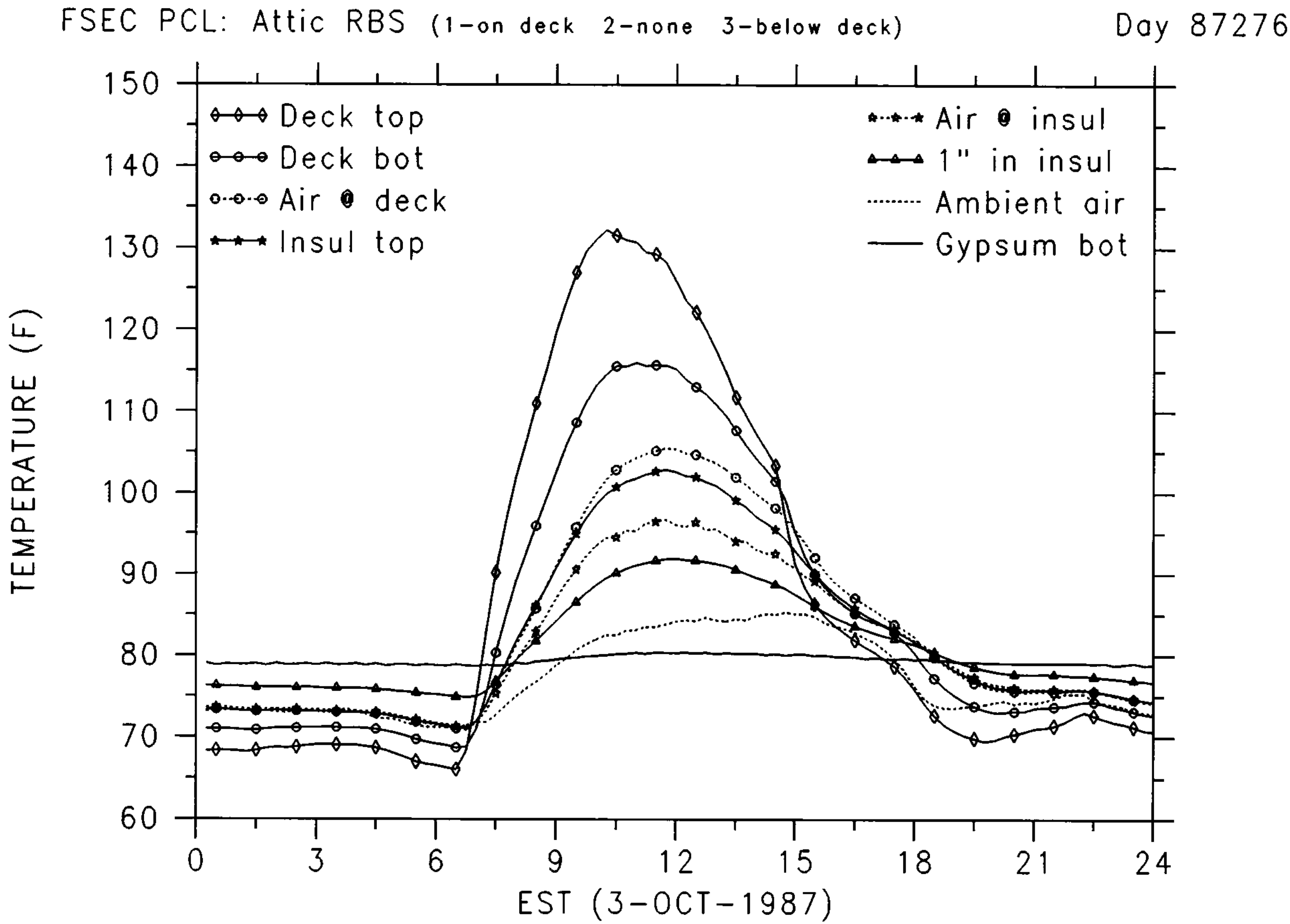
Measured central ceiling heat fluxes for test attics.



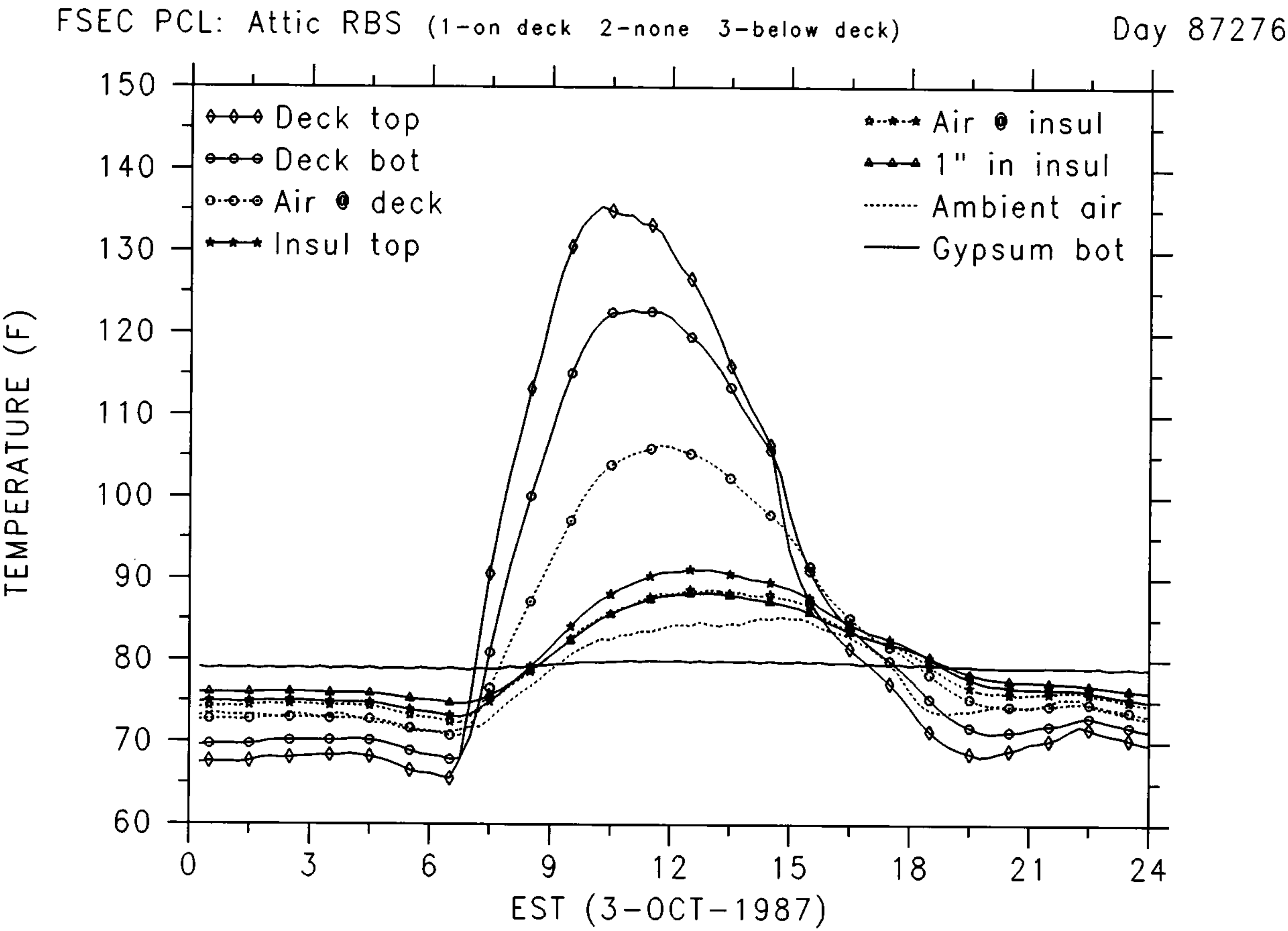
Normalized central ceiling heat fluxes for test attics.



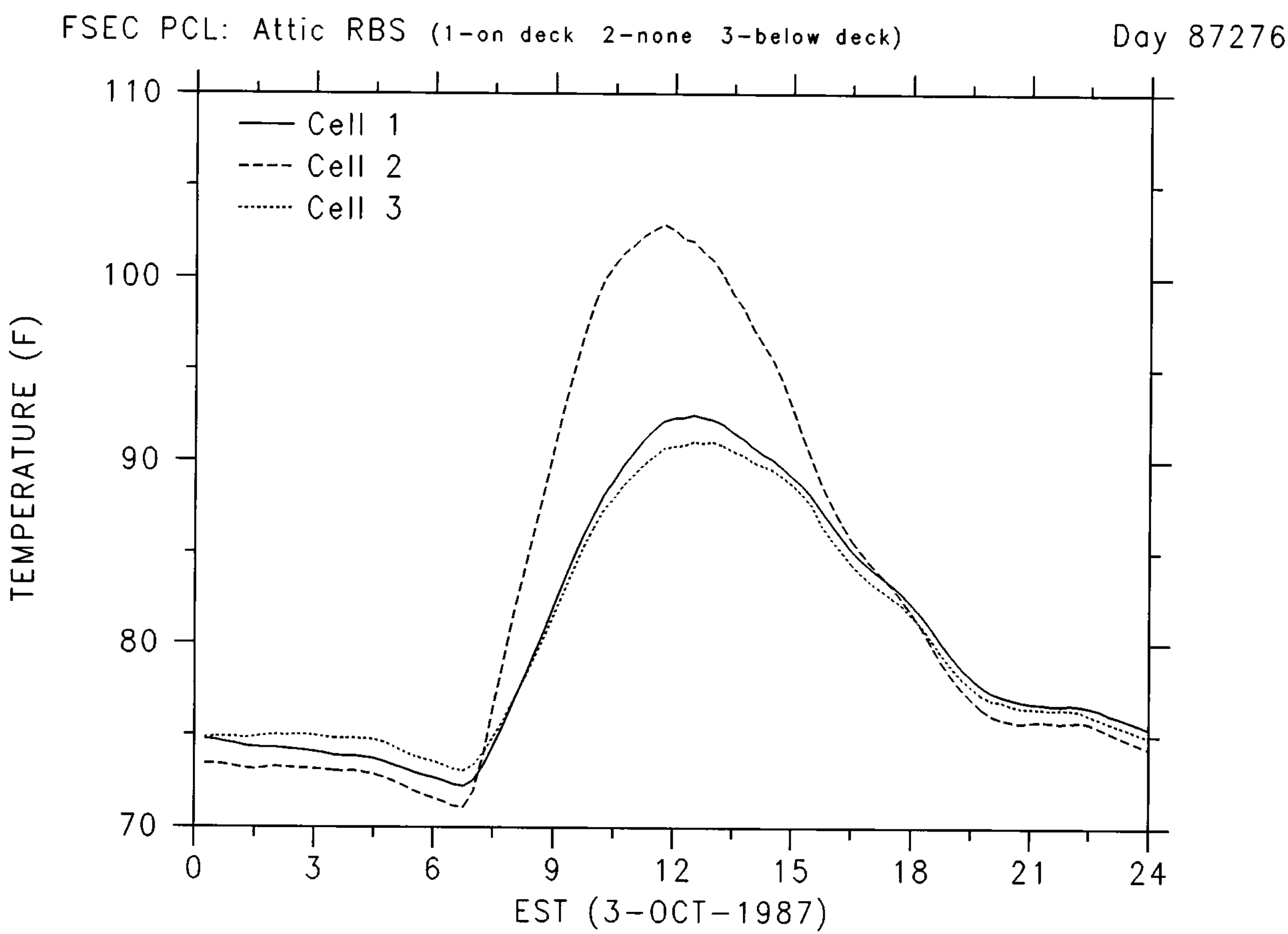
Distribution of cell 1 attic component temperatures.



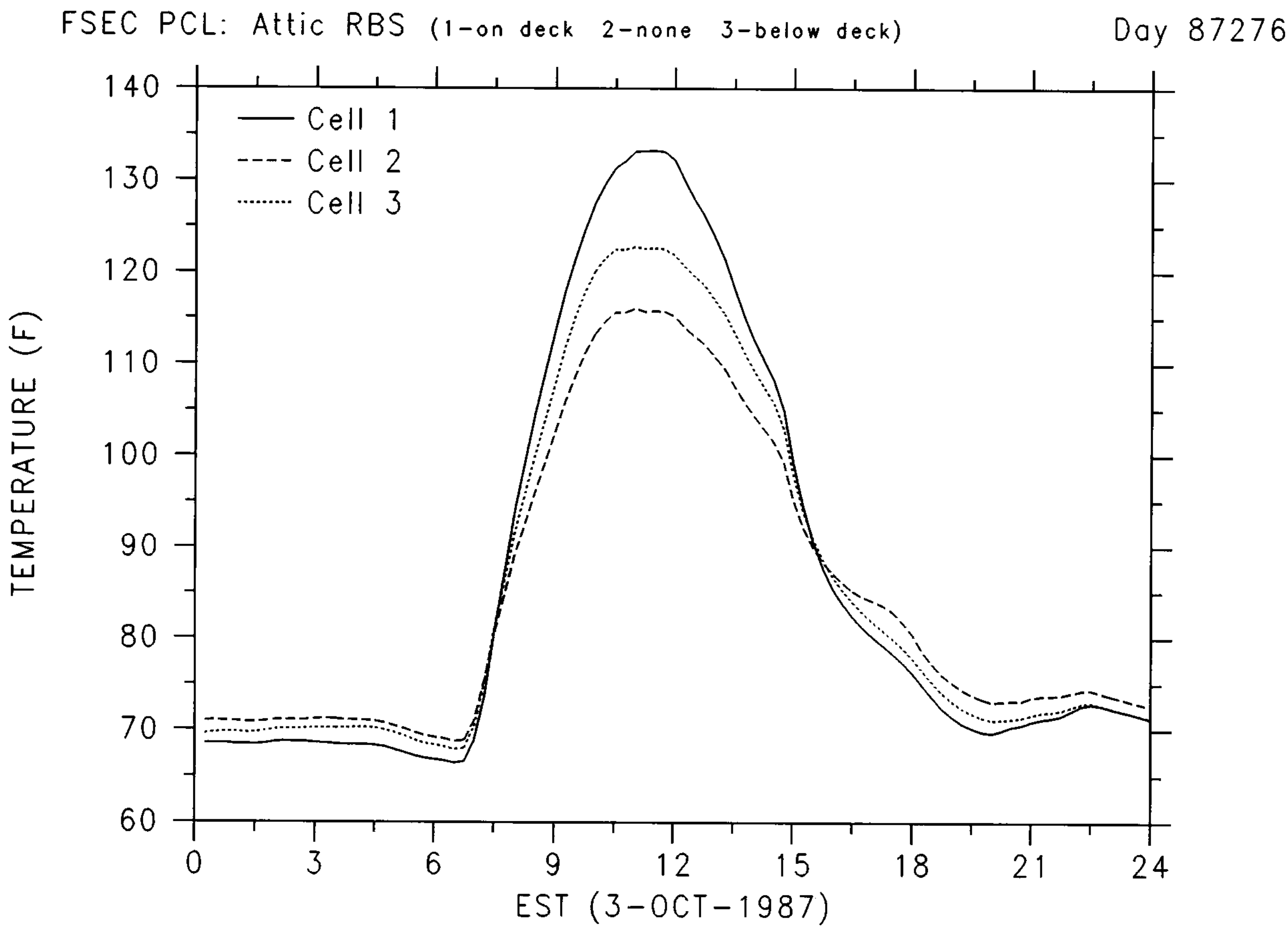
Distribution of cell 2 attic component temperatures.



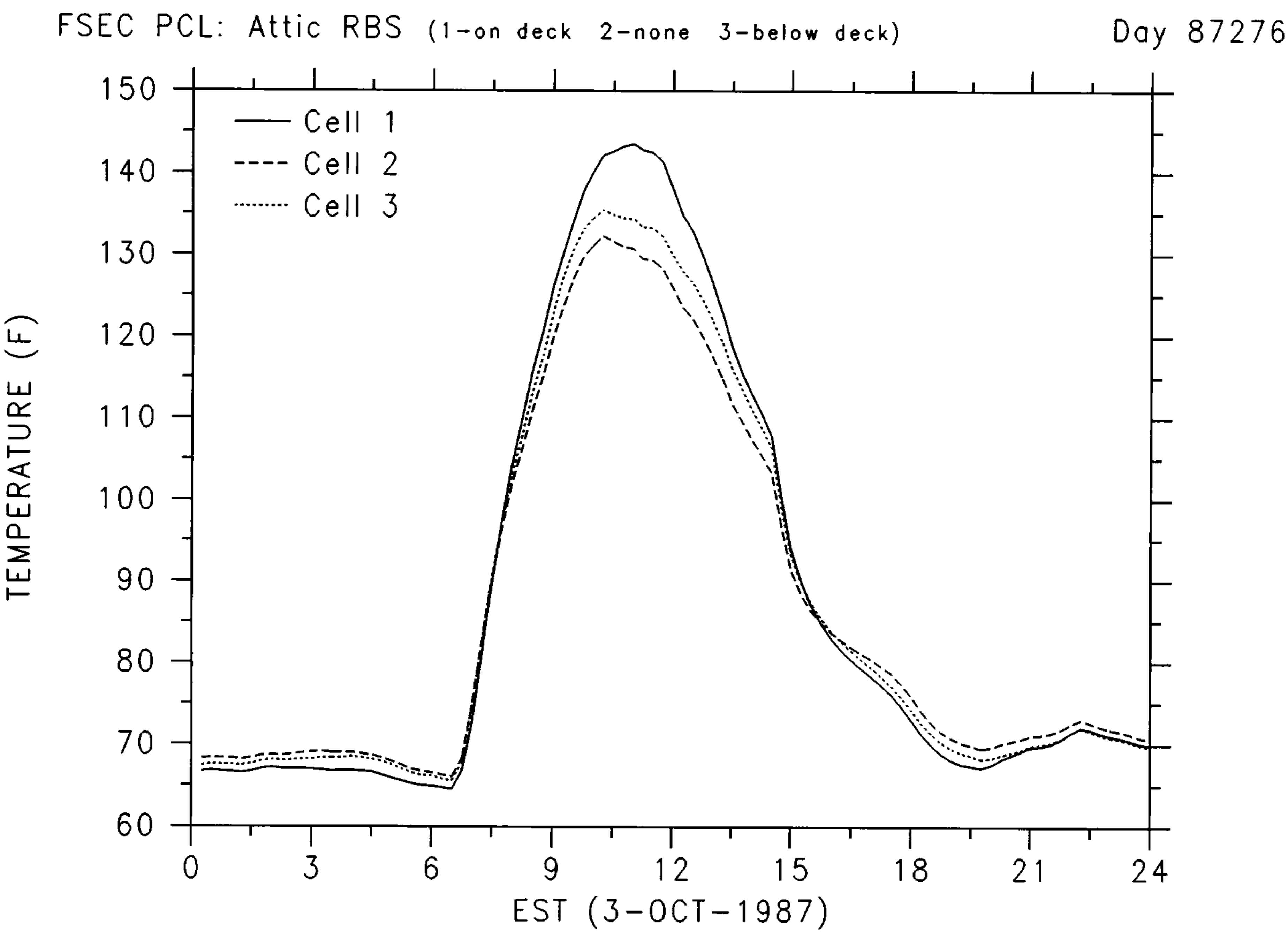
Distribution of cell 3 attic component temperatures.



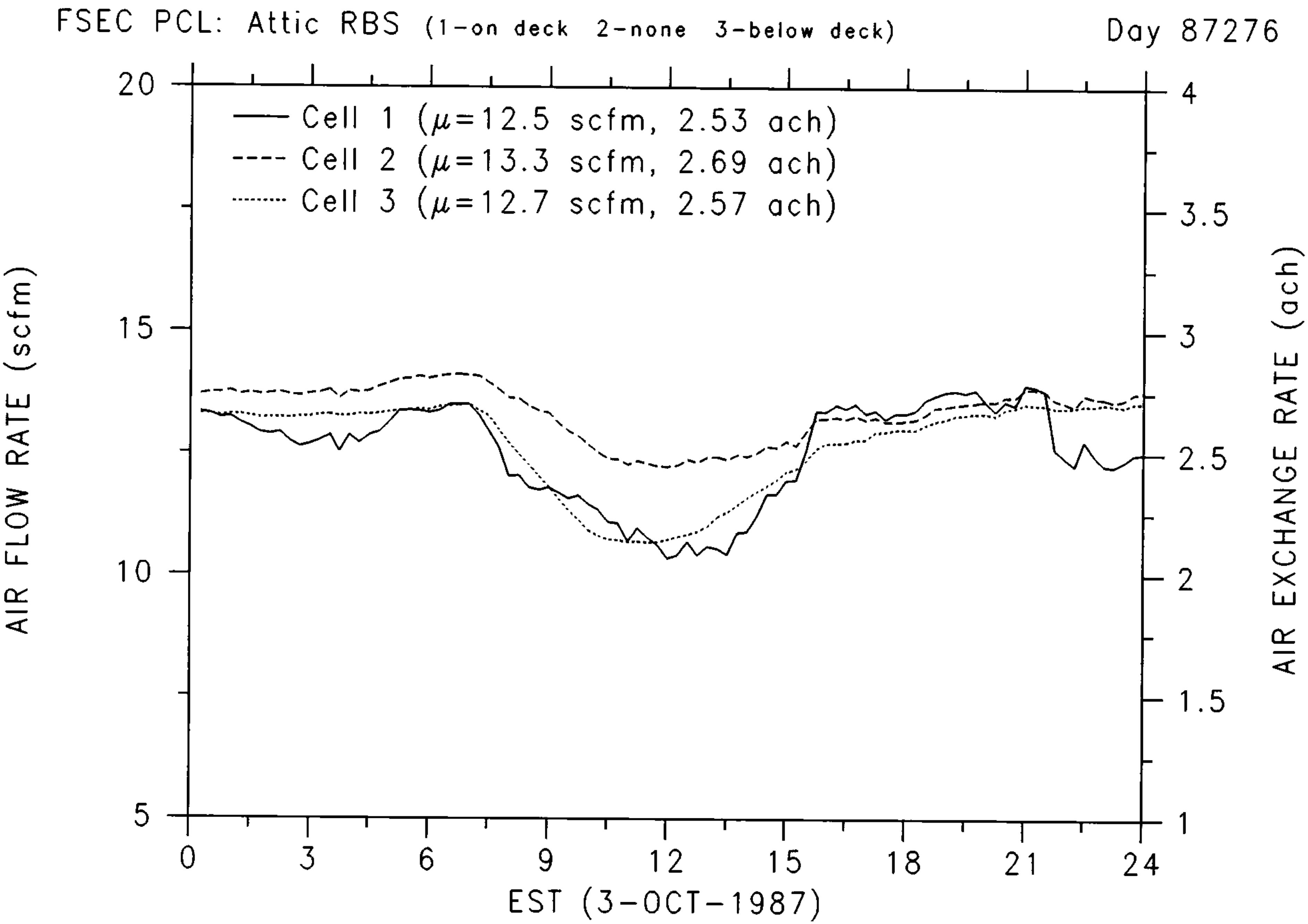
Insulation top surface temperatures in attic test cells.



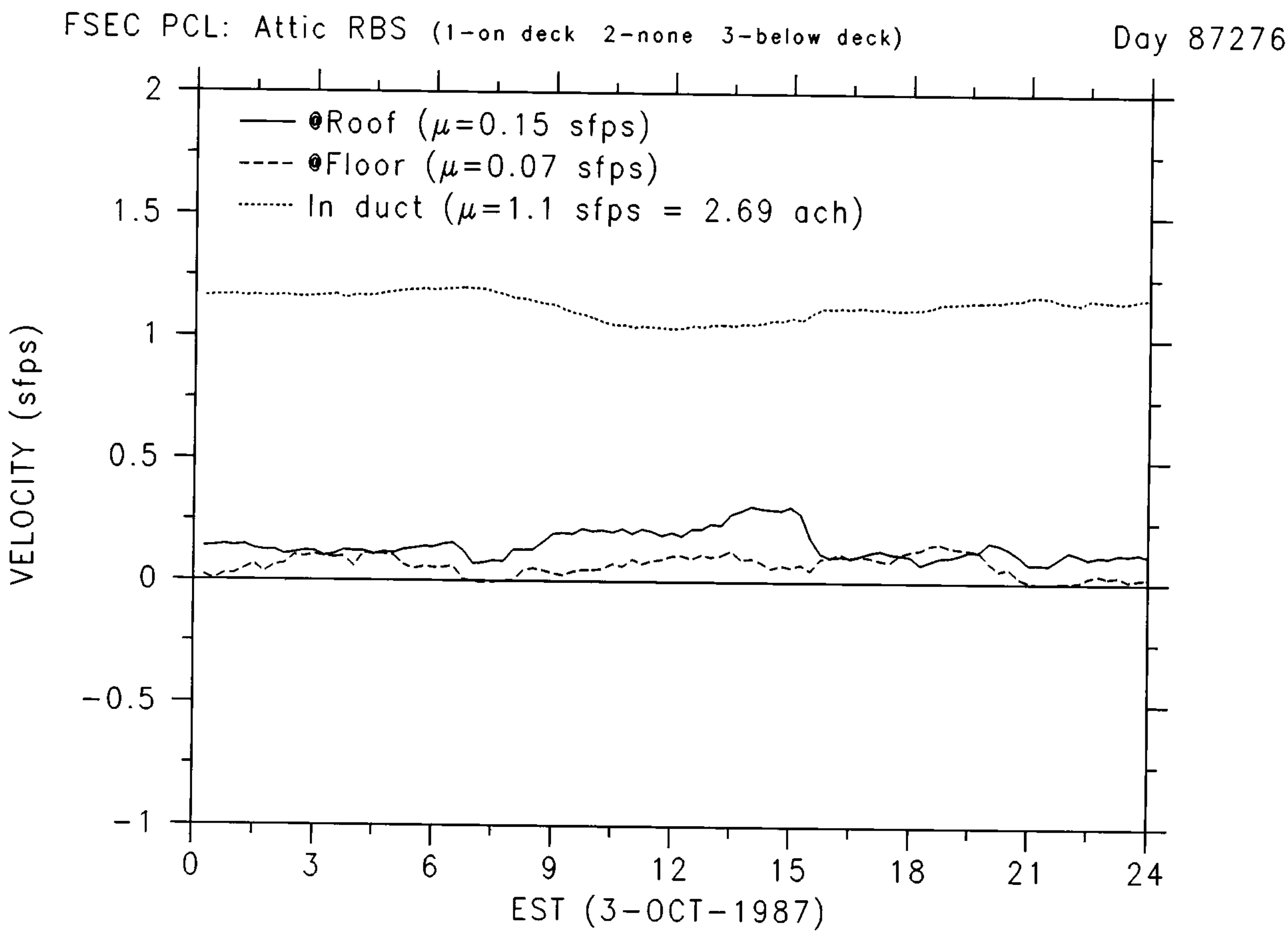
Inside roof decking temperatures in attic test cells.



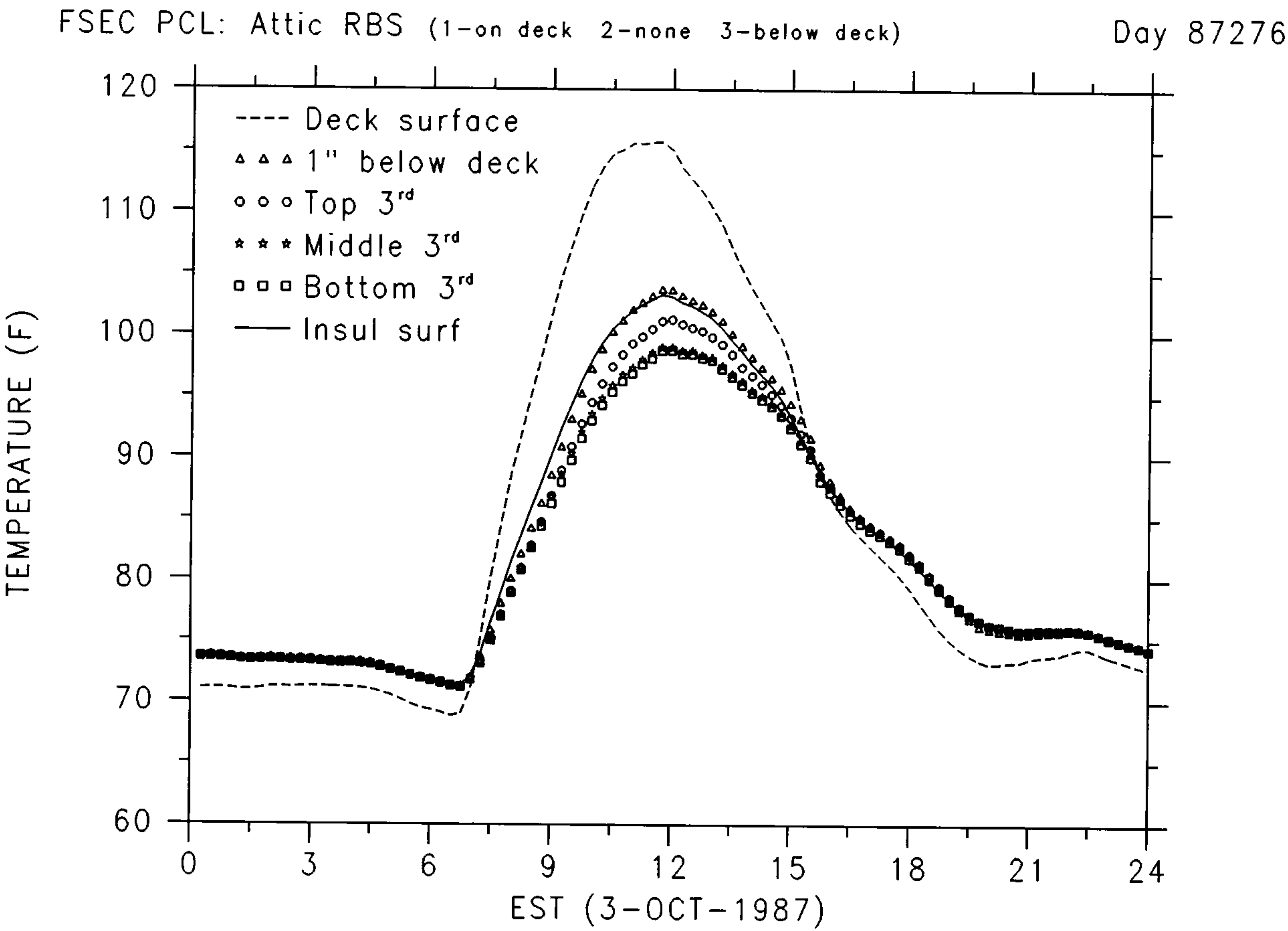
Outside roof decking temperatures in attic test cells.



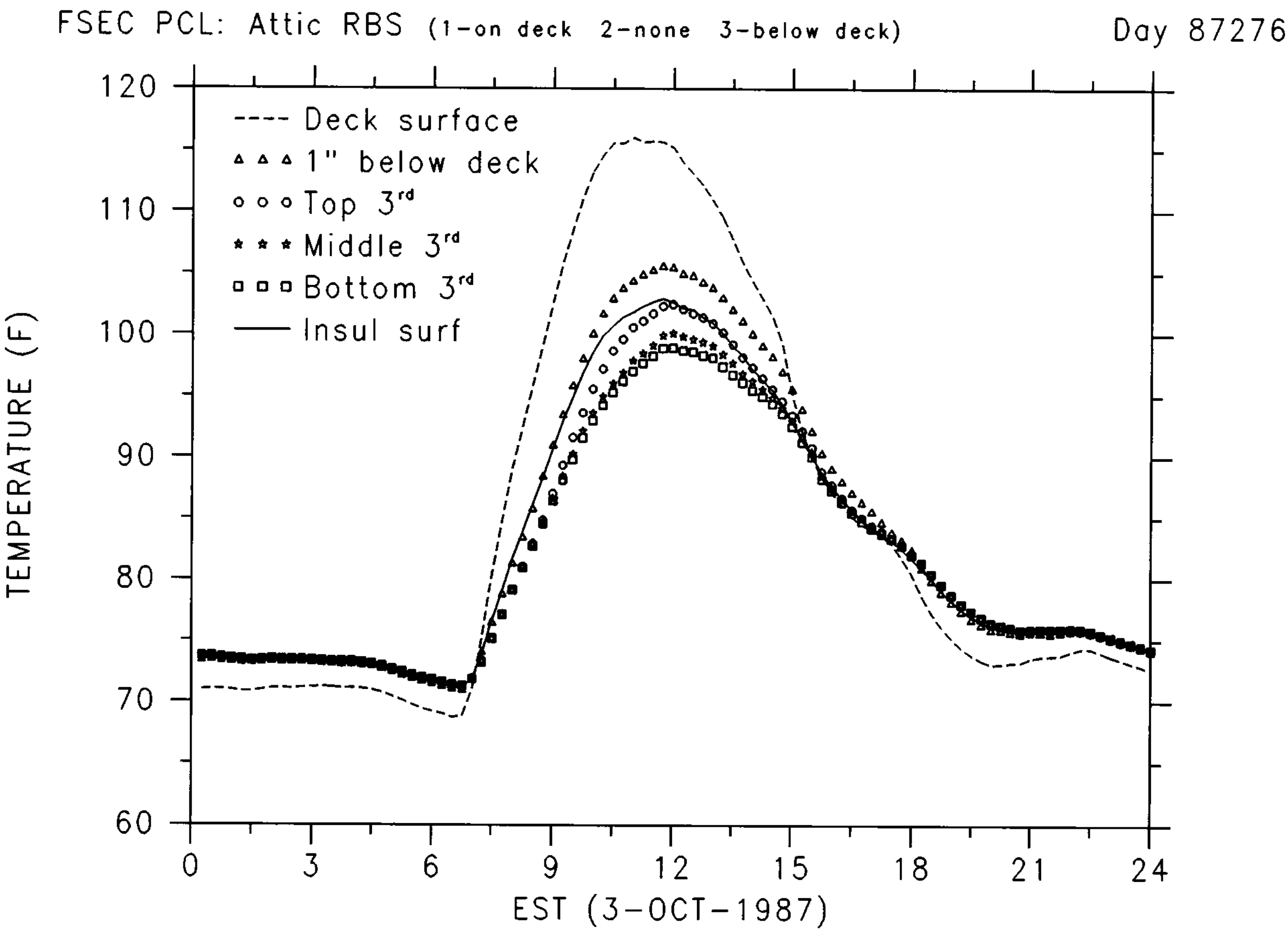
Attic bulk air ventilation rates for attic test cells.



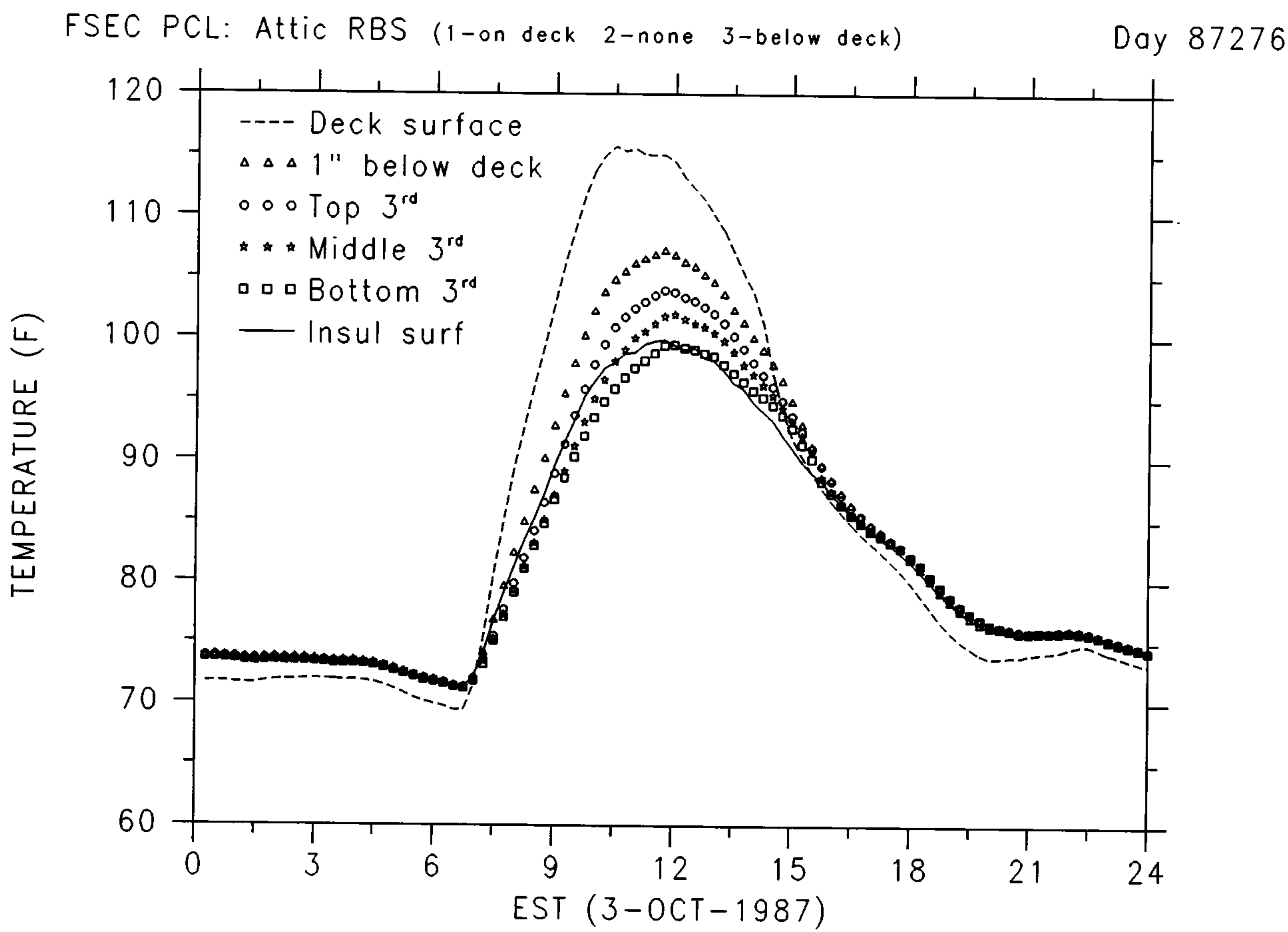
Cell 2 attic velocity profiles at three locations.



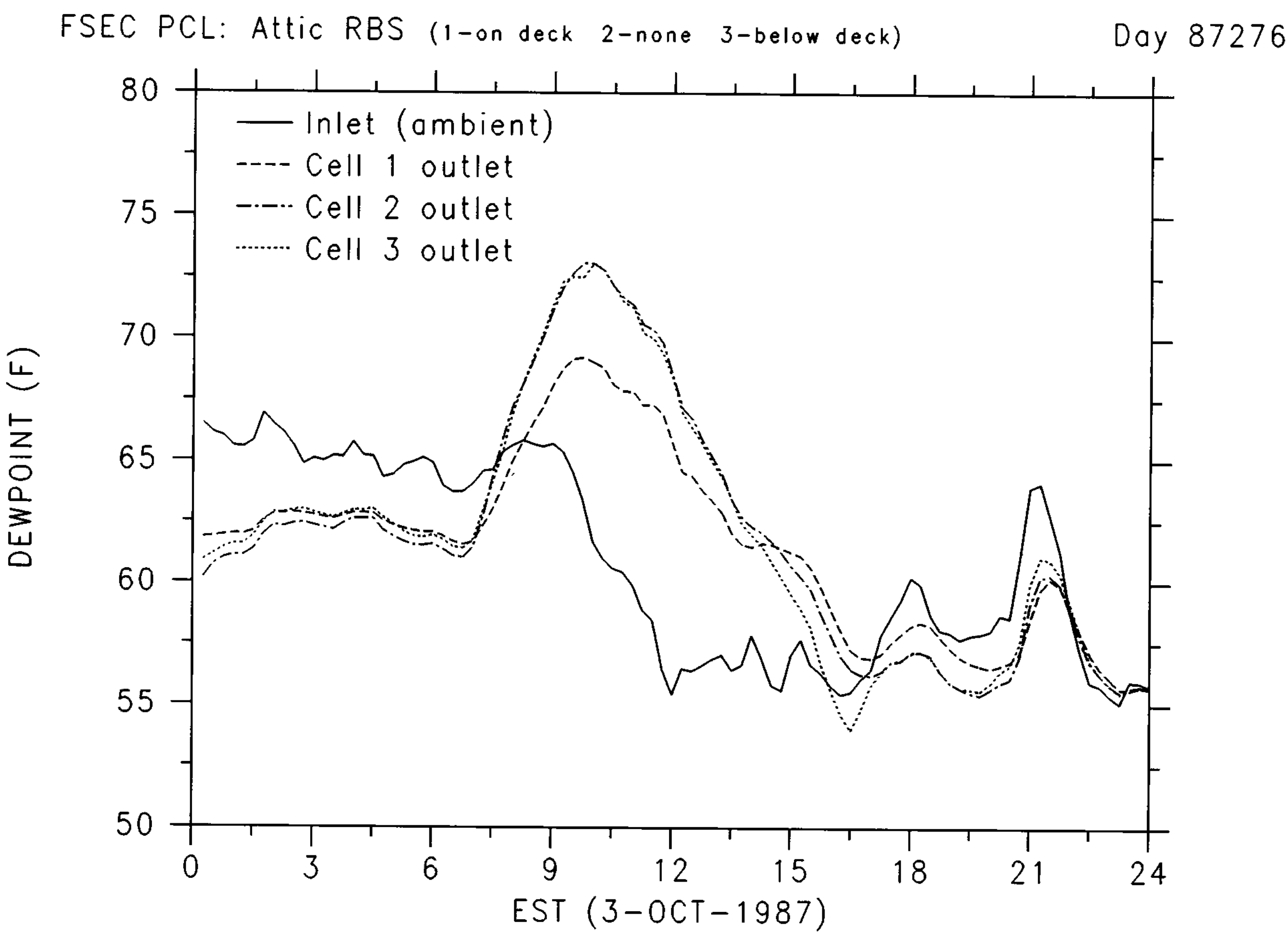
Cell 2 air temperature stratification at inlet end of attic.



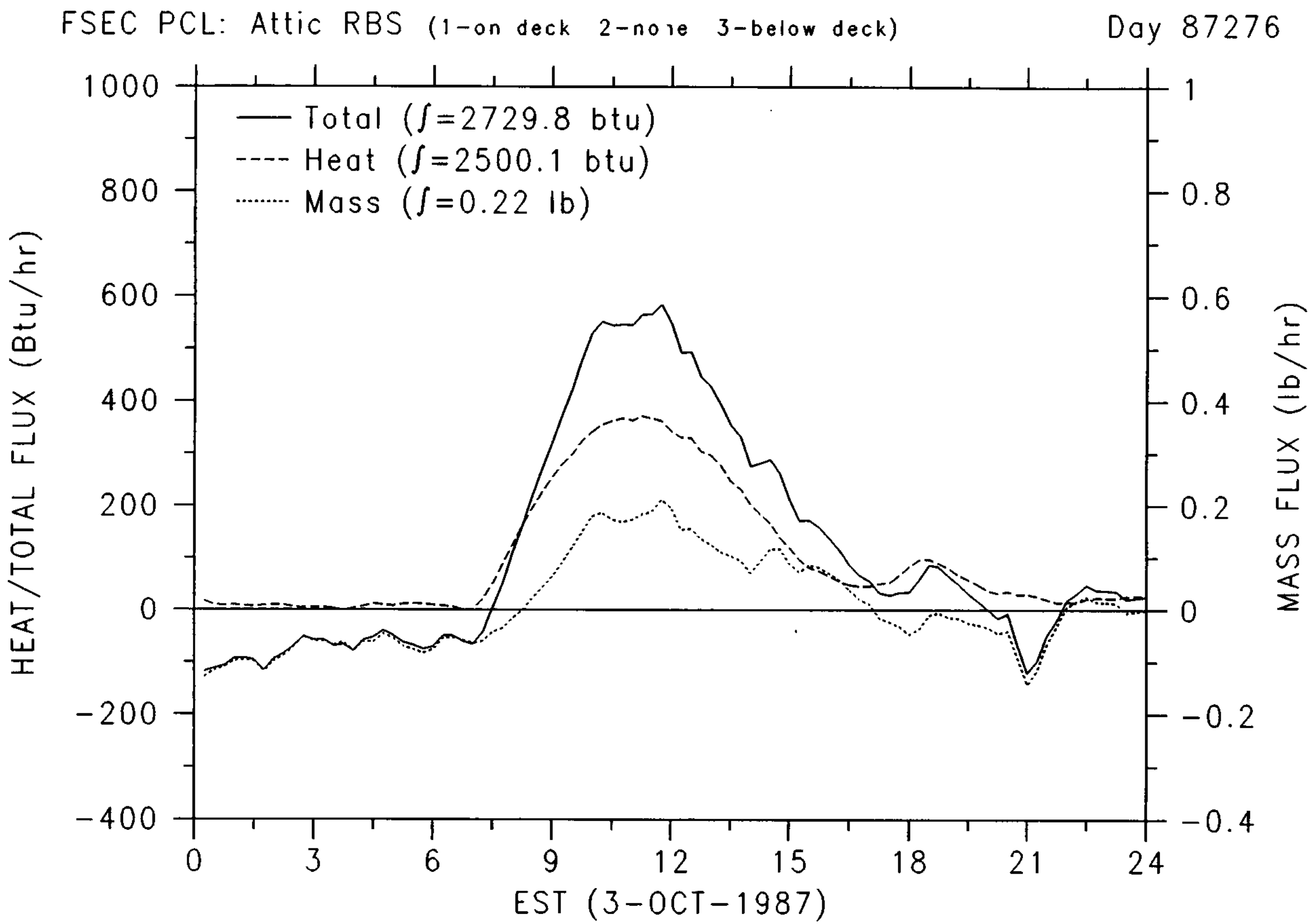
Cell 2 air temperature stratification at attic middle.



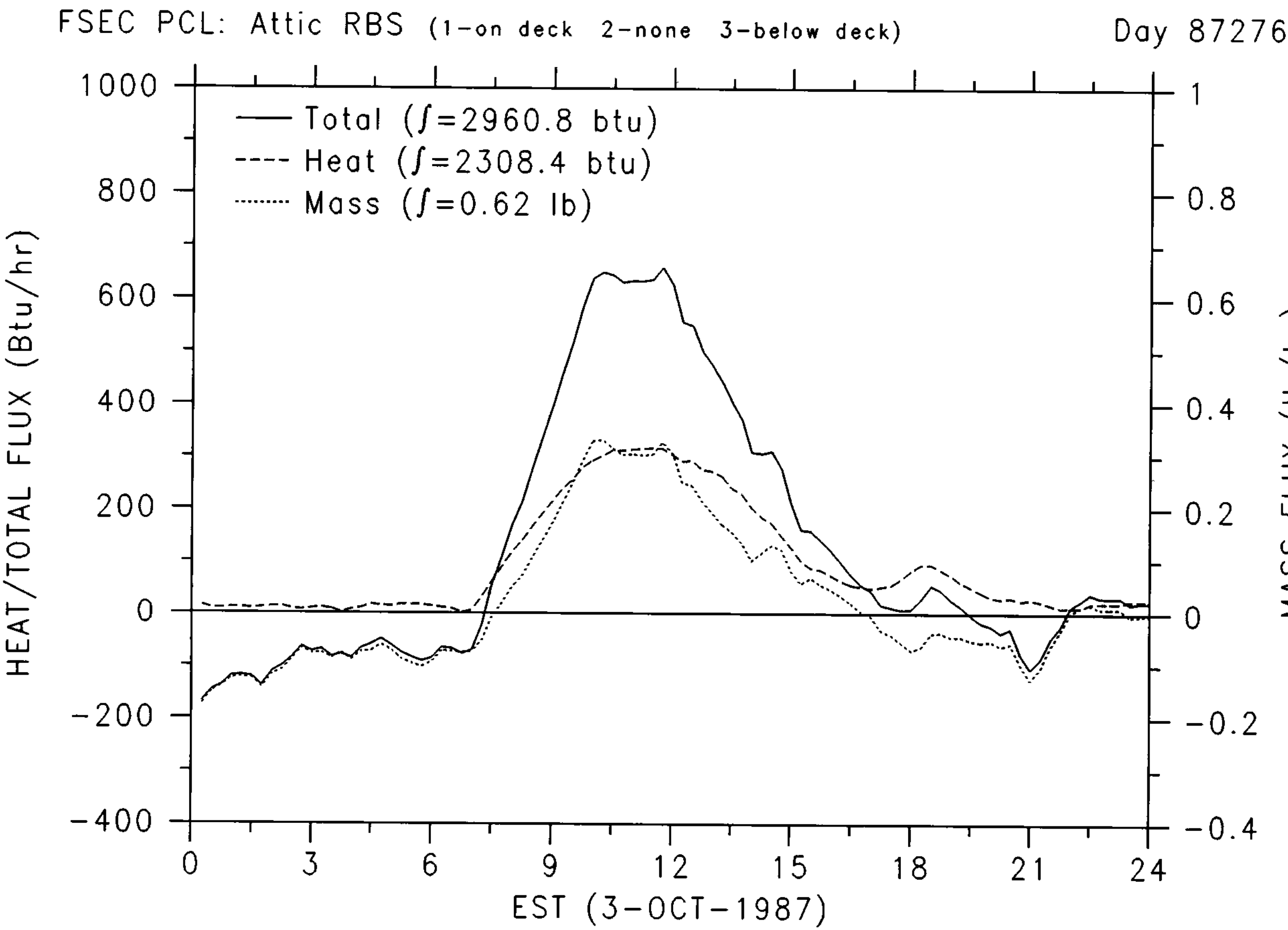
Cell 2 air temperature stratification at outlet end of attic.



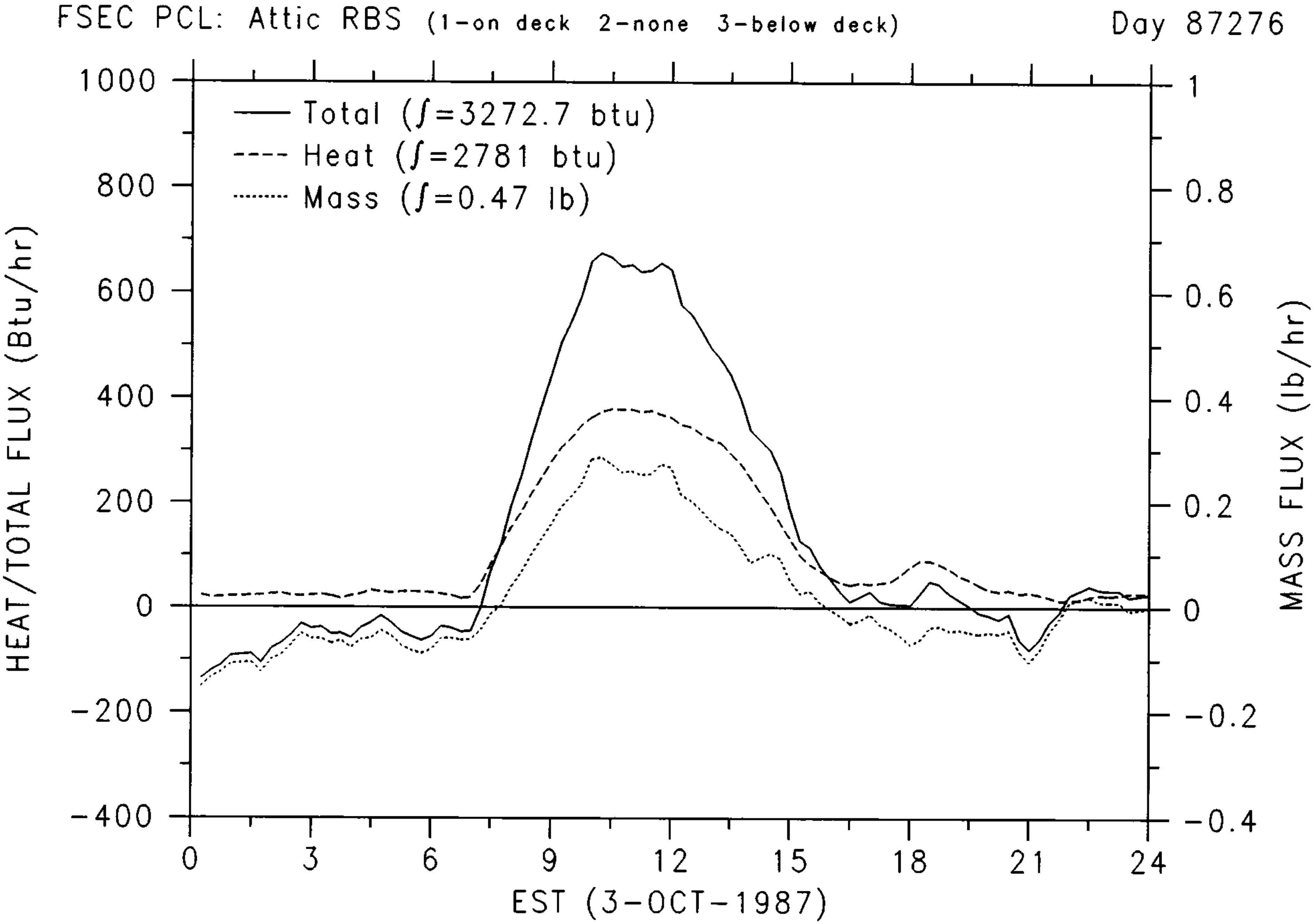
Inlet and outlet dewpoint temperatures for attic test cells.



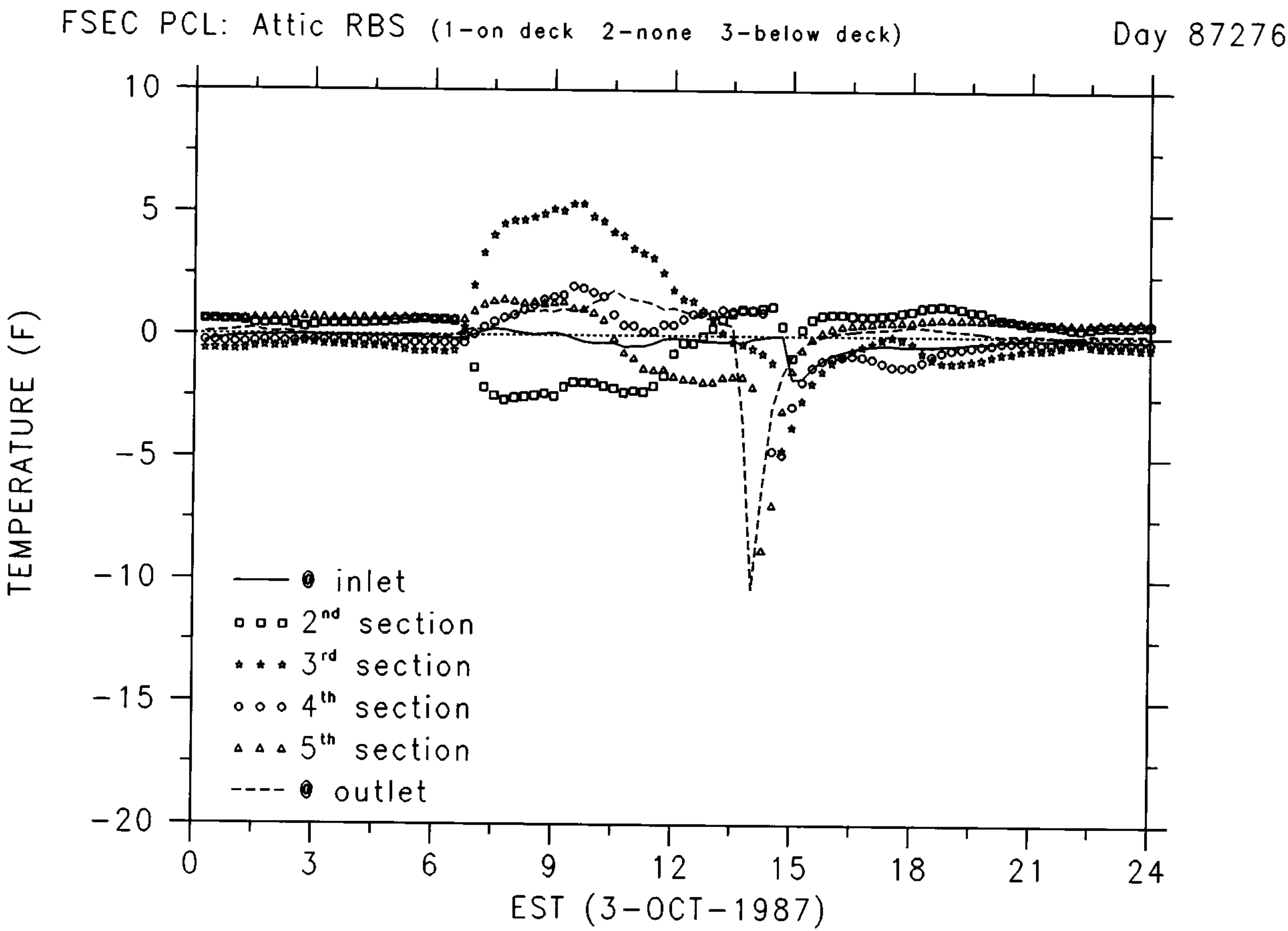
Cell 1 vent airstream heat and mass removal rates.



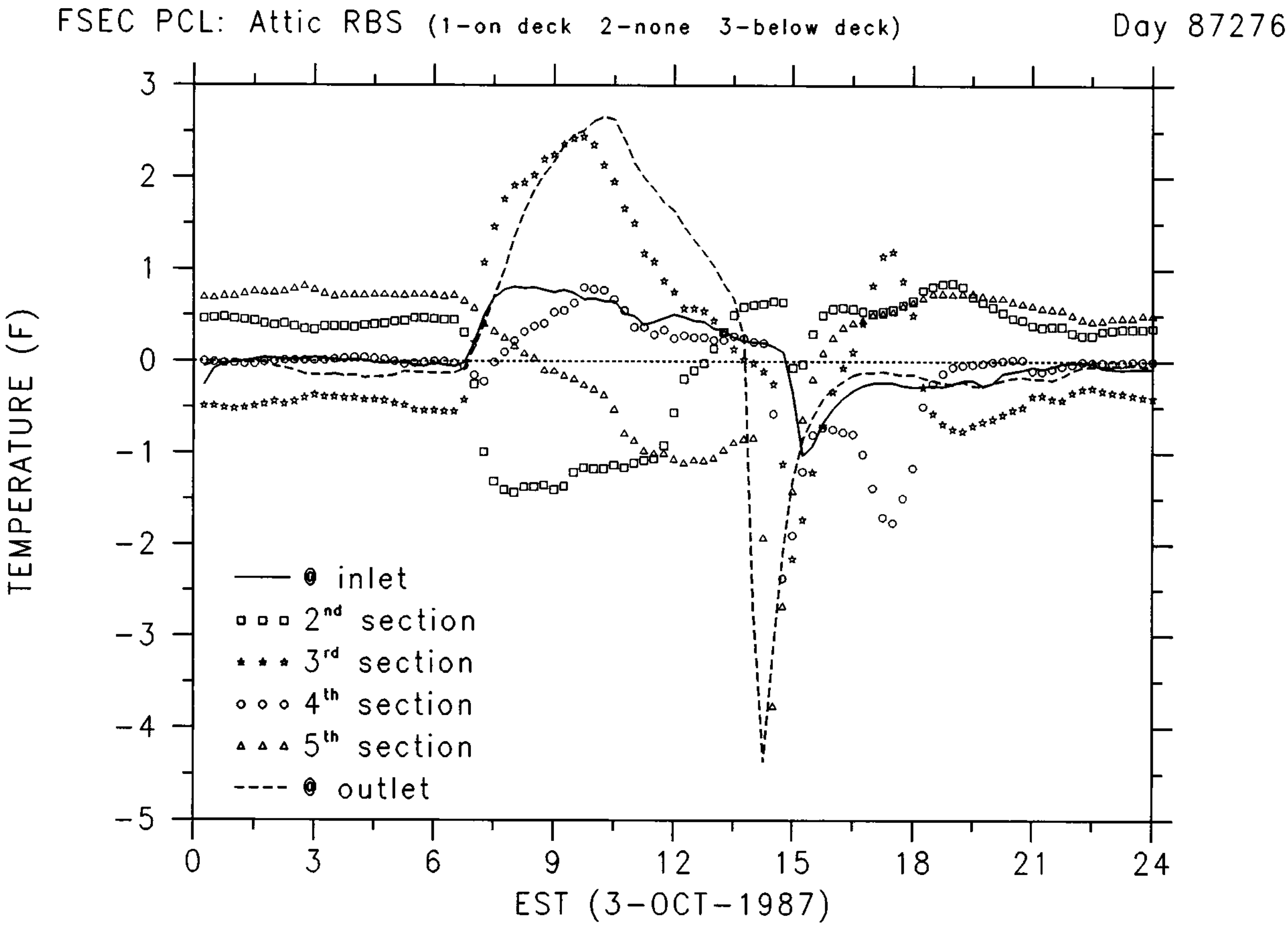
Cell 2 vent airstream heat and mass removal rates.



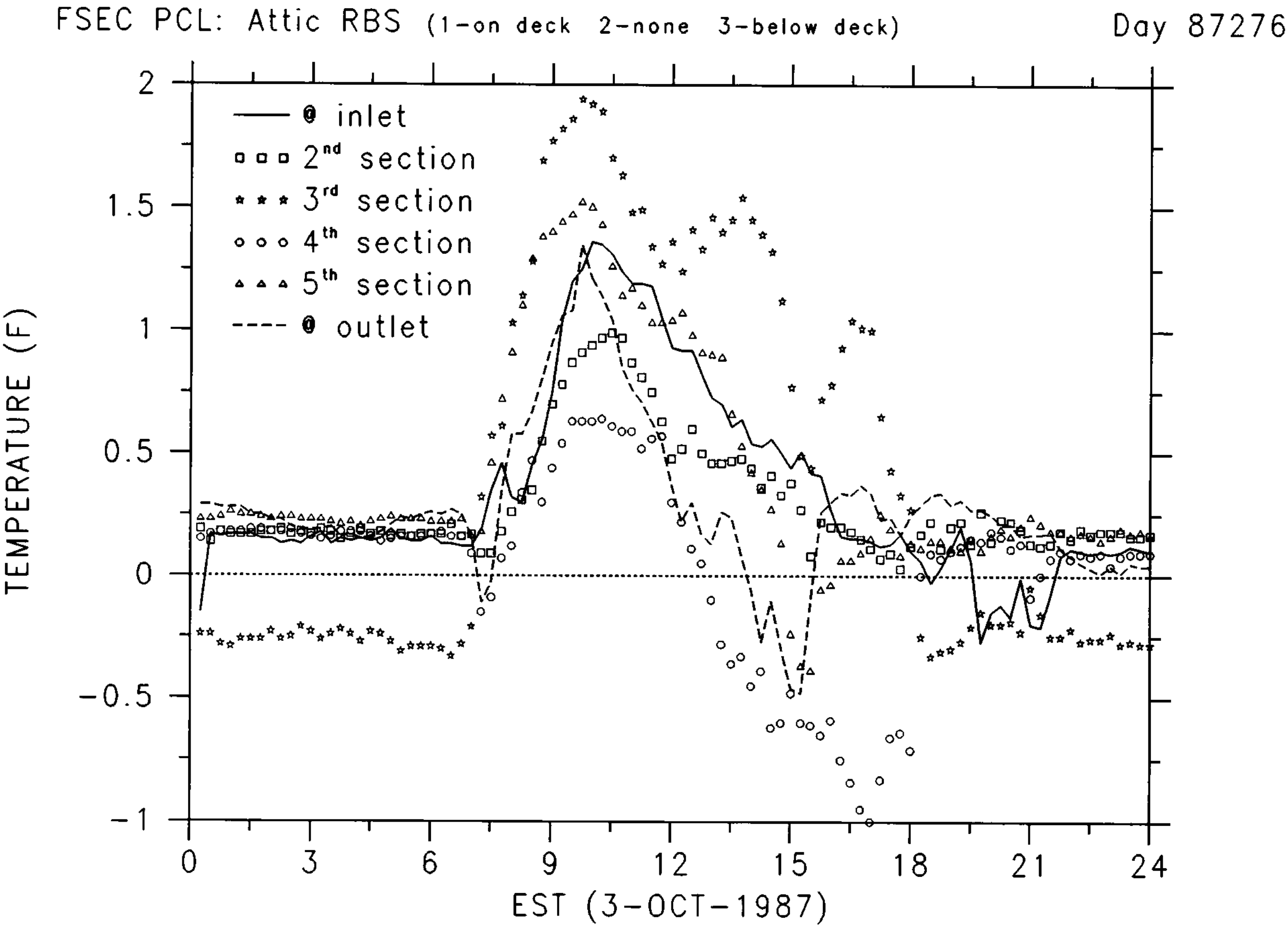
Cell 3 vent airstream heat and mass removal rates.



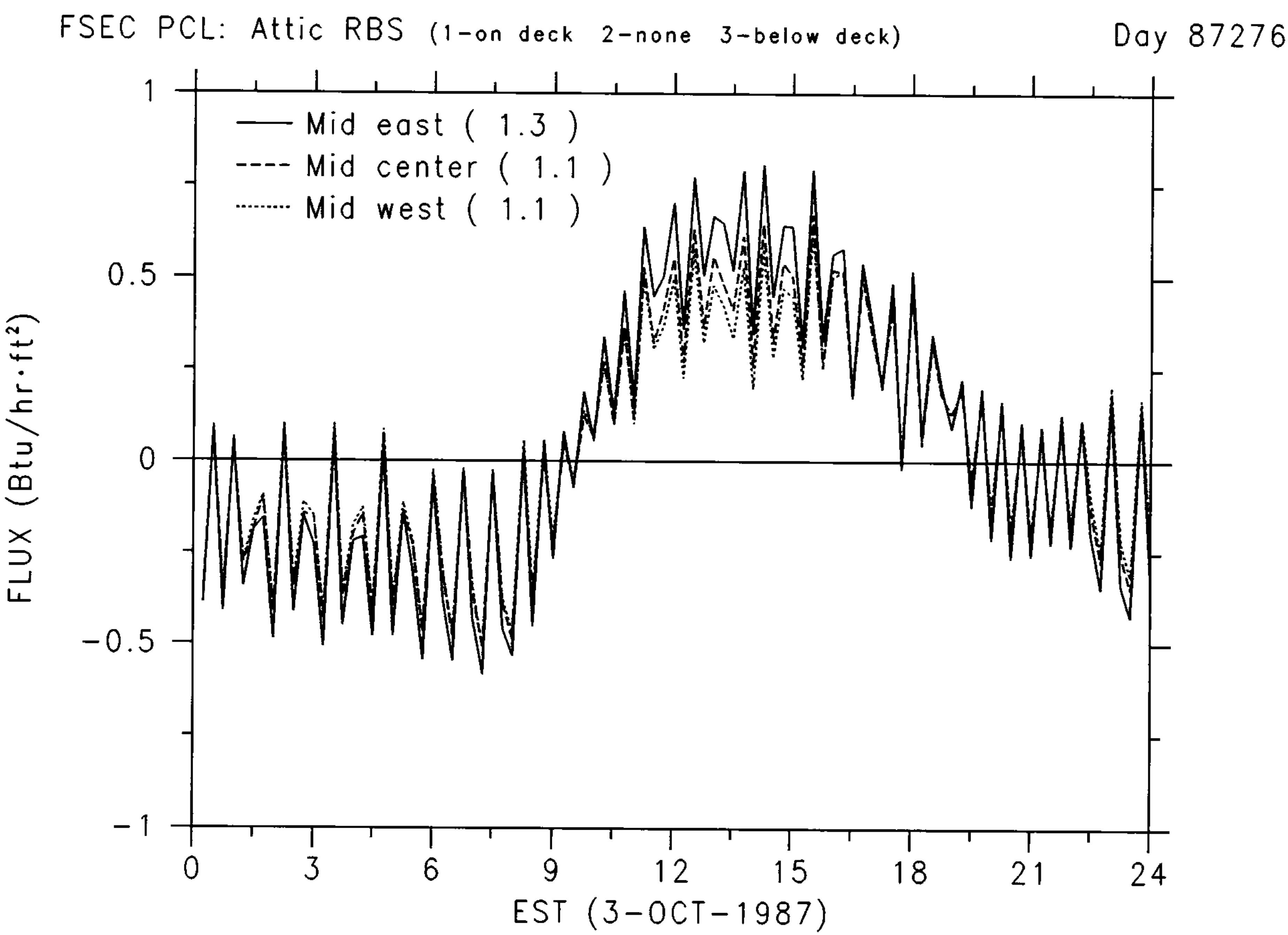
Temperature gradients between measurements at outside decking.



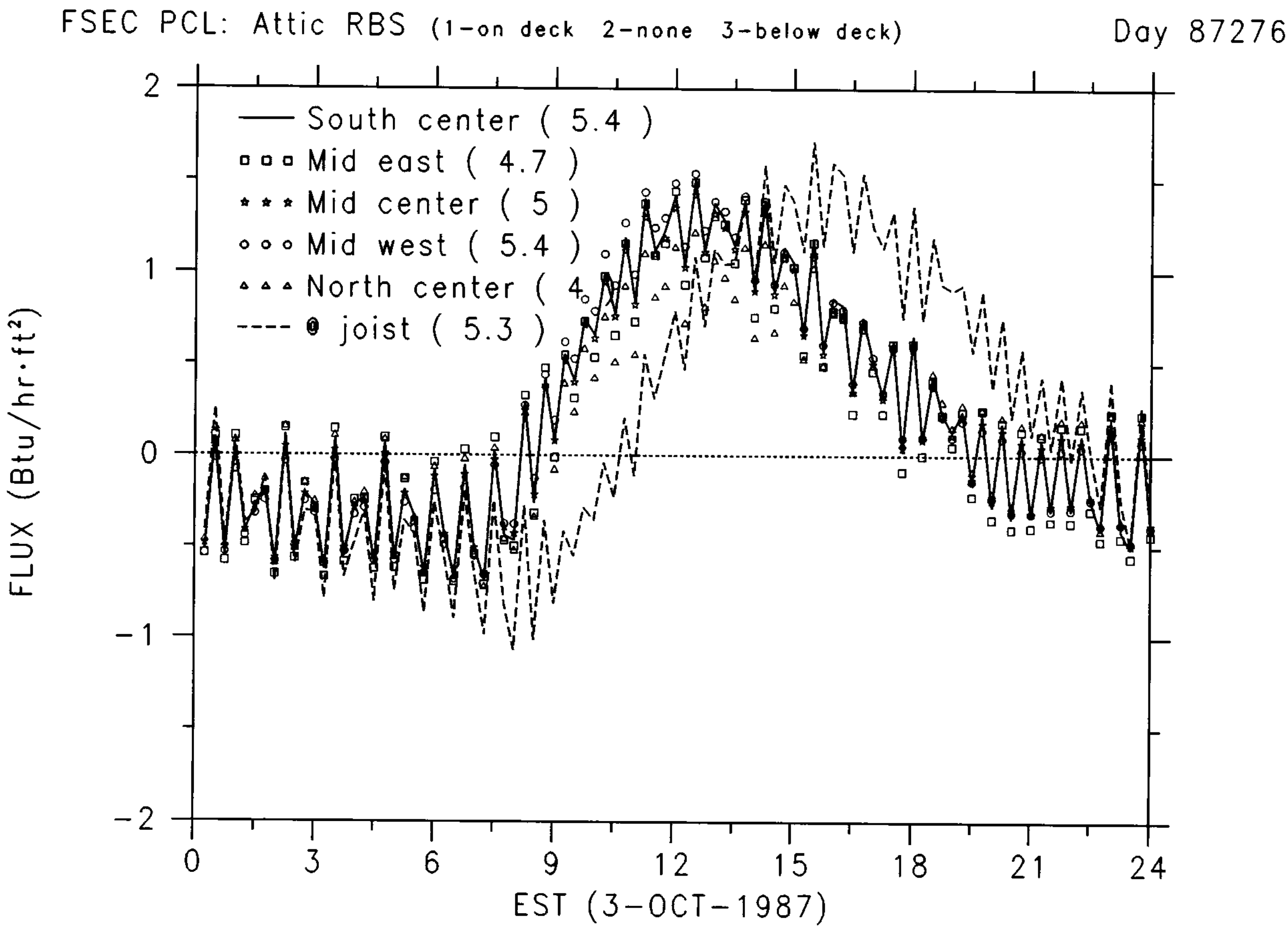
Temperature gradients between measurements at inside decking.



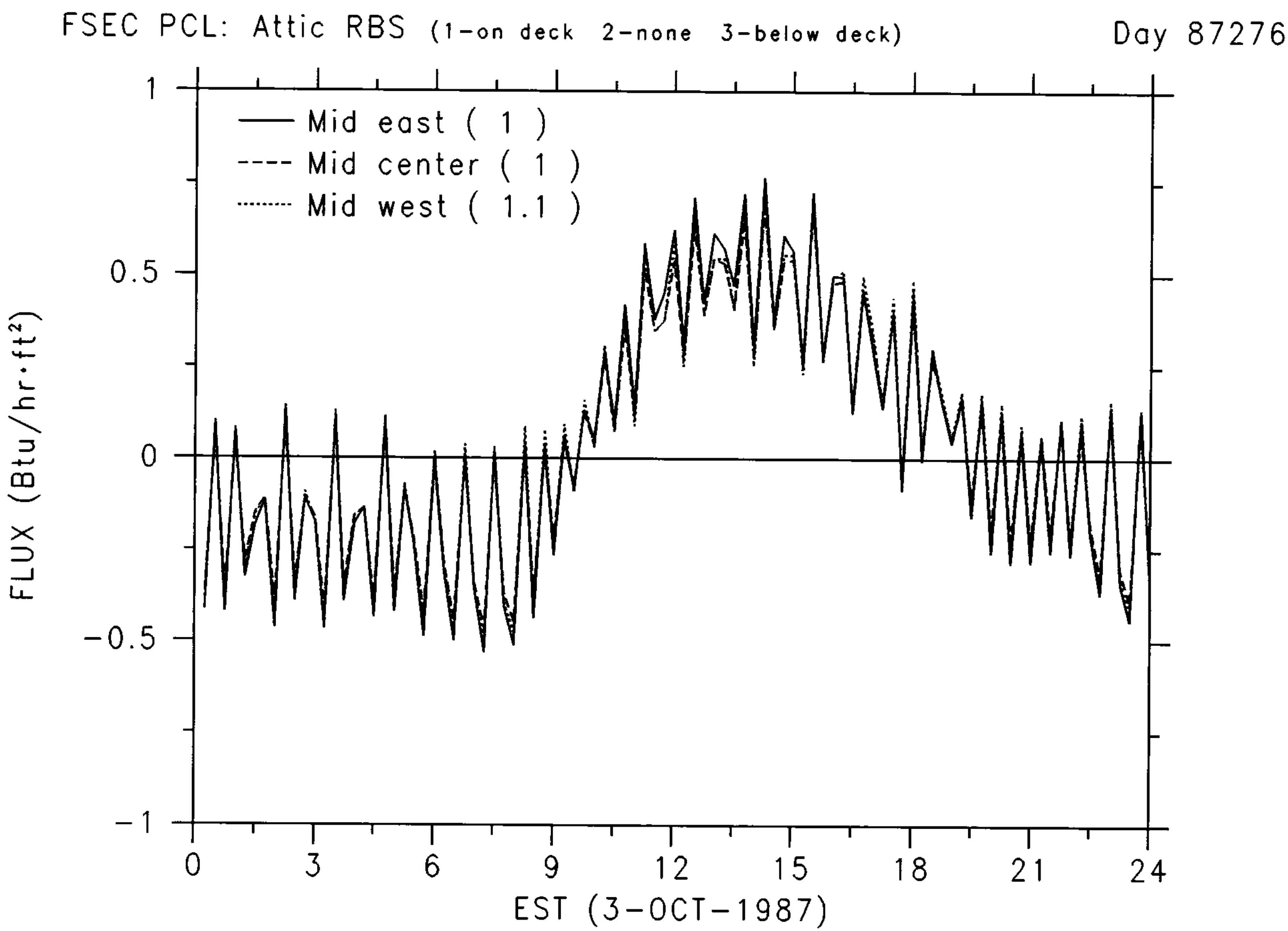
Temperature gradients between measurements in vent air.



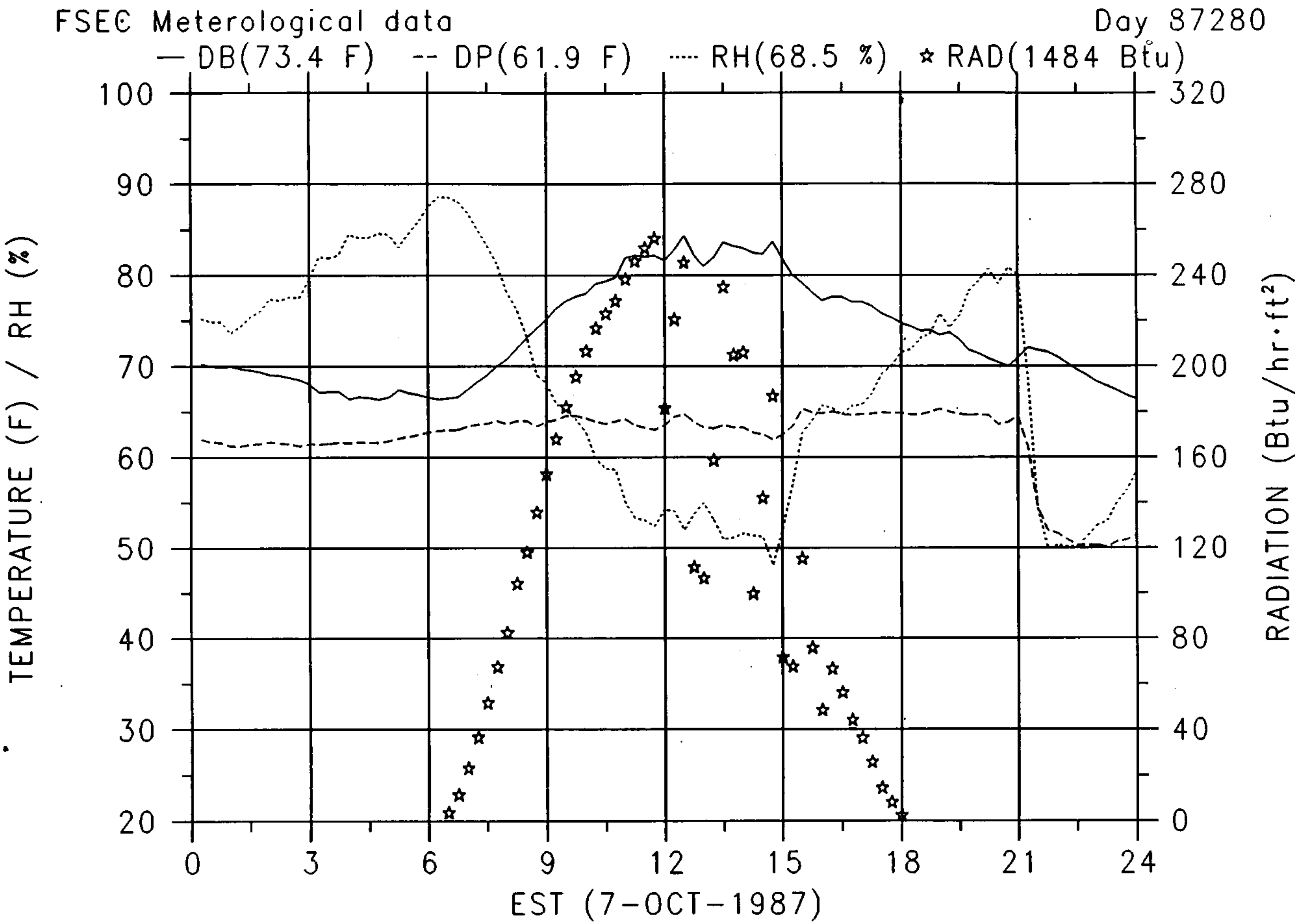
Cell 1 ceiling flux measurements at three locations.



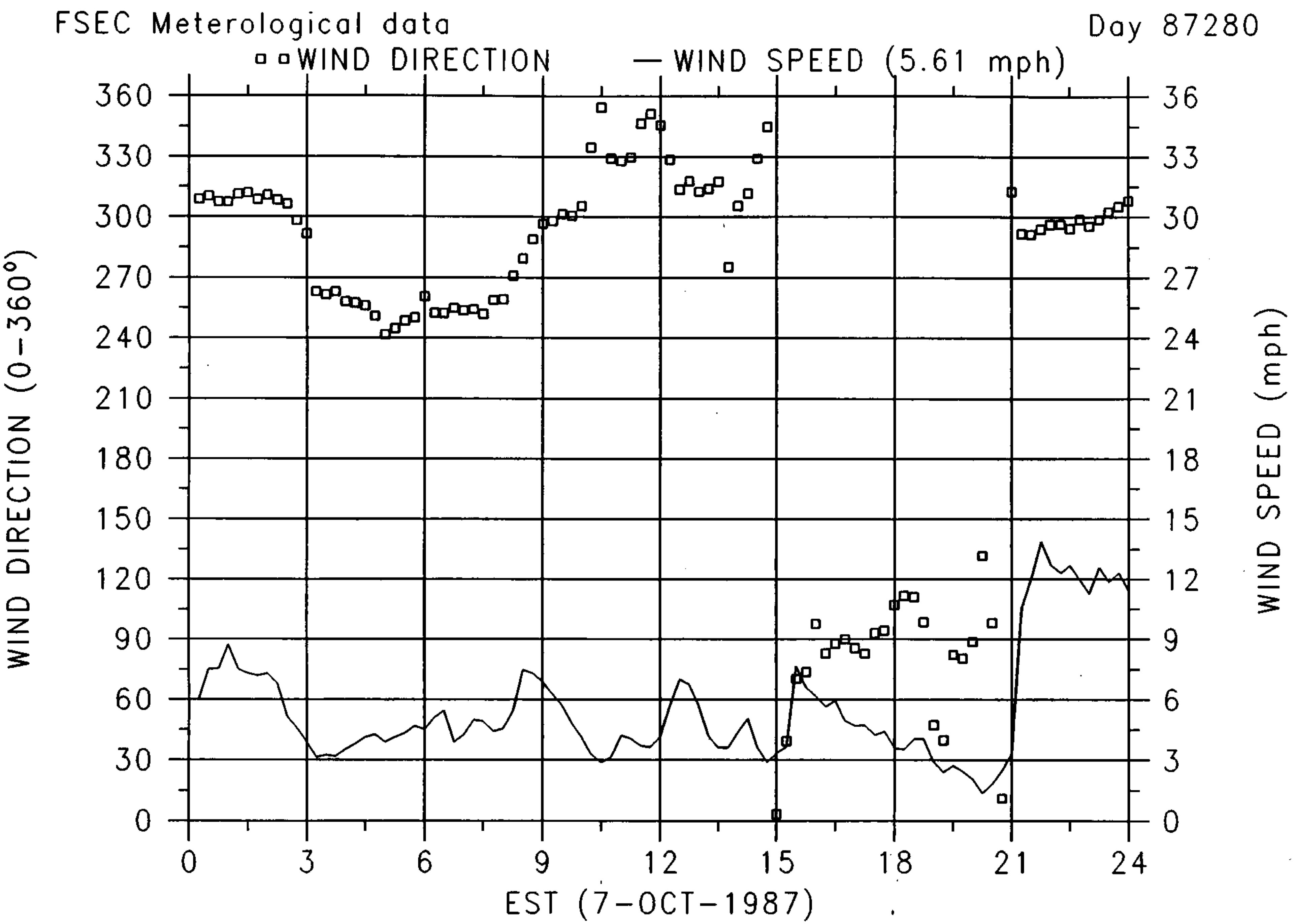
Cell 2 ceiling flux measurements at six ceiling locations.



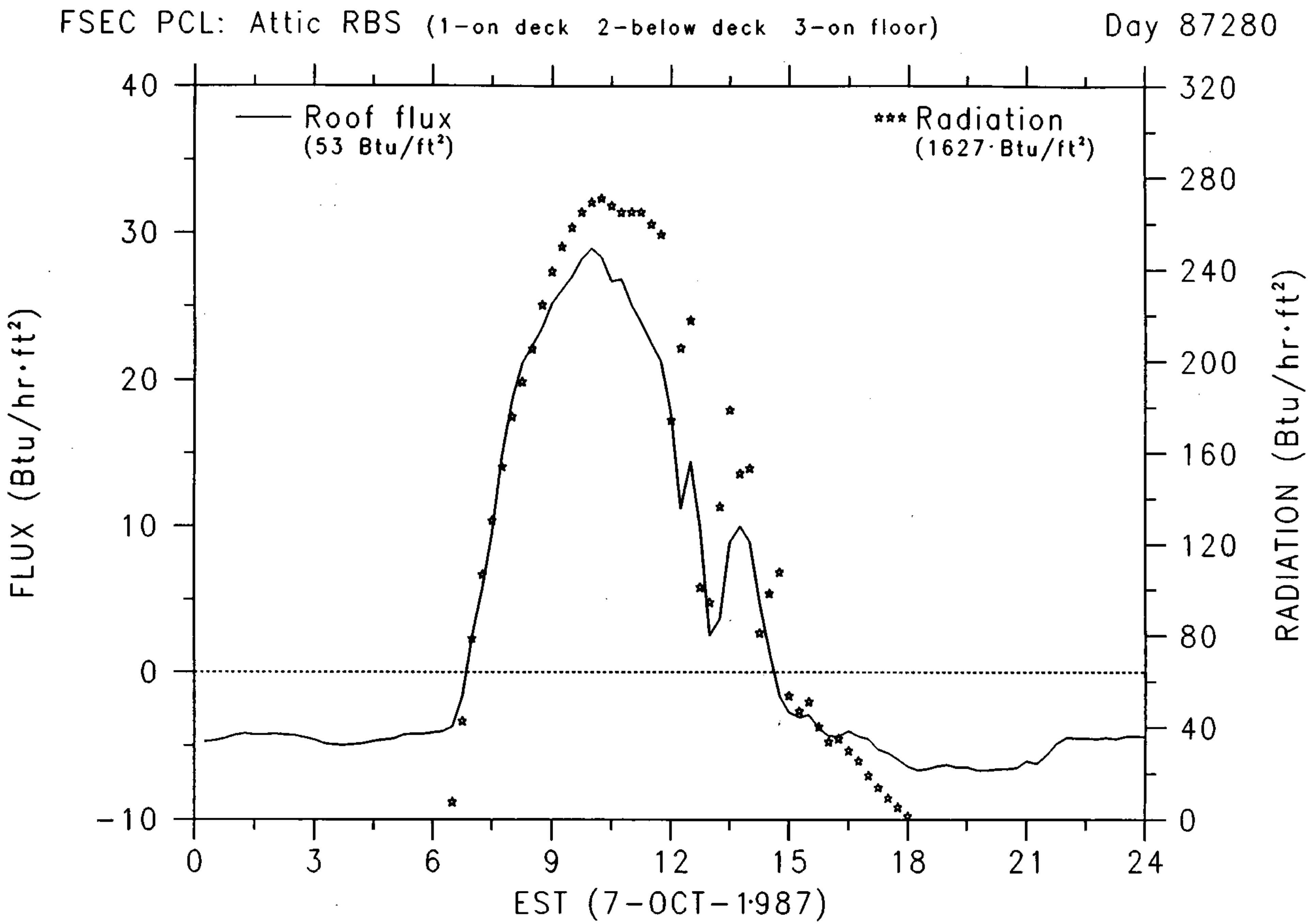
Cell 3 ceiling flux measurements at three locations.



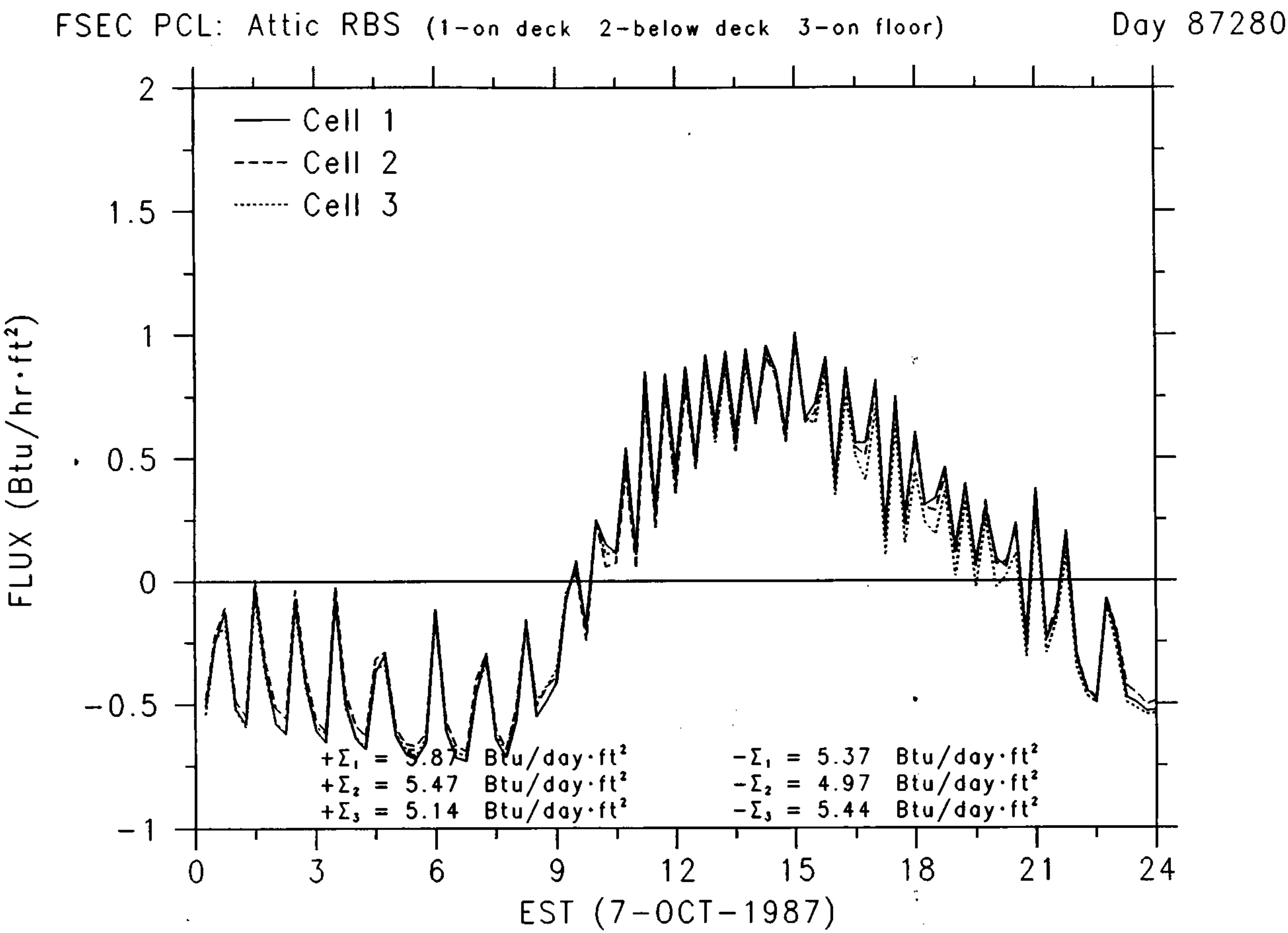
Ambient air conditions and horizontal solar radiation.



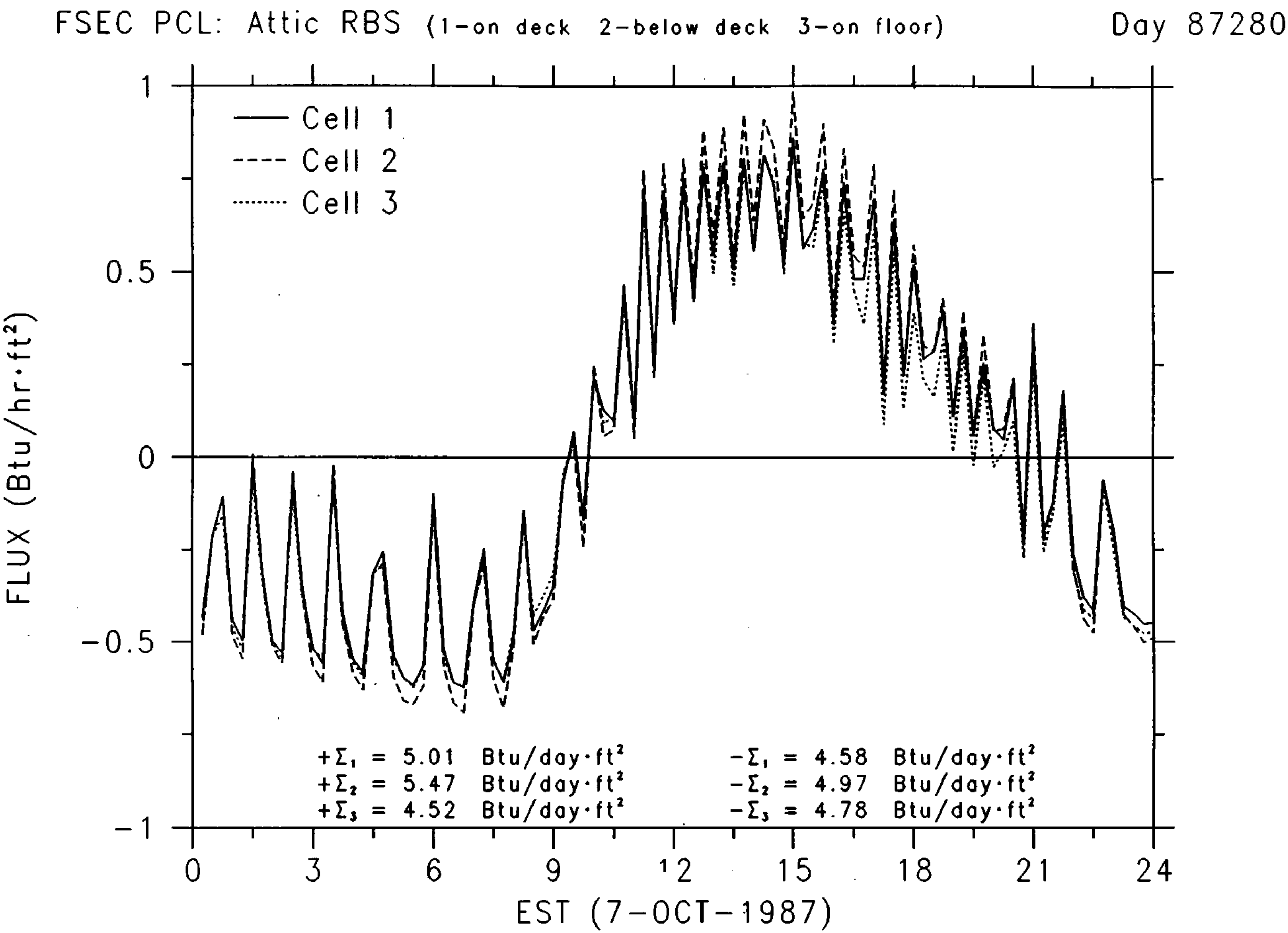
Local 10 meter wind measurements.



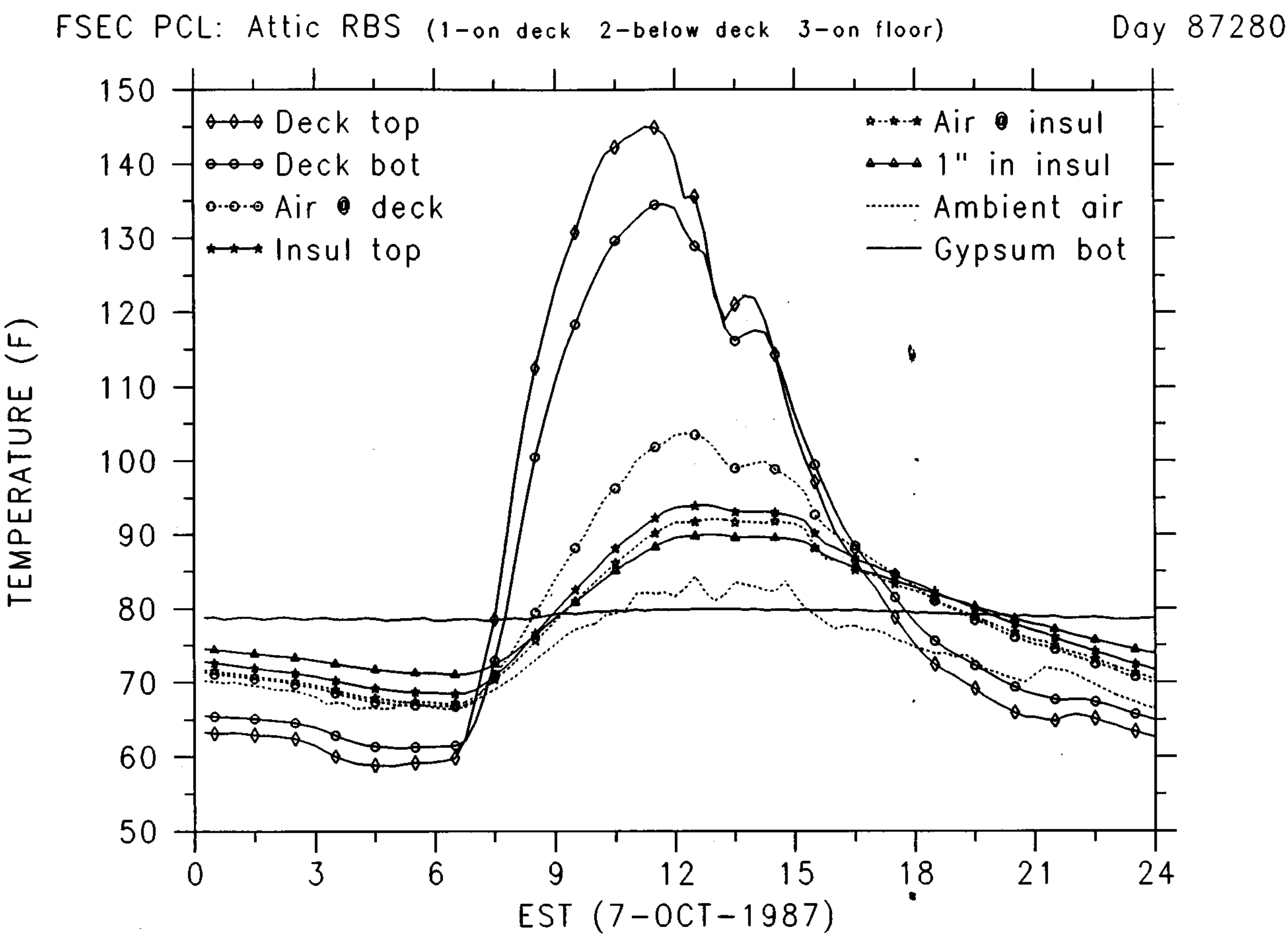
Cell 2 roof flux and incident solar radiation measurements.



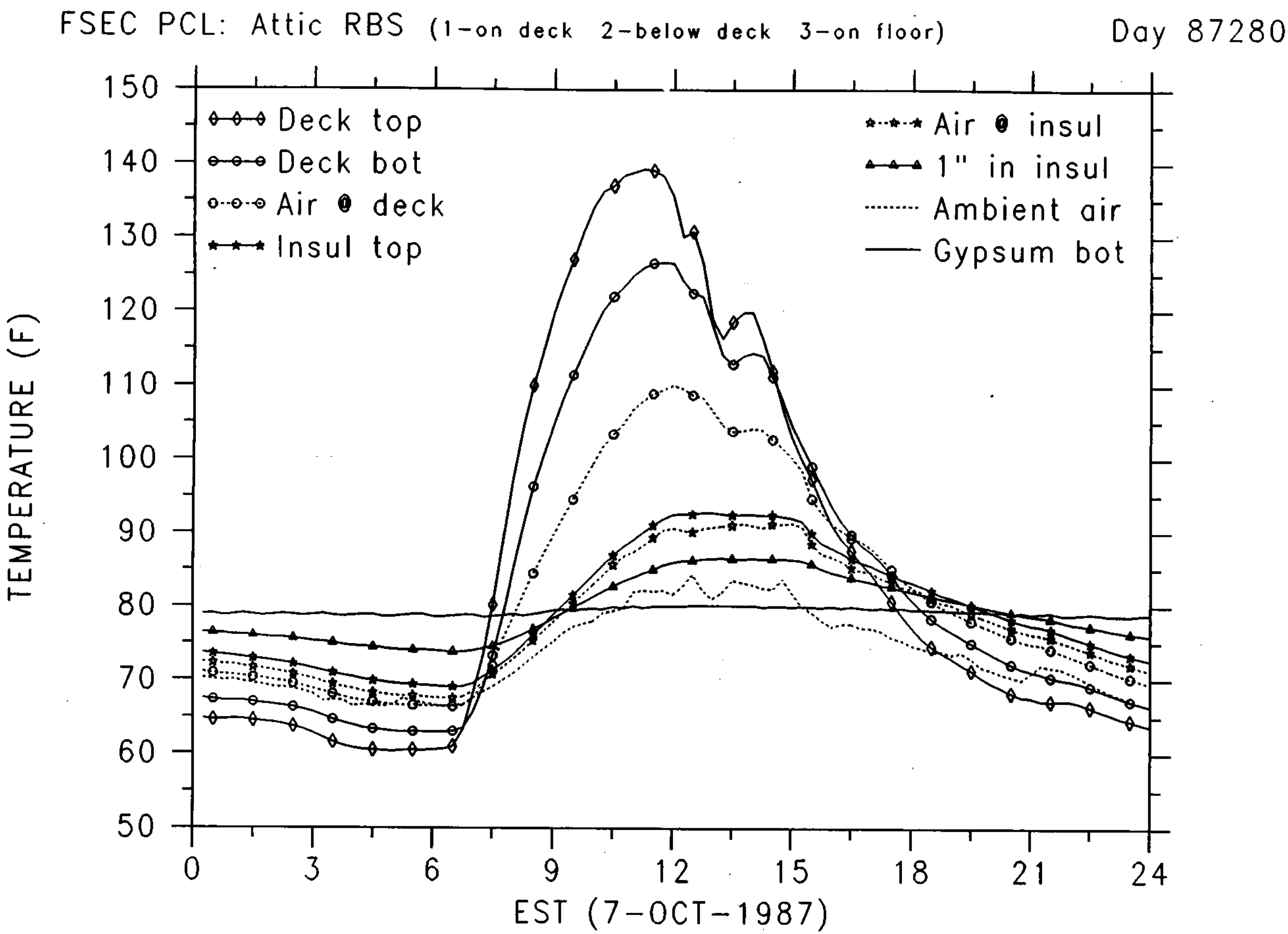
Normalized central ceiling heat fluxes for test attics.



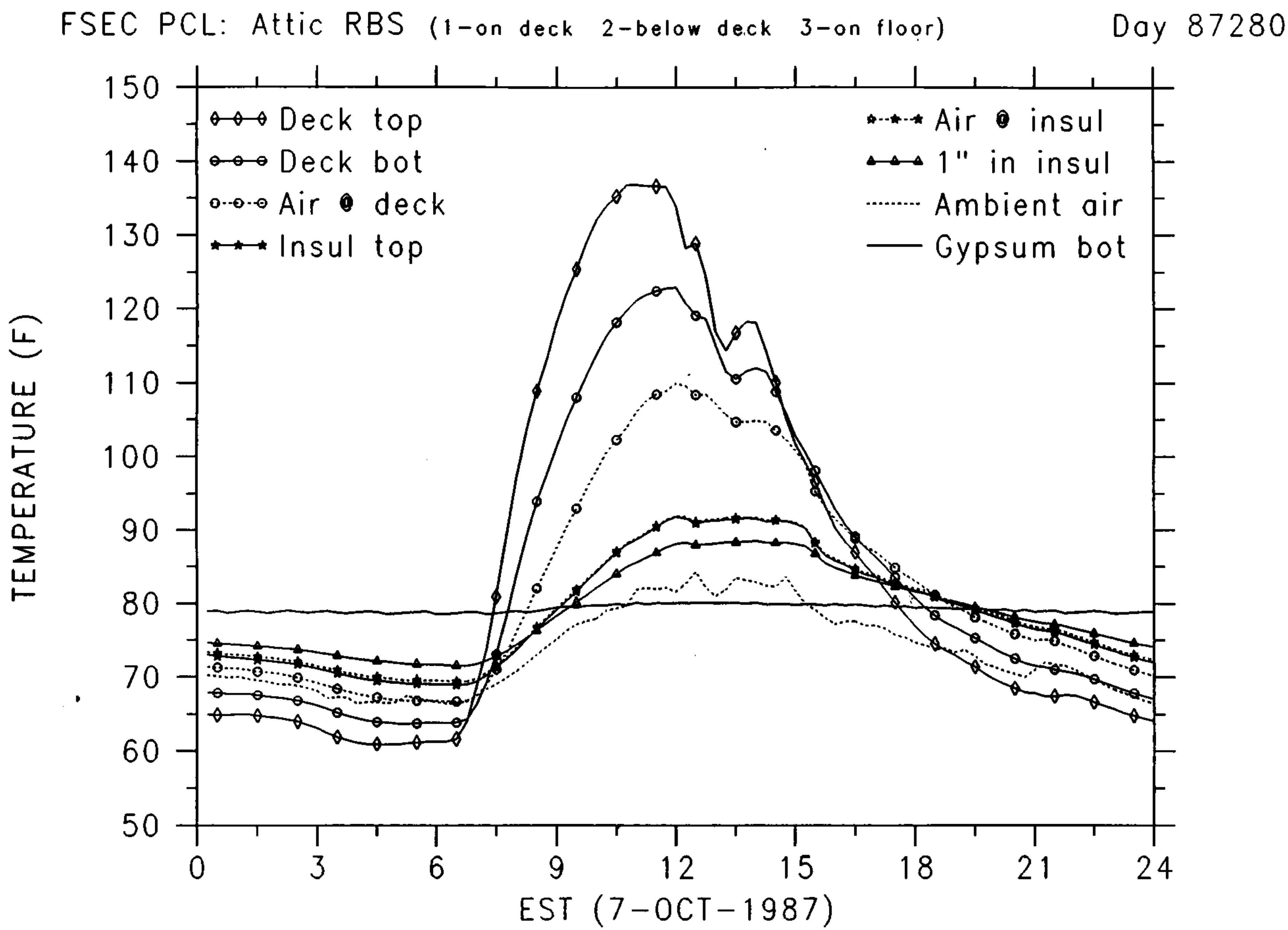
Measured central ceiling heat fluxes for test attics.



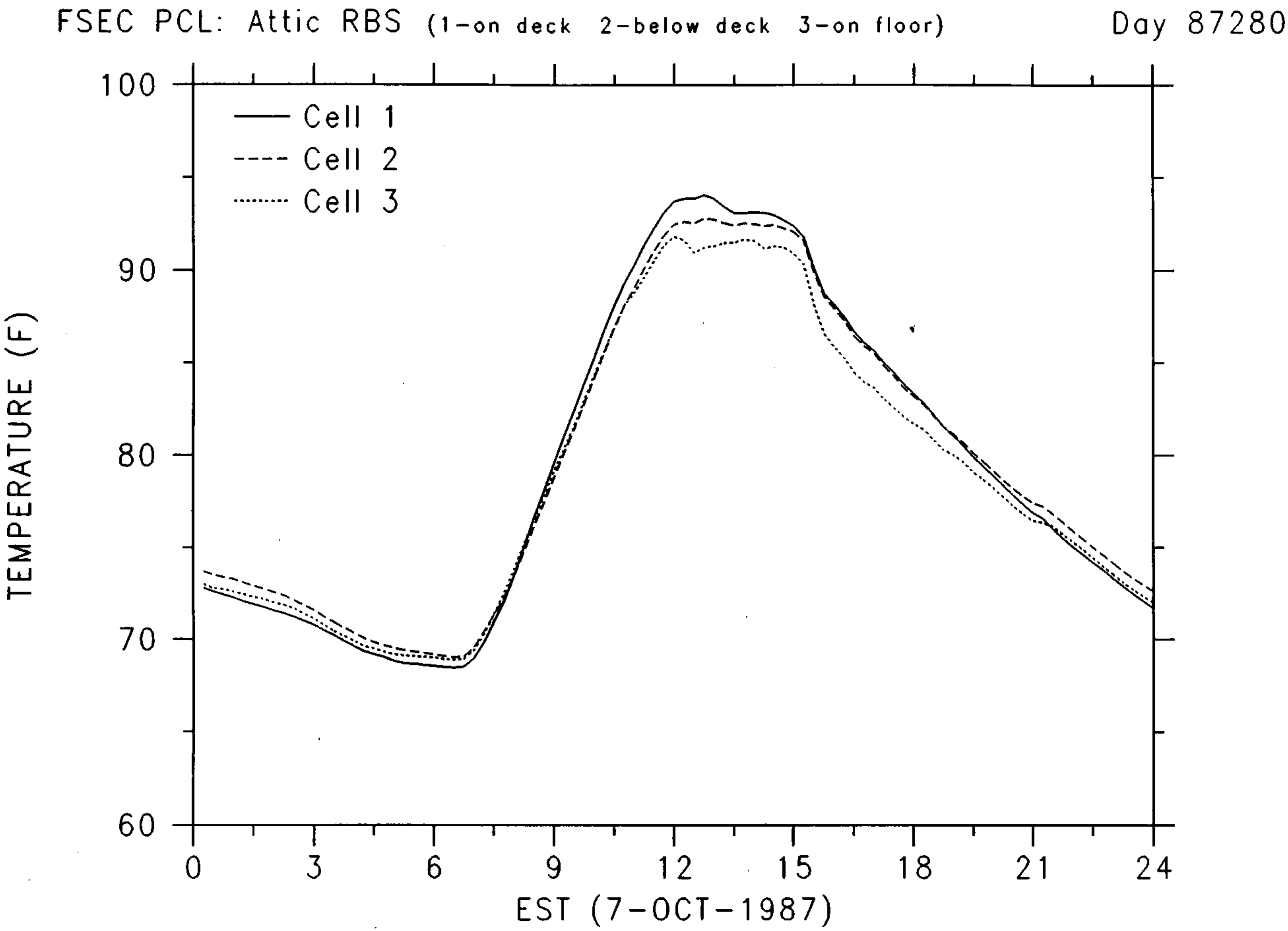
Distribution of cell 1 attic component temperatures.



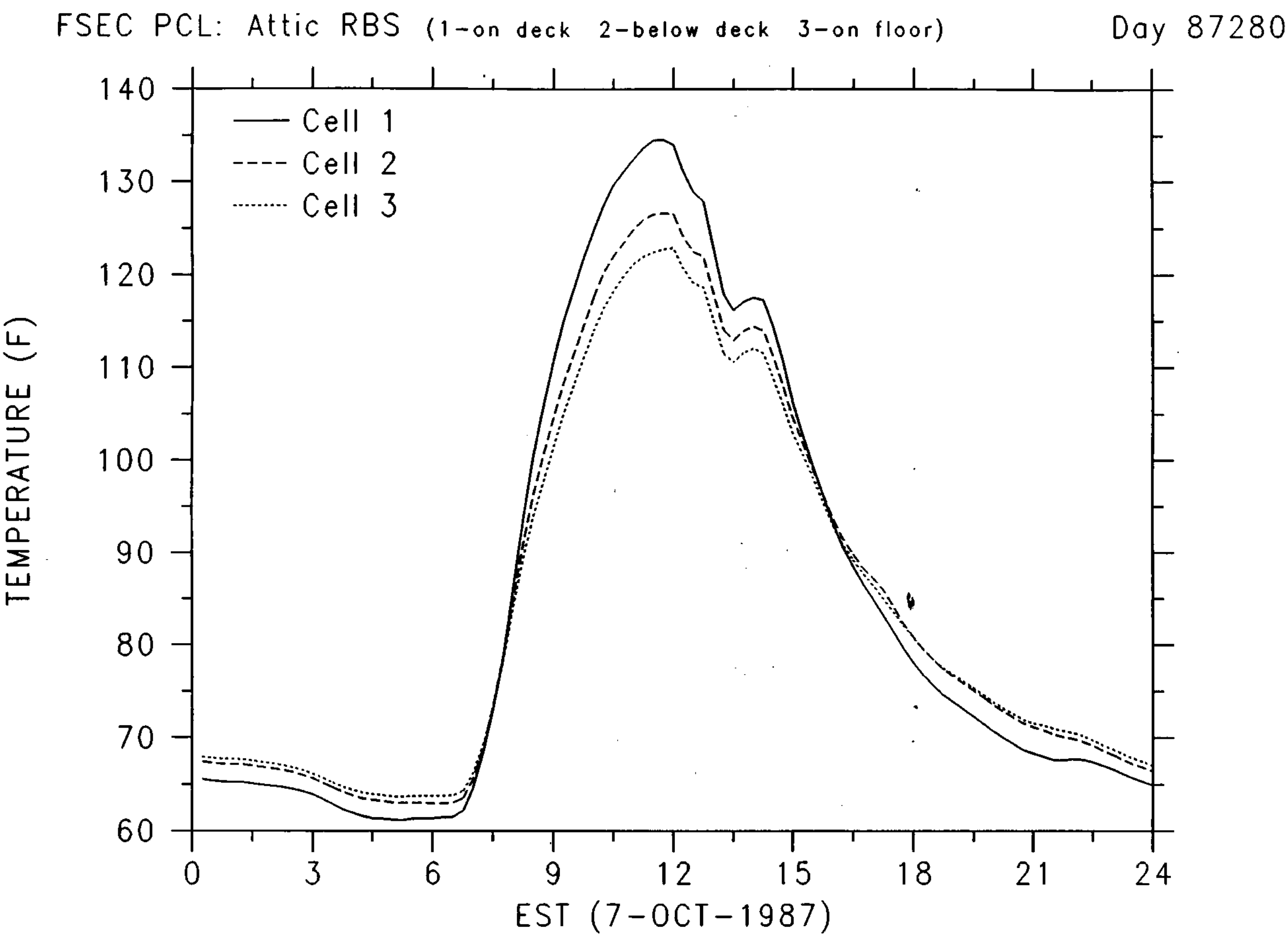
Distribution of cell 2 attic component temperatures.



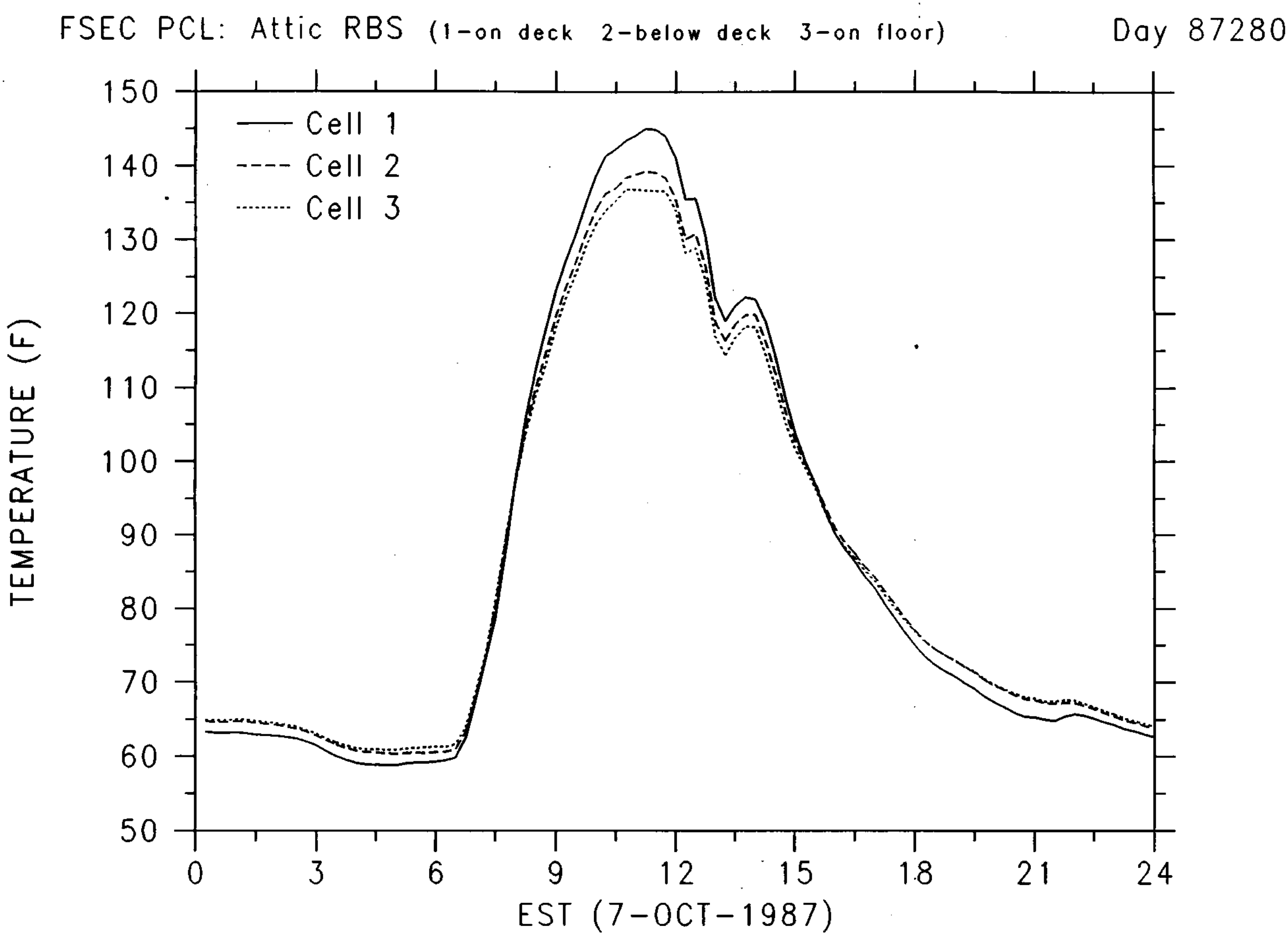
Distribution of cell 3 attic component temperatures.



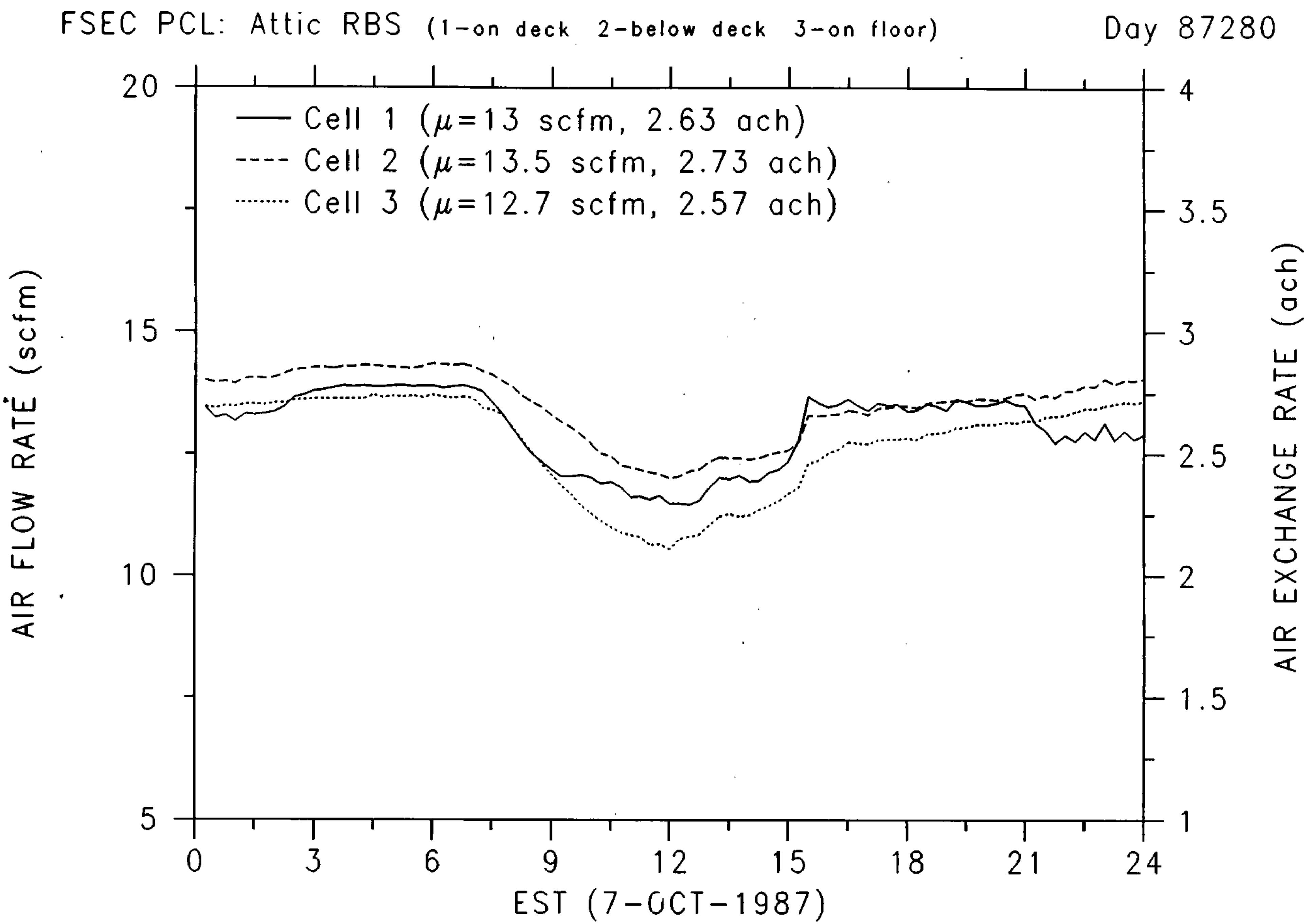
Insulation top surface temperatures in attic test cells.



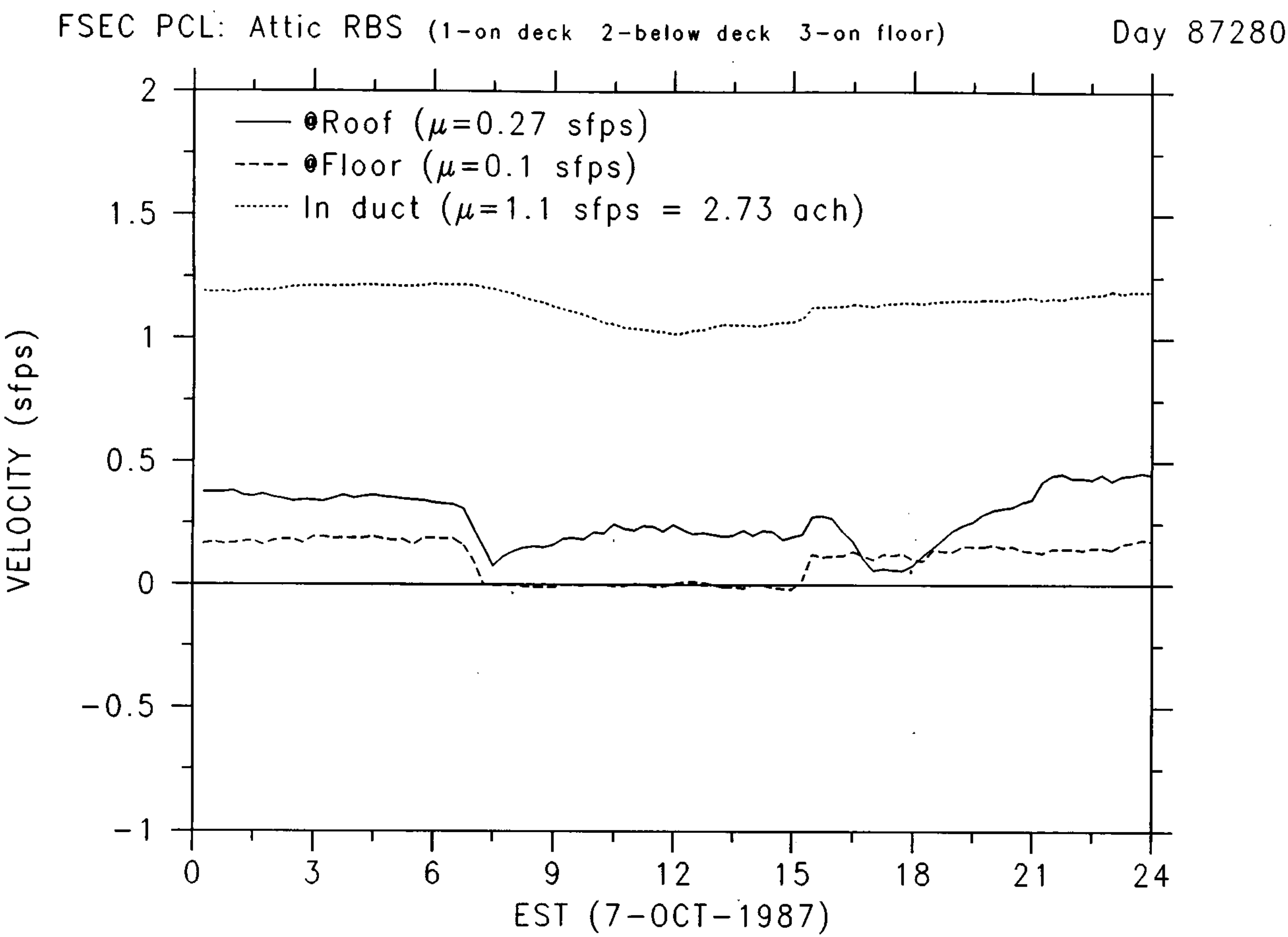
Inside roof decking temperatures in attic test cells.



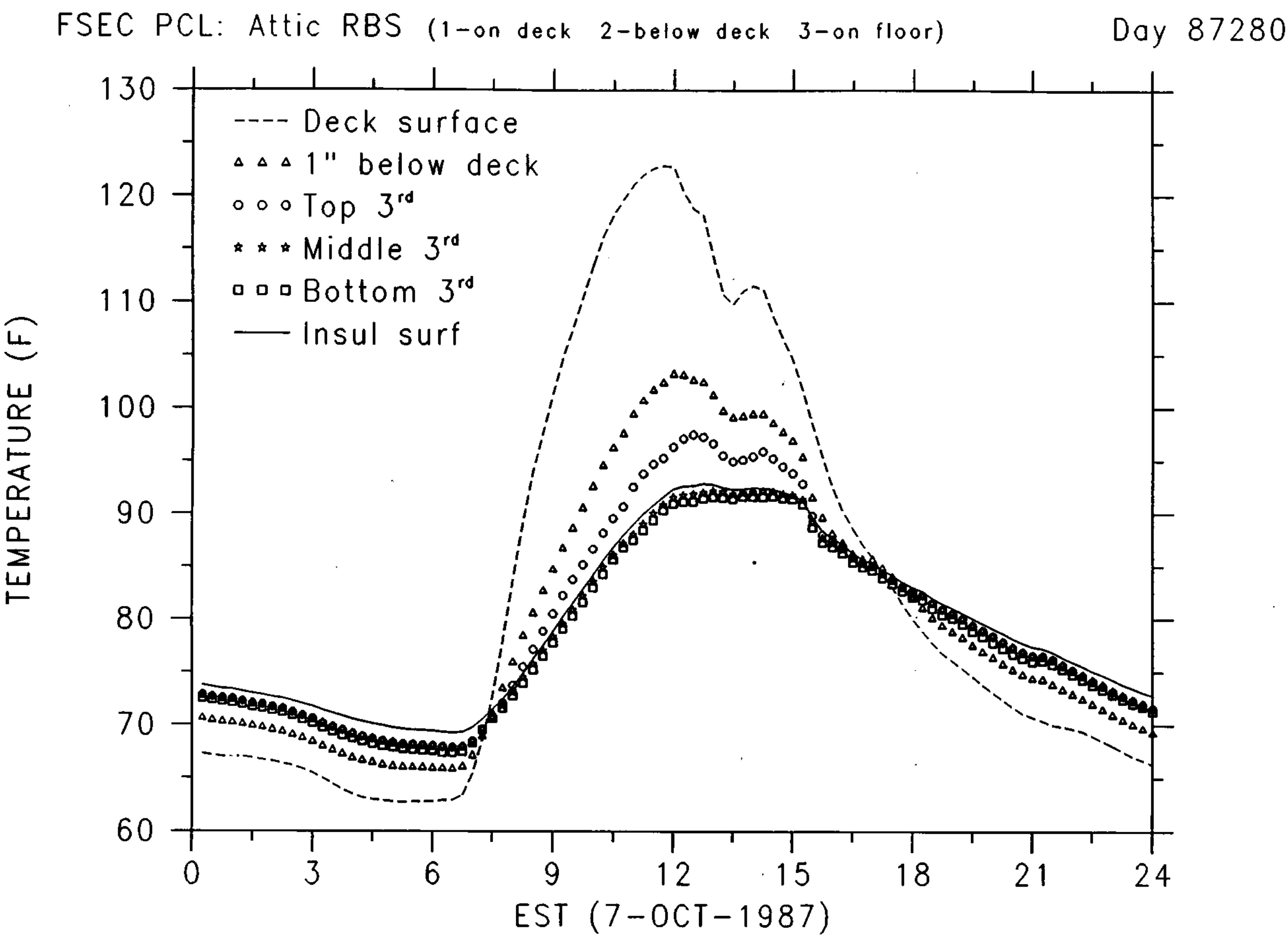
Outside roof decking temperatures in attic test cells.



Attic bulk air ventilation rates for attic test cells.

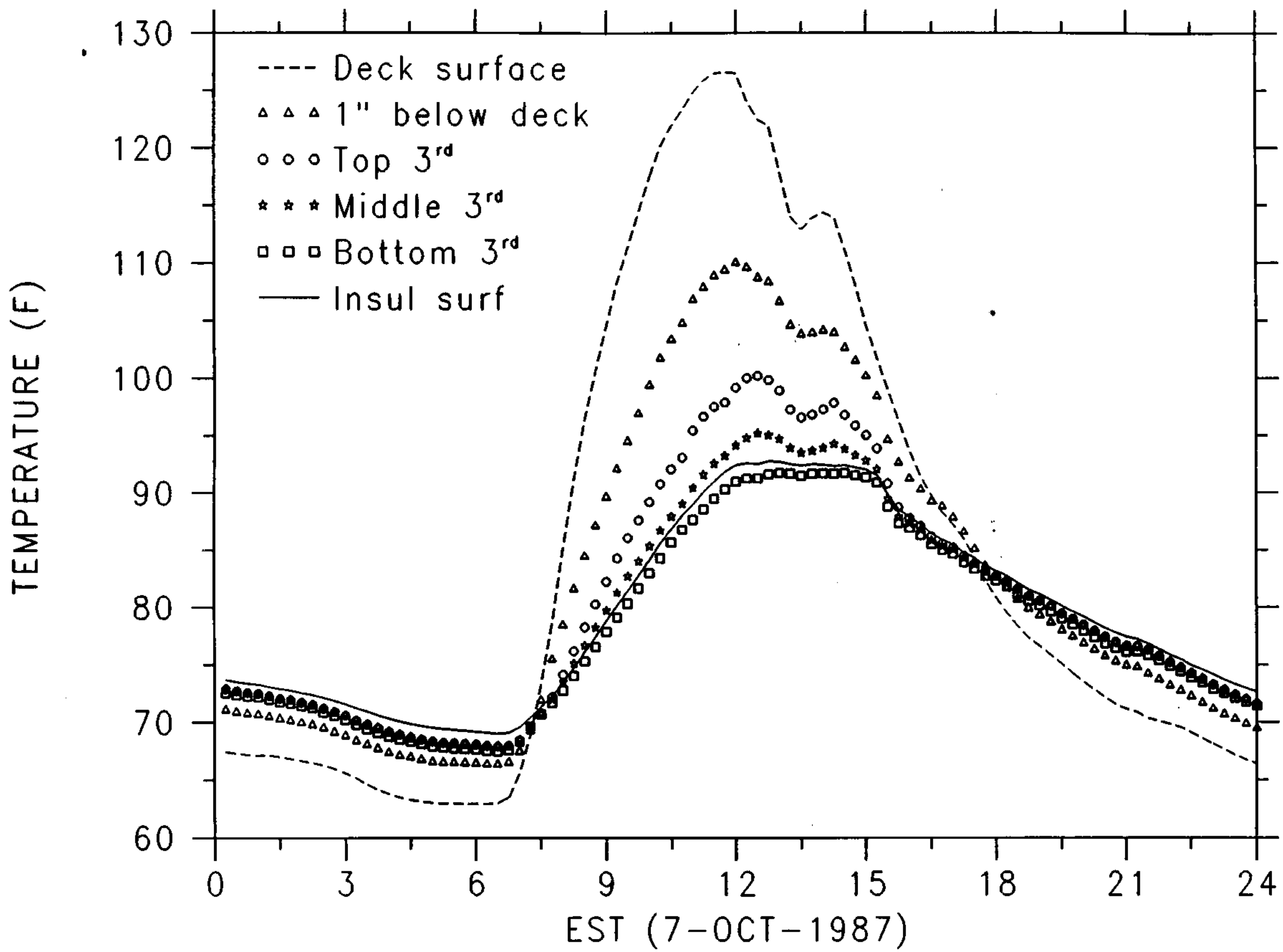


Cell 2 attic velocity profiles at three locations.

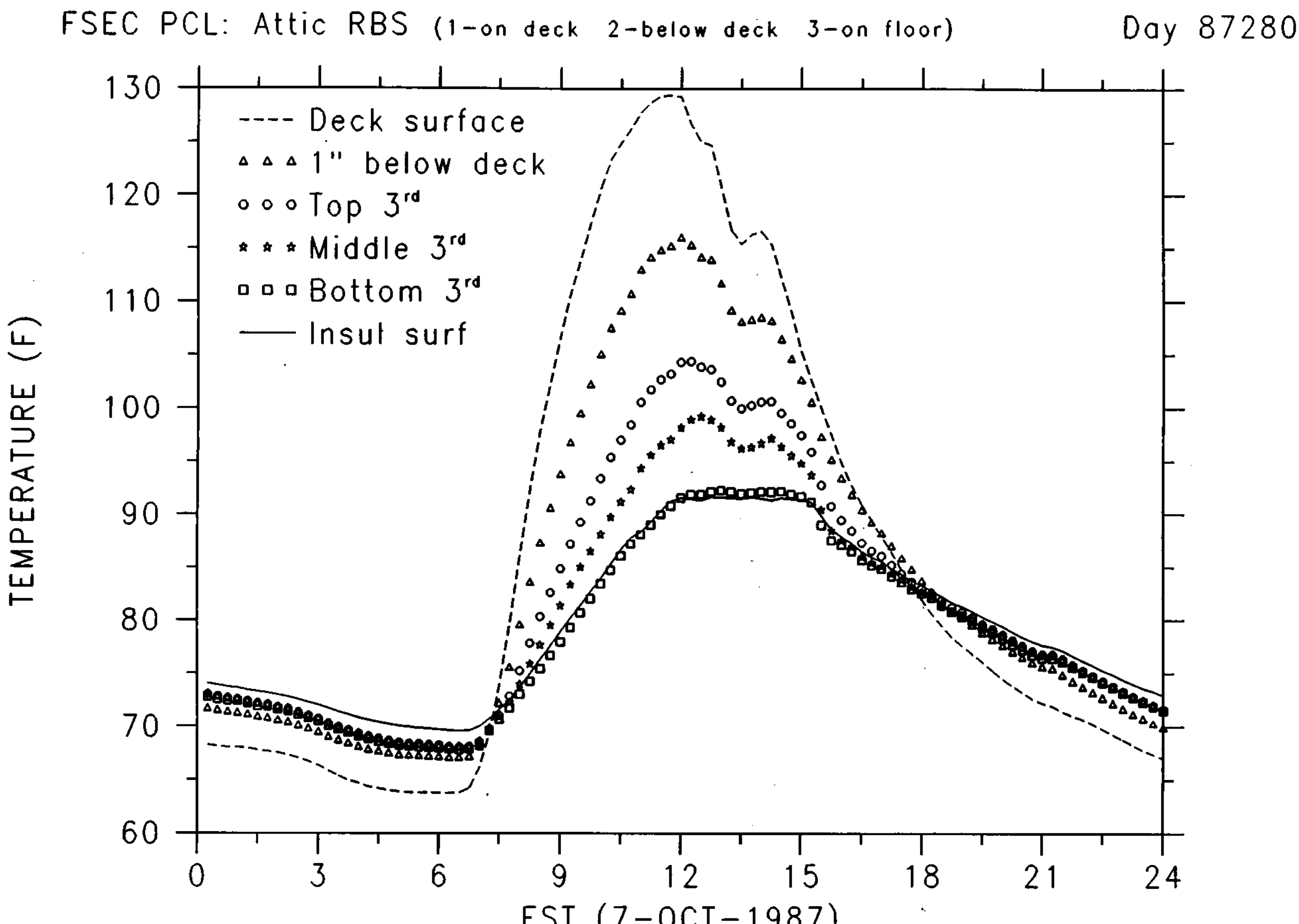


Cell 2 air temperature stratification at inlet end of attic.

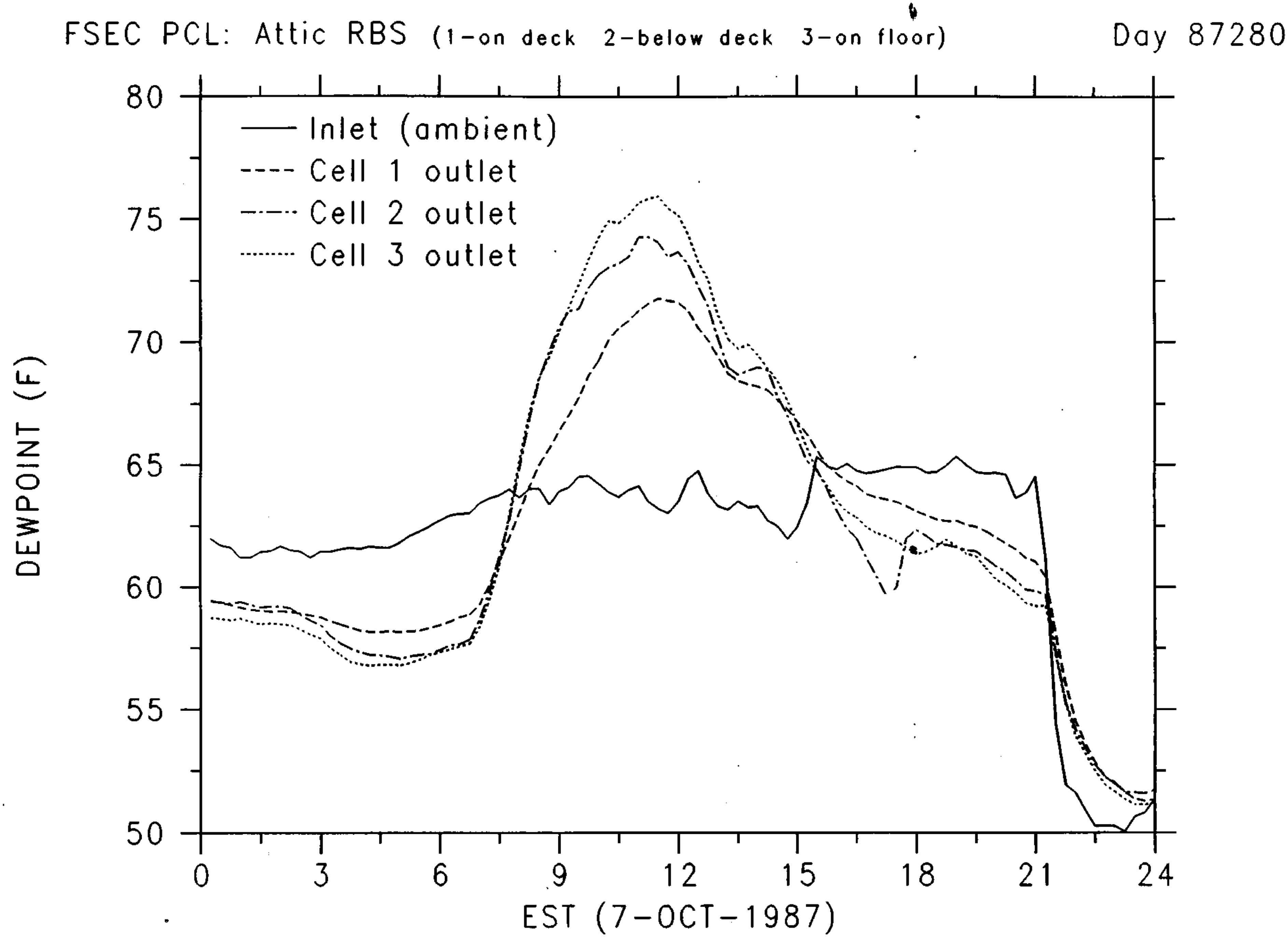
FSEC PCL: Attic RBS (1-on deck 2-below deck 3-on floor) Day 87280



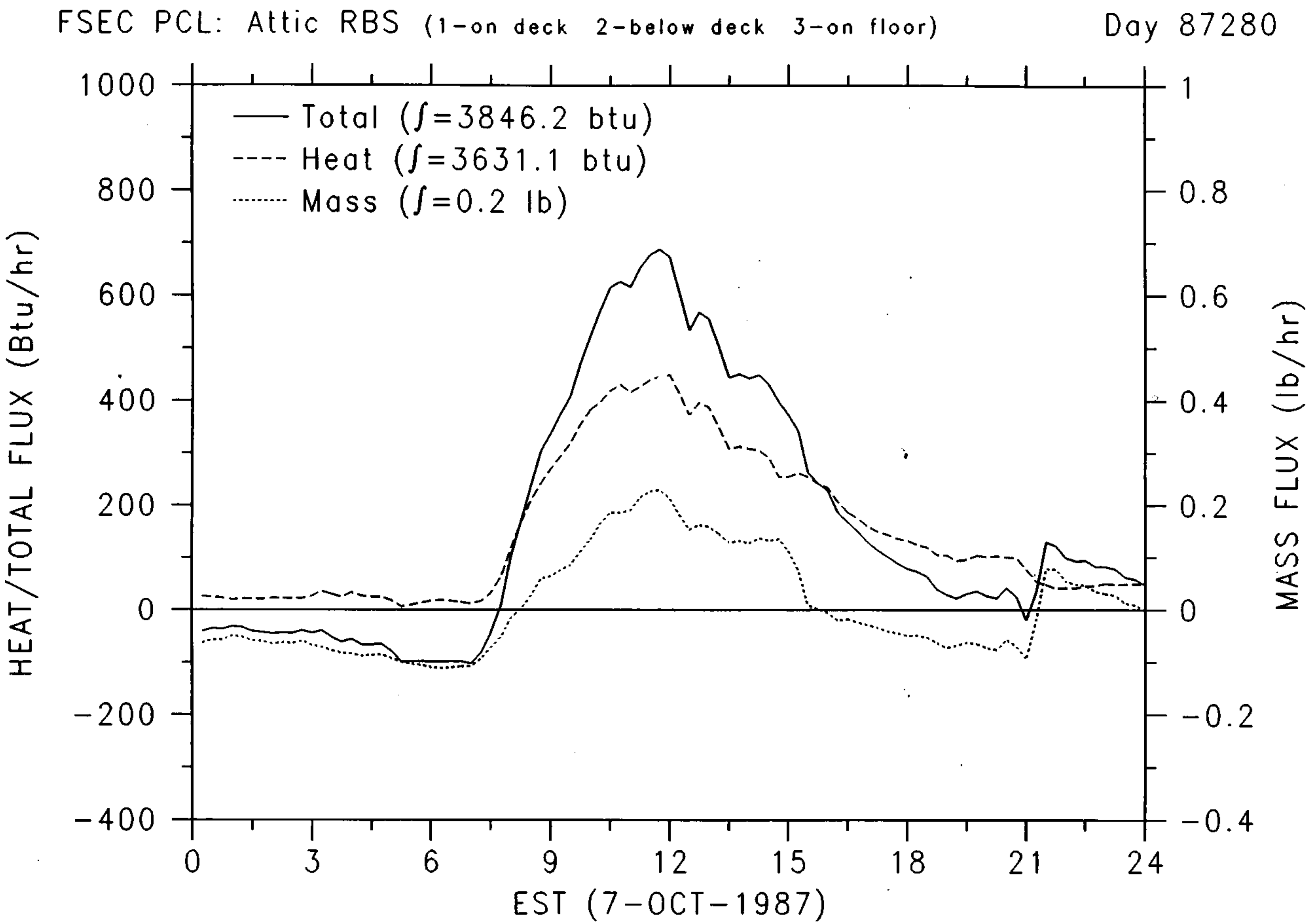
Cell 2 air temperature stratification at attic middle.



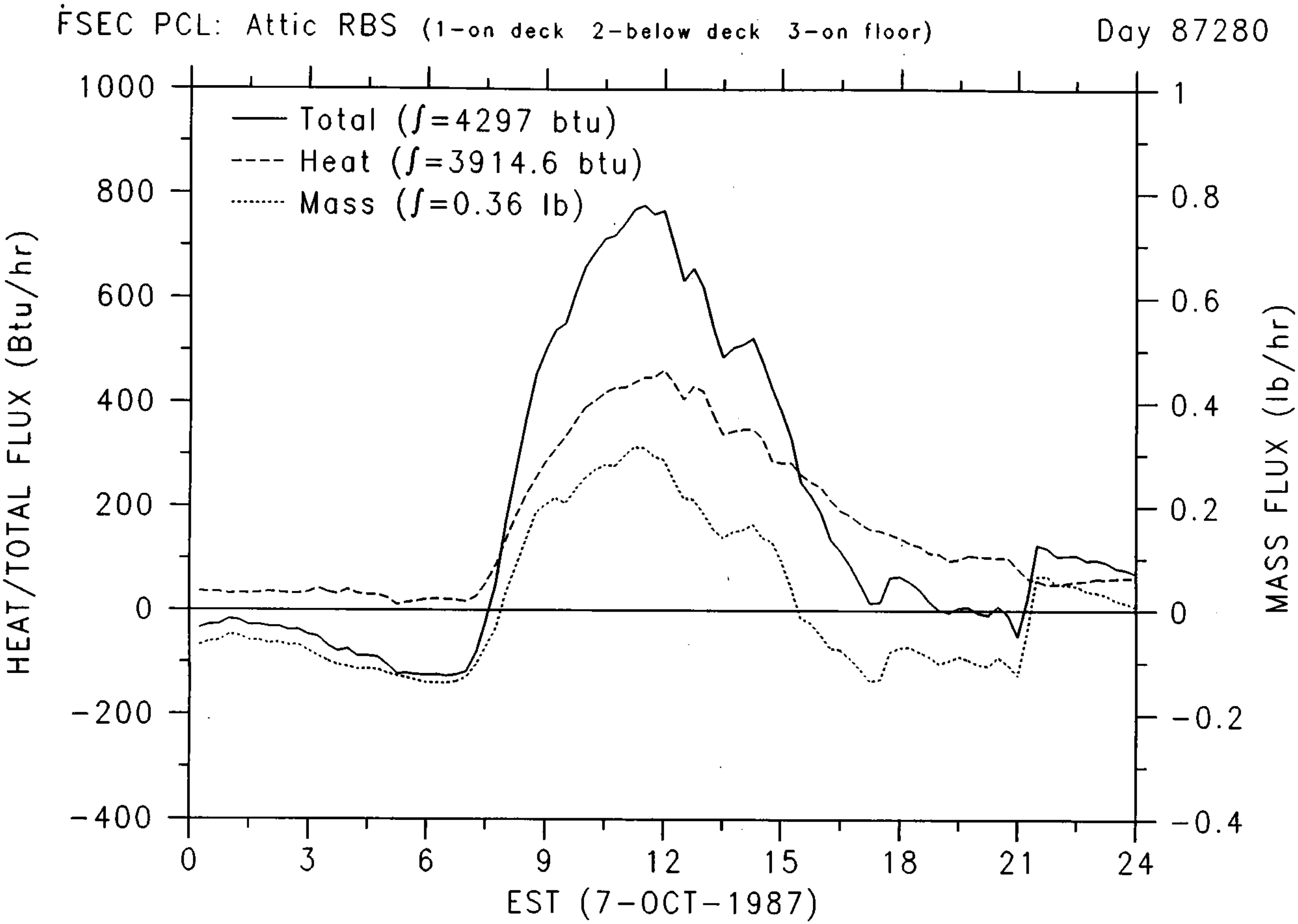
Cell 2 air temperature stratification at outlet end of attic.



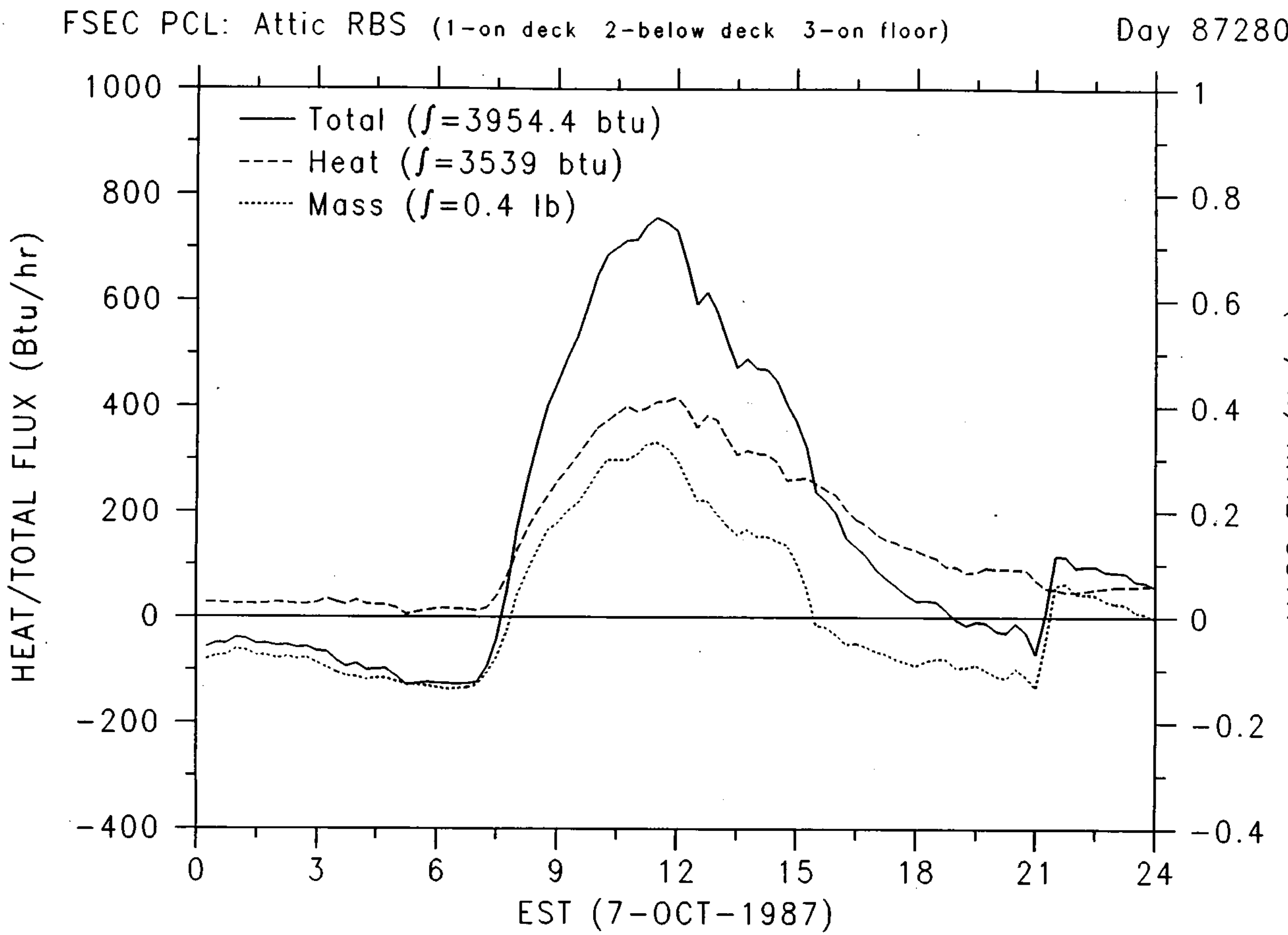
Inlet and outlet dewpoint temperatures for attic test cells.



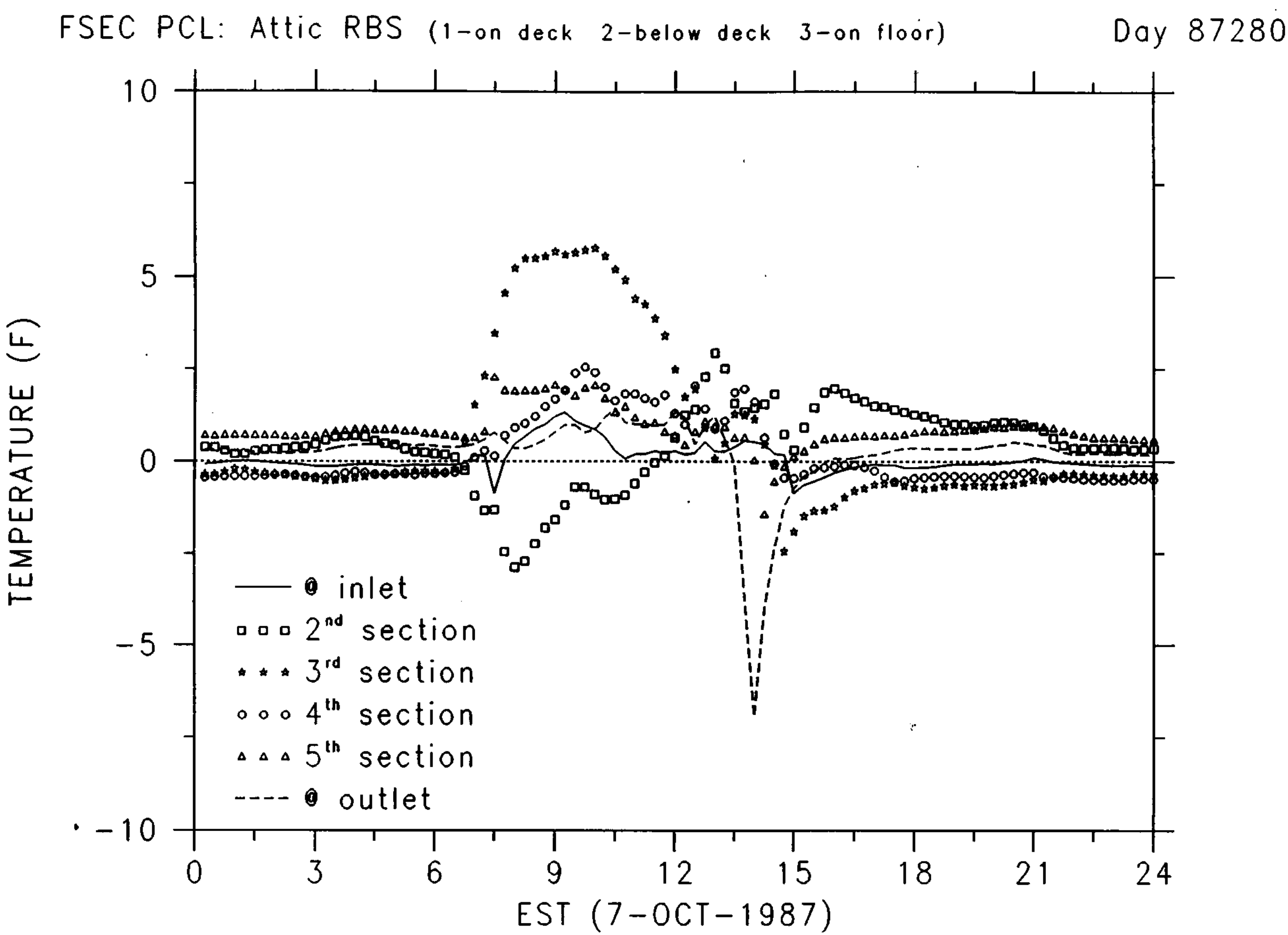
Cell 1 vent airstream heat and mass removal rates.



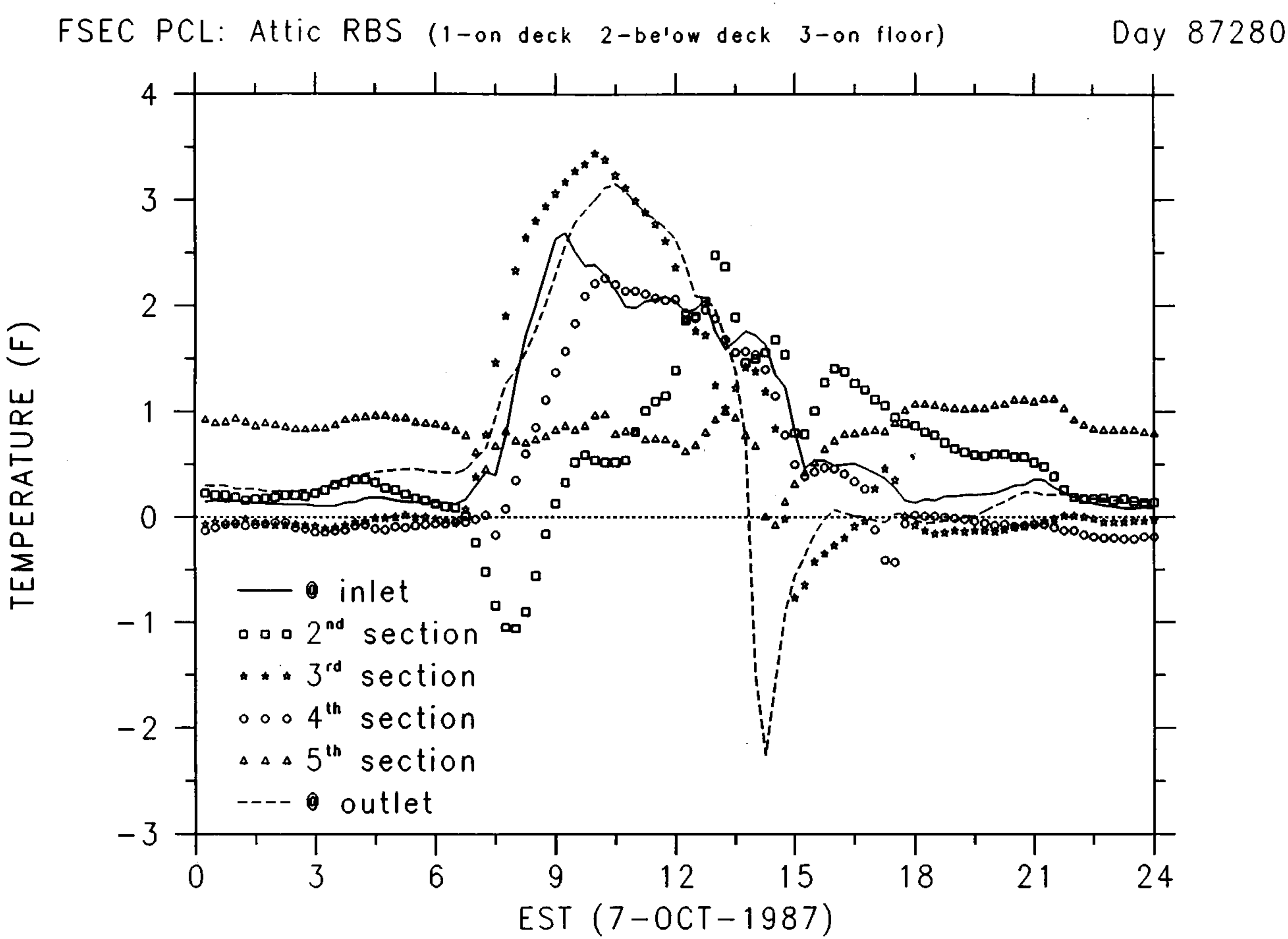
Cell 2 vent airstream heat and mass removal rates.



Cell 3 vent airstream heat and mass removal rates.

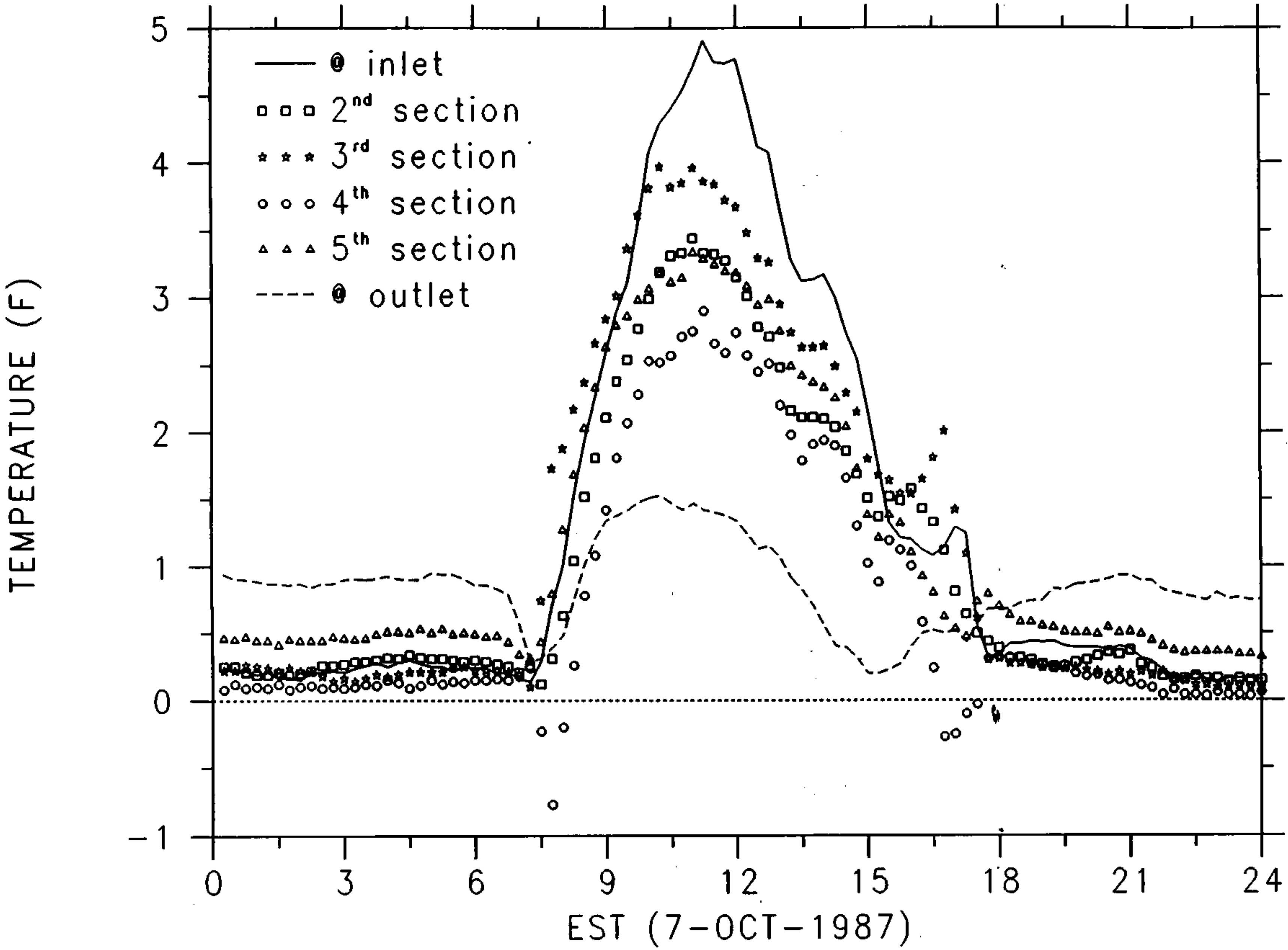


Temperature gradients between measurements at outside decking.

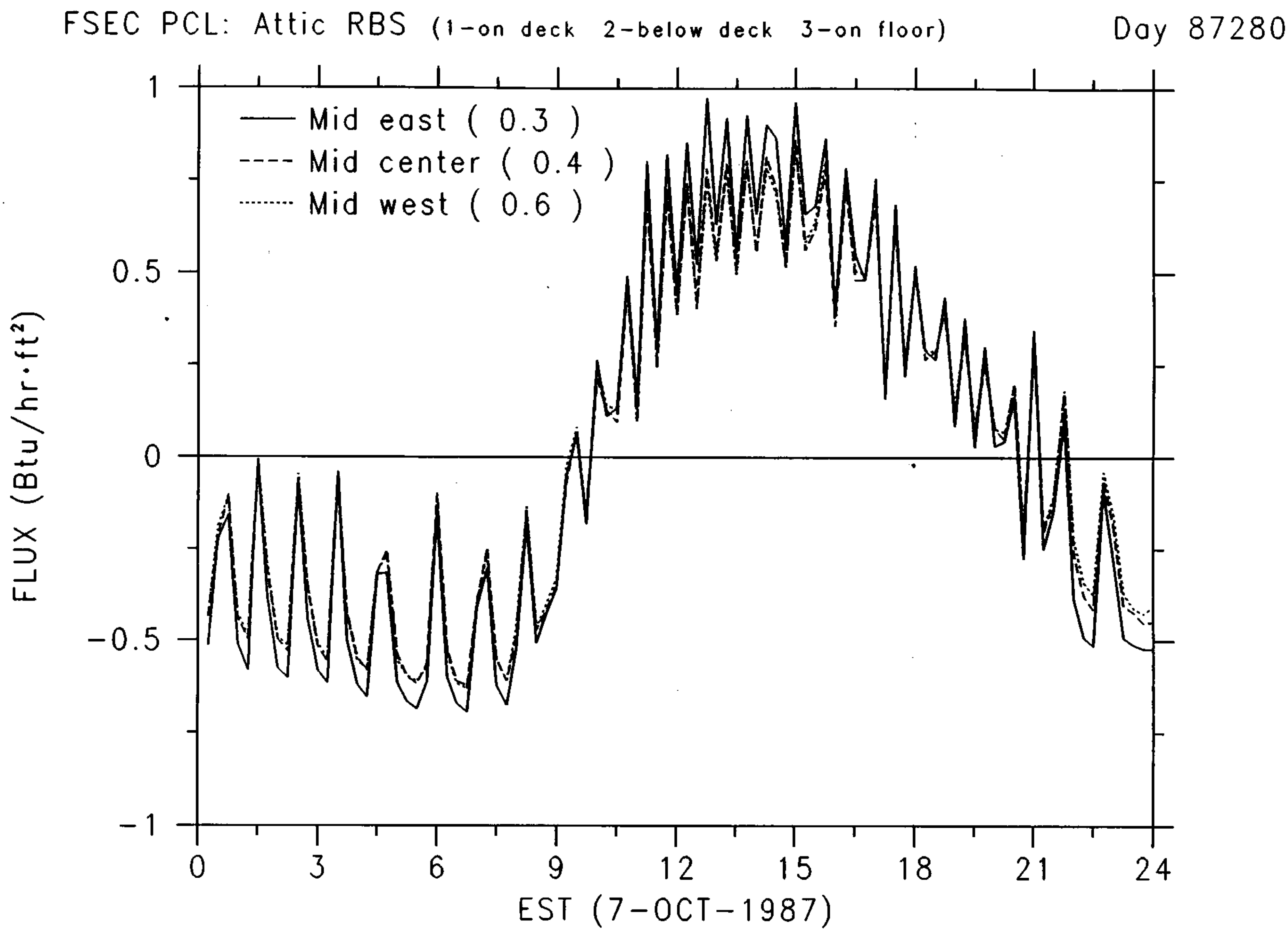


Temperature gradients between measurements at inside decking.

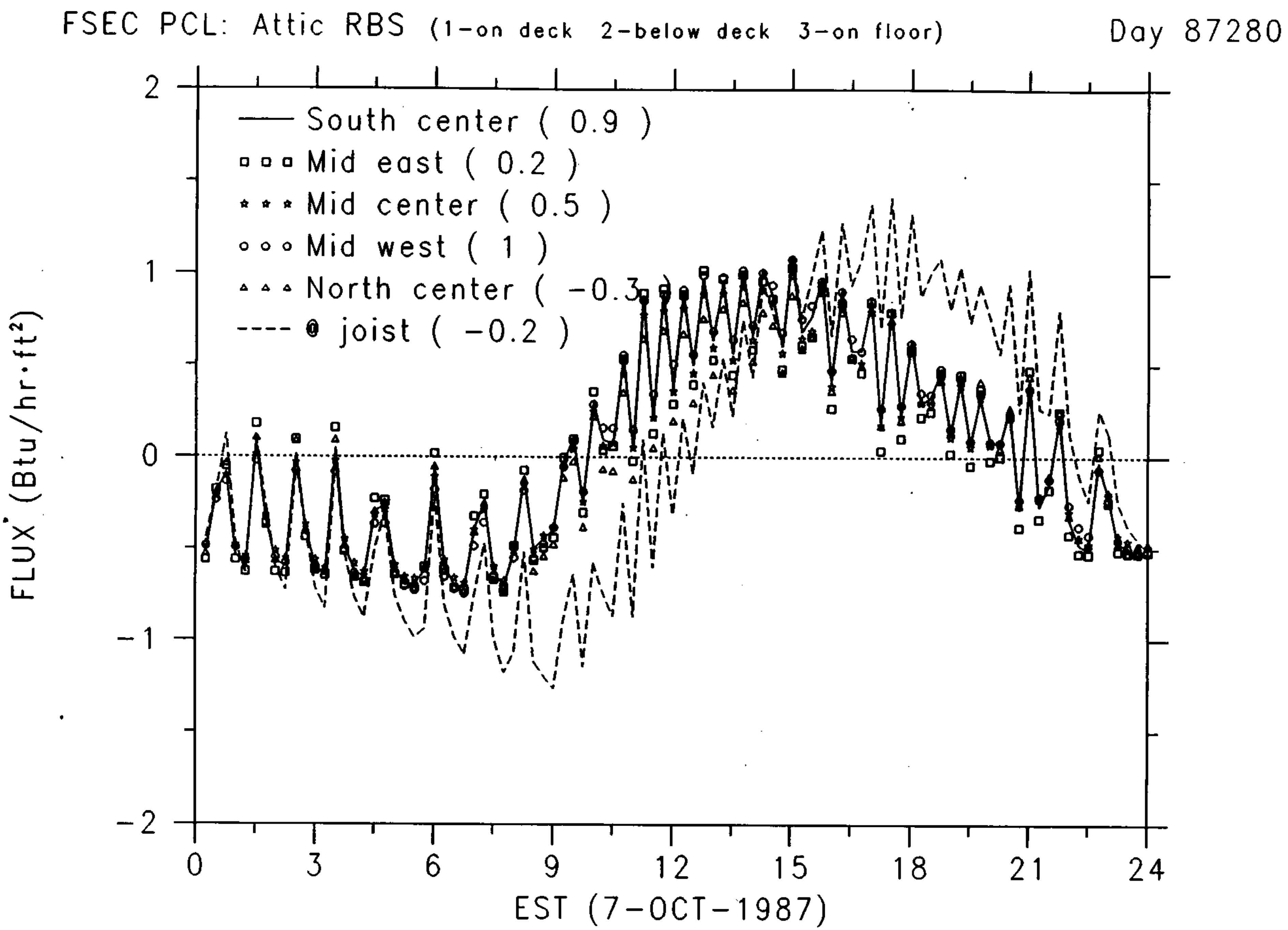
FSEC PCL: Attic RBS (1-on deck 2-below deck 3-on floor) Day 87280



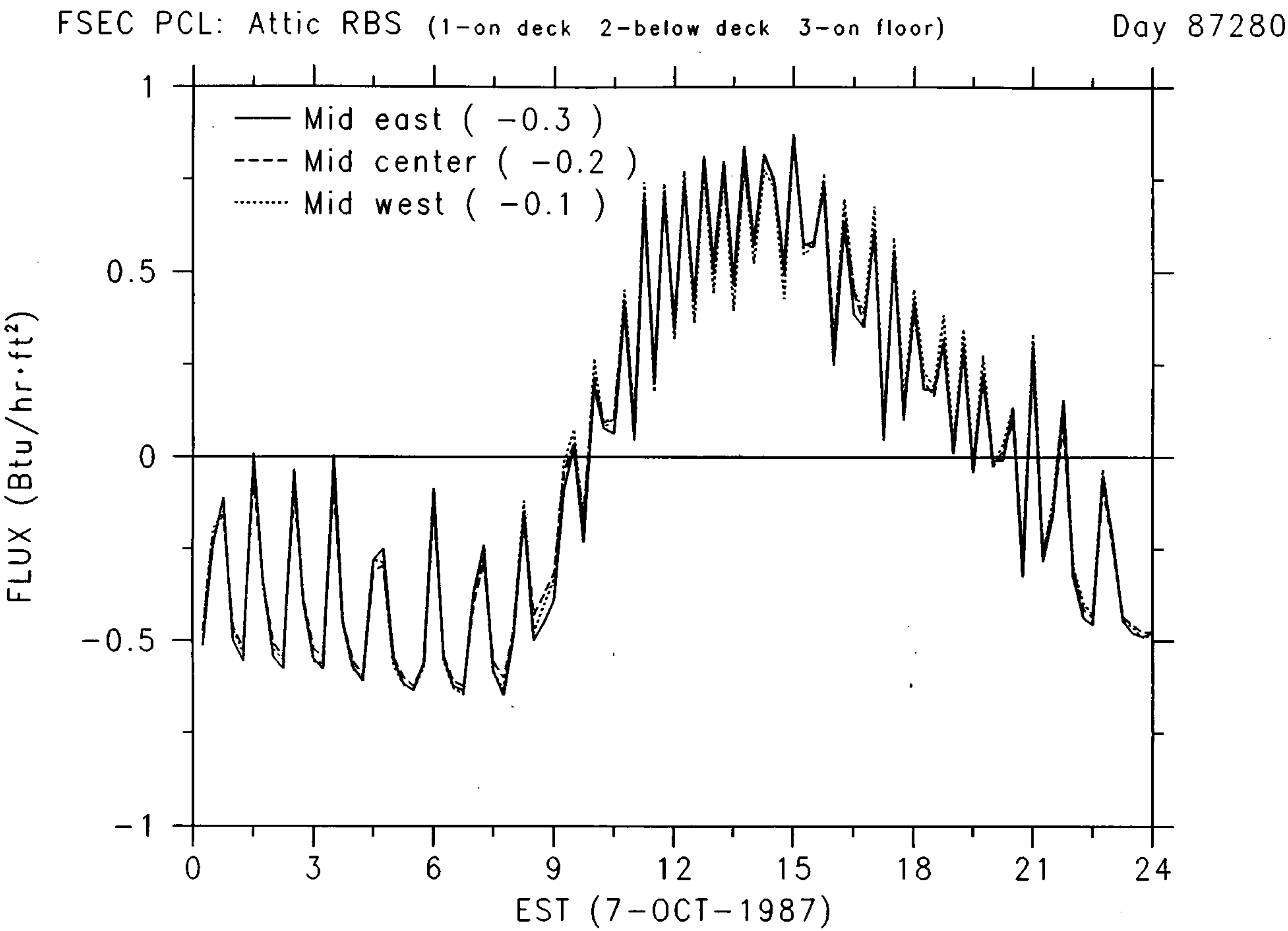
Temperature gradients between measurements in vent air.



Cell 1 ceiling flux measurements at three locations.



Cell 2 ceiling flux measurements at six ceiling locations.



Cell 3 ceiling flux measurements at three locations.

APPENDIX B

RBS FACILITY CONSTRUCTION DRAWINGS

OMITTED