Dr. 1427-3

DOE/CS/32117-2
(DE83008484)

THE DEVELOPMENT OF LOW COST INTEGRATED ZEOLITE COLLECTOR

Supplement to Final Report for the Period September 25, 1980–September 24, 1981

By
Dimiter I. Tchernev

February 1983

Work Performed Under Contract No. AC03-78CS32117

The Zeopower Company
Natick, Massachusetts

U.S. Department of Energy

Solar Energy

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DOE/CS/32117-2
(DOE/SAN-2117-2)
(DE83008484)
Distribution Category UC-59c

THE DEVELOPMENT OF LOW COST INTEGRATED ZEOLITE COLLECTOR

SUPPLEMENT TO FINAL REPORT
FOR THE PERIOD September 25, 1980 - September 24, 1981

DIMITER I. TCHERNEV

FEBRUARY 1983

THE ZEOPOWER COMPANY
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PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
SOLAR ENERGY
UNDER CONTRACT DE-AC03-78CS32117

ABSTRACT

Contract No. DE-AC03-78CS32117 to The Zeopower Company started on September 25, 1978 with the goal to design, construct and test an integrated solar zeolite collector, capable of providing hot water during the day and chilled water at night, which will act as one-for-one replacement for existing hot water solar collectors. This goal was achieved during the first year of the Contract.

During the second year (Amendment A003) of the Contract, the goal was to evaluate the performance of the integrated zeolite collector under different climatic conditions in different parts of the U.S.A. This goal was achieved by constructing 10 integrated zeolite collectors, testing them individually at the plant, and installing a completely instrumented pair at each of the following locations: The Anaconda Company Research Lab in Tucson, Arizona, SERI in Golden, Colorado, and The Zeopower Company in Natick, Massachusetts.

During the third year (Amendment A005) of the Contract, the goal was to design and build a low cost zeolite collector and to collect and analyze the experimental data from the collectors at the different test sites in the U.S.A. This goal was achieved on time using the following steps: The suitability of different methods of corrosion protection of low cost materials was studied. The phenolic coating found to be suitable is more expensive than the copper it replaces. Fiber glass-epoxy is suitable as a container material for the zeolite, however, there are some problems with the vacuum seal due to the mismatch of thermal expansion coefficients. Low cost collectors were constructed and when tested performed as expected. Cost reduction of a factor of six is possible in mass production. The test data from all test sites was collected and analyzed.

This work was confirmed during the fourth year (Modification M008) and the analysis indicates that despite the wide varying climatic conditions in Boston, Tucson, and Denver, the results can be represented very well by a normalized input-output curve on a total daily basis. This representation of the relationship between

input and output is approximately a straight line starting at an input of between 200 and 400 BTU/ft^2 day and having a slope of 0.2 to 0.3. The first complete system utilizing the integrated zeolite collector was designed and installed at a private residence in the suburban Denver area. Some preliminary test data indicates that the cooling performance is as good or better than expected from the design calculations using individual collector input/output performance curves.

ACKNOWLEDGMENT

The author would like to acknowledge the financial support of the Department of Energy, the support of the program coordinators Conrad Dankowski and Fred Glaski and the technical support of the technical monitors Kirk Collier and Dennis Schlepp. The author would like further to acknowledge the valuable contribution of many of the employees of The Zeopower Company during the development, construction and testing of the collectors. Special thanks are due to William LaFleur, without whose masterful assistance this work would not have been possible, and to Patricia Trundy who prepared the manuscript skillfully despite the numerous revisions and corrections.

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Objectives and Tasks

The goal of the third-year effort was to produce a design for the integrated solar zeolite collector capable of reducing its cost when mass-produced to at least one-third of its present cost. Another goal of the third-year effort was to collect and analyze the experimental data from the existing collectors at the three different test sites in the U.S.A.: Tucson, Arizona; Golden, Colorado; and Natick, Massachusetts.

Task 7.

The detailed description of Task 7 was as follows:

To investigate the use of different low cost materials for the construction of the panel and to experimentally determine the suitability of different methods for corrosion protection to the environment of waste, vacuum and zeolite.

To complete a detailed cost analysis of the present design.

In order to achieve this task, the following steps were taken:

A detailed cost analysis of the present design of the panel was performed. The results are as follows: The 1980 cost of materials for a panel of 16.4 ft^2 aperture is \$708.60. The required hours of assembly are about 70. Therefore, the cost of labor is about \$500 and the cost overhead is about \$300. The total cost of the panel is about \$1,500 or about \$90/ft^2. Of this total about one-half or \$43.20/ft^2 is the cost of materials. A large contribution to this material cost comes from the large amount of copper used in the present design (about 5 lb/ft^2) and the large cost per pound of prefabricated copper parts. For example, the cost of the 2" deep copper pan with cover which contains the zeolite and uses about 2 lb/ft^2 of copper is about \$120 for 32 lb. copper or about \$3.75/lb. while the price of the raw material, in this case copper sheet 16 oz/ft^2, is less than \$1.00/lb.

The detailed cost analysis therefore concluded that the cost of materials can be reduced by more than half (actually by over 60%) if all fabrication of parts and other manufacturing operations are performed in-house. Under such circumstances, material costs at production levels of 1,000 collectors per month or more will be below $300/panel, while still using copper, low-iron glass, aluminum frame and other high quality materials in the present design.

A different approach for reducing the material cost is to replace the presently used materials by others of lower cost per panel. Three general substitutions were considered:

1) To replace the 2" deep copper pan containing the zeolite with a fiber glass-epoxy pan of the same design. The copper of the cover of the pan could not be replaced by fiber glass-epoxy because its heat collection, distribution, and transfer capabilities are of critical importance. This substitution was considered feasible and collectors using the fiber glass-epoxy pan were constructed during Task 8.
2) To replace the low-iron glass used in the present design with plastic films of low weight and cost. For this purpose, samples of Tedlar and Mylar films were ordered and evaluated. The results were not promising, since in a double-glazed collector the plastic film can be used only as the inner glazing and the support requirements for the plastic film are so much different than for glass that the whole structure of the collector becomes extremely complicated and will increase the manufacturing cost of the collector by considerably larger amounts than the savings realized by the replacement of glass with plastic.
3) To replace the flat black-velvet paint by selective black chrome coating. The performance of the collector has been analyzed by disabling the sorption-desorption part of the collector and plotting the performance of the energy collecting part of the panel in the form of ASHRAE Standard 93-77. Such plot confirms the large specific heat of the zeolite-filled collector to be 54 BTU/^{o}F and gives for the slope $F_R(U_L)$ the value of 1.1^{o}F hr ft^2/BTU which is comparable to the standard of the industry for double-glazed collectors with flat black surface. A reduction of $F_R(U_L)$ to about

0.6 ÷ 0.7 is possible by the use of black chrome selective surface of an increase of cost of about $\$1.50/ft^2$. The material is available in 6" wide strip with adhesive backing and alleged optical properties of 96% absorptivity and only 15% emissivity. The increase in cost is offset by the increase in performance efficiency at high temperatures. This substitution was tested during Task 8 and it was established that the performance of the collector increased by 5 to 10% over the flat black paint panels. Therefore, there is a real benefit in using black chrome when the cost of the collector is more than $\$20/ft^2$.

Task 7 was successfully completed on schedule and within the allowed cost.

Task 8.

The detailed description of Task 8 was as follows:

To investigate methods for reductions of the number of manhours needed to construct a panel roughly by half.

To make design changes to reduce the required labor cost for the construction of a collector including studies of different ways of sealing and evacuation and the feasibility of elimination of silver solder in the construction.

To study mass production techniques, including stamping and extrusion, applicable to the manufacturing of the zeolite collector.

To test the corrosion protection of iron by heavy electroplating of copper on it.

To test the corrosion protection for iron and aluminum by different plastics for the packaging, sealing and glazing of the zeolite panel.

To fabricate at least two collectors using the new inexpensive design.

In order to achieve this task, the following steps were taken:

The design of the evaporator-condenser assembly was changed to reduce the required labor necessary for assembly by over 50%. The detailed cost analysis also indicated that it takes 25 manhours of labor to fill the panel with zeolite and seal it vacuum tight. These hours were reduced by changing the production technique. The manual drain valve of the evaporator-condenser assembly was replaced with a thermostatically controlled automatic one which opens at $35^{o}F \pm 1^{o}F$ and protects the panel from freezing, both during cold winter weather and during periods of external loop failure in the cooling season. The cost of the automatic valve is about 1/5 of the cost of the manual one it replaces and the installation time is reduced by a factor of 4 by changes in the design and the positioning of the valve. Further reductions in labor costs were identified in the preparation of the collector frame. By automation of the aluminum extrusion cut-off process and the drilling and tapping of holes, the necessary manhours can be reduced by a factor of 3.

A new fin coil for the evaporator-condenser assembly was designed. This fin coil has only 2 copper fins per inch instead of the customary 6 to 8 fins per inch. The cost of the heat exchanger was reduced by half, according to the manufacturer, Anderson-Snow in Chicago. Experimental testing verified the physical integrity of the fin coil in the evaporator-condenser assembly under vacuum conditions and during stress.

It was further established that silver solder can be successfully eliminated in the construction of the panel. Brazing alloys made of copper and containing phosphorus (like Harris Stay-Silv 6) do not require any flux when used for joining copper to copper, thus reducing cost and manhours required. Furthermore, the cost per pound is less than 1/3 of the cost of silver solder while the performance of the panel under ordinary circumstances is not affected in any way. The only drawback of the copper-phosphorus alloys is the higher brazing temperature required and the consequent softness of the copper resulting from the high temperature annealing process. This, however, is not considered serious and it does not affect the performance of the collector in any detectable way.

The study of mass production techniques applicable to the manufacturing of the zeolite collector was successfully completed. The results of this study can be summarized as follow: Stamping of the copper pans requires such enormous sizes of die sets and presses that it is not feasible until the volume of production reaches at least 3,000 to 5,000 collectors per month. For smaller volumes, hydraulic, vacuum or explosive forming are preferable.

Most steps of the manufacturing process can be automated and the degree of automation depends mainly on the manufacturing volume and on the trade-off between capital cost depreciation and labor cost savings per panel. For example, at a production level of 1,000 collectors/month the labor necessary for the construction of one panel is reduced from the present 70 manhours to about 20 manhours. The capital cost for such degree of automation, however, is about $2 million and when depreciated over 10 years at $200,000/year, the capital cost per collector is $200,000/12,000 = $17 per collector. In this example of mass production using the same labor cost as before ($11.50/hour including overhead), we will replace 70 manhours at $800 by 20 manhours at $230 plus $17 capital cost or a total of $247 for a total saving of $553 per collector. Material cost is also reduced to about $300 per collector so that the projected manufacturing cost of the integrated zeolite collector is $545 at a volume of 1,000/month. The cost is further reduced to $350 at a volume of 10,000 collectors per month and for a 16.4 ft^2 collection area this amounts to slightly over $21/$ft^2$.

The next step in this task was the testing of different methods of corrosion protection for iron and aluminum with the long range hope of substituting these materials for copper. Because of its higher thermal conductivity, aluminum would be the material of greater interest. However, the low chemical stability of this element made the corrosion problem more severe than with iron. Of the many coatings from the plastics to epoxy paint, the only satisfactory one found is HERESITE P-413, a brown, backed phenolic resin finish. Aluminum samples coated with HERESITE P-413 have withstood both short term, accelerated corrosion testing and long term, natural corrosion testing with no failure. When the manufacturer was asked to quote prices for coating the parts of one collector, the cost was so prohibitively high that it was considerably cheaper to use pure copper instead of HERESITE coated aluminum. The manufacturer of this proprietary coating, after examining a number of our separators refused to quote a price for a number of technical reasons on a variety of our parts. Despite the excellent corrosion protection results, this material was abandoned.

Close cooperation with a number of companies which are experts in the corrosion protection field resulted in a number of suggestions and many samples. Coatings from the vinyl and urethane family indicated initially some promise, however, prolonged testing in hot water with zeolite under vacuum indicated slow corrosion, possibly by water diffusion through the coating at high temperatures. For this reason, the plastic coatings of aluminum and iron were found to be unsatisfactory for long term corrosion protection at high temperatures and low cost.

Iron can be easily electroplated with copper in a single step. (Aluminum, on the other hand, has to undergo a multiple step process and the aluminum-copper sandwich represents an electrical battery, always ready for electrolytic corrosion whenever moisture is available.) For this reason, heavy electroplating of copper on iron was investigated as an inexpensive method of corrosion protection. Samples of iron shim stock were electroplated with copper of 0.3, 0.5 and 0.7 mil thickness. These samples were next tested for corrosion at elevated temperatures and in contact with water and zeolite under vacuum.

The results from the accelerated tests over a period of more than six months are as follow: If iron samples are plated with copper of any thickness in a single step, the resulting pinholes in the copper plating will permit water to penetrate behind the electroplated coating and to attack the iron surface resulting in rusting and corrosion. If, on the other hand, the plating is built up from multiple layers and the samples are carefully cleaned and treated between each plating step, it is possible to produce a pinhole-free multiple layer in thicknesses as small as 0.3 mil (0.0003 inches). This carefully plated multilayer can provide adequate corrosion protection to the iron metal under our normal operating conditions.

The low thermal conductivity of iron makes it of limited usefulness in the manufacturing of the integrated zeolite collector, with the exception of the metal pan itself. While the electroplating with copper of parts 2x8 ft large has been done commercially, there are some questions about the quality of multiple layer plating in the corners and around the edges of the pan. For these reasons, it is not clear at this time if replacing the copper pan with an iron, copper-plated one will result in any materials cost savings and how will this replacement affect the reliability of the final product, especially with respect to corrosion effects and long lifetimes. No further discussions can be made at this point until planning for mass production has begun.

The study of the use of plastics for the packaging of the panel directed us next to investigate the use of fiber glass-epoxy materials instead of copper or iron, for the zeolite pan. Since fiber glass-reinforced epoxy has been used extensively for boats in salt water environments and has shown no signs of corrosion, it was considered, despite its very low thermal conductivity, as a candidate material for the zeolite panel. There is a considerable cost advantage in using this material -- it costs less than 1/4 of the price of a similar copper pan. The cover to the pan, which collects and conducts the solar energy in the zeolite and is the active black surface of the collector, has to have high thermal conductivity and is therefore made always from copper. The creation of a vacuum tight seal between the copper cover and the fiber glass-epoxy container of the zeolite pan subject to multiple temperature cycling proved to be an almost impossible job.

Two fiber glass-epoxy pans 2x8 ft were ordered and a number of adhesives were tested in the attempt to attach copper parts to them. Hard epoxy-type adhesives form good bond to both the fiber glass-epoxy and to the copper parts. During rapid temperature cycling, however, they failed due to the large mismatch of thermal expansion coefficients of the two materials. The resulting stress proved too much for all adhesives. The flexible adhesives of the silicone rubber type proved to be more promising. A series of tests were conducted with different primers for the copper cover and a variety of silicone rubbers. The most commonly used silicone rubbers produce acetic acid during cure which attack the copper metal and forms copper acetate. This corrosive process could not be prevented by the use of any of the primers. Therefore, special one- and two-parts silicone rubbers were obtained, intended for the use of encapsulating and sealing electronic components. While more expensive, these silicones proved to be satisfactory and did not interact with the copper cover. The best results were obtained on copper surfaces treated with G.E. SS 4004 primer, and using G.E. RTV 162 electronic grade one-part silicone rubber. Next best was the two-parts G.E. RTV 602 silicone potting compound again used on surfaces prepared with the SS 4004 silicone primer. The adhesion of the silicone compounds after curing was excellent and therefore the construction of the low cost collector was started.

The fiber glass-epoxy panels were next filled with zeolite and the copper covers attached with silicone rubber. First, leak tests determined that the fiber glass-epoxy pans were full of small pinholes caused by insufficient epoxy resin in the bottom of the pans. To seal the pinholes, the fiber glass-epoxy pans were painted on the outside with a two-part epoxy paint intended for marine use. After two coats of cured epoxy paint, the pans were vacuum tight. The evaporator-condenser of the low cost fin coil design was attached to the back of the panels and the system evacuated. Since the fiber glass-epoxy panels were available in sizes slightly different from our regular panels, special frames had to be constructed for them. For the same reason, our regular low-iron glass was impossible to use for glazing, so the collectors were initially glazed with 3/16" float glass obtained locally. During actual testing, however, the float glass, which is not annealed, repeatedly shattered and proved to be useless. Custom size, low-iron annealed glass was then ordered and it arrived shortly before the end of the contract.

The low cost collector was then tested indoors with the solar simulator and after a number of thermal cycles the silicone rubber seal between the cover and the fiber glass-epoxy panel failed. The cover was removed, cleaned up and cemented again to the panel with a new silicone rubber seal.

The low cost collector was then erected outdoors, completely instrumented and tested for one complete week. The performance was exactly equal to our regular all-copper collector and the task was successfully completed.

After one week of thermal cycling outdoors, the silicone rubber seal failed again. The cover was again removed and after cleaning, sealed anew with silicone rubber adhesive to the fiber glass-epoxy pan. This time the collector lasted ten days of thermal cycling before the seal failed again.

Since the failure occurred always along the length of the cover close to the corners, it appears that the mismatch of thermal expansion coefficients is too large and that the differential change in length along the 8-foot panel between the cover and the pan is beyond the shearing stress capability of the silicone rubber seal.

Because of the expiration of the contract and since all labor funds were already used up, no further attempts were made to seal the panel. It is possible to use this approach, however, with either shorter panels, using covers of materials with smaller thermal expansion coefficient, or special design of the cover with a structure to provide relief of the stress created during the thermal cycling of the cover.

Task 9.

The detailed description of Task 9 was as follows:

To collect operational performance data from the three different sites in the U.S.A. every month of the year.

To analyze the performance data from the test sites.

In order to achieve this task, the following steps were taken:

During the month of August 1980 three different geographic sites in the U.S.A. were equipped with a pair of collectors each and instrumented with automatic recording equipment. One site was at SERI in Golden, Colorado, another at the Anaconda Co. Research Laboratory in Tucson, Arizona, and the last site at the Zeopower Company in Natick, Massachusetts.

All input solar data and the heating and cooling output of the collectors was recorded on a strip chart recorder which has automatic data recording capability of 31 days. It was anticipated during the preparation of the third-year proposal and budget that there would be monthly visits to each test site during which time the recorded charts would be recovered, new charts installed and the equipment would be calibrated with maintenance performed when necessary.

Because of budget limitations within DOE, however, the funds available for the third year were only 50% of what was originally requested. For this reason, the number of visits to the sites was reduced to only one per year and the monthly chart replacement and equipment performance verification was entrusted to SERI and Anaconda Laboratory research personnel.

From the very first day, test equipment malfunctions plagued the project. At the SERI site during the installation and start up of the panels the transformer of the BTU meter burned out. The same thing occurred in July to the BTU meter in Natick. The manufacturer replaced both parts; however, months of valuable data during the summer of 1980 was lost. In June 1980, three out of five brand new flow meters failed. The manufacturer replaced all five, but in September 1980 the flow meter at SERI failed. Two of the integrating recorders were returned in August 1980 to the manufacturer for repair and replacement and were received back in late September 1980.

Two of the flow meters failed again in February 1981. The manufacturer replaced them and then another one failed. The failure was found to be always in a reed switch, activated by the piston of the flow meter and after this failure we purchased a large number of those switches and repaired the flow meters ourselves.

Eventually most of the bugs in the test equipment and instrumentation were worked out and the performance was remarkably reliable for the last year and one-half of the project.

The second major problem encountered with this set up was the monthly change of chart paper on the recorders. On numerous occasions the new chart was not properly installed and at times the recorder was damaged during the installation of new chart paper. Since the equipment was visited by local personnel in

Golden and Tucson only once per month, usually a whole month of data was lost before the errors were detected and corrected. The recorder in Tucson had to be repaired twice and the wires attached to it were broken off once during the change of paper charts.

The third major problem encountered was with the reliability and integrity of the collectors themselves. One of the two panels in Tucson failed after one week of operation. Either a very small leak in the vacuum tight panel or the accumulation of noncondensable gases during passivation blocked the condenser with noncondensable gases. The resulting steam in the panel built up until the pressure exceeded one atmosphere and the cover of the panel ballooned upwards, forcing the glazing and weather tight gaskets out of the frame of the collector. Fortunately, the tempered low iron glass used in the construction of the collector proved to be stronger than expected. It withstood numerous ballooning of the covers and severe hail in Golden, Colorado without a single breakage.

In October 1980, the panel in Tucson was repaired and evacuated. After one week, again it ballooned and pushed the glass out of the frame. The pump-out valve was then opened and the panel vented to the atmosphere. The tests continued with only one panel until replaced with a new collector, shipped from Natick in February 1981. The test site in Tucson operated successfully until July 1981 when a new building was constructed by the Anaconda Company exactly to the south of the collectors, thus blocking the solar access to the panels. In September 1981 a new foundation was prepared for the collectors in an area with unobstructed solar exposure. In October 1981 the collectors in Tucson were moved to the new location and a complete rewiring of the test instrumentation was performed. During the move, one of the two collectors was damaged and the vacuum was lost. Attempts to repair it in the field were not successful and because of lack of funds the collector could not be shipped to Natick for repairs.

The least amount of data was collected at SERI. As mentioned above, the transformer of the BTU meter burned out during start-up. The manufacturer replaced it and the unit was repaired in September 1980; however, shortly thereafter the flow meter failed. In October 1980 the flow meter at SERI was replaced and the equipment was restarted. After one month of data collection, one of the collectors failed and attempts to repair the vacuum leak in the field were not successful.

The problems with the collectors at SERI and Tucson were traced to the place where 3/8" diameter copper tubing is attached to the copper sheet metal. The tubing, which is used for freeze protection during the winter and drains the evaporator back to the zeolite panel through a shut-off valve, was attached to the panel originally with Stay-Brite (registered trademark of the J. W. Harris Co. of Cincinnati, Ohio), a silver containing solder with a melting point of 420^{O}F and exceptionally high strength up to temperatures of 50^{O}F below its melting point. This silver solder has proved itself in many other applications in the collector, and under normal conditions will perform satisfactorily. In this particular application, however, a torque was formed during thermal cycling since the condenser-evaporator remains relatively cool while the collector cycles daily between room temperature and about 100^{O}C. The thermal expansion of the panel against the cool drain tube produces the torque which tends to tear off the tubing from its point of attachment to the panel. In a number of attempts to correct this problem, flanges were made and used to attach the tubing to the panel, however, they were only partially successful. Eventually, the problem was resolved by brazing the 3/8" tubing to the panel at 1250^{O}F. Unfortunately, this has to be done before the panel is filled with zeolite; therefore, the collectors under test could not be repaired using this method.

It was decided to replace the two collectors at SERI with two new ones which would include all the improvements made during the one year that passed since the original collectors under test were designed and built. This also included the addition of selective absorbing surface of black chrome, instead of the Nextel black velvet flat black paint used originally and experimentation with single versus double glazing.

The new collectors for SERI were built and tested during the summer of 1981.

During testing at Natick, some minor problems were discovered and before these problems could be corrected, the contract expired in September 1981. A one year no-cost extension was obtained for additional data collection. During this period the test site at SERI was broken into and all test equipment stolen. The collectors were therefore shipped in the summer of 1982 to Phoenix, Arizona where they will be tested under a separate contract.

The end result of this experience is that only one month of good reliable data is available from the test site at SERI. Since neither the installation nor the removal date was recorded on the paper chart, the exact dating of the data is not possible. It was received in Natick in January 1981 and it is estimated that the data was obtained during the month of October 1980.

The best data was obtained in Natick, Massachusetts since test equipment failure was discovered immediately and corrected as soon as possible. Again, reliability of test equipment and collectors proved to be the major problems. In addition, during the severe cold spells of winter, there were a number of freeze-up problems with the collectors resulting in the loss of vacuum. It was discovered that the drain angle of the 3/8" diameter tubing, discussed previously, was too small and the surface tension of water sometimes prevented the complete drainage of the tube. The result was burst tubing and loss of vacuum. The tubing was replaced a number of times and the drainage angle was increased considerably on future panels.

During most of the time from August 1980 to September 1982 the data collected in Natick was accurate and reliable.

The following tables summarize the collected data:

Table I.1 is the only data from SERI in Golden, Colorado and covers 32 consecutive days, most likely during October 1980. The exact dates are not known. The heating daily efficiencies vary between 18 and 25% on sunny days for inputs between 1100 and 2140 BTU/ft^{2}day. A slow deterioration of the efficiency is visible with the last 6 days dropping mostly to the 18% efficiency range. This is consistent with the observation of slow accumulation of noncondensable gases in the condenser due to outgassing, passivation or small leaks. The cooling efficiencies are extremely low, possibly for the same reason. The effect of noncondensable gases is more severe during the cooling cycle when the pressure in the system is lowest.

Another explanation for the low cooling efficiency is that since the data was taken in late fall or early winter, the freeze protection valve was opened to protect the collector from freezing during the winter months. This will disable the cooling cycle and the small readings obtained during the night are the result of left-over water in the evaporator or simply equipment random noise. This possibility seems the most likely since there is no correlation between the cooling output and the solar input in the collector.

The data from Table I.1 is summarized in Figure 1. Here we have plotted the output of the collectors at SERI in BTU/ft^{2}day as a function of solar input also in BTU/ft^{2}day.

Within the experimental error and random scatter the data is pretty well represented by a straight line with a slope of 0.285 starting at a solar input of about 350 BTU/ft^{2}day. Since this input corresponds to a cloudy day with possibly some rain, the conclusion reached is that the collectors will produce no output on days with less than 400 BTU/ft^{2}day. For higher solar inputs the output is linearly proportional to the input with an efficiency of 28.5%. The overall daily efficiency for heating varies from 18.5% at 1000 BTU/ft^{2}day input to 23.5% at 2000 BTU/ft^{2}day.

Tables II.1 through II.20 represent the collected data from Tucson, Arizona from August 19, 1980 through March 31, 1982. Despite the many problems with the test equipment and the collectors at this test site, adequate data was collected from August 1980 until the end of May 1981. The chart for June 1981 was improperly placed in the recorder by the Anaconda Company personnel and the data for that month was all lost. In July 1981 the new building to the south of the collectors blocked the solar input to the

TABLE I.1

DENVER

(Received in Natick January 15, 1981 - Undated)

DAY	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1438	280	20	64	4
2	1365	290	21	40	3
3	2028	369	18	67	3
4	2139	415	19	67	3
5	369	30	8	52	14
6	147	6	4	52	35
7	1881	354	19	49	3
8	2139	387	18	88	4
9	2102	430	20	91	4
10	1623	366	23	67	4
11	2139	463	22	70	3
12	996	183	18	73	7
13	1106	204	18	58	5
14	1475	314	21	61	4
15	1770	427	24	73	4
16	1106	229	21	82	7
17	1254	305	24	85	7
18	1880	482	26	70	4
19	1844	412	22	64	3
20	1733	390	23	64	4
21	1770	384	22	82	5
22	959	189	20	52	5
23	185	0	0	21	11
24	332	0	0	40	12
25	1033	82	8	24	2
26	922	79	9	37	4
27	1992	360	18	18	1
28	1880	335	18	52	3
29	1844	338	18	58	3
30	1880	351	19	73	4
31	1918	363	19	73	4
32	1070	162	15	0	0

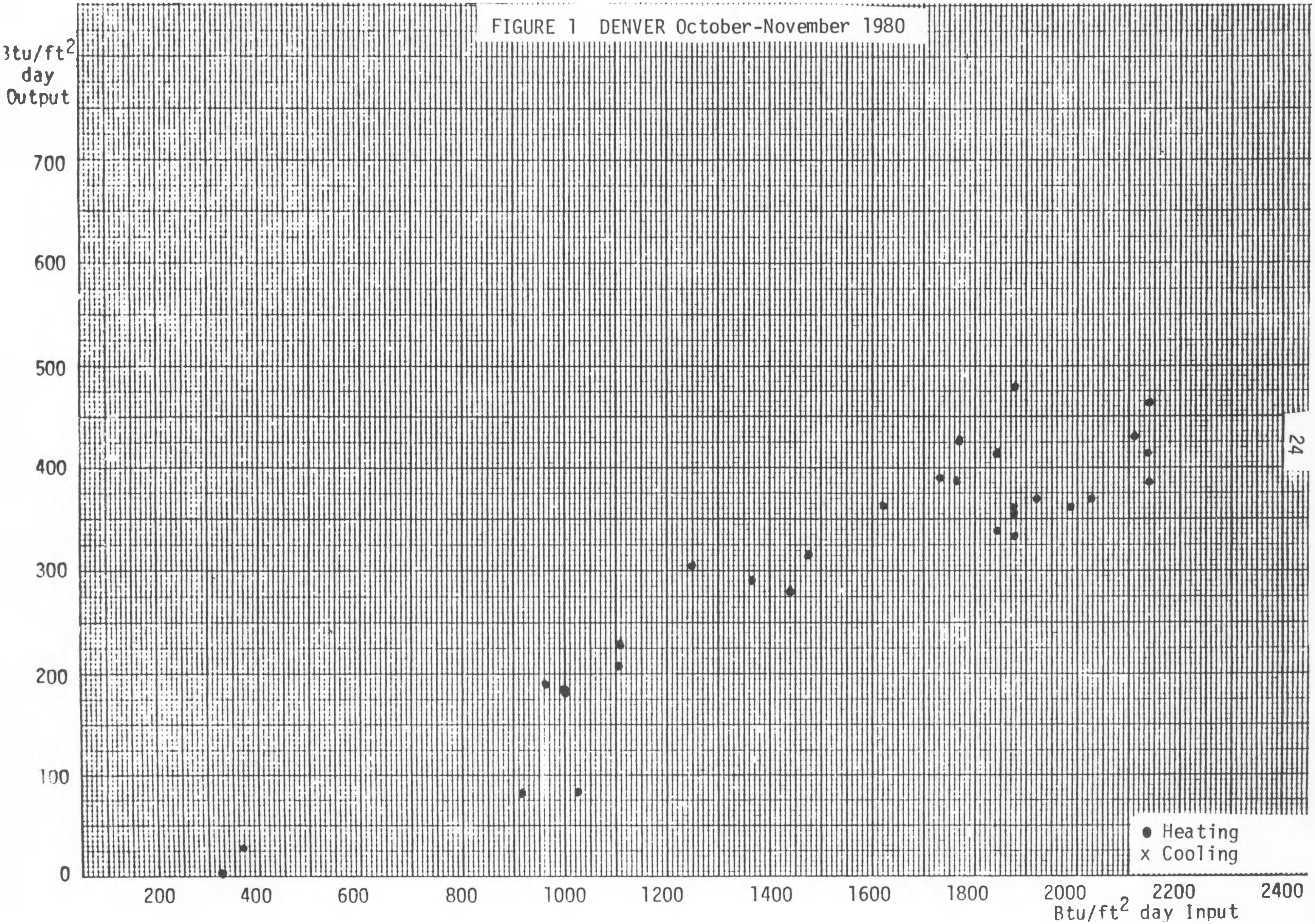


FIGURE 1 DENVER October-November 1980

collectors and the rest of the data until November 1981 is useless. After the move of the collectors to the new location and the rewiring of the test equipment in November the data indicates that the collectors were damaged during the move and could not be repaired within the time and funds allowed, despite a number of attempts to do so.

The data from Tables II.1 through II.9 is presented in graphic form in Figures 2 through 10. The remaining Tables II.10 through II.20 could not be analyzed in a useful manner.

The data most appropriate for analysis of the heating performance of the collectors is given in Figures 3, 4, 7, 8, and 10 for the months of October and November 1980 and February, March and May 1981. It is best represented by a straight line passing through the origin with a slope of 0.28 and the overall daily heating efficiency is approximately constant at about 28 to 30%.

The least experimental scatter and therefore the data most useful for analysis of the cooling performance of the collectors is given in Figures 3, 4, and 10, corresponding to the months of October and November 1980 and May 1981. The best representation is by a straight line starting at about an input of 200 BTU/ft^2 day with a slope of 0.2. This corresponds to a total overall daily cooling efficiency varying from about 25% at 1000 BTU/ft^2 day solar input to about 20% at 2200 BTU/ft^2 day.

Typically, on sunny days, with solar inputs above approximately 1400 BTU/ft^2 day, the heating output during the day was larger than the cooling output by about 150 BTU/ft^2 day. For example, in October 1980 Figure 3, for a solar input of 2200 BTU/ft^2 day the heating output is between 575 and 600 BTU/ft^2 day while the cooling output is between 425 and 450 BTU/ft^2 day. Similar differences are observed for the other figures chosen for analysis, i.e. Figures 4 and 10.

This difference can be explained by the fact that the condenser-evaporator is always cooler than the zeolite panel and therefore heat flow from the panel to the evaporator by conduction will add to the heating output and subtract

TABLE II.1

TUCSON

AUGUST 1980

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19	1549	756	49	427	28
20	2250	780	35	311	14
21	2323	500	22	323	14
22	1696	427	25	250	15
23	959	317	33	213	22
24	1475	433	29	256	17
25	2250	500	22	287	13
26	2250	470	21	305	14
27	2250	476	21	317	14
28	2250	482	21	335	15
29	2176	463	21	360	17
30	2250	494	22	323	14
31	2287	500	22	348	15

TABLE II.2

TUCSON

SEPTEMBER 1980

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	2360	500	21	317	13
2	2213	463	21	329	15
3	1881	409	22	293	16
4	516	122	24	122	24
5	1696	463	27	268	16
6	1992	500	25	299	15
7	959	329	34	220	23
8	2176	585	27	329	15
9	1623	433	27	305	19
10	1733	476	27	305	18
11	2213	537	24	341	15
12	2065	518	25	311	15
13	2250	494	22	354	16
14	2065	512	25	329	16
15	2250	512	23	335	15
16	2287	500	22	323	14
17	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
18	2250	488	22	323	14
19	2250	482	21	299	13
20	2287	482	21	311	14
21	2360	488	21	293	12
22	2287	512	22	274	12
23	2139	488	23	305	14
24	1254	323	26	220	18
25	1549	378	24	220	14
26	2139	549	26	335	16
27	2176	524	24	348	16
28	2213	506	23	323	15
29	2176	476	22	335	15
30	2213	500	23	323	15

TABLE II.3

TUCSON

OCTOBER 1980

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	2213	445	20	372	17
2	2250	591	26	0	0
3	2176	732	34	543	25
4	2213	701	32	378	17
5	2176	543	25	360	17
6	2139	506	24	421	20
7	2176	549	25	390	18
8	2139	537	25	396	19
9	2139	512	24	396	19
10	2028	549	27	384	19
11	2102	561	27	378	18
12	1733	494	29	366	21
13	1660	482	29	341	21
14	1623	482	30	311	19
15	959	287	30	299	31
16	885	274	31	268	30
17	2213	591	27	427	19
18	2176	537	25	0	0
19	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
20					
21					
22					
23					
24	2213	585	26	372	17
25	1475	439	30	299	20
26	1180	354	30	287	24
27	1881	524	28	402	21
28	2176	561	26	421	19
29	2213	579	26	433	20
30	2250	579	26	390	17
31	2102	591	28	372	18

TABLE II.4

TUCSON

NOVEMBER 1980

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	2028	567	28	396	20
2	2139	585	27	409	19
3	1992	567	28	402	20
4	2065	543	26	372	18
5	2065	567	27	372	18
6	1881	512	27	348	18
7	1992	555	28	384	19
8	2028	549	27	360	18
9	1881	543	29	354	19
10	1070	329	31	232	22
11	1770	543	31	354	20
12	1512	451	30	323	21
13	1623	463	29	360	22
14	1955	543	28	427	22
15	1180	348	29	323	27
16	1844	512	28	396	22
17	2065	543	26	427	21
18	1881	439	23	409	22
19	1992	537	27	427	21
20	959	287	30	293	31
21	1844	537	29	0	0
22	- - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - -				
23					
24					
25	1955	500	26	409	21
26	1992	512	26	402	20
27	1992	488	25	415	21
28	1955	530	27	366	19
29	1918	549	29	378	20
30	1365	402	30	311	23

TABLE II.5

TUCSON

DECEMBER 1980

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1918	543	28	372	19
2	1955	549	28	378	19
3	1918	512	27	366	19
4	1733	494	29	354	20
5	1512	457	30	335	22
6	959	293	31	268	28
7	1696	494	29	378	22
8	1660	476	29	384	23
9	1918	494	26	372	19
10	1992	543	27	390	20
11	1623	439	27	335	21
12	295	37	12	146	50
13	1180	427	36	317	27
14	1807	488	27	396	22
15	1881	494	26	378	20
16	1918	518	27	329	17
17	1881	543	29	354	19
18	1844	494	27	354	19
19	1365	244	18	299	22
20	1660	451	27	323	19
21	1844	512	28	360	20
22	1844	518	28	366	20
23	1733	463	27	348	20
24	1881	518	28	348	18
25	1918	530	28	384	20
26	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
27	1807	500	28	348	19
28	1696	482	28	305	18
29	1070	293	27	207	19
30	1881	524	28	280	15
31	1475	433	29	293	20

TABLE II.6

TUCSON

JANUARY 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1770	512	29	299	17
2	1770	524	30	311	18
3	1733	488	28	341	20
4	811	250	31	159	20
5	1328	445	34	317	24
6	774	207	27	177	23
7	406	116	29	159	39
8	1475	402	27	317	22
9	1881	500	27	341	18
10	1033	348	34	274	27
11	332	61	18	79	24
12	295	43	14	85	29
13	885	287	32	171	19
14	1401	439	31	293	21
15	1696	518	31	335	20
16	701	189	27	195	28
17	1770	476	27	232	13
18	1992	488	25	384	19
19	1992	500	25	384	19
20	1918	488	25	384	20
21	1992	494	25	384	19
22	2065	543	26	378	18
23	1696	451	27	354	21
24	1586	433	27	341	22
25	1365	238	17	305	22
26	1844	482	26	372	20
27	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
28	1586	420	27	177	22
29	2065	512	25	198	19
30	1918	476	25	171	18
31	1623	396	24	168	21

TABLE II.7

TUCSON

FEBRUARY 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	2176	500	23	183	17
2	2102	476	23	201	19
3	1401	372	27	159	23
4	2139	524	25	192	18
5	2176	500	23	198	18
6	959	235	25	201	21
7	2138	588	28	293	14
8	1032	290	28	210	20
9	368	88	24	101	27
10	1290	415	32	235	18
11	1953	564	29	265	14
12	1622	485	30	265	16
13	2138	628	29	262	12
14	2211	646	29	262	12
15	2064	631	31	271	13
16	2138	616	29	277	13
17	2100	628	30	262	13
18	2175	634	29	262	12
19	2285	646	28	250	11
20	1916	558	29	268	14
21	2285	609	27	323	14
22	2322	686	30	314	14
23	2322	649	28	305	13
24	2359	640	27	296	13
25	2138	579	27	262	12
26	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
27	1254	415	33	229	18
28	1844	555	30	241	13

TABLE II.8

TUCSON

MARCH 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	2065	595	29	271	13
2	664	180	27	168	25
3	959	280	29	201	21
4	1365	387	28	259	19
5	1475	454	31	268	18
6	1070	268	25	204	19
7	2028	521	26	296	15
8	2360	619	26	323	14
9	2360	646	27	268	11
10	2360	655	28	287	12
11	2323	671	26	265	11
12	1844	540	29	262	14
13	2250	625	28	229	10
14	2397	625	26	265	11
15	1807	524	29	244	14
16	2065	610	30	259	13
17	2028	588	29	259	13
18	2360	662	28	265	11
19	1844	534	29	226	12
20	516	131	25	232	45
21	2250	631	28	241	11
22	2360	659	28	247	11
23	2397	655	27	259	11
24	2360	613	26	253	11
25	2397	659	28	238	10
26	2360	649	28	238	10
27	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
28	2323	601	26	253	11
29	2360	637	27	259	11
30	2397	643	27	238	10
31	2397	652	27	223	9

TABLE II.9

TUCSON

APRIL 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	2434	622	26	238	10
2	1328	323	24	140	11
3	1844	405	22	210	11
4	2471	628	25	253	10
5	2545	625	25	220	9
6	2323	604	26	216	9
7	2471	625	25	220	9
8	2471	631	26	220	9
9	2471	613	25	216	9
10	2397	564	24	204	8
11	2397	607	25	195	8
12	996	274	28	128	13
13	2323	622	27	192	8
14	2102	494	24	177	9
15	2287	582	26	238	10
16	1844	470	26	223	12
17	1365	338	25	165	12
18	2397	558	23	192	8
19	2250	497	22	201	9
20	2287	463	20	213	9
21	2323	482	21	204	9
22	2176	457	21	204	9
23	2323	476	21	223	10
24	2323	466	20	232	10
25	2360	387	16	271	12
26	2287	451	20	128	6
27	- - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - -				
28	2360	366	16	256	11
29	2213	348	16	256	12
30	1881	317	17	214	11

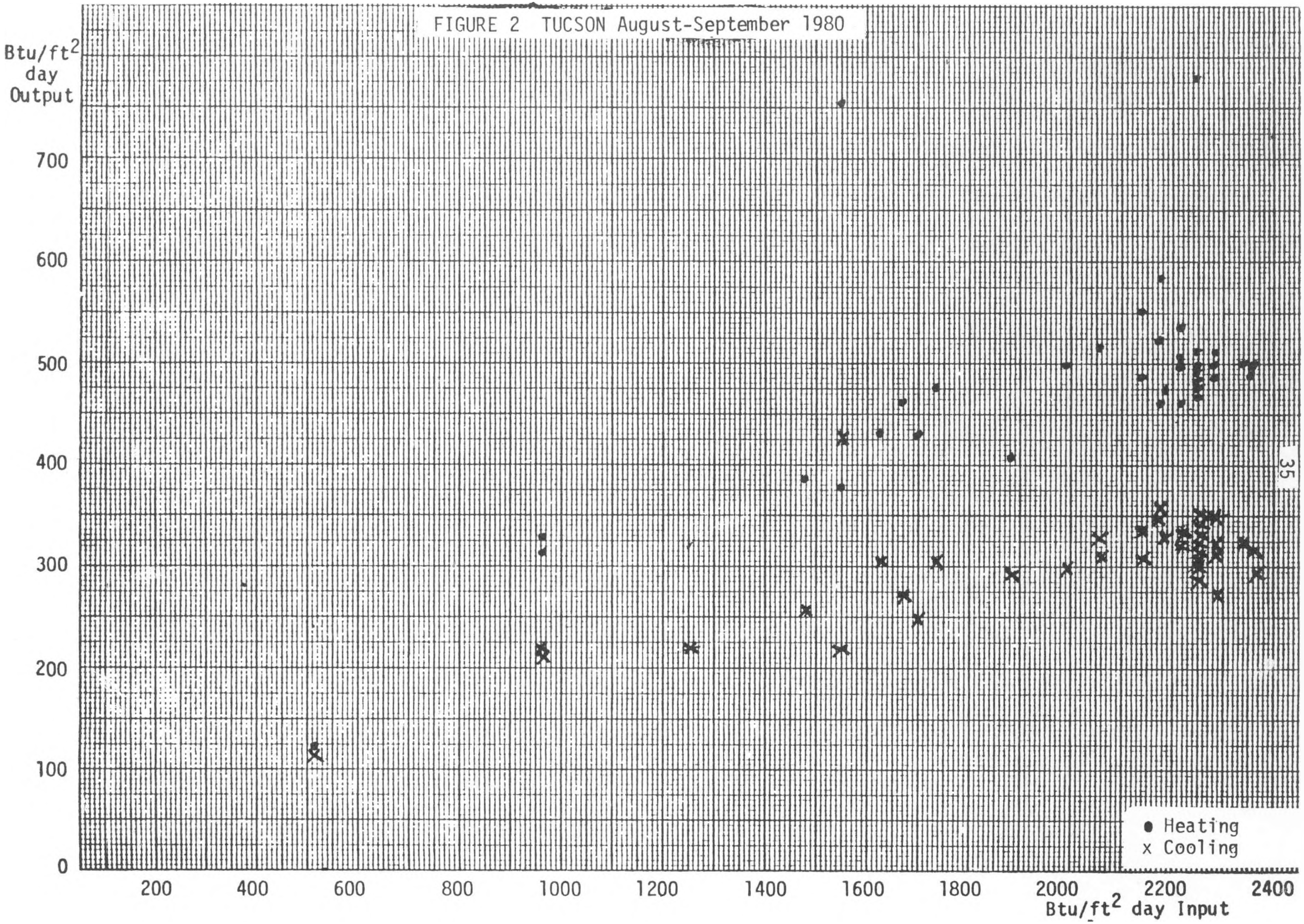


FIGURE 2 TUCSON August-September 1980

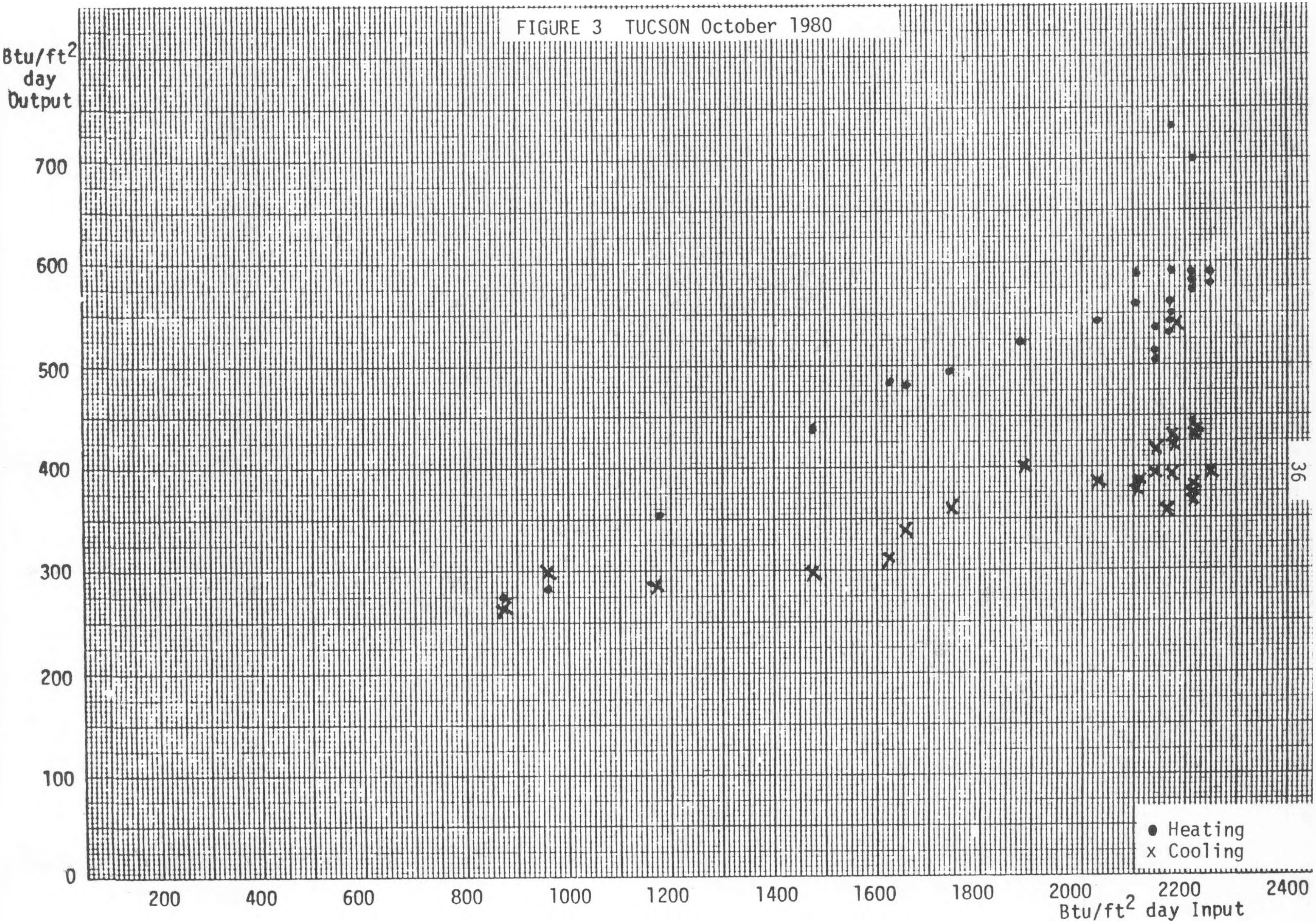


FIGURE 3 TUCSON October 1980

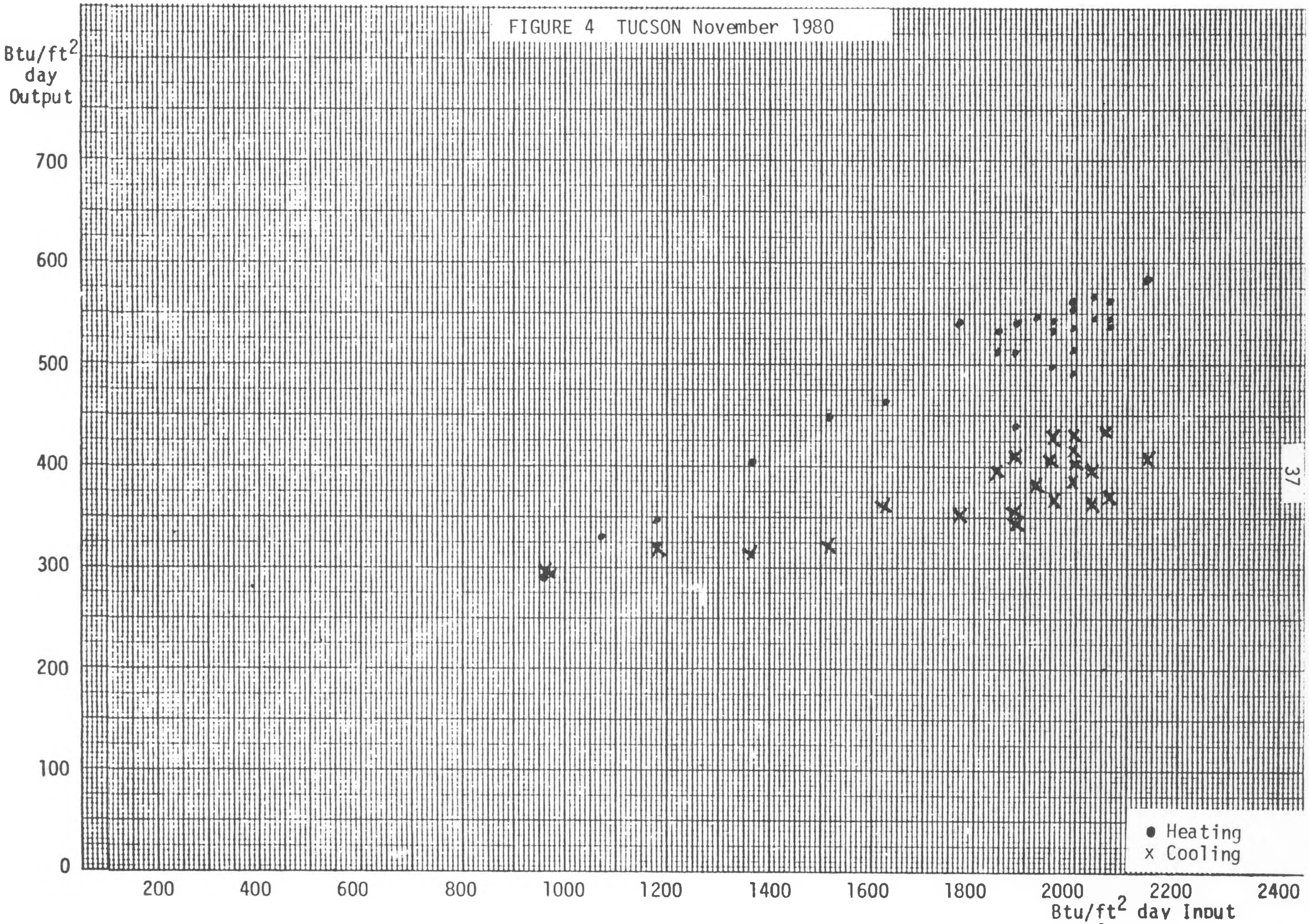


FIGURE 4 TUCSON November 1980

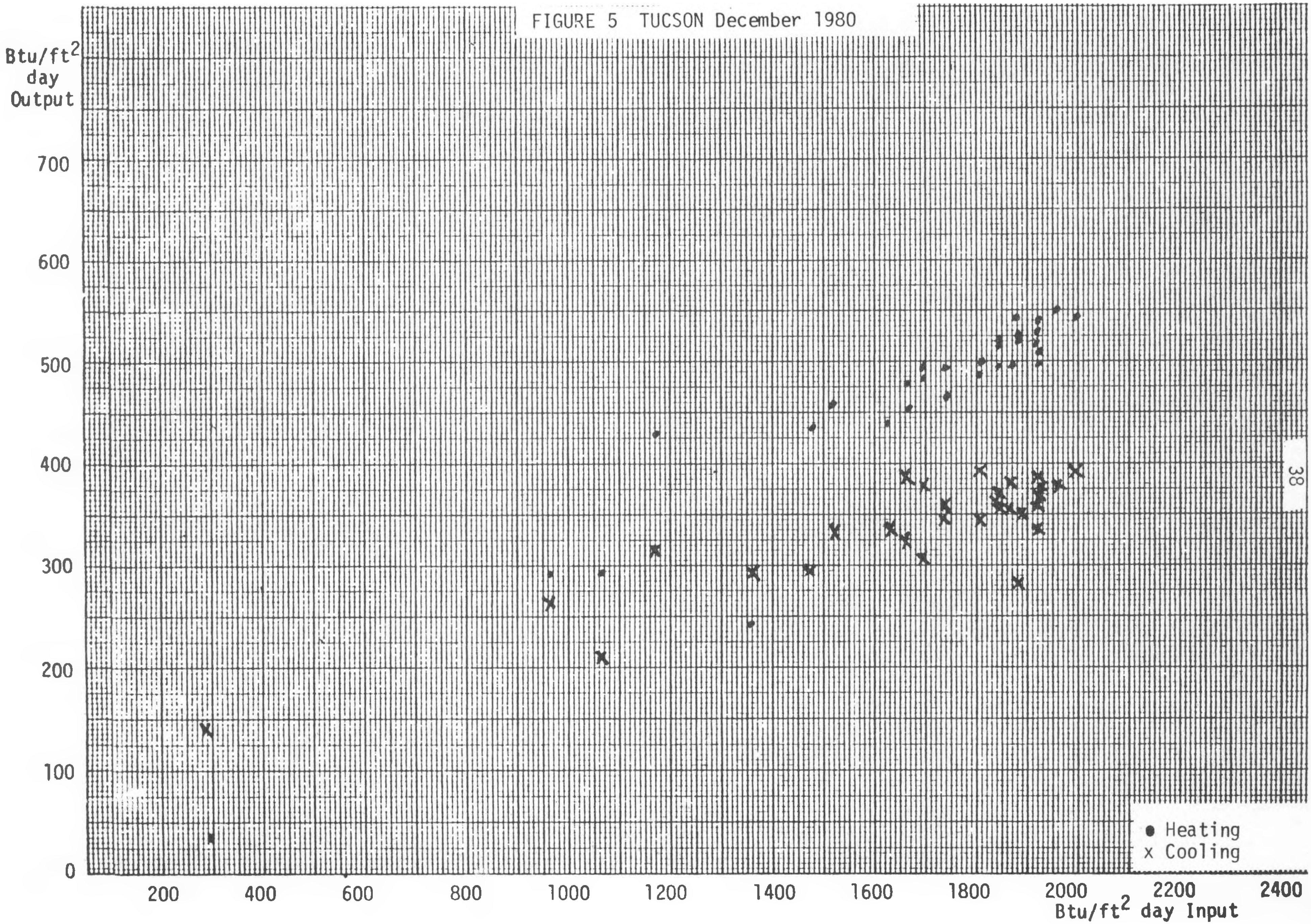


FIGURE 5 TUCSON December 1980

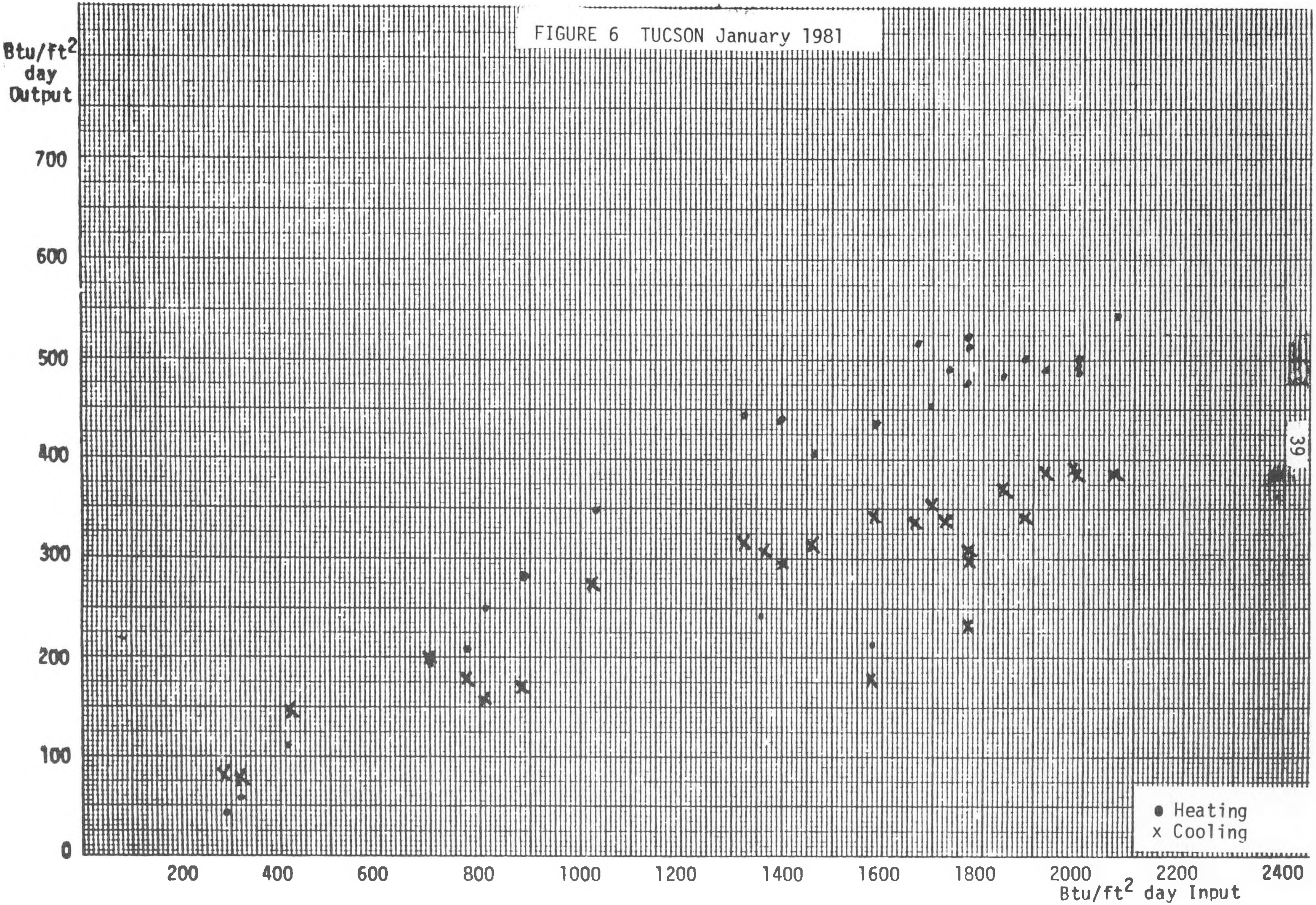


FIGURE 6 TUCSON January 1981

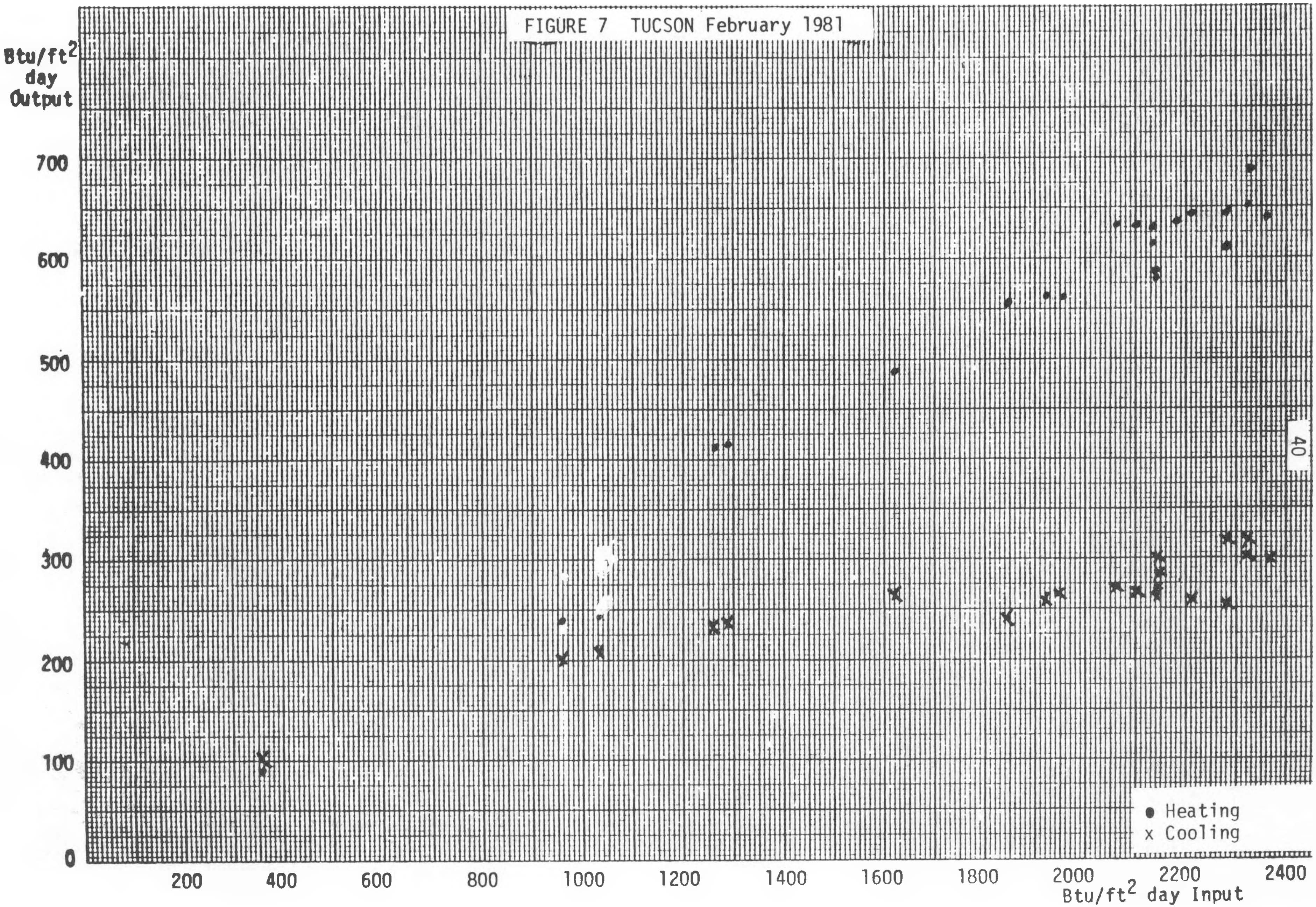


FIGURE 7 TUCSON February 1981

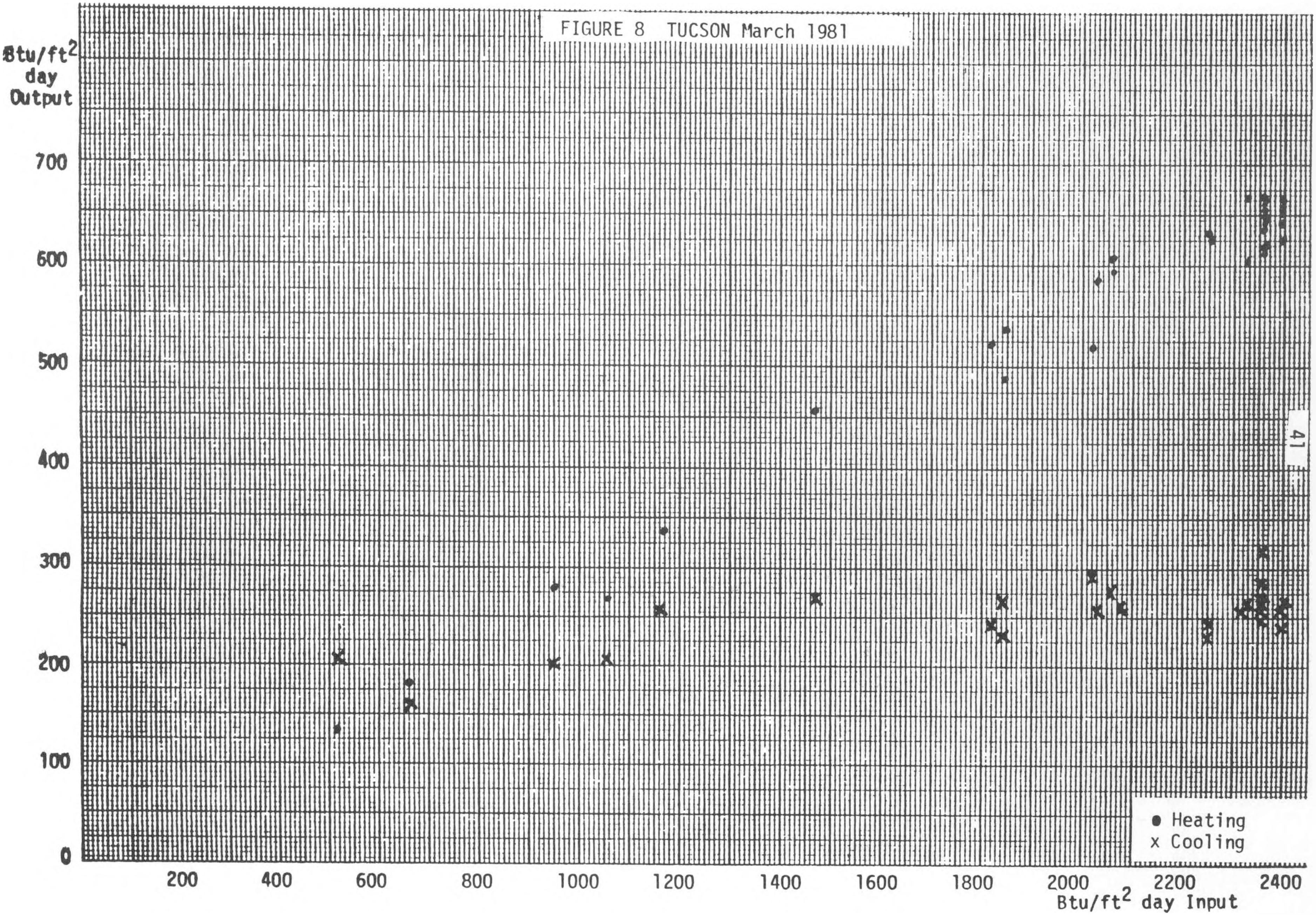


FIGURE 8 TUCSON March 1981

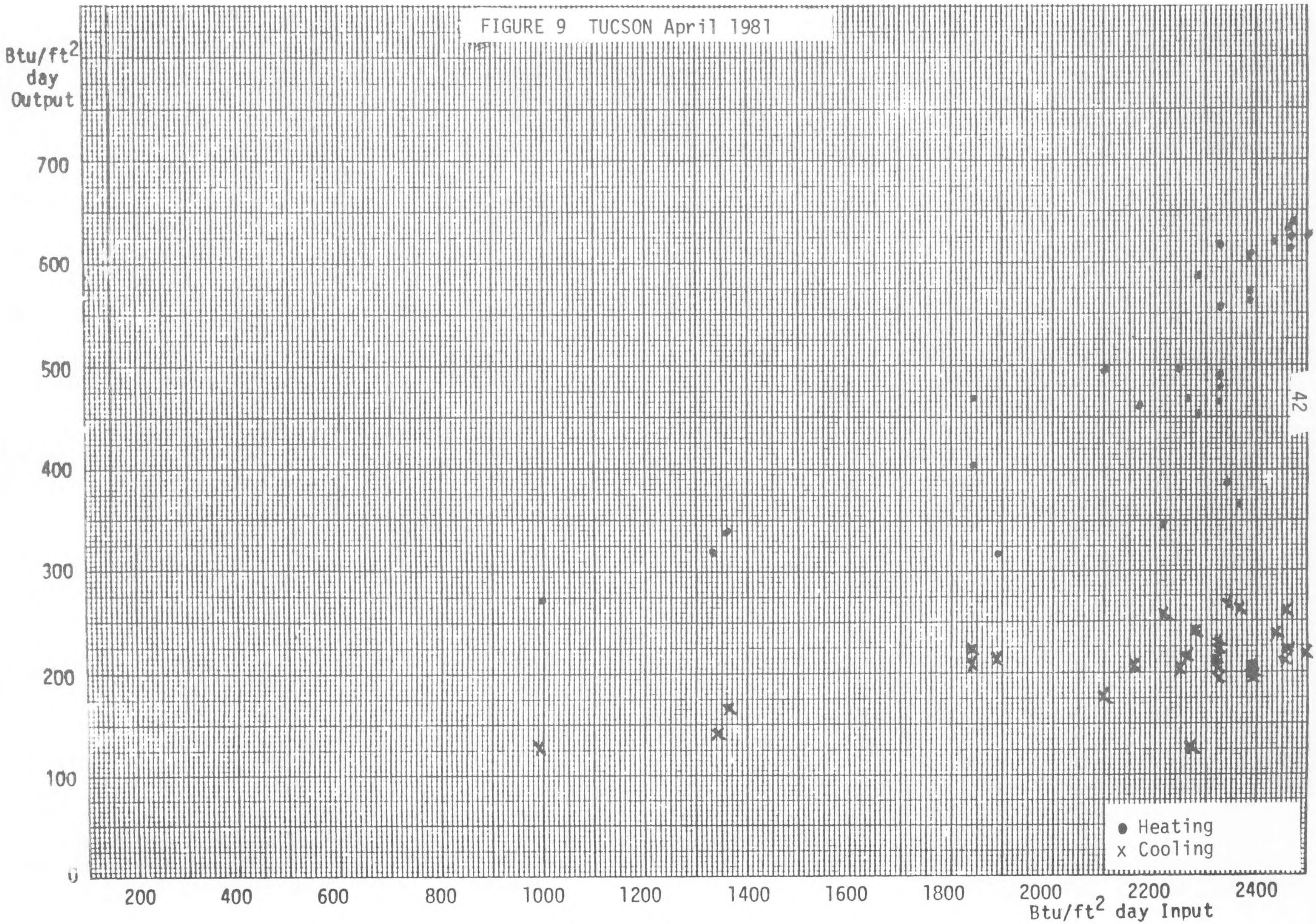


FIGURE 9 TUCSON April 1981
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

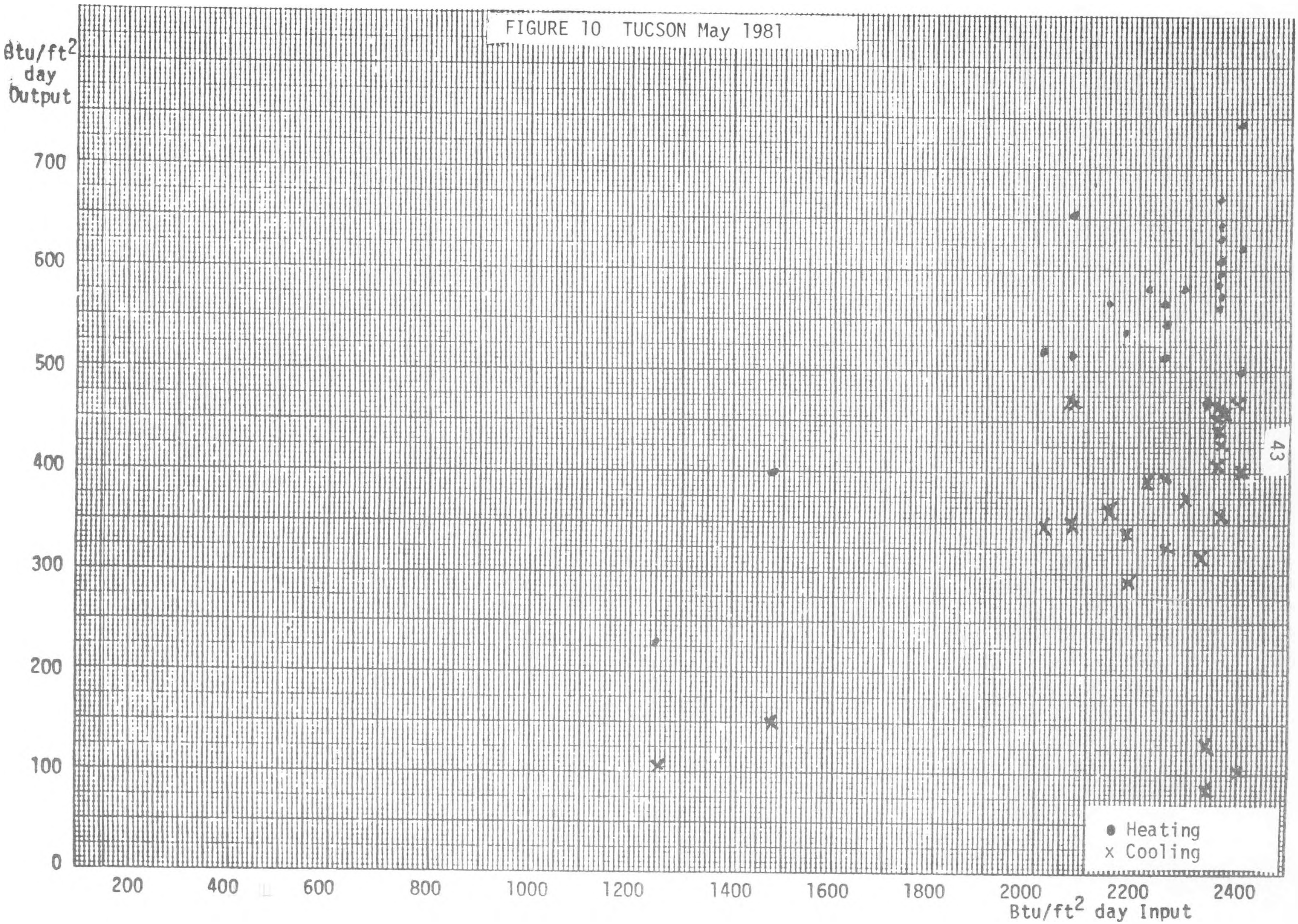


FIGURE 10 TUCSON May 1981
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

TABLE II.10

TUCSON

MAY 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1254	278	22	110	9
2	2323	470	20	131	6
3	2323	467	20	86	4
4	2397	494	21	104	4
5	- - - - - - - - - - - - CHART OFF FOR REPAIR OF PEN - - - - - - - - - - - - - - -				
6	2397	744	32	470	20
7	2360	671	28	445	18
8	2360	646	28	463	20
9	2397	622	26	409	18
10	2065	652	32	470	22
11	2360	585	24	457	20
12	2360	610	26	451	20
13	2360	628	26	427	18
14	2250	567	26	396	18
15	2139	567	26	366	18
16	2287	579	26	372	16
17	2213	579	26	390	18
18	2360	591	26	409	18
19	2028	518	26	354	18
20	2360	573	24	360	16
21	2360	567	24	360	16
22	2065	518	26	348	16
23	2250	543	24	323	14
24	2250	518	24	323	14
25	2176	488	22	293	14
26	2176	451	20	244	12
27	1475	396	26	152	10
28	2323	415	18	268	12
29	- - - - - - - - - - - - - - - - ILLEGIBLE - - - - - - - - - - - - - - - - - - -				
30					
31					

TABLE II.11

TUCSON

JUNE 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	CHART PAPER IMPROPERLY INSTALLED. WENT UNNOTICED UNTIL FOLLOWING MONTH.				
2	"	"	"	"	"
3	"	"	"	"	"
4	"	"	"	"	"
5	"	"	"	"	"
6	"	"	"	"	"
7	"	"	"	"	"
8	"	"	"	"	"
9	"	"	"	"	"
10	"	"	"	"	"
11	"	"	"	"	"
12	"	"	"	"	"
13	"	"	"	"	"
14	"	"	"	"	"
15	"	"	"	"	"
16	"	"	"	"	"
17	"	"	"	"	"
18	"	"	"	"	"
19	"	"	"	"	"
20	"	"	"	"	"
21	"	"	"	"	"
22	"	"	"	"	"
23	"	"	"	"	"
24	"	"	"	"	"
25	"	"	"	"	"
26	"	"	"	"	"
27	"	"	"	"	"
28	"	"	"	"	"
29	"	"	"	"	"
30	"	"	"	"	"

TABLE II.12

TUCSON

JULY 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1					
2					
3					
4					
5					
6					
7	1660	146	9	6	0
8	2065	152	7	0	0
9	2139	195	9	0	0
10	1475	207	14	12	1
11	1770	183	10	12	1
12					
13	1955	177	9	0	0
14	2176	207	10	0	0
15	1733	293	17	18	1
16					
17	1881	256	14	0	0
18	2176	226	10	0	0
19	1992	274	14	0	0
20	2102	189	9	0	0
21	1992	232	12	6	0
22	1586	116	7	0	0
23	2102	268	13	18	1
24	1844	256	14	6	0
25	1033	91	9	0	0
26	1696	232	14	0	0
27	2028	274	14	0	0
28	2028	244	12	6	0
29	1918	213	11	6	0
30	1623	165	10	0	0
31	1844	213	12	0	0

TABLE II.13

TUCSON

AUGUST 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1549	226	15	0	0
2	2065	226	11	0	0
3	2213	232	11	0	0
4	2028	207	10	0	0
5					
6	2028	250	12	0	0
7	2028	238	12	0	0
8	1992	238	12	0	0
9	2213	256	12	0	0
10	996	134	13	0	0
11	1881	195	10	0	0
12	1770	201	11	0	0
13	1623	195	12	0	0
14	2028	226	11	0	0
15	2213	220	10	0	0
16	2213	220	10	0	0
17	1955	195	10	0	0
18	2102	238	11	0	0
19	2065	238	12	0	0
20	2176	250	11	0	0
21	2176	238	11	0	0
22	1660	146	9	0	0
23	2139	201	9	0	0
24	1955	195	10	0	0
25	2028	165	8	0	0
26	2176	195	9	0	0
27	2139	195	9	0	0
28	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
29	2176	189	9	0	0
30	1844	183	10	0	0
31	1881	171	9	0	0

TABLE II.14

TUCSON

SEPTEMBER 1981

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	2176	177	8	0	0
2	2065	177	9	0	0
3	1955	152	8	0	0
4	2102	232	11	0	0
5	1328	177	13	0	0
6	2139	244	11	0	0
7	2213	207	9	0	0
8	1807	220	12	0	0
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					

TABLE II.15

TUCSON

OCTOBER 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29	2102	262	13	6	0
30	2139	189	9	12	1
31	2250	146	6	0	0

TABLE II.16

TUCSON

NOVEMBER 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	2213	152	7	0	0
2	2250	152	7	0	0
3	1955	140	7	0	0
4	2102	140	7	0	0
5	1586	122	8	0	0
6	1955	146	7	0	0
7	1955	128	7	0	0
8	1696	110	6	0	0
9	2065	134	6	0	0
10	2102	134	6	0	0
11	1992	134	7	6	0
12	2065	122	6	0	0
13	2065	122	6	6	0
14	1696	98	6	0	0
15	2028	104	5	0	0
16	2028	85	4	0	0
17	2028	110	5	0	0
18	1992	91	5	6	0
19	1696	67	4	0	0
20	2028	85	4	0	0
21	1881	79	4	0	0
22	1549	61	4	6	0
23	2028	67	3	0	0
24	2028	85	4	6	0
25	1807	98	5	6	0
26	1881	98	5	0	0
27	516	0	0	0	0
28	1180	43	4	0	0
29					
30					

TABLE II.17

TUCSON

DECEMBER 1981

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1					
2					
3					
4					
5					
6					
7					
8	1992	73	4	0	0
9	1918	61	3	0	0
10	1881	49	3	0	0
11	701	0	0	0	0
12	590	12	2	0	0
13	1770	91	5	30	2
14					
15	1955	24	1	37	2
16	1844	30	2	0	0
17	1844	37	2	30	2
18	1844	49	3	30	2
19	1512	12	1	24	2
20	1844	6	0	55	3
21	1881	73	4	37	2
22	1881	55	3	43	2
23	1992	85	4	43	2
24	1992	67	3	61	3
25	1512	30	2	49	3
26	1660	18	1	55	3
27	1807	67	4	24	1
28	1918	24	1	43	2
29	1955	30	2	55	3
30	1512	49	3	0	0
31	1623	67	4	0	0

TABLE II.18

TUCSON

JANUARY 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	332	6	2	0	0
2	996	49	5	12	1
3	1844	18	1	73	4
4	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
5					
6	774	24	3	0	0
7	1660	37	2	6	0
8	1881	37	2	43	2
9	1291	18	1	18	1
10	1217	55	5	0	0
11	996	37	4	6	1
12	516	12	2	37	7
13	2065	49	2	43	2
14	2028	49	2	55	3
15	2065	37	2	55	3
16	2028	37	2	55	3
17	1733	61	4	0	0
18	1918	61	3	37	2
19	369	12	3	0	0
20	2102	85	4	37	2
21	1992	67	3	67	3
22	2028	55	3	55	3
23	2139	49	2	61	3
24	2065	24	1	43	2
25	2028	12	1	55	3
26	2065	18	1	61	3
27	2065	12	1	67	3
28	738	12	2	37	5
29	774	12	2	6	1
30	2139	43	2	61	3
31	1807	61	3	49	3

TABLE II.19

TUCSON

FEBRUARY 1982

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	2176	67	3	61	3
2	2250	55	2	67	3
3	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
4	2139	61	3	43	2
5	774	0	0	6	1
6	1475	43	3	18	1
7	1660	49	3	30	2
8	516	0	0	6	1
9	2139	24	1	55	3
10	1549	18	1	55	4
11	959	0	0	18	2
12	1586	30	2	6	0
13	2213	30	1	61	3
14	1733	24	1	37	2
15	2065	24	1	55	3
16	2102	24	1	43	2
17	1918	24	1	61	3
18	1106	30	3	0	0
19	2139	37	2	49	2
20	2213	37	2	61	3
21	2065	30	1	37	2
22	2028	30	1	55	3
23	1586	43	3	37	2
24	443	0	0	6	1
25	1586	12	1	0	0
26	2250	37	2	73	3
27	1623	6	0	30	2
28	2250	6	0	67	3

TABLE II.20

TUCSON

MARCH 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1438	12	1	24	2
2	1512	18	1	24	2
3	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
4	2360	73	3	0	0
5	2176	37	2	37	2
6	2508	24	1	49	2
7	2434	55	2	37	2
8	1770	12	1	24	1
9	2250	18	1	30	1
10	1955	24	1	6	0
11	1143	0	0	0	0
12	443	0	0	6	1
13	1070	6	1	6	1
14	1106	0	0	0	0
15	1696	37	2	12	1
16	2323	73	3	49	2
17	2065	67	3	30	1
18	1623	61	4	24	2
19	2471	85	3	0	0
20	2471	43	2	67	3
21	2434	49	2	43	2
22	2471	37	2	67	3
23	1992	12	1	43	2
24	2397	24	1	61	3
25	2250	18	1	37	2
26	406	0	0	0	0
27	2397	24	1	43	2
28	1844	55	3	30	2
29	1807	6	0	18	1
30	2471	6	0	30	1
31	2250	6	0	24	1

from the cooling output. A detailed calculation of these heat flow losses showed that about one-third of the difference was due to heat flow through the thin-wall copper pipes connecting the evaporator-condenser to the zeolite panel while two-thirds was due to heat flowing through the insulation surrounding the evaporator-condenser assembly.

The losses have been reduced in newer models of the collector by doubling the thickness of the insulation and by using 90% copper 10% nickel alloy pipes with low thermal conductivity to replace the copper thin wall pipes.

The cooling data for December 1980, January and February 1981 was not analyzed since cooling performance in winter is not useful even in Tucson, Arizona. However, a slow steady deterioration of cooling performance is noticeable with the cooling output in April 1981 dropping to only 250 BTU/ft^2 day even on days with solar inputs of over 2400 BTU/ft^2 day. This is due to slow accumulation of non-condensable gases (most likely hydrogen) generated during passivation of the copper in the collectors when it reacts with water vapor at high temperatures. The heating performance is not affected since condensation occurs at 120 to 140^{0}F when the pressure of water vapor is more than 10 times larger than during the cooling part of the cycle and therefore the volume of the non-condensable gases if reduced more than tenfold. Therefore, even in the worst month, April 1981, the heating output is about 625 BTU/ft^2 day for a solar input of 2450 BTU/ft^2 day for an overall heating efficiency of 25.5% while the cooling output for the same input is only 260 BTU/ft^2 day or about 10% overall efficiency. After the panels were pumped out at the beginning of May 1981, the cooling output was restored to about 475 BTU/ft^2 day for a 2400 BTU/ft^2 day input or an overall cooling efficiency of almost 20%.

It is not clear at this time and with the present level of experience if the process of passivation in the collectors will stop in time and exactly when this will happen. In accelerated laboratory tests done both by us and by the McDonald-Douglas Company for NASA (in a study of heat pipes), copper pipes in contact with water vapor under vacuum passivated relatively fast at 250^0 to

350^{o}F while forming copper oxides and releasing hydrogen during the reaction $Cu + H_2O = Cu\ O + H_2$ and the reaction sloped completely in a few days. It is therefore expected that the collector will passivate in time and will need no pumping out whatsoever for the rest of its 20 to 50 year lifetime. It is possible, however, that the small quantities of silver solder and soft solder used in the construction of the collector even with a very small surface area exposed to the vacuum, are the cause for the noncondensable gas production by an oxidation reaction with water, analogous to the one above. In this case, the passivation in time is less likely and in a worst case scenario, it may never stop. This is not a cause for alarm, however, since a look through Figures 2 through 10 shows clearly that the high efficiency driving the cooling cycle is not noticeably reduced until after January 1981 which is about six months after the panels were installed. Therefore, a routine maintenance schedule once a year in the spring (before the cooling season begins) with a corresponding pump-out (purging of hydrogen) similar to the state of the art with lithium bromide systems, should be considered satisfactory to guaranteeing optimum performance during the entire cooling and heating season, anywhere in the United States. Annual maintenance is a requirement of any HVAC system (even of heating-only systems) and it will be necessary independently of the collectors, in order to keep the pumps, fans, valves and other moving mechanical parts of the system operating properly.

The most extensive experimental data was collected at our facility in Natick and is presented in Tables III.1 through III.23 from October 1980 through August 1982. The data is also presented in graphic form in Figures 11 through 30.

The first deep freezing weather occurred on the night of December 19, 1980 and the heat exchangers of both collectors were damaged during that night since the ethylene glycol concentration of the heat transfer loop was not sufficient to prevent freezing in the lines during the -16^{o}F low for that night. The resulting cracks in the pipes of the heat exchangers caused loss of vacuum and

TABLE III.1

NATICK

OCTOBER 1980

DATE	INPUT BTU/FT² DAY	HEATING OUTPUT BTU/FT² DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT² DAY	COOLING OUTPUT % EFFICIENCY
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14	- - - - - - - START OF REGULAR DATA TAKING - - - - - - - - - - - - - - - - - -				
15	1733	183	11	15	0
16	996	118	12	0	0
17	1254	152	12	85	7
18	74	0	0	9	12
19	1254	305	24	70	6
20	1623	149	9	24	1
21	480	98	20	27	6
22	1881	436	23	18	1
23	1955	463	24	18	1
24	1770	433	24	24	1
25	74	0	0	0	0
26	1106	293	26	55	5
27	1660	345	21	30	2
28					
29	1770	366	21	12	1
30	- - - - - - - - - - - - - - - - - - DISCONNECTED -				
31	- - - - - - - - - - - - - - - - - - " -				

TABLE III.2

NATICK

NOVEMBER 1980

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	- - - - - - - -	- - - - - - - -	DISCONNECTED	- - - - - - - -	- - - - - - - -
2	- - - - - - - -	- - - - - - - -	"	- - - - - - - -	- - - - - - - -
3	- - - - - - - -	- - - - - - - -	"	- - - - - - - -	- - - - - - - -
4	479	116	24	0	0
5	1328	424	32	0	0
6	1696	527	31	24	1
7	996	302	30	9	1
8	516	119	23	0	0
9	590	116	20	40	7
10	922	302	33	0	0
11	1217	344	28	0	0
12	1512	476	31	0	0
13	406	70	17	0	0
14	110	6	5	0	0
15	1328	442	33	0	0
16					
17					
18	74	3	4	0	0
19	1733	488	28	0	0
20	1438	430	30	0	0
21	1070	290	27	0	0
22	1254	332	26	0	0
23	738	152	21	0	0
24	74	0	0	0	0
25	295	76	26	0	0
26	1623	515	32	0	0
27	516	116	22	0	0
28	37	0	0	0	0
29	1106	372	34	0	0
30	738	183	25	0	0

TABLE III.3

NATICK

DECEMBER 1980

DATE	INPUT BTU/FT² DAY	HEATING OUTPUT BTU/FT² DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT² DAY	COOLING OUTPUT % EFFICIENCY
1	1033	305	30	0	0
2	258	24	10	0	0
3	406	86	21	0	0
4	1660	442	27	0	0
5	1512	210	14	0	0
6	1512	198	13	0	0
7	1328	177	13	0	0
8	480	24	5	0	0
9	1070	146	14	0	0
10	738	82	11	0	0
11	1660	207	13	0	0
12	1106	131	12	0	0
13	701	61	9	0	0
14	1365	170	13	0	0
15	996	94	10	0	0
16	74	0	0	0	0
17	1512	180	12	0	0
18	406	3	1	0	0
19	369	15	4	0	0
20	- - - - FREEZE DAMAGE. DISCONNECTED FOR REPAIR. - - - - - - - - - - - - - -				
21	- - - - " " " " " - - - - - - - - - - - - - -				
22	- - - - " " " " " - - - - - - - - - - - - - -				
23	- - - - " " " " " - - - - - - - - - - - - - -				
24	- - - - " " " " " - - - - - - - - - - - - - -				
25	- - - - " " " " " - - - - - - - - - - - - - -				
26	- - - - " " " " " - - - - - - - - - - - - - -				
27	- - - - " " " " " - - - - - - - - - - - - - -				
28	- - - - " " " " " - - - - - - - - - - - - - -				
29	- - - - " " " " " - - - - - - - - - - - - - -				
30	- - - - " " " " " - - - - - - - - - - - - - -				
31	- - - - " " " " " - - - - - - - - - - - - - -				

TABLE III.4

NATICK

JANUARY 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	- - - -	FREEZE DAMAGE. DISCONNECTED	FOR REPAIR.	- - - - - - -	- - - - - - -
2	- - - -	" "	" "	" - - - - - - -	- - - - - - -
3	- - - -	" "	" "	" - - - - - - -	- - - - - - -
4	- - - -	" "	" "	" - - - - - - -	- - - - - - -
5	- - - -	" "	" "	" - - - - - - -	- - - - - - -
6	- - - -	" "	" "	" - - - - - - -	- - - - - - -
7	- - - -	" "	" "	" - - - - - - -	- - - - - - -
8	- - - -	" "	" "	" - - - - - - -	- - - - - - -
9	- - - -	" "	" "	" - - - - - - -	- - - - - - -
10	- - - -	" "	" "	" - - - - - - -	- - - - - - -
11	- - - -	" "	" "	" - - - - - - -	- - - - - - -
12	- - - -	" "	" "	" - - - - - - -	- - - - - - -
13	- - - -	" "	" "	" - - - - - - -	- - - - - - -
14	738	79	11	0	0
15	258	0	0	0	0
16	332	0	0	0	0
17	295	0	0	0	0
18	1106	137	12	0	0
19	1696	323	19	0	0
20	1401	226	16	0	0
21	1770 -	FREEZE DAMAGE. DISCONNECTED	FOR REPAIR.	- - - - - - -	- - - - - - -
22	148 -	" "	" "	" - - - - - - -	- - - - - - -
23	443 -	" "	" "	" - - - - - - -	- - - - - - -
24	221 -	" "	" "	" - - - - - - -	- - - - - - -
25	553 -	" "	" "	" - - - - - - -	- - - - - - -
26	- - - -	" "	" "	" - - - - - - -	- - - - - - -
27	- - - -	" "	" "	" - - - - - - -	- - - - - - -
28	- - - -	" "	" "	" - - - - - - -	- - - - - - -
29	- - - -	" "	" "	" - - - - - - -	- - - - - - -
30	- - - -	" "	" "	" - - - - - - -	- - - - - - -
31	- - - -	" "	" "	" - - - - - - -	- - - - - - -

TABLE III.5

NATICK

FEBRUARY 1981

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	- - - - FREEZE DAMAGE. DISCONNECTED FOR REPAIR. - - - - - - - - - - - - - - -				
2	- - - - " " " " " - - - - - - - - - - - - - - -				
3	- - - - " " " " " - - - - - - - - - - - - - - -				
4	- - - - " " " " " - - - - - - - - - - - - - - -				
5	- - - - " " " " " - - - - - - - - - - - - - - -				
6	- - - - - - - - - - - - - - DISCONNECTED FOR REPAIR - - - - - - - - - - - - - - -				
7	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
8	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
9	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
10	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
11	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
12	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
13	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
14	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
15	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
16	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
17	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
18	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - - - -				
19	258	27	11	0	0
20	296	12	4	0	0
21	369	24	7	0	0
22	74	0	0	0	0
23	184	0	0	0	0
24	148	0	0	0	0
25	74	0	0	0	0
26	148	0	0	0	0
27	1656	201	12	0	0
28	774	61	8	18	2

TABLE III.6

NATICK

MARCH 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	% EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	% EFFICIENCY
1	1254	146	12	3	0
2	811	70	9	0	0
3	1733	238	14	0	0
4					
5	701	61	9	0	0
6	369	21	6	0	0
7	296	3	1	0	0
8	258	3	1	0	0
9	443	18	4	0	0
10					
11					
12	1106	128	12	46	4
13	1696	323	19	46	3
14	1291	244	19	34	3
15	2102	415	20	67	3
16	442	43	10	9	2
17	2249	476	21	18	1
18	2286	277	12	40	2
19	2102	363	17	46	2
20	1254	262	21	0	0
21	442	18	4	0	0
22	2212	518	23	27	1
23	1254	201	16	27	2
24	1438	250	17	34	2
25	406	24	6	6	1
26	1881	436	23	61	3
27	332	27	8	0	0
28	2213	591	27	52	2
29	1106	360	33	46	4
30	1106	277	25	58	5
31	1660	460	28	40	2

TABLE III.7

NATICK

APRIL 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1475	390	26	64	4
2	959	186	19	61	6
3	1955	570	29	34	2
4	664	113	17	0	0
5	369	30	8	0	0
6	811	161	20	43	5
7	2323	631	27	49	2
8	2139	634	30	46	2
9	1696	506	30	30	2
10	2250	655	29	30	1
11					
12	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
13	1106	341	31	55	5
14	406	9	2	0	0
15	2323	610	26	27	1
16	2065	488	24	61	3
17	553	52	9	0	0
18	1549	396	26	21	1
19	2250	607	27	37	2
20	922	183	20	37	4
21	2323	573	25	24	1
22	2065	524	25	55	3
23	738	137	19	46	6
24	406	49	12	0	0
25	406	30	8	0	0
26	1918	509	27	55	3
27	1807	448	25	43	2
28	922	168	18	0	0
29	738	143	19	0	0
30	1217	293	24	37	3

TABLE III.8

NATICK

MAY 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT2 DAY	% EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	% EFFICIENCY
1	1106	265	24	52	5
2	1106	220	20	40	4
3	2176	622	29	52	2
4	738	101	14	15	2
5	738	110	15	37	5
6	1696	360	21	110	7
7	2287	378	17	64	3
8	2176	436	20	177	8
9	1992	357	18	216	11
10	516	12	3	49	9
11	- - - - - - - - - - - - - - - - PAPER STUCK -				
12	- - - - - - - - - - - - - - - - " " -				
13	701	91	13	183	26
14	2028	351	17	198	10
15	- - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - - - - -				
16	479	34	7	3	1
17	2176	427	20	192	9
18	2213	363	16	204	9
19	1992	34	2	198	10
20	2213	387	18	223	10
21	1881	341	18	195	10
22	1881	335	18	220	12
23	2028	378	19	223	11
24	2250	351	16	201	9
25	2028	290	14	235	12
26	1586	229	14	174	11
27	1807	274	15	305	17
28	1512	360	27	241	16
29	553	116	21	128	23
30	1586	415	26	253	16
31	922	216	24	168	18

TABLE III.9

NATICK

JUNE 1981

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	1881	479	25	253	14
2	627	98	16	119	19
3	922	223	24	149	16
4	1549	369	24	259	17
5	1955	448	23	280	14
6	959	238	25	192	20
7	1807	460	26	238	13
8	2102	445	21	284	14
9	848	186	22	155	18
10	1955	470	24	308	16
11	1955	390	20	287	15
12	1844	421	23	280	15
13	2102	445	21	284	14
14	996	189	19	189	19
15	1143	274	24	137	12
16	1291	271	21	299	23
17	1586	34	2	253	16
18	2028	473	23	287	14
19	1881	384	20	274	15
20	479	107	22	113	24
21	1291	345	27	213	17
22	1143	341	30	232	22
23	1660	402	24	253	15
24	1918	427	22	290	15
25	406	58	14	70	17
26	1844	460	25	253	14
27	2139	442	21	287	14
28	1955	381	20	265	13
29	1660	396	24	305	18
30	1549	329	21	226	15

TABLE III.10

NATICK

JULY 1981

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	1696	399	24	262	16
2	1254	290	23	220	18
3	1033	241	23	189	18
4	848	232	27	171	20
5	627	155	25	119	19
6	1660	387	23	284	17
7	1918	357	19	284	15
8	2065	384	19	308	15
9	1844	- - POWER FAILURE AT 6:00 P.M. - - - - - - - - - - - -			
10	1955	317	16	299	15
11	1992	369	19	290	15
12	1733	366	21	277	16
13	701	- - POWER FAILURE AT 6:00 P.M. - - - - - - - - - - - -			
14	1291	274	21	226	15
15	1881	- - POWER FAILURE AT 6:00 P.M. - - - - - - - - - - - -			
16	2102	296	14	287	13
17	- - - - - - - - - - - - - CHANGED RECORDER CHART THIS DATE - - - - - - - - -				
18	1586	299	19	232	15
19	1955	399	20	284	15
20	352	76	22	155	44
21	1612	360	22	256	16
22	1016	290	29	241	24
23	1922	491	26	162	8
24	1970	445	23	277	14
25	1696	372	22	256	15
26	1623	369	23	274	17
27	1700	412	24	271	16
28	1789	454	25	296	17
29	366	82	23	149	41
30	1295	378	29	232	18
31	1979	451	23	280	14

TABLE III.11

NATICK

AUGUST 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	2103	555	26	296	14
2	1955	378	19	284	15
3	1178	271	23	232	20
4					
5	- 835	223	27	198	24
6	1199	323	27	232	19
7	1720	454	26	277	16
8	812	198	24	177	22
9	996	262	26	192	19
10	1748	415	24	311	18
11	1492	326	22	280	19
12	1163	293	25	235	20
13	1296	323	25	284	22
14	2028	- - BTU METER NOT WORKING - - - - - - - - - - - - - - - -			
15	590	- - " " " " - - - - - - - - - - - - - - - -			
16	1402	- - " " " " - - - - - - - - - - - - - - - -			
17	1897	- - " " " " - - - - - - - - - - - - - - - -			
18	2102	- - " " " " - - - - - - - - - - - - - - - -			
19	1983	463	23	287	14
20	2023	466	23	0	0
21	1983	299	15	311	16
22	1033	250	24	192	19
23	2066	488	24	284	14
24	488	110	23	143	29
25	1010	290	29	201	20
26	1808	497	27	293	16
27	1429	366	26	268	19
28	1742	476	27	284	16
29	2028	463	23	287	14
30	1106	284	26	207	19
31	1540	457	30	287	19

TABLE III.12

NATICK

SEPTEMBER 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	424	110	26	128	30
2	257	73	29	91	36
3	328	98	30	88	27
4	863	293	34	162	19
5	1512	427	28	238	16
6	1217	296	24	207	17
7	1401	375	27	241	17
8	828	244	30	174	21
9	1888	558	30	184	15
10	1937	488	25	293	15
11	1537	390	25	259	17
12	1254	305	24	235	19
13	1992	494	25	280	14
14	1286	302	24	232	18
15	195	30	16	98	50
16	236	58	25	49	21
17	1791	570	32	268	15
18	409	67	16	95	23
19	221	15	7	61	28
20	1365	463	34	210	15
21	1643	399	24	259	16
22	906	223	25	171	19
23	188	27	15	82	44
24	582	183	31	125	22
25	1933	558	29	244	13
26	516	247	48	204	40
27	1700	439	26	253	15
28	1094	259	24	192	18
29	1805	433	24	259	14
30	1675	354	21	253	15

TABLE III.13

NATICK

OCTOBER 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	162	0	0	107	66
2	301	67	22	61	20
3	479	122	25	70	15
4	2065	552	27	253	12
5	284	43	15	85	30
6	253	30	12	43	17
7	1095	338	31	195	18
8	1142	265	23	195	17
9	1147	235	21	189	17
10	1217	262	22	183	15
11	1696	348	21	204	12
12	1586	280	18	165	10
13	1949	372	19	171	9
14	1942	341	18	216	11
15	1949	372	19	235	12
16	675	104	15	143	21
17	1992	457	23	235	12
18	443	46	10	125	28
19	1395	360	26	213	15
20	1881	381	20	265	14
21	1756	396	23	262	15
22	1379	357	26	247	18
23	185	24	13	49	26
24	1881	485	26	143	8
25	1217	162	13	235	19
26	184	0	0	67	36
27	148	18	12	3	2
28	615	220	36	116	19
29	1257	329	26	201	16
30	232	27	12	79	34
31	1623	415	26	186	12

TABLE III.14

NATICK

NOVEMBER 1981

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	443	64	14	107	24
2	1575	399	25	229	15
3	1699	363	21	241	14
4	1682	363	22	216	13
5	1507	314	21	250	17
6	178	34	19	76	43
7	443	101	23	88	20
8	1881	454	24	226	12
9	1172	259	22	174	15
10	848	140	17	168	20
11	479	95	20	85	18
12	1752	427	24	116	7
13	1632	290	18	0	0
14	516	49	9	0	0
15	148	0	0	0	0
16	20	0	0	0	0
17	114	3	3	0	0
18	123	0	0	0	0
19	979	21	2	3	0
20	21	0	0	0	0
21	221	27	12	0	0
22	590	82	14	0	0
23	1442	274	19	0	0
24	1509	229	15	12	1
25	1334	204	15	0	0
26	1586	287	18	0	0
27	510	67	13	0	0
28	369	43	12	0	0
29	553	110	20	0	0
30	1531	457	30	0	0

TABLE III.15

NATICK

DECEMBER 1981

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	233	0	0	6	3
2	55	0	0	0	0
3	334	40	12	0	0
4	1399	320	23	0	0
5	- 148	0	0	0	0
6	184	104	57	0	0
7	1490	0	0	3	0
8	215	12	6	0	0
9	399	46	12	0	0
10	944	146	15	0	0
11	265	9	3	0	0
12	518	82	16	0	0
13	1586	15	1	0	0
14	368	- - -	FREEZE DAMAGE.	DISCONNECTED FOR REPAIR.	- - - -
15	89	- - -	" "	" " "	- - - -
16	346	- - -	" "	" " "	- - - -
17	386	- - -	" "	" " "	- - - -
18	6	- - -	" "	" " "	- - - -
19	1660	- - -	" "	" " "	- - - -
20	1586	- - -	" "	" " "	- - - -
21	1337	- - -	" "	" " "	- - - -
22	131	- - -	" "	" " "	- - - -
23	184	- - -	" "	" " "	- - - -
24	443	- - -	" "	" " "	- - - -
25	221	- - -	" "	" " "	- - - -
26	664	- - -	" "	" " "	- - - -
27	111	- - -	" "	" " "	- - - -
28	1118	- - -	" "	" " "	- - - -
29	950	- - -	" "	" " "	- - - -
30	1598	- - -	" "	" " "	- - - -
31	1185	- - -	" "	" " "	- - - -

TABLE III.16

NATICK

JANUARY 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	111	- - - FREEZE DAMAGE. DISCONNECTED FOR REPAIR. - - - -			
2	1586	- - - " " " " " - - - -			
3	258	- - - " " " " " - - - -			
4	111	- - - " " " " " - - - -			
5	930	- - - " " " " " - - - -			
6	127	- - - " " " " " - - - -			
7	259	- - - " " " " " - - - -			
8	1598	- - - " " " " " - - - -			
9	258	- - - " " " " " - - - -			
10	959	- - - " " " " " - - - -			
11	1048	- - - " " " " " - - - -			
12	1651	- - - " " " " " - - - -			
13	667	- - - " " " " " - - - -			
14	113	- - - " " " " " - - - -			
15	1655	- - - " " " " " - - - -			
16	369	- - - " " " " " - - - -			
17	1475	- - - " " " " " - - - -			
18	1625	- - - " " " " " - - - -			
19	1493	- - - " " " " " - - - -			
20	1537	- - - " " " " " - - - -			
21	790	- - - " " " " " - - - -			
22	1752	- - - " " " " " - - - -			
23	111	- - - " " " " " - - - -			
24	1106	- - - " " " " " - - - -			
25	1809	- - - " " " " " - - - -			
26	1733	- - - " " " " " - - - -			
27	1828	- - - " " " " " - - - -			
28	548	- - - " " " " " - - - -			
29	1786	- - - " " " " " - - - -			
30	- - - - - - - - - - -	- - - " " " " " - - - -			
31	- - - - - - - - - - -	- - - " " " " " - - - -			

TABLE III.17

NATICK

FEBRUARY 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	651	- - - FREEZE DAMAGE. DISCONNECTED FOR REPAIR. - - - -			
2	811	- - - " " " " " - - - -			
3	- - - - - - - - - - - - - - DISCONNECTED FOR REPAIR - - - - - - - - - - - - -				
4	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
5	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
6	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
7	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
8	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
9	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
10	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
11	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
12	- - - - - - - - - - - - - - " " " - - - - - - - - - - - - -				
13	221	61	28	0	0
14	1476	131	9	0	0
15	812	67	8	0	0
16	996	125	13	0	0
17	775	34	4	0	0
18	959	58	6	0	0
19	221	0	0	0	0
20	1439	238	17	0	0
21	258	0	0	0	0
22	185	0	0	0	0
23	812	104	13	0	0
24	554	67	12	0	0
25	2140	448	21	0	0
26	2103	418	20	0	0
27	1402	280	20	0	0
28	2066	433	21	0	0

TABLE III.18

NATICK

MARCH 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1550	369	24	0	0
2	1218	262	22	0	0
3	2140	442	21	0	0
4	1181	250	21	0	0
5	1365	332	24	0	0
6	590	85	14	0	0
7	148	0	0	0	0
8	1919	448	23	0	0
9	554	24	4	0	0
10	1624	378	23	0	0
11	959	207	22	0	0
12					
13	185	0	0	0	0
14	1771	421	24	0	0
15	1956	427	22	0	0
16	1882	500	27	0	0
17	258	0	0	0	0
18	2177	543	25	0	0
19	664	79	12	0	0
20	1993	485	24	0	0
21	258	0	0	0	0
22	1365	277	20	0	0
23	2177	497	23	0	0
24	1919	494	26	0	0
25	1697	430	25	0	0
26	258	18	7	0	0
27	2030	479	24	0	0
28	2288	488	21	0	0
29	2103	473	22	0	0
30	2103	497	24	0	0
31	443	27	6	0	0

TABLE III.19

NATICK

APRIL 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1808	424	23	0	0
2	2214	466	21	0	0
3	738	79	11	0	0
4	406	52	13	0	0
5	2214	479	22	0	0
6	221	0	0	0	0
7	738	49	7	0	0
8	1661	293	18	0	0
9	1032	201	19	0	0
10	0	165	0	0	0
11	0	415	0	0	0
12	921	210	23	0	0
13	315	21	7	0	0
14	1791	180	10	0	0
15	1840	494	27	0	0
16	2030	436	21	0	0
17	1033	183	18	0	0
18	1956	424	22	0	0
19	2214	454	21	0	0
20	1796	402	22	0	0
21	455	98	22	0	0
22	1674	345	21	0	0
23	1879	418	22	0	0
24	1767	403	23	0	0
25	1872	366	18	0	0
26	664	73	11	0	0
27	664	85	13	0	0
28	332	3	1	0	0
29	2177	378	18	0	0
30	1993	314	16	0	0

TABLE III.20

NATICK

MAY 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1771	329	19	0	0
2	1808	274	15	0	0
3	1661	79	5	0	0
4	1070	70	7	0	0
5	2177	418	19	0	0
6	2066	274	14	0	0
7	2103	250	12	0	0
8	1882	232	13	0	0
9	775	76	10	0	0
10	554	40	7	0	0
11	1255	140	11	0	0
12	1513	152	10	0	0
13					
14	1993	426	21	0	0
15	1733	402	23	0	0
16	1660	360	22	0	0
17	1712	414	24	0	0
18	1771	402	23	18	1
19	1509	220	15	24	2
20	853	54	6	42	5
21	1405	116	8	48	3
22	1255	80	6	42	3
23	295	0	0	48	16
24	295	0	0	6	2
25	1328	134	10	36	3
26	2140	604	28	68	3
27	1734	360	21	164	9
28	1107	176	16	116	10
29	221	0	0	116	52
30	517	110	21	42	8
31	369	24	7	42	11

TABLE III.21

NATICK

JUNE 1982

DATE	INPUT BTU/FT2 DAY	HEATING OUTPUT BTU/FT2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT2 DAY	COOLING OUTPUT % EFFICIENCY
1	627	122	19	36	6
2	1181	280	24	92	8
3	1560	280	18	85	5
4	1303	232	18	0	0
5	258	0	0	67	26
6	258	6	2	61	24
7	149	18	12	67	45
8	1337	341	26	134	10
9	1857	354	19	79	4
10	1719	201	12	91	5
11	1752	372	21	256	15
12	1771	451	25	262	15
13	406	30	7	0	0
14	336	55	16	98	29
15	1515	628	41	268	18
16	1041	323	31	329	32
17	408	79	19	140	34
18	1372	561	41	354	26
19	701	152	22	201	29
20	2066	665	32	280	14
21	710	201	28	220	31
22	1515	555	37	299	20
23	1533	506	33	305	20
24	1610	537	33	134	8
25	1686	384	23	128	8
26	738	146	20	104	14
27	1808	518	29	171	9
28	906	201	22	110	12
29	381	91	24	134	35
30	1728	494	29	183	11

TABLE III.22

NATICK

JULY 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1860	573	31	323	17
2	1635	524	32	311	19
3	1255	372	30	238	19
4	2030	604	30	280	14
5	2066	555	27	299	14
6	1683	512	30	317	19
7	1723	488	28	323	19
8	1438	384	27	287	20
9	1566	439	28	274	17
10	1882	500	27	280	15
11	1771	457	26	280	16
12	604	122	20	159	26
13	1688	500	30	220	13
14	1453	360	25	213	15
15	1314	287	22	207	16
16	1540	384	25	207	13
17	1489	372	25	195	13
18	1808	372	21	226	13
19	950	207	22	201	21
20	151	0	0	0	0
21	1255	427	34	238	19
22					
23	1132	396	35	201	18
24	2102	204	10	73	3
25	2065	186	9	113	5
26	1475	140	9	155	11
27	2102	232	11	171	8
28	221	6	3	70	32
29	1807	436	24	223	12
30	1660	363	22	216	13
31	1696	372	22	250	15

TABLE III.23

NATICK

AUGUST 1982

DATE	INPUT BTU/FT^2 DAY	HEATING OUTPUT BTU/FT^2 DAY	HEATING OUTPUT % EFFICIENCY	COOLING OUTPUT BTU/FT^2 DAY	COOLING OUTPUT % EFFICIENCY
1	1696	375	22	250	15
2	1549	357	23	223	14
3	590	110	19	113	19
4	1328	345	26	210	16
5	959	259	27	171	18
6	1623	396	24	220	14
7	1660	396	24	241	15
8	1660	348	21	268	16
9	443	119	27	122	28
10	1770	448	25	238	13
11	738	192	26	155	21
12	1070	317	30	183	17
13	959	287	30	186	19
14	1918	457	24	232	12
15	1992	430	22	250	13
16	1918	399	21	235	12
17	1696	378	22	238	14
18	1623	396	24	226	14
19	2028	451	22	287	14
20	811	207	26	137	17
21	1844	427	23	238	13
22	1696	326	19	229	14
23	664	155	23	165	25
24	1660	415	25	226	14
25	295	27	9	79	27
26	2139	552	26	268	13
27	590	140	24	101	17
28	1955	488	25	213	11
29	1955	369	19	238	12
30					
31					

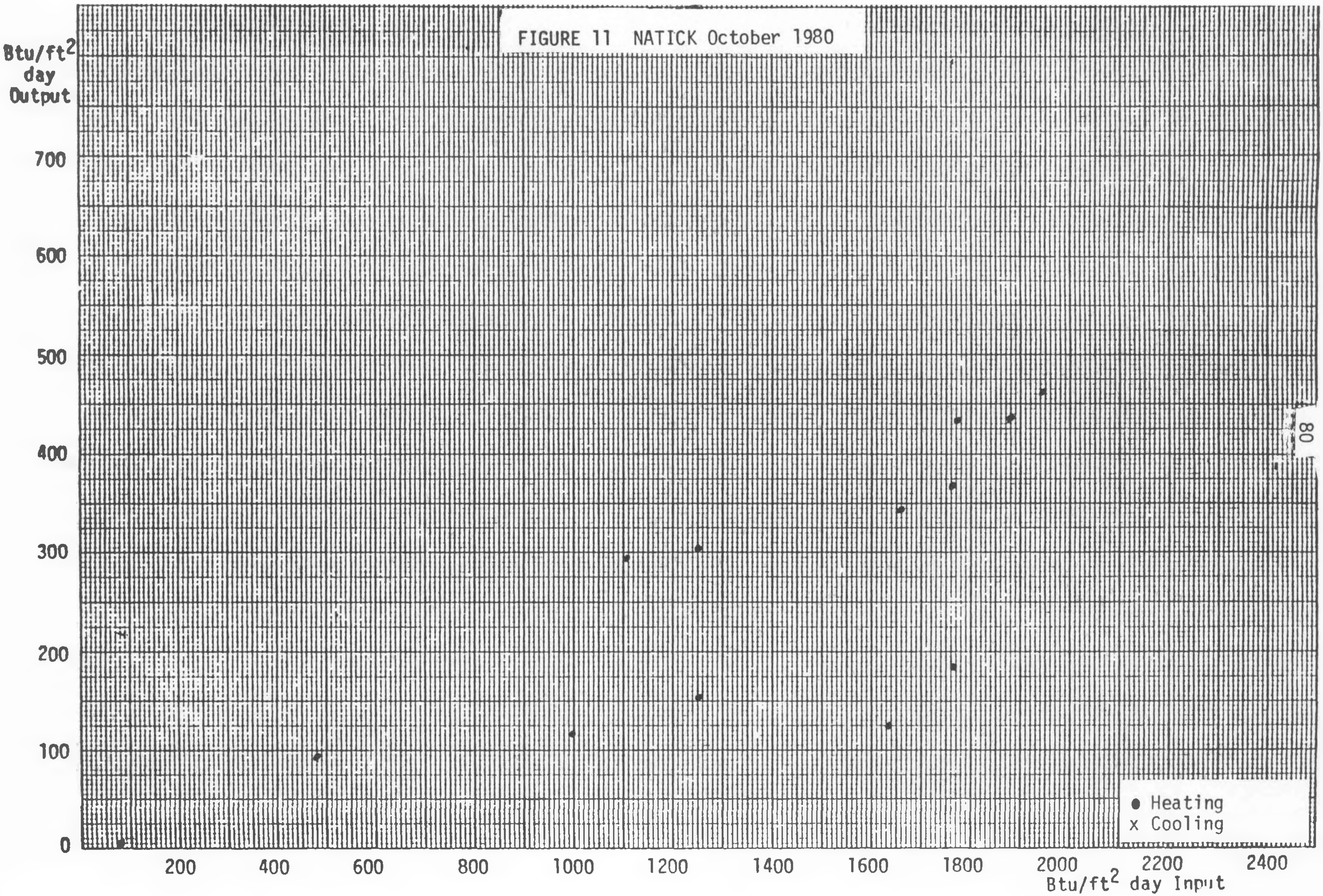


FIGURE 11 NATICK October 1980

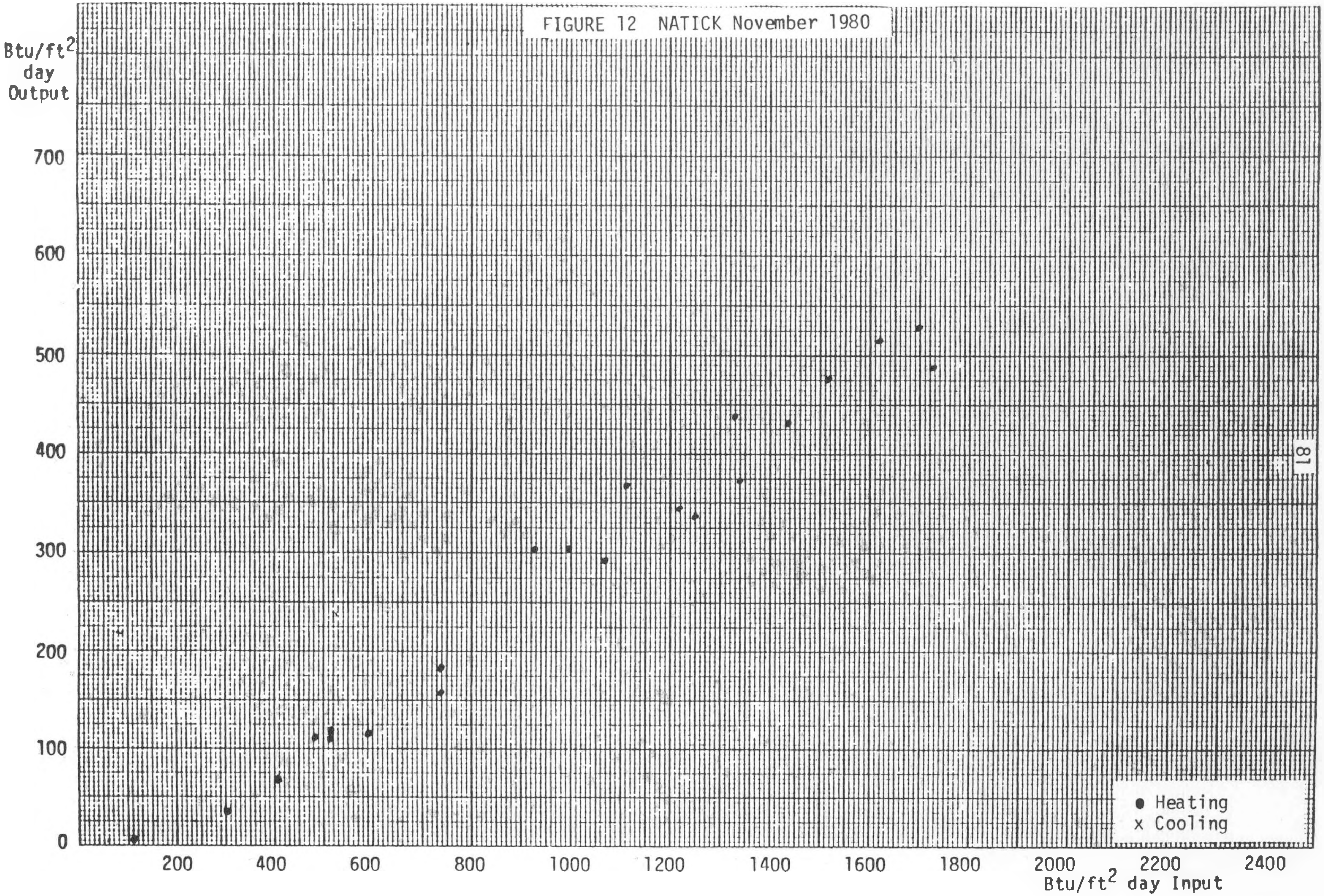
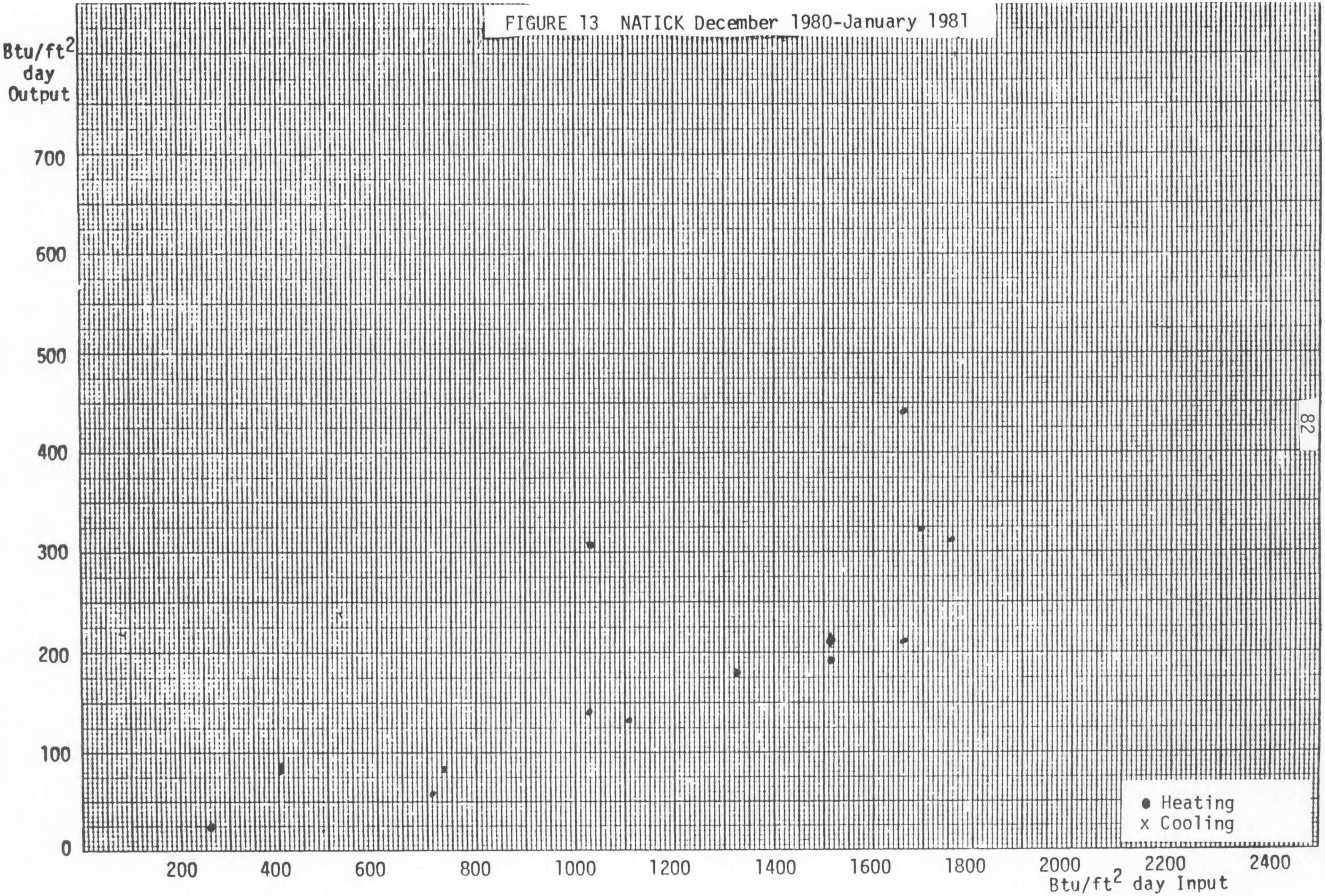


FIGURE 12 NATICK November 1980

FIGURE 13 NATICK December 1980-January 1981



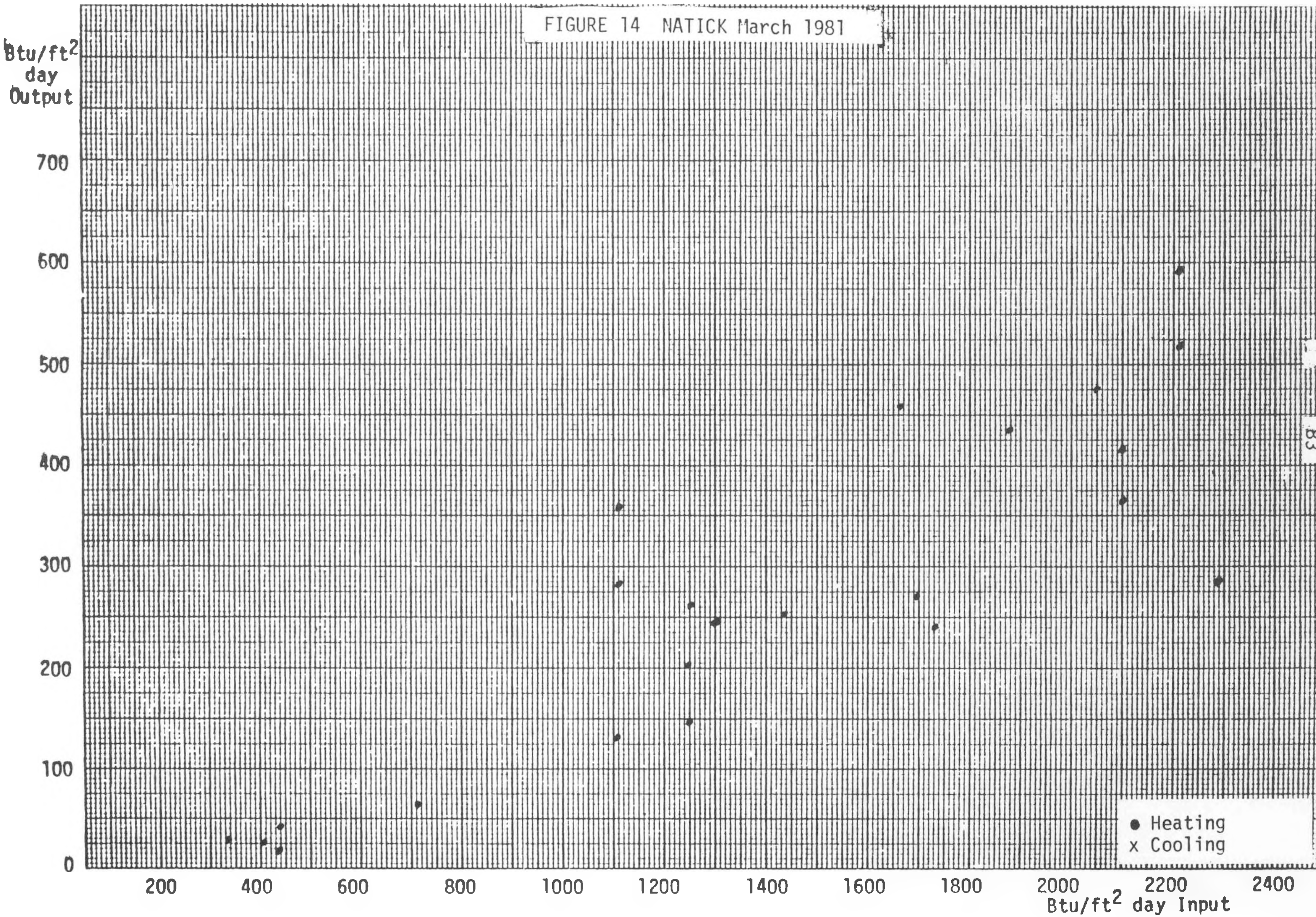


FIGURE 14 NATICK March 1981
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

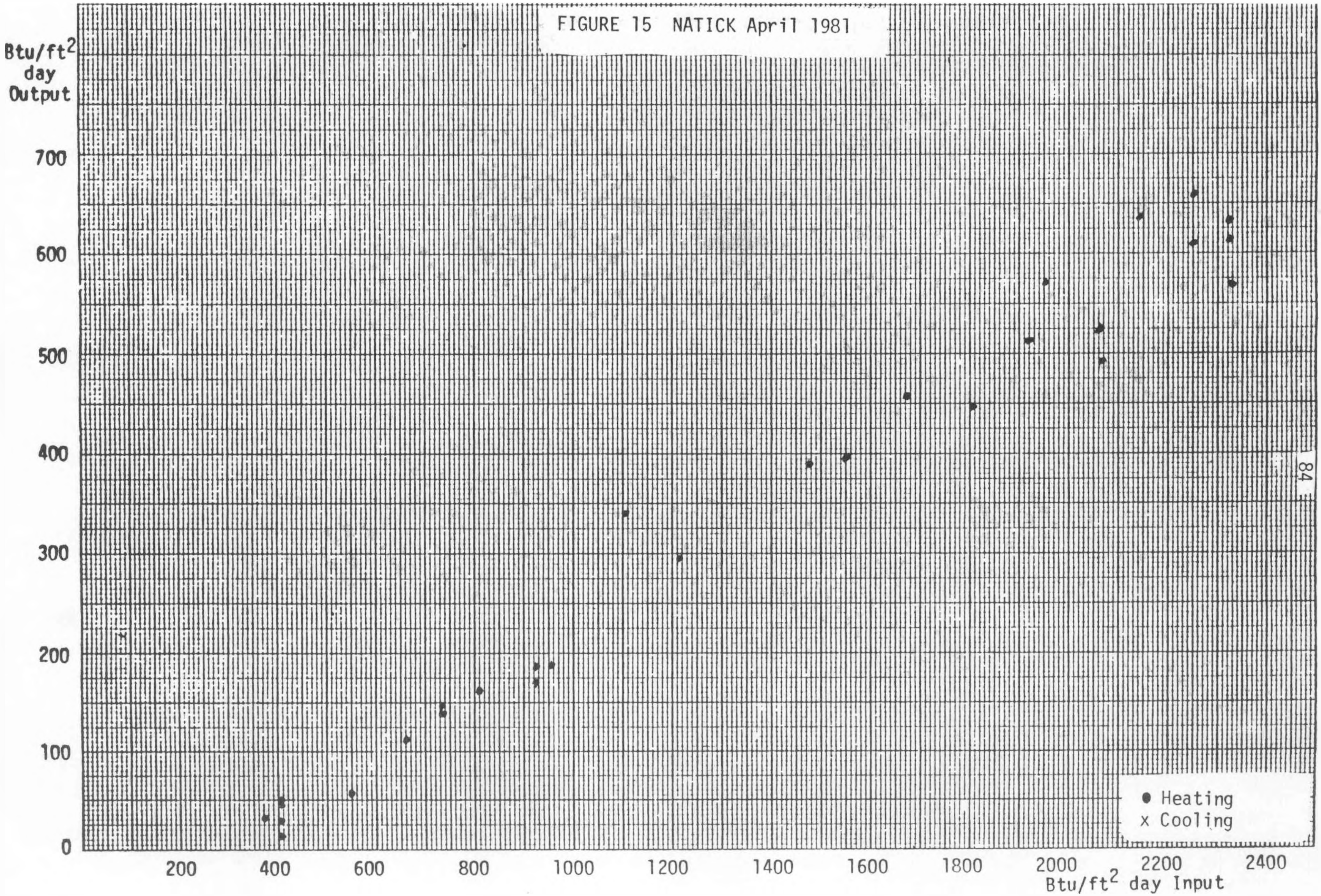


FIGURE 15 NATICK April 1981
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

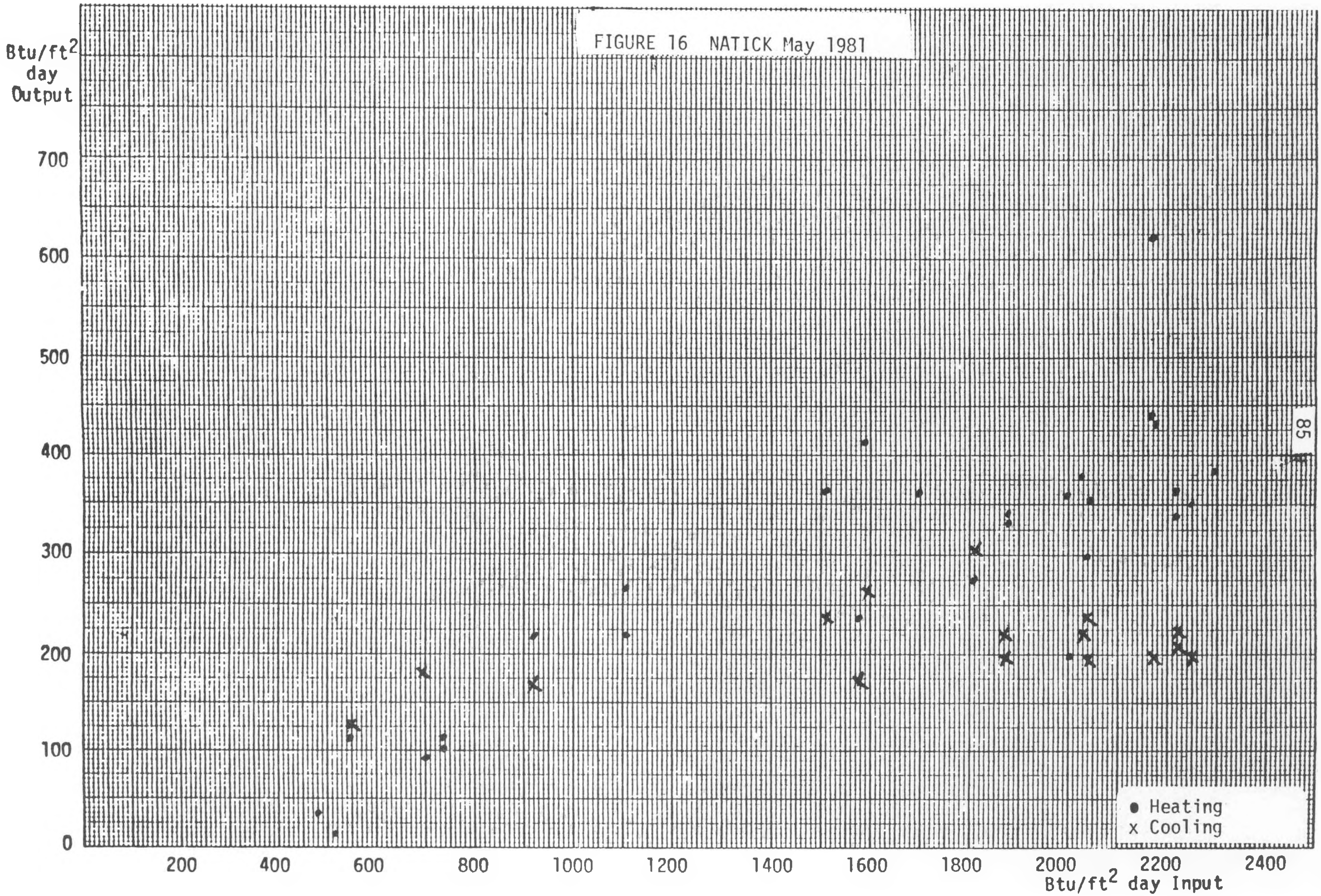


FIGURE 16 NATICK May 1981

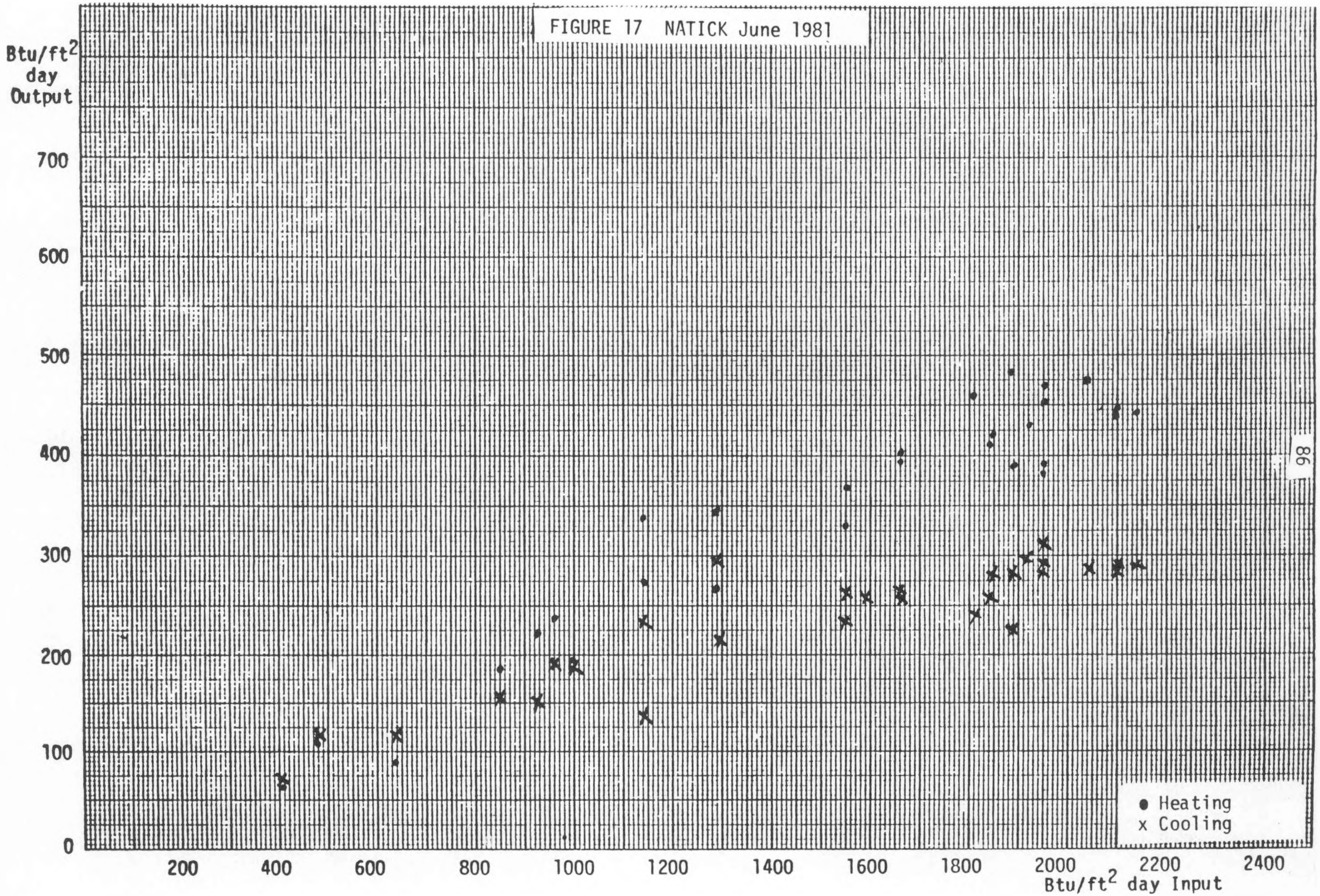


FIGURE 17 NATICK June 1981
Btu/ft2 day Output
0
100
200
300
400
500
600
700
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

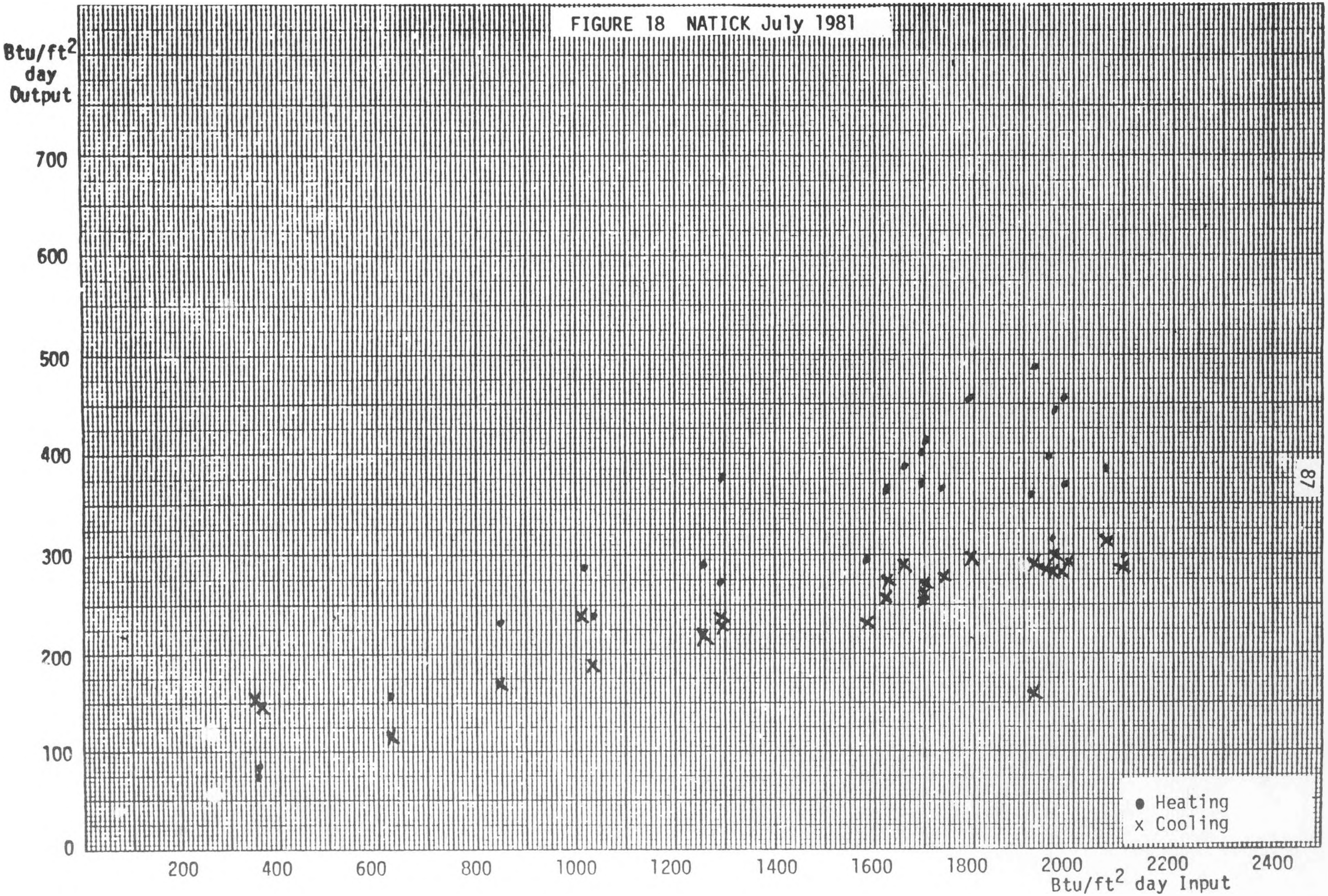


FIGURE 18 NATICK July 1981

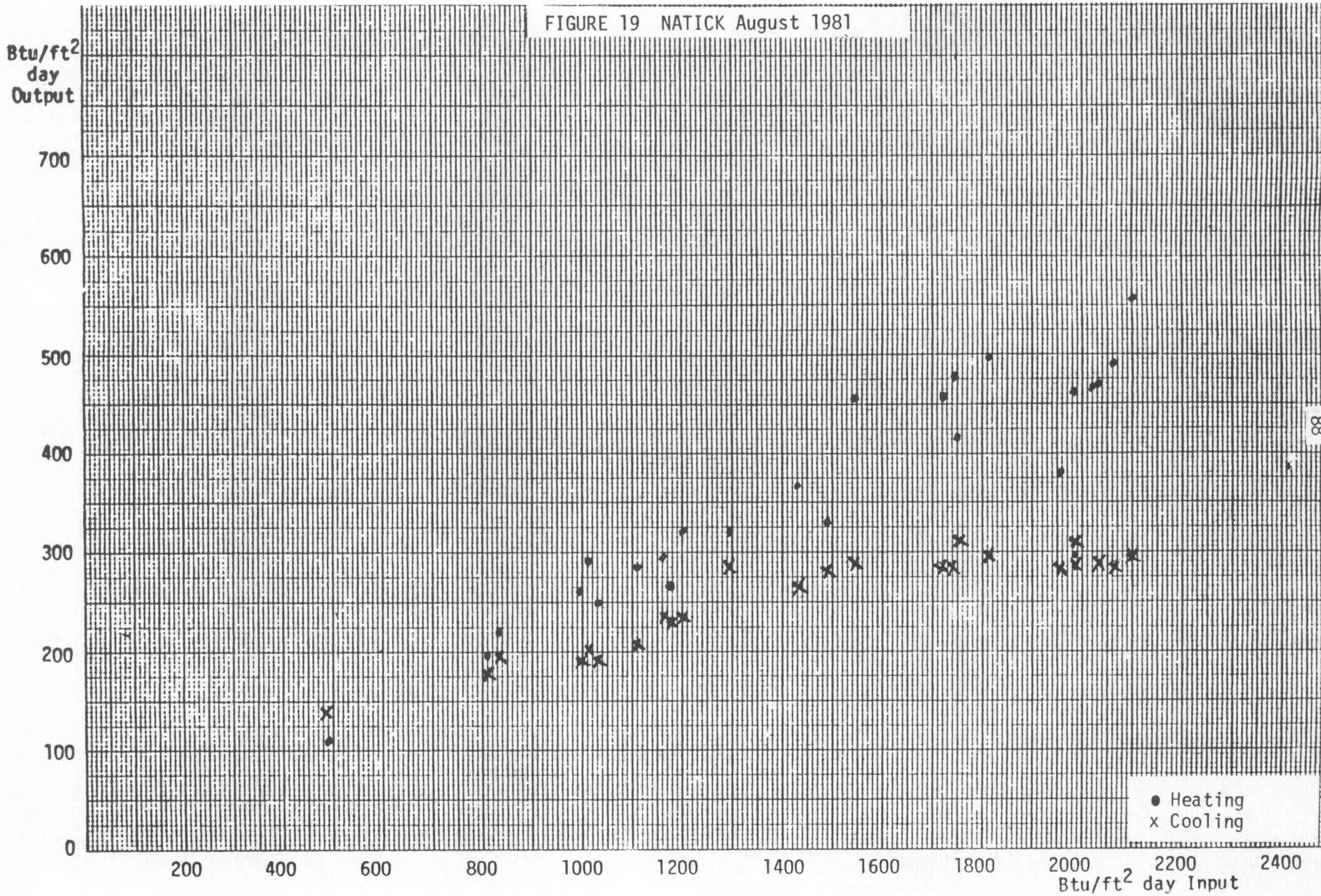


FIGURE 19 NATICK August 1981
Btu/ft² day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft² day Input
● Heating
x Cooling

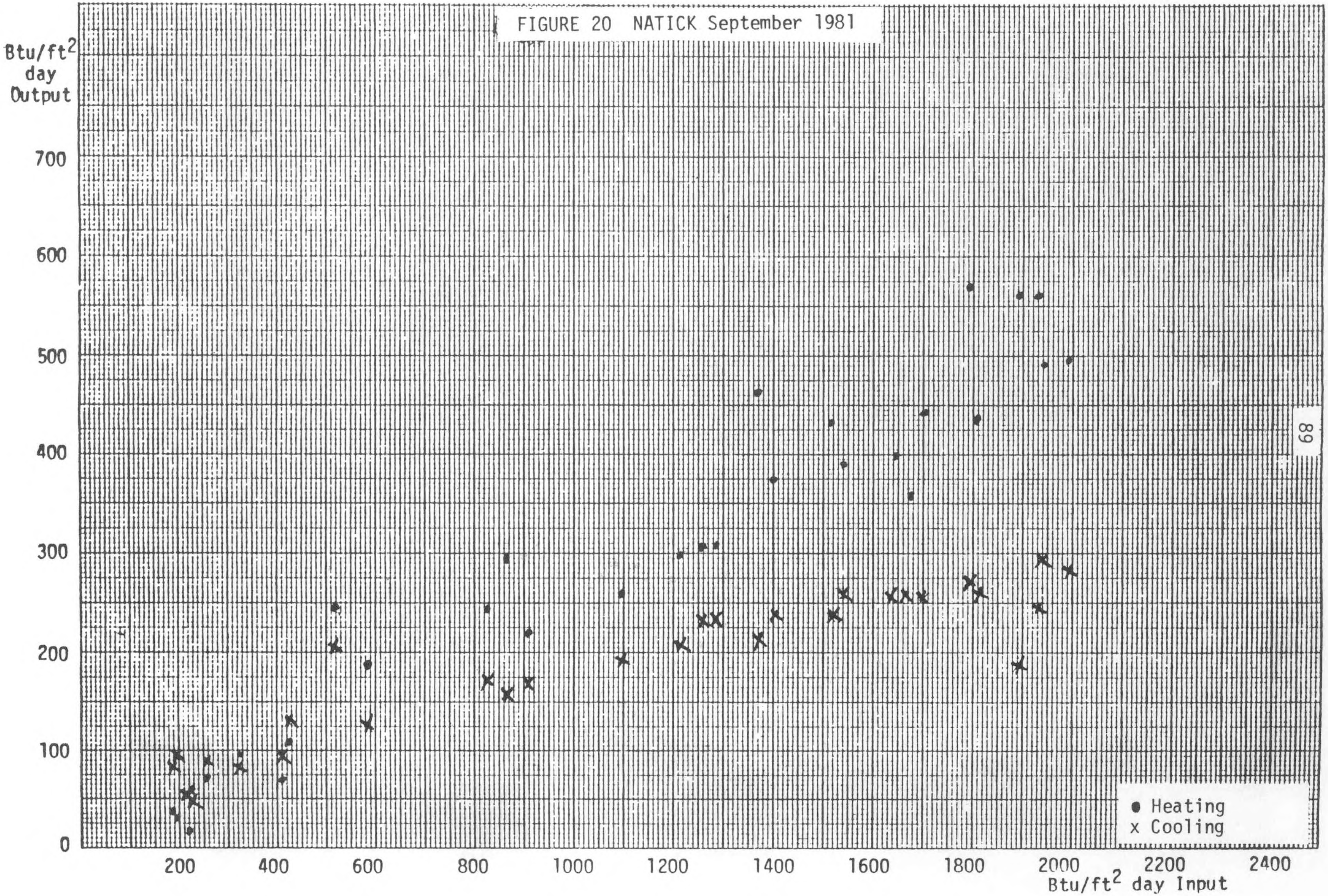


FIGURE 20 NATICK September 1981

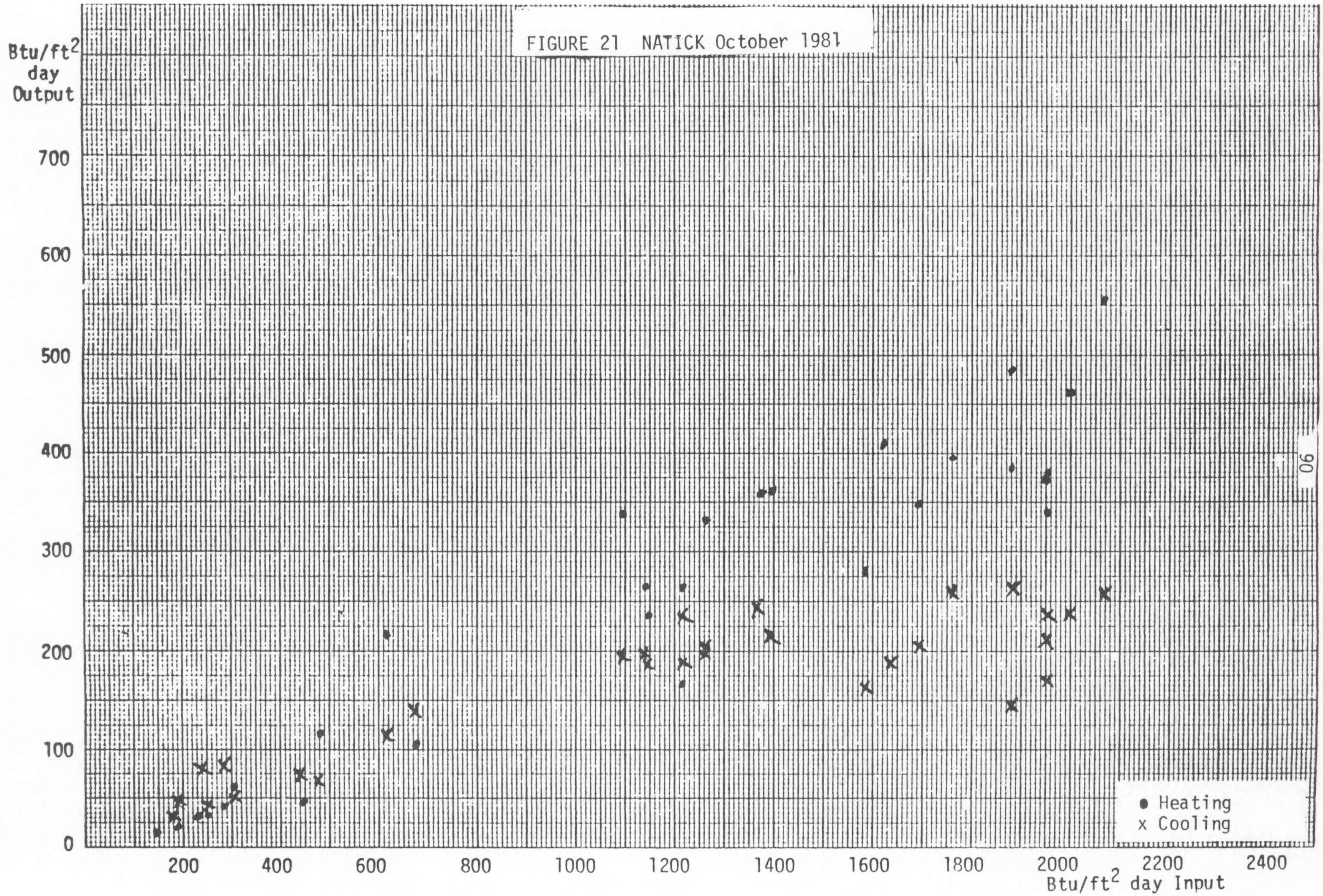
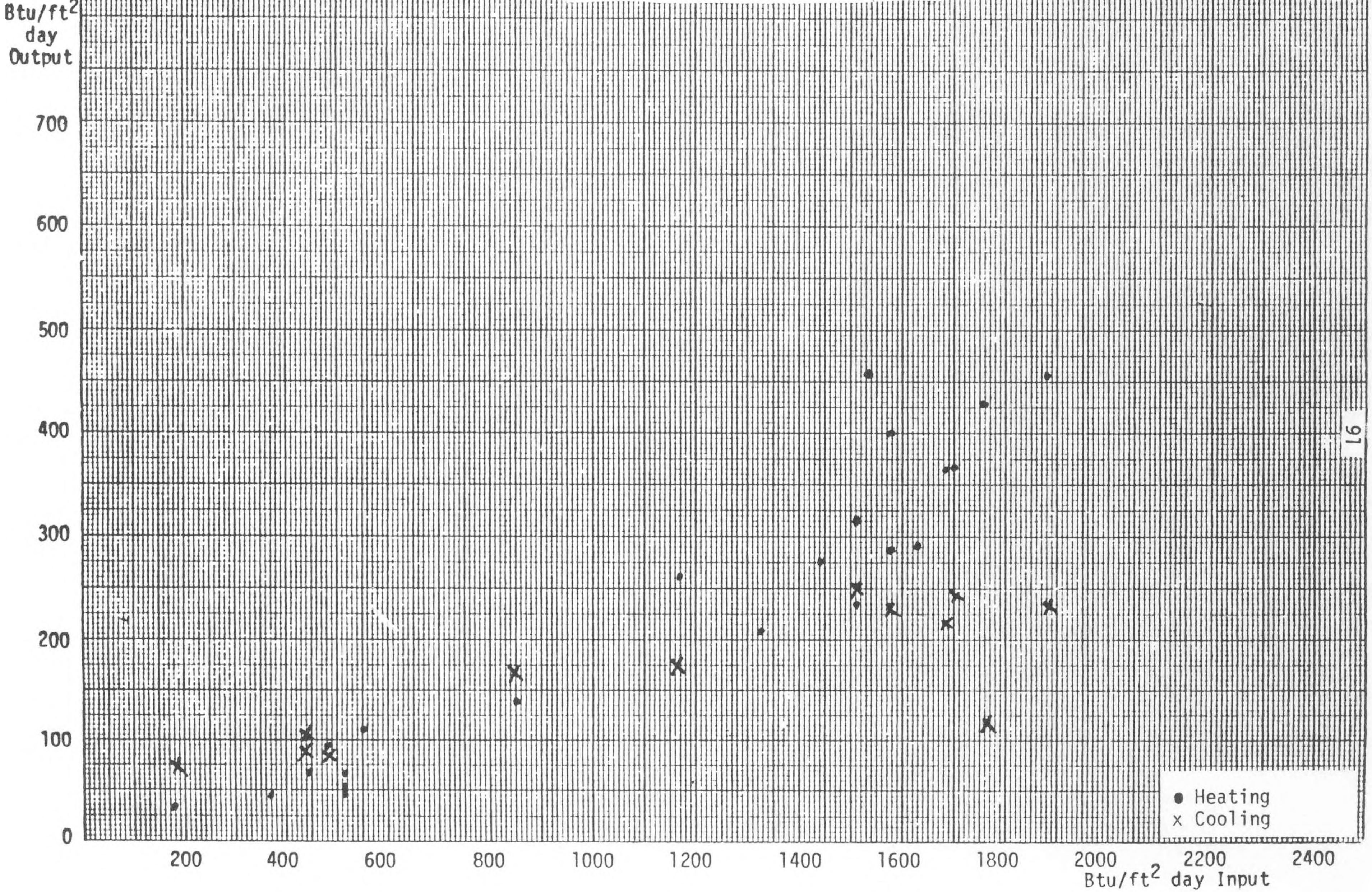


FIGURE 21 NATICK October 1981
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
• Heating
x Cooling

FIGURE 22 NATICK November 1981



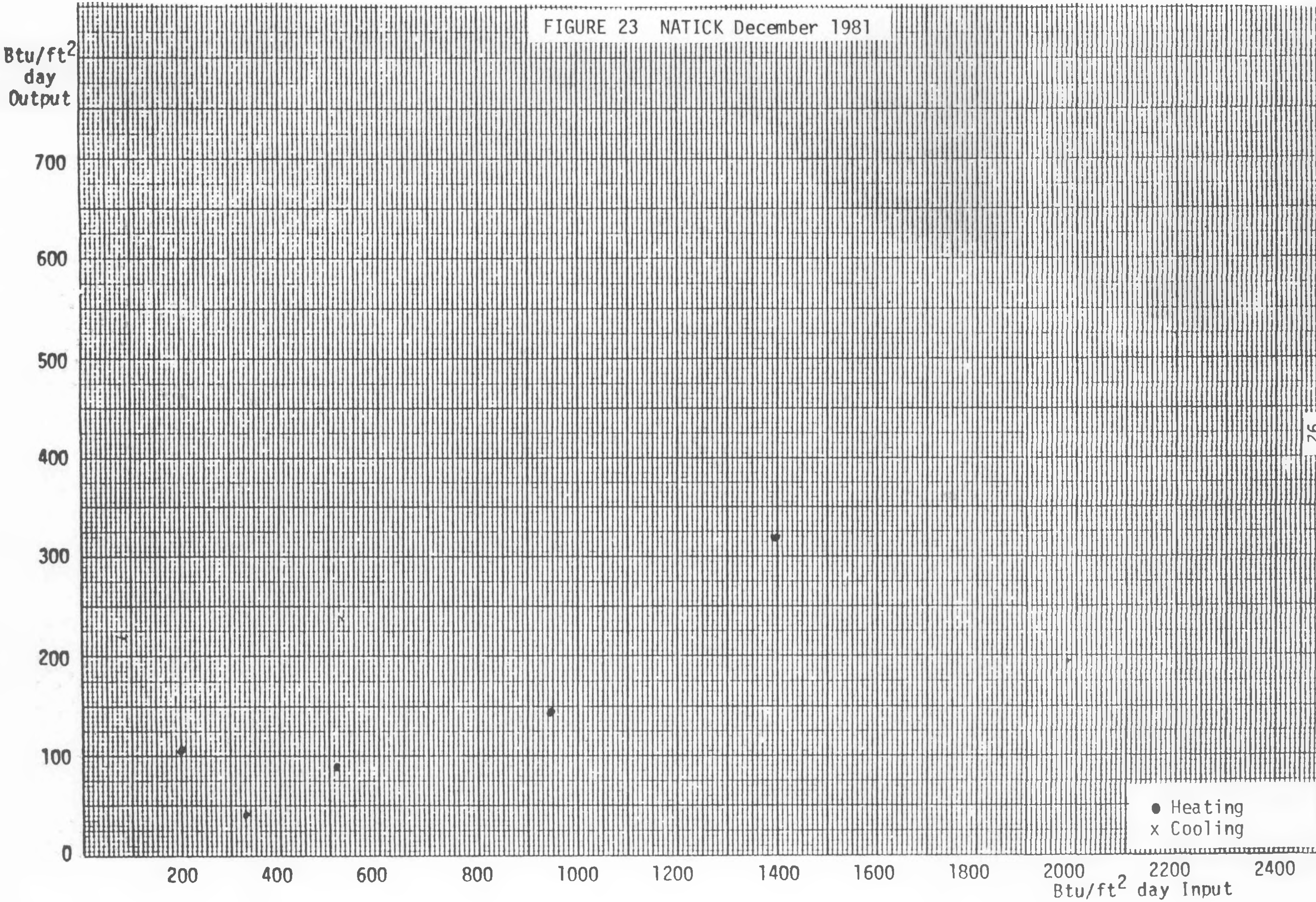


FIGURE 23 NATICK December 1981
Btu/ft² day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft² day Input
● Heating
x Cooling

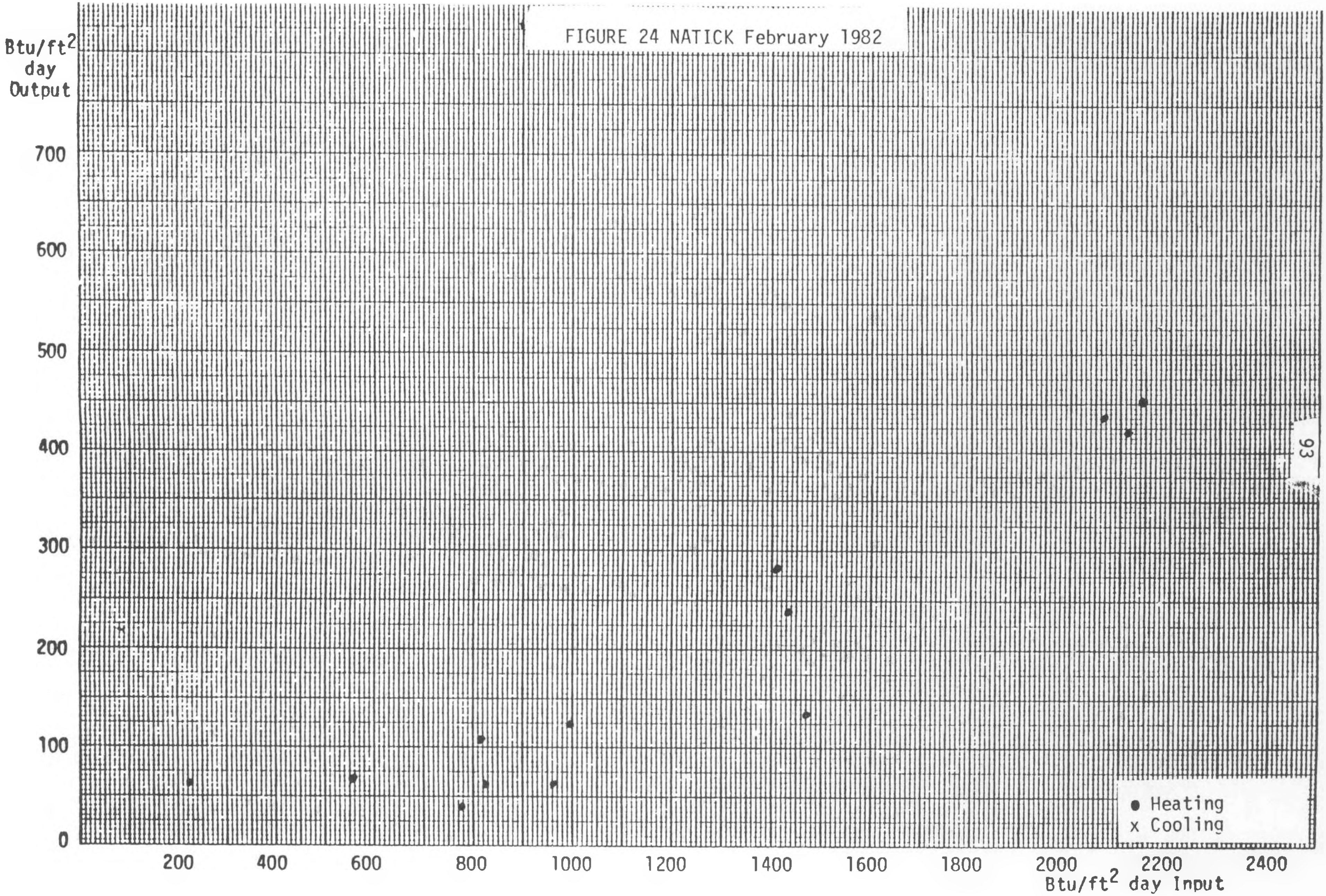


FIGURE 24 NATICK February 1982
Btu/ft^2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft^2 day Input
● Heating
x Cooling

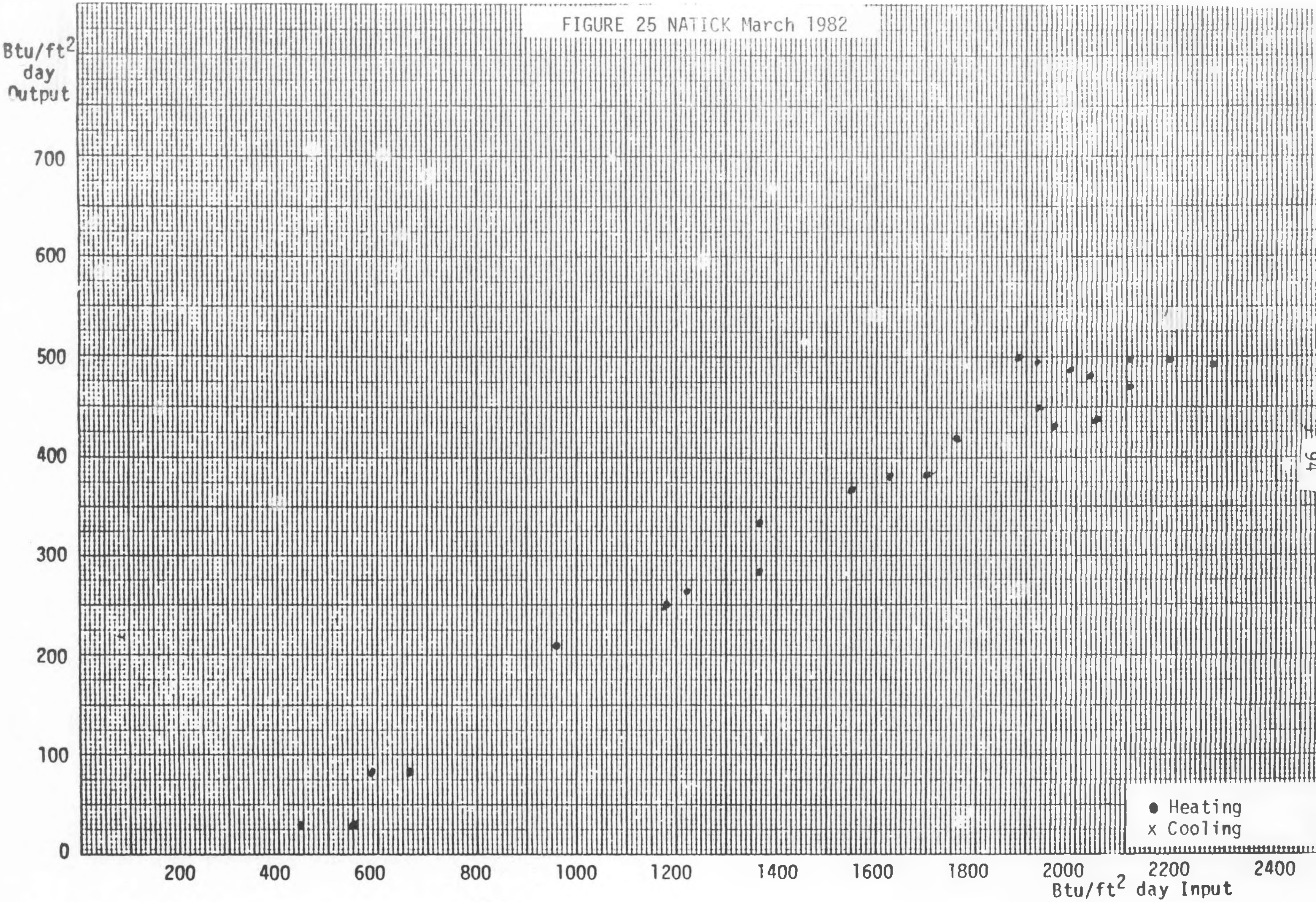


FIGURE 25 NATICK March 1982

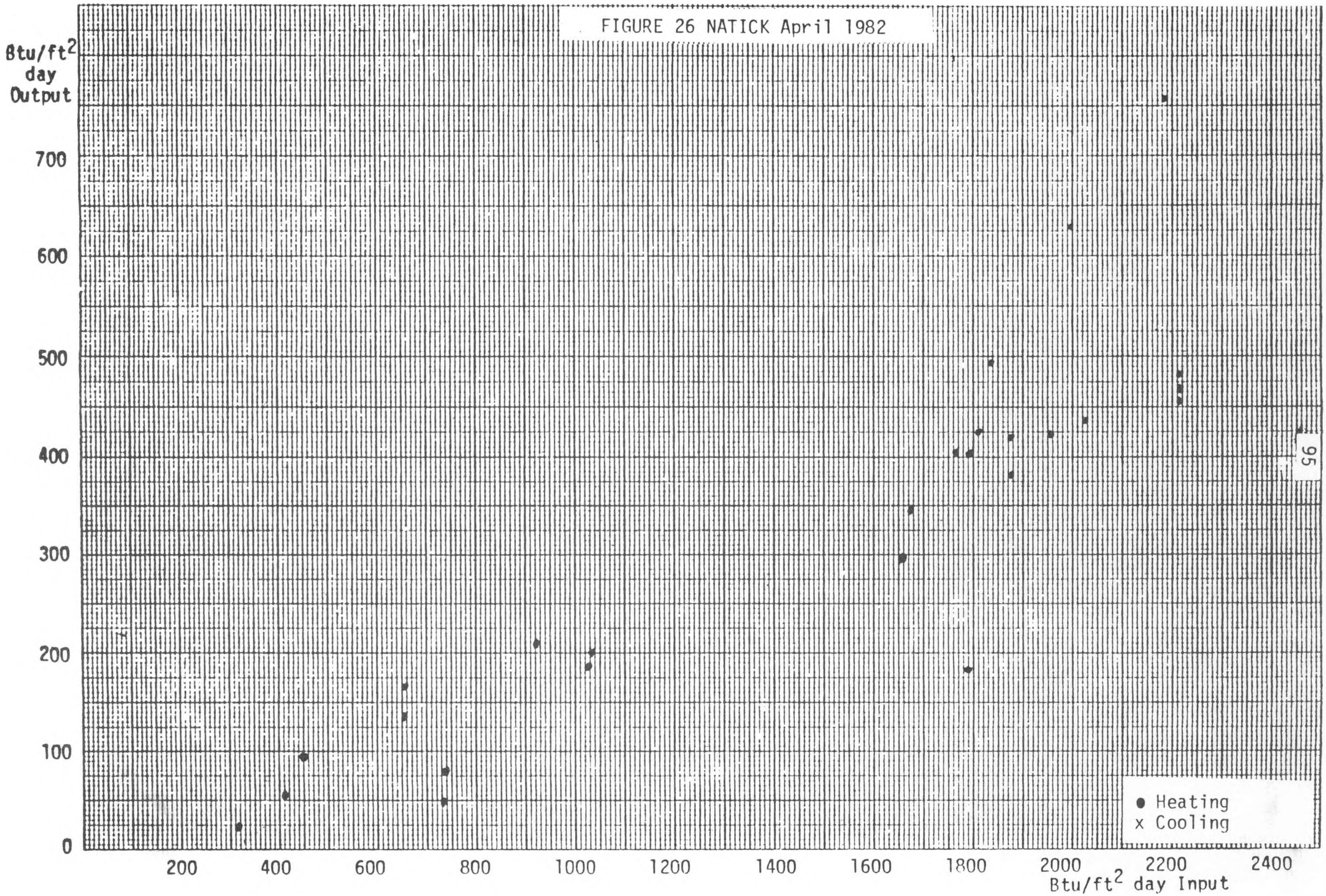


FIGURE 26 NATICK April 1982
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

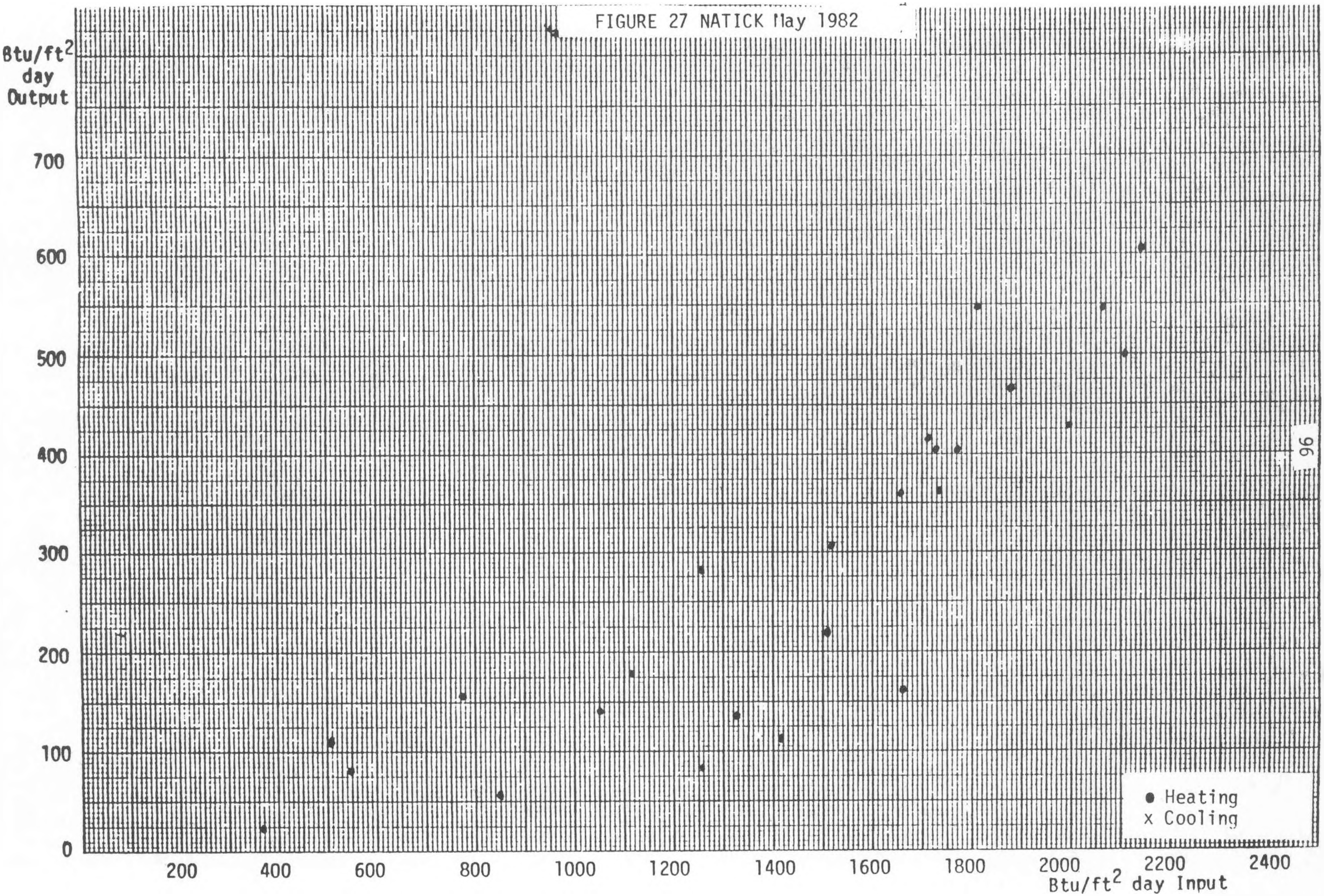


FIGURE 27 NATICK May 1982
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

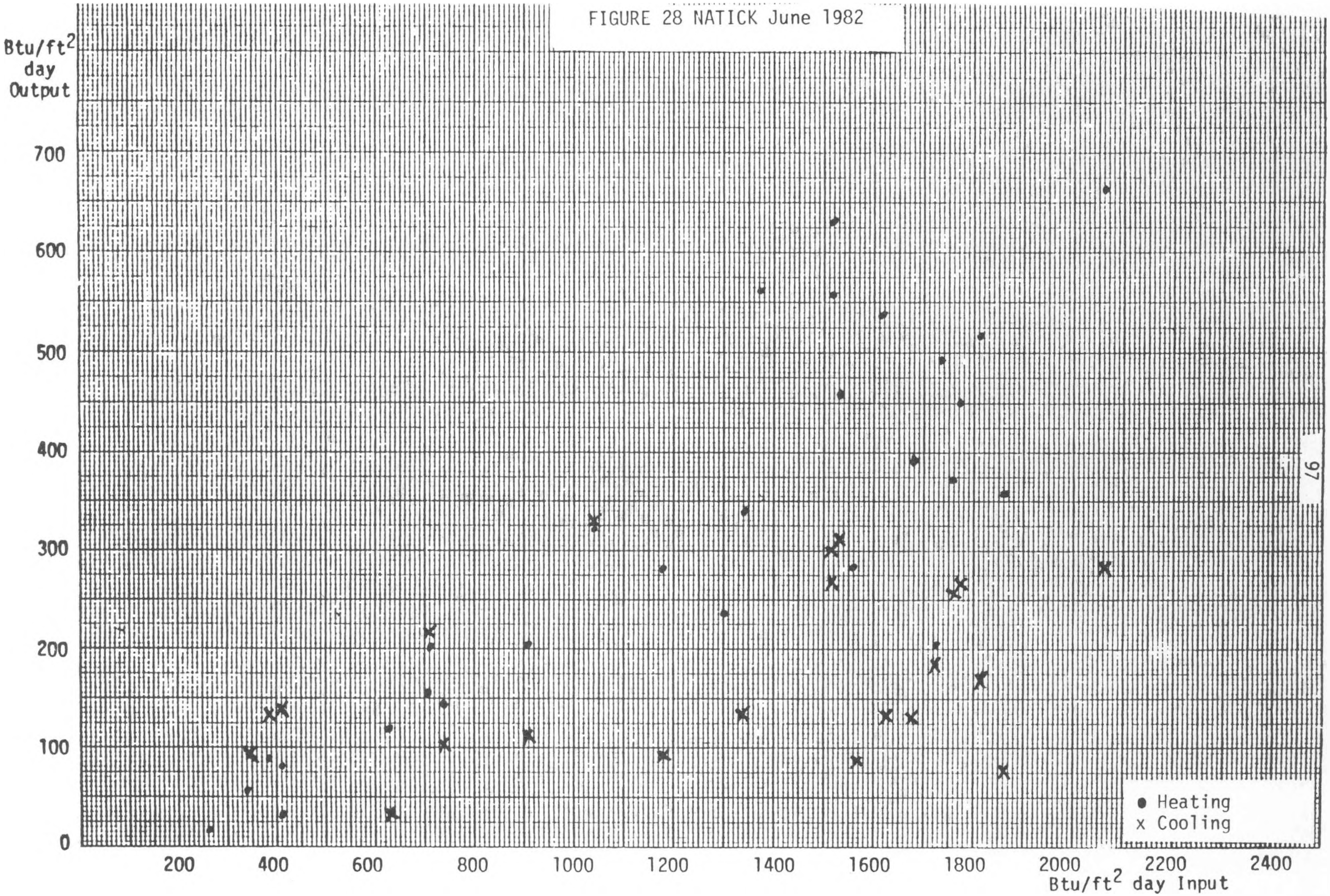
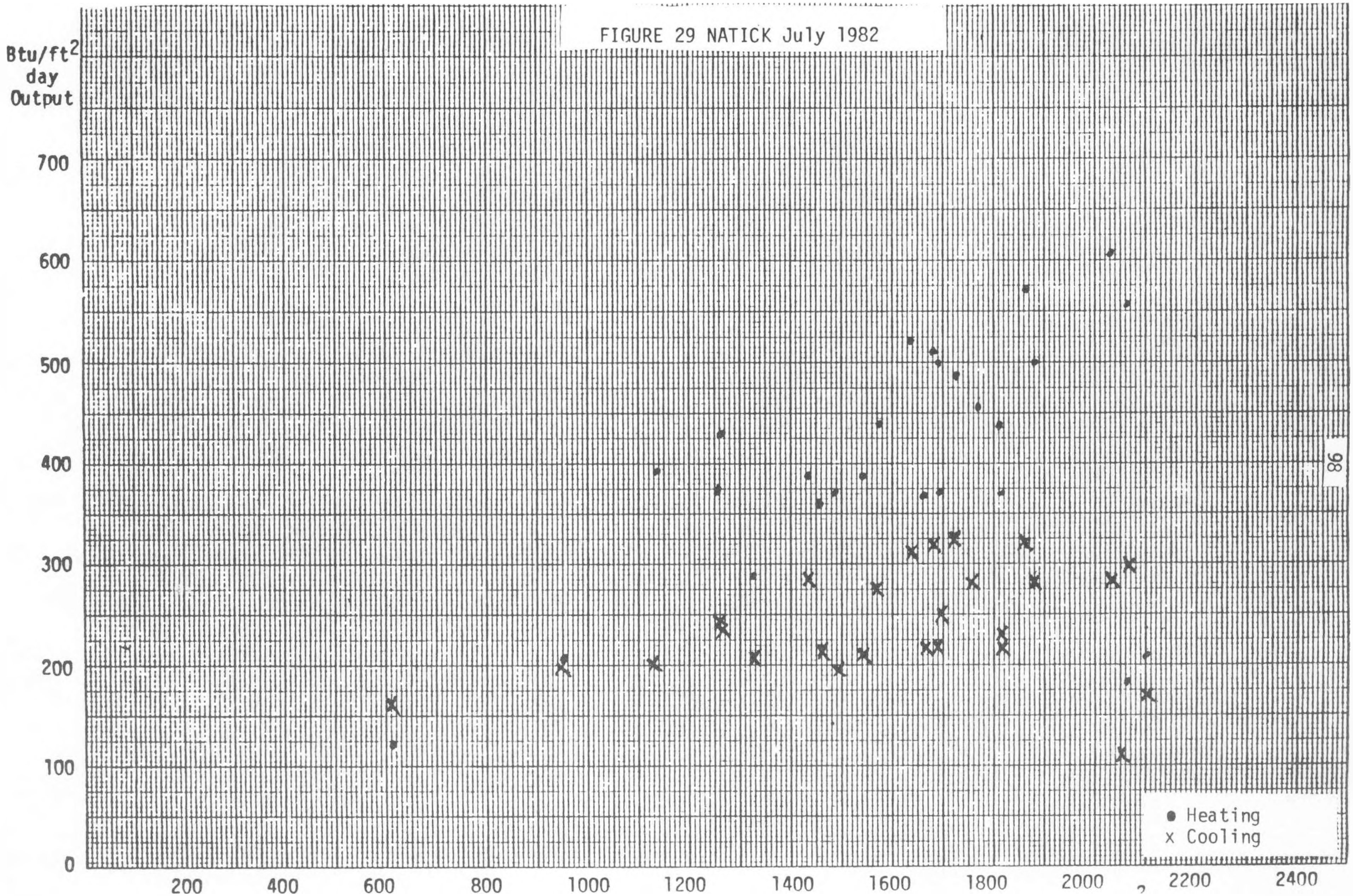


FIGURE 28 NATICK June 1982
Btu/ft^2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft^2 day Input
● Heating
x Cooling

FIGURE 29 NATICK July 1982



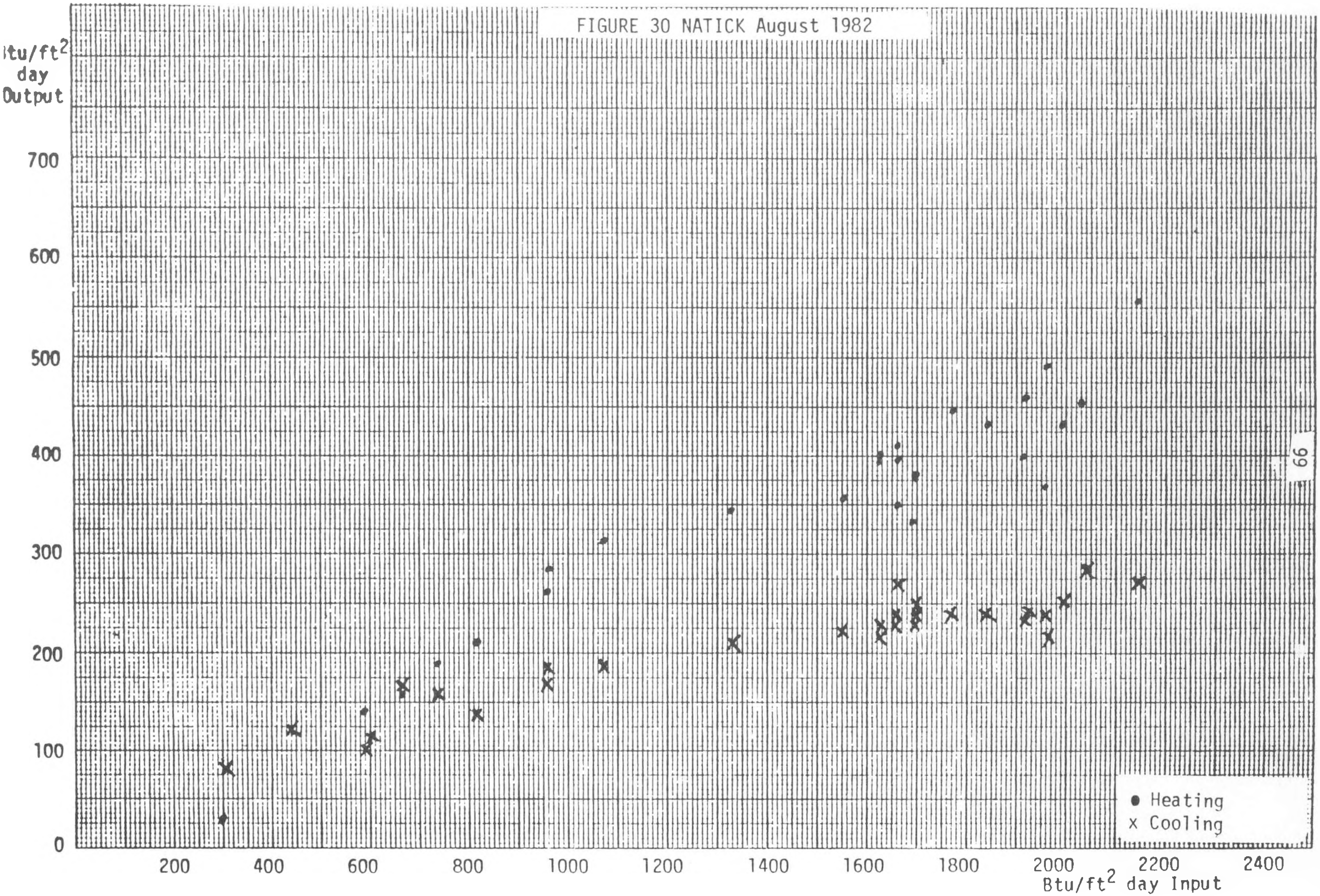


FIGURE 30 NATICK August 1982
Btu/ft² day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft² day Input
● Heating
x Cooling

failure of the panels. The heavy snow on the roof of the building and the slippery unsafe conditions prevented us from bringing the collectors down for repair until January 12, 1981 and the repaired collectors were installed again on the roof on January 14, 1981. The cold weather prevented us from restoring normal operation. Water vapor froze into ice in the pump-out valves, preventing the removal of the last small quantities of non-condensable gases. Furthermore, during the night of January 21, 1981, another severe cold spell caused freezing in the drain pipes and loss of vacuum. The collectors were brought down from the roof for repair on February 6, 1981 and after disassembling them it was discovered that the drain pipes of the heat exchangers, whose purpose is to drain the condensate back in the zeolite in order to prevent freezing, had frozen and split open. It was concluded that the draining angle of about 1" in 12" or 5 degrees was sufficient for complete removal of all the water in the evaporator, but because of surface tension, some water in the 3/8" diameter pipe itself did not drain and froze at temperature below 0^{O}F, sometimes only deforming the soft copper pipe, but other times also splitting the pipe open. The position, size, and shape of the drain pipe was determined during the design of the collector and could not be changed without rebuilding the panel completely from the beginning. For this reason, the pipes were just replaced at the same drain angle and the collectors were installed back on the roof on February 18, 1981. The testing began on February 19 and went uninterrupted until December 1981 when again the first below 0^{O}F weather caused the pipes to freeze and split open. The collectors could not be brought down for repair until February 3, 1982 and weré repaired and operating again on February 13, 1982 for the rest of the test period without any failures.

It is obvious, in hindsight, that a much steeper drain angle and/or larger diameter drain pipe could have been used; however, in many tests before the original design was finalized, the full evaporator drained completely every time and the moving column of water never left any residual parts in the drain pipe at the chosen angle, and therefore it was considered a satisfactory solution. Also, the drain slope of one inch per foot drop in the pipe is in common usage throughout the industry. In actual operation, however, the condensed water drips from the heat exchanger drop by drop, there is no column of moving water, and the surface tension seems to prevent all water drops to return to the zeolite panel, creating the freezing problem. Unfortunately, the reason drain pipes with the supposedly proper slope did not drain completely and froze was not established until all collectors for the Denver house (to be discussed later) were already constructed and freezing problems with these collectors were also observed.

Since the drain valves in the drain pipe were open from October until April every year, no cooling data could be obtained for this period. During the cooling season from June to September, however, these normal valves were closed and good cooling performance data was obtained.

The data chosen for heating performance analysis is for the months of November 1980, April and June 1981, and March 1982. The best representation of the heating data by a straight line is with one starting at an input of about 300 BTU/ft^2 day with a slope of 30 to 32%. The overall daily heating efficiency varies between 20% at 1000 BTU/ft^2 day input and 28% at 2200 BTU/ft^2 day input. The scatter of experimental data points in Natick is larger than the data from Tucson. This possibly is caused by the larger variety of weather conditions in New England. On the other hand, it is remarkable how little difference there is between the data from Denver, Tucson, and Natick, even though the weather patterns and climatic conditions are so widely different.

The cooling data chosen for analysis in Natick is for the months of June, July, and August 1981, and July and August 1982. The best straight line representation is given by one starting at the origin with a slope of about 18 to 19%. This corresponds to an overall daily cooling efficiency of 18 to 20%. The performance of the collectors in Natick indicates lower cooling output than the Tucson test site. While the maximum cooling output obtained in Tucson was about 425 to 450 BTU/ft^2 day for a solar input of 2200 BTU/ft^2 day the Natick site rarely delivered more than 300 BTU/ft^2 day cooling for a 2000 BTU/ft^2 day input. Part of the reason for this difference is that the collectors in Natick are at an angle of 45^0 with the horizontal (close to the latitude angle of 42^0) and therefore never received an input over 2100 BTU/ft^2 day. The collectors in Tucson, on the other hand, were installed at an angle of 30^0 with the horizontal (again, close to the latitude of 32^0) and routinely reached and exceeded 2400 BTU/ft^2 day solar input in the summer. Another reason for the lower cooling output in Natick is the difference in climate. The dry, desert climate in Tucson results in very low nightly minimum temperatures and therefore the zeolite in the collector can be cooled to a lower temperature toward the end of the cycle, thereby increasing the cooling capacity of the system. In Natick, the relative humidity is much hiaher during the summer, the minimum night air temperature remains higher than in Tucson, and consequently also the lowest obtainable zeolite temperature thus reducing the capacity of the system.

While the zeolite cycle is very little dependent upon the condenser pressure and therefore on the daily air temperature (for an air-cooled condenser), it is considerably more dependent on the minimum air and zeolite temperature during the night. (This fact was also observed in the reduced performance of our solar refrigerator in very humid tropical climates such as equatorial Africa and India.) It is expected that the integrated zeolite collector will perform better in the desert climate of thé southwestern part of the U.S.A. than in the more humid climate of the Gulf of Mexico area.

During a period of sunny weather July 23-24, 1981, continuous data was taken around the clock in Natick. The results of this test are shown in Figure 31. The points of most interest are: During the morning period from 8:00 a.m. to about 2:00 p.m. (with solar noon at about 11:30 a.m.), the rise in panel temperature is almost linear with time with a slope of about

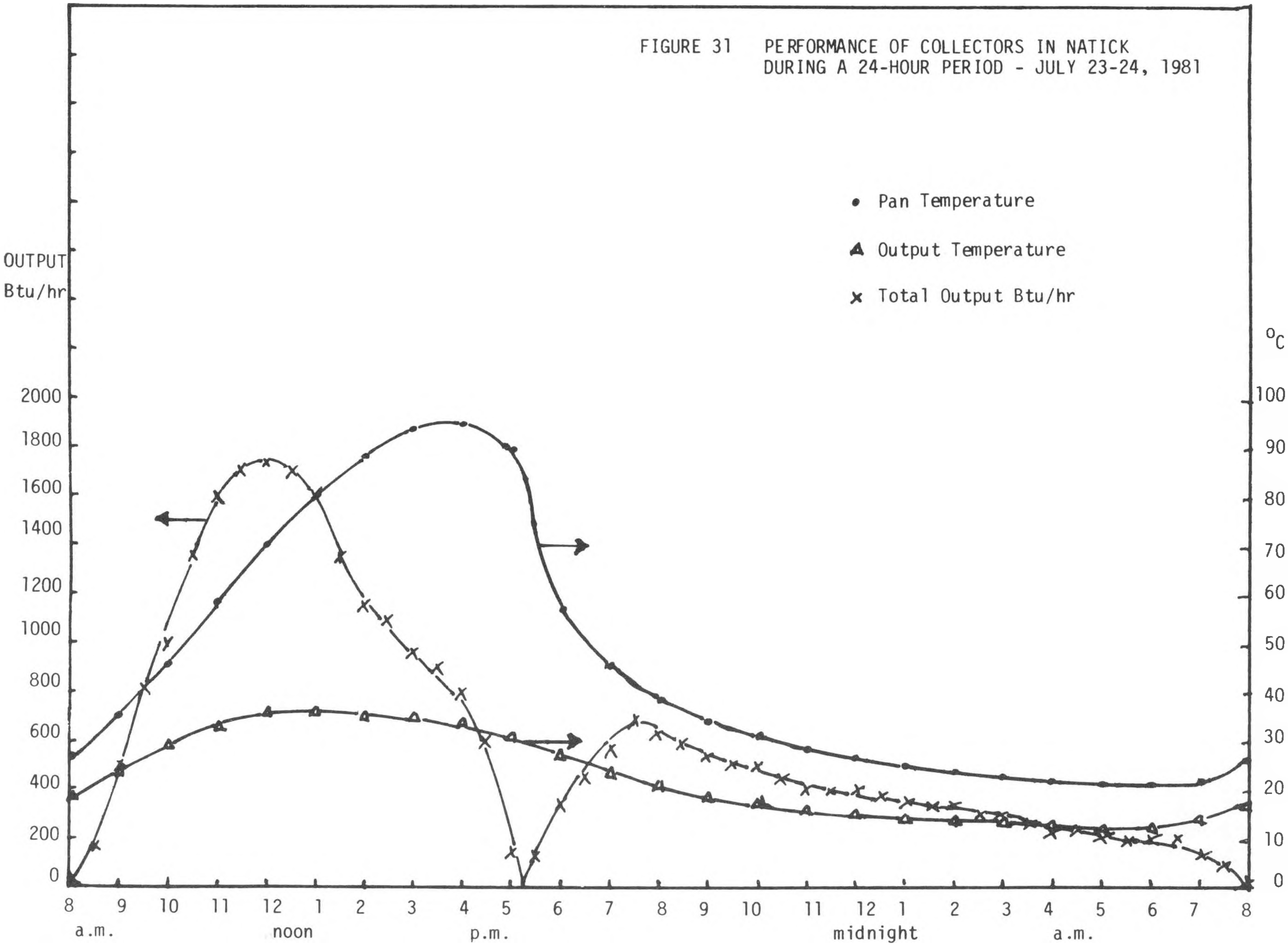


FIGURE 31 PERFORMANCE OF COLLECTORS IN NATICK
DURING A 24-HOUR PERIOD - JULY 23-24, 1981
Pan Temperature
Output Temperature
Total Output Btu/hr
OUTPUT
Btu/hr
°C
2000
1800
1600
1400
1200
1000
800
600
400
200
0
100
90
80
70
60
50
40
30
20
10
0
8
9
10
11
12
1
2
3
4
5
6
7
8
9
10
11
12
1
2
3
4
5
6
7
8
a.m.
noon
p.m.
midnight
a.m.

12^{o}C/hr (21.6^{o}F/hr). It reaches about 95^{o}C (203^{o}F) at about 3:30 p.m. local time (4:00 p.m. solar time) and the desorption part of the cycle terminates at about 5:00 p.m. local time. The temperature of the air cooled condenser reaches a peak of 35^{o}C (95^{o}F) at noon and remains constant until about 3:00 p.m. while the air temperature (now shown on the figure) peaks at about 3:00 p.m. The rejected heat output per collector peaks at 1750 BTU/hr (280 BTU/ft^{2} hour) at about noon and thereafter decreases so that the condenser temperature remains constant while the air temperature increases from 12:00 to 3:00 p.m.

The changeover from the heating to the cooling portion of the cycle is very fast -- it takes place in only ½ hour, from 5:00 to 5:30 p.m. The peak in cooling output is obtained between 7:00 and 8:00 p.m. and thereafter declines slowly until about 5:00 - 6:00 a.m. on the following day. The evaporator output temperature at that time is 12^{o}C (53.6^{o}F) and is tied to the air temperature of the fin-coil heat exchanger. Lower temperatures can be obtained if the cooling output is fed to a storage tank as we have observed in later experiments.

Another experiment was run during the same time period in order to gain a better understanding of the details of the absorption process. A thermocouple was inserted through a vacuum tight seal into the zeolite itself and a second thermocouple was attached to the back of the copper panel at the point where we usually measure the panel temperature. Again, during the 24-hour period of July 23-24, 1981 data was taken every half-hour and the results are represented in Figure 32. Since this was one of our new panels with selective black chrome coating the copper panel, temperature increased almost linearly with time during the morning but with a slope of 15^{o}C/hr (27^{o}F/hr) and reached a peak temperature of 135^{o}C (275^{o}F) at about 3:00 p.m. local time (3:30 p.m. solar time). The zeolite temperature during the morning lagged the copper panel temperature by about 20^{o}C (36^{o}F) and reached a peak of 125^{o}C (257^{o}F) at about 4:00 p.m. local time, i.e. about one hour

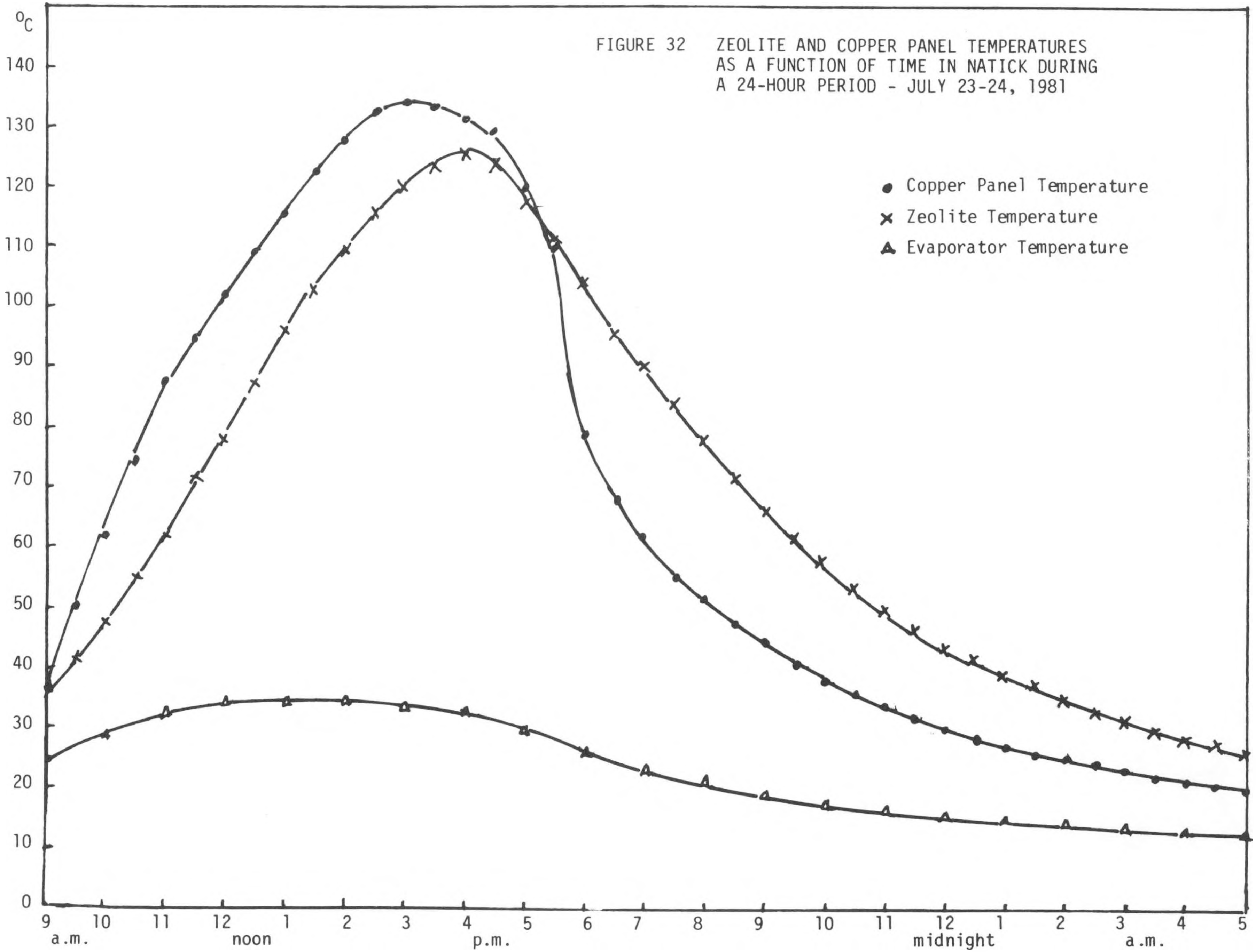


FIGURE 32 ZEOLITE AND COPPER PANEL TEMPERATURES AS A FUNCTION OF TIME IN NATICK DURING A 24-HOUR PERIOD - JULY 23-24, 1981

after the copper panel peak temperature. Thereafter the zeolite temperature decreased slower than the copper panel temperature lagging by as much as 25^{o}C (45^{o}F) during the late afternoon. Even at 2:00 a.m. the zeolite temperature was still 10^{o}C (18^{o}F) higher than the copper panel, reading a minimum of 6^{o}C (10.8^{o}F) at 5:00 a.m. local time. Because of the low thermal conductivity of zeolite, these results were not unexpected and confirmed the need for the copper separator network described in the previous report.

A separate test performed during this period measured the temperature profile of the copper panel at 1:00 p.m. local time and confirmed the expected results that the edges of the copper panel are cooler than the central part by as much as 15^{o}C and that the lower end of the panel is also cooler by about 10^{o}C than the upper end. The losses through the insulation along the edges where the weight of the panel is supported are larger than in the middle and since the frame and glazing are not air tight, small air leakage and the chimney effect result in lower temperatures at the bottom of the collector.

An attempt was made to measure the pressure drop between the zeolite part of the collector and the heat exchanger on the back. For this purpose, a water manometer was connected between the bottom of the zeolite panel and the pump-out valve of the heat exchanger and the system was evacuated. During desorption, condensation in the manometer prevented accurate measurements of dynamic pressure differences; however, at any time during the cycle the pressure drop did not exceed 1" of water (about 2 mm Hg). This indicates that the dynamic rate limiting step is not vapor transport between the heat exchanger and the panel, but most likely the thermal flow of heat in and out of the zeolite.

The purpose of these tests was to validate experimentally the design of the collector and the results indicate that both temperature distribution and pressure differences during the complete 24-hour cycle are well within the design specifications of the integrated collector.

Discussion of the Operational Performance and Analysis

The specific heat of the collector was both calculated and measured to be about 52 to 54 BTU/^{o}F or about 3.3 BTU/ft^{2o}F without desorption. It has been shown by a number of authors that for adsorption cooling systems, the temperature difference between the absorbent and the condenser must exceed by 120% the temperature difference between evaporator and absorbent before any desorption and condensation can occur. Since the lowest temperature the zeolite reaches in the early morning hours is between 25 and 35^{o}C while the evaporator is at 10^{o}C, the zeolite must be heated to 20 to 30^{o}C above the condenser temperature, i.e. to 50-65^{o}C before desorption will occur. During the time the zeolite is heated through this range of 45-60^{o}F, no desorption will occur and therefore there will be no heating or cooling output. In other words, the first 150 to 200 BTU/ft^{2} net energy will be lost to the absorption system. Since the average temperature above ambient during this time is about 25-30^{o}F and the heat loss coefficient of the collector is slightly above 1.1 BTU/ft^{2}hr^{o}F, we should expect additional losses of 50-65 BTU on a sunny day (and more on a cloudy day), raising the total energy needed in the collector to 200-265 BTU/ft^{2} before desorption begins. If we take into account the losses through the glass covers and the absorptivity of the black surface, the minimum solar input in the collector has to exceed 300-350 BTU/ft^{2} day before any output can be expected.

From our actual experimental data, we find that most input-output data can be reasonably well represented by a straight line starting at between 250 and 400 BTU/ft^{2} day. Considering the large variations in ambient temperatures from one site to another during the different seasons, the measured data is in very good agreement with the theoretical prediction.

The desorption part of the cycle takes place at higher temperatures where the collection efficiency of the collector varies between 20 and 50%, for an average value of about 35%. The COP of the absorption system is about 0.7 and the total overall daily output should be 0.35 X 0.7 = 0.245. We measure from the experimental data a slope on heating of about 30% and on cooling about 20%. Assuming that the difference occurs because of heat flow from the warmer collector to the cooler evaporator-condenser, the true slope should be somewhere in between or at about 25%, again in excellent agreement with the theoretical prediction.

When selective surface black chrome is used for the absorbing part of the collector, the heat loss coefficient is reduced to about 0.82 BTU/ft^{2}hr^{o}F and the collection efficiency of the panel is increased. In tests of later models of the collector with black chrome, the input/output data can be represented very well by a straight line starting at an input of 300 to 400 BTU/ft^2 day and with a slope of 35% on heating and 25% on cooling. From this, one can infer an average daily collection efficiency of 43% for a COP of 0.7, or a variation in the range of from 30 to 55%.

Further improvements in the design of the integrated collector are definitely feasible, with the major one being the reduction in losses between the evaporator-condenser and the zeolite panel, thereby further increasing the cooling output.

APPENDIX - THE DENVER HOUSE

The goals of the contract covered only the design, construction, and testing of a component -- The Integrated Solar Zeolite Collector. While it is important to have well characterized components, the ultimate goal is for a complete system to operate satisfactorily and to provide comfortable living conditions in an occupied building. The performance of many good components has been obstructed by poor system design and construction. For these reasons it was decided to test the collector in a complete system for a private residence independently from this contract and not funded by it. While this system, later nicknamed The Denver House, is not part of the contract, the limited operational data available from it proves the validity of the collectors test procedure and the usefulness of it for complete system performance prediction and design criteria verification. Therefore, the data available on the Denver House is included in an appendix to this contract.

The first full-scale residential system utilizing the integrated zeolite collector was constructed with private funding by Mr. Joseph K. Fannin and Mr. Allen L. Meyer of the Natural Energy Corporation, Lakewood, Colorado. The system was to be installed on a custom designed and built residential building of over 4,000 ft^2 of space conditioned floor area. After the house was partially completed with storage tanks installed in the basement before construction of the house began, unfortunate family problems and divorce proceedings forced the abandonment of the dwelling, and the relocation of the system as a retrofit to a different existing residential building. The storage tanks were cut into pieces in order to be relocated to the new site and the collector field was located next to the existing building instead of on the roof (as planned in the original design).

The system is located in Morrison, Colorado, a suburb of Denver. The house has a space conditioned floor area of 2,400 ft^2 and the collector field was reduced accordingly to 36 collectors of 16.4 ft^2 net area for a total of 590 ft^2 net collector area. The total storage of 3,000 gallons consists of two fiber glass-epoxy storage tanks of 1,500 gallons each in series insulated with 6" polyurethane foam in a box buried in the ground between the rows of collectors. The storage capacity corresponds to 5 gallon/ft^2 of collector and is designed to provide 415 BTU/ft^2 cooling storage at a temperature differential from 45 to 55^{o}F in the chilled water temperature. A view of the storage tanks with the cover to the box open is shown in Figure 33. Each tank is equipped with a manhole to permit easy maintenance and repair, and the cover of the storage tank box when closed is useful as a service walk between the collectors.

The 36 collectors are divided into two rows of 18 collectors each. The rows consist of 3 groups each of 6 collectors on the same support structure. A view of the collector field is shown in Figure 34. Most of the collectors are covered with black plastic sheet in order to reduce stagnation while the manifolding and installation are being completed. A single group of 6 collectors is shown in Figure 35. The support structure consists of one iron angle on the bottom, carrying most of the weight and one I-beam at about 75% of the height of the collector. This leaves the top 25% of the collector where the input/output of the condenser-evaporator and the pump-out valve are located free of obstructions for manifolding and experimentation. The I-beam and angle irons are attached to concrete columns cast in the ground. A view of the back support structure of the first row is shown in Figure 36. The support structures for each group of collectors is terraced in order for the field to follow the contour of the land and reduce the visual impact of the collectors in accordance with local zoning laws. This has been achieved to a remarkable degree as seen from the overall view of the collector field as shown in Figure 37.

FIGURE 33 STORAGE TANKS AT DENVER HOUSE

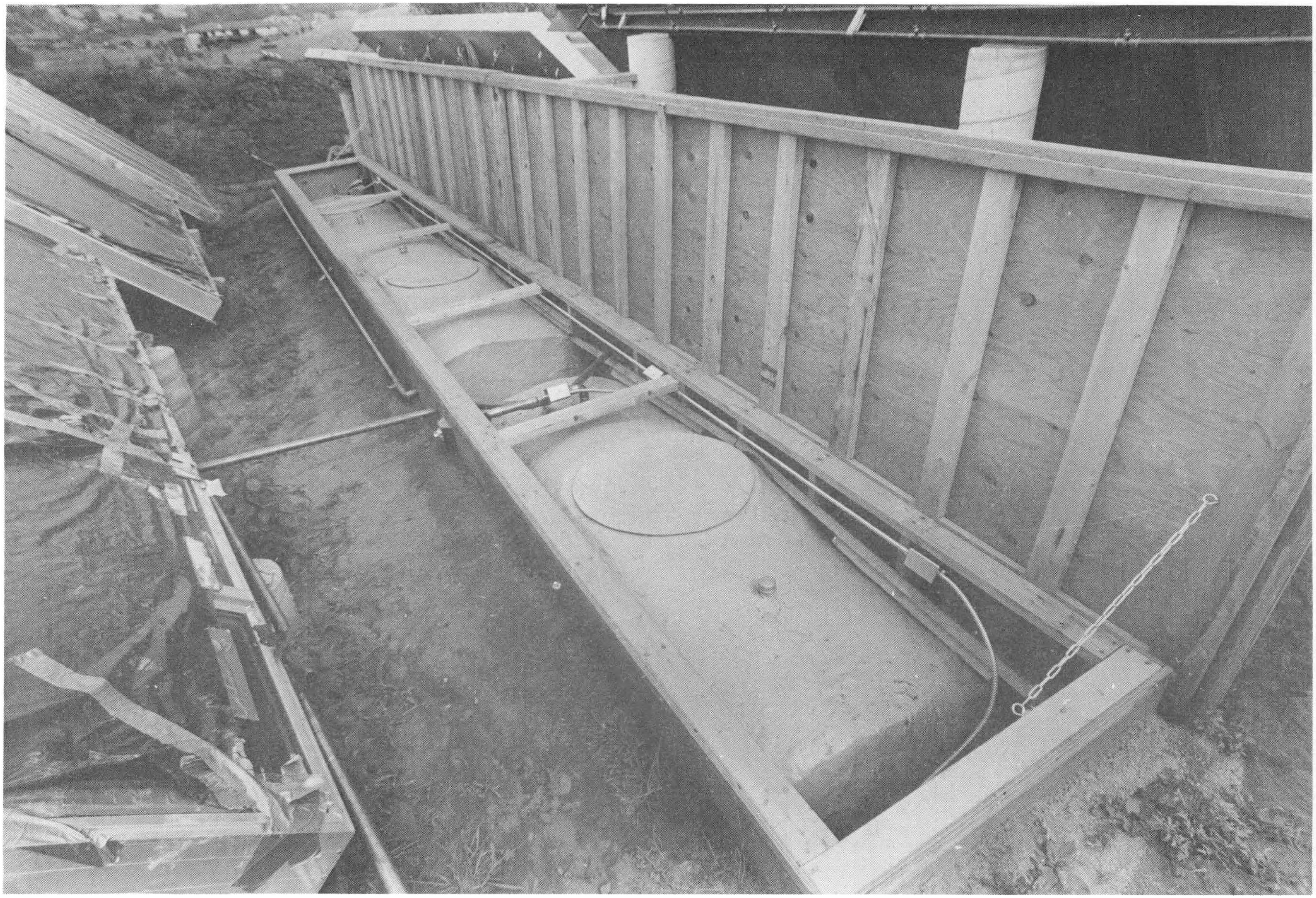


FIGURE 34 COLLECTOR FIELD DURING INSTALLATION AT DENVER HOUSE

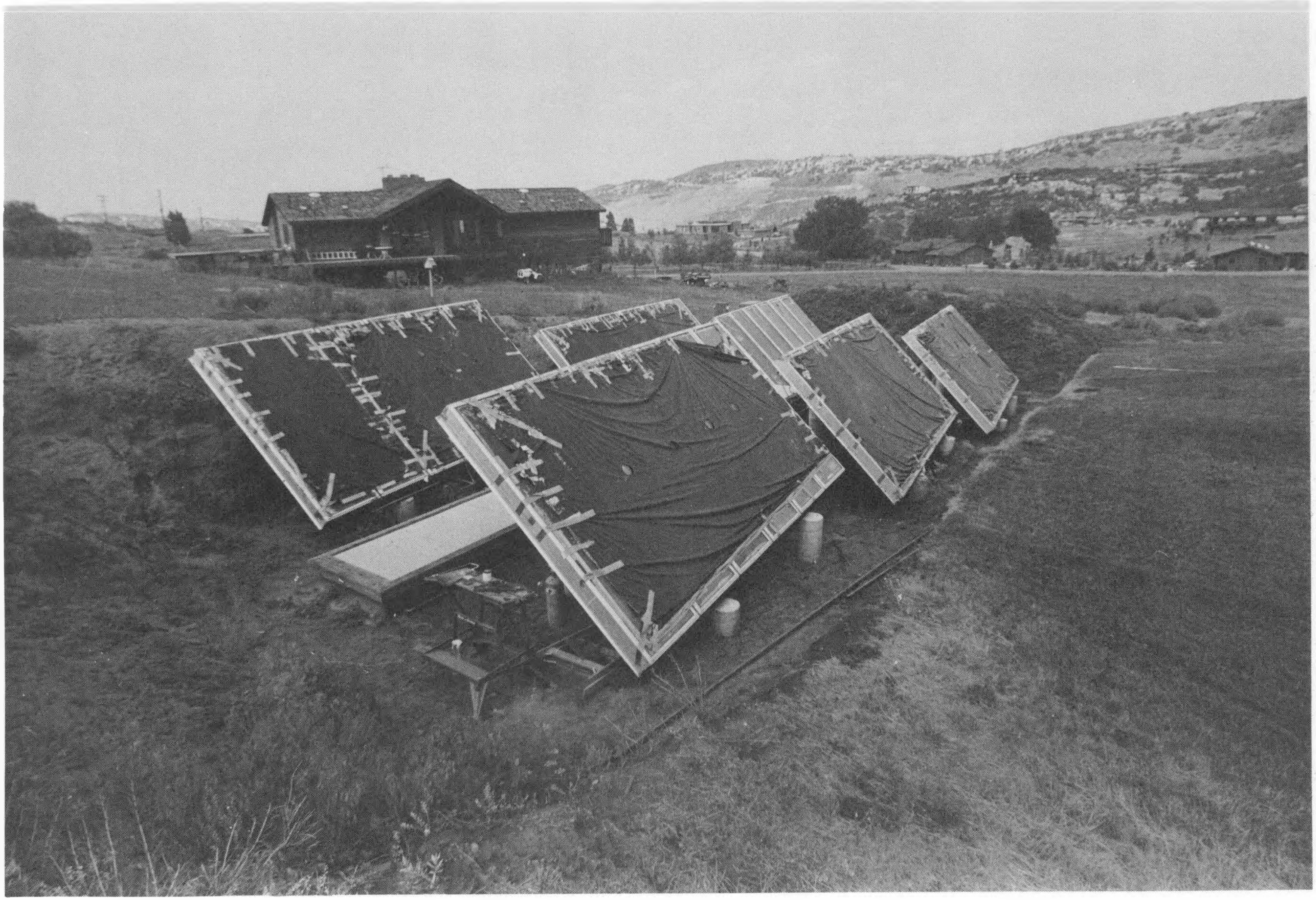


FIGURE 35 GROUP OF 6 COLLECTORS AT DENVER HOUSE

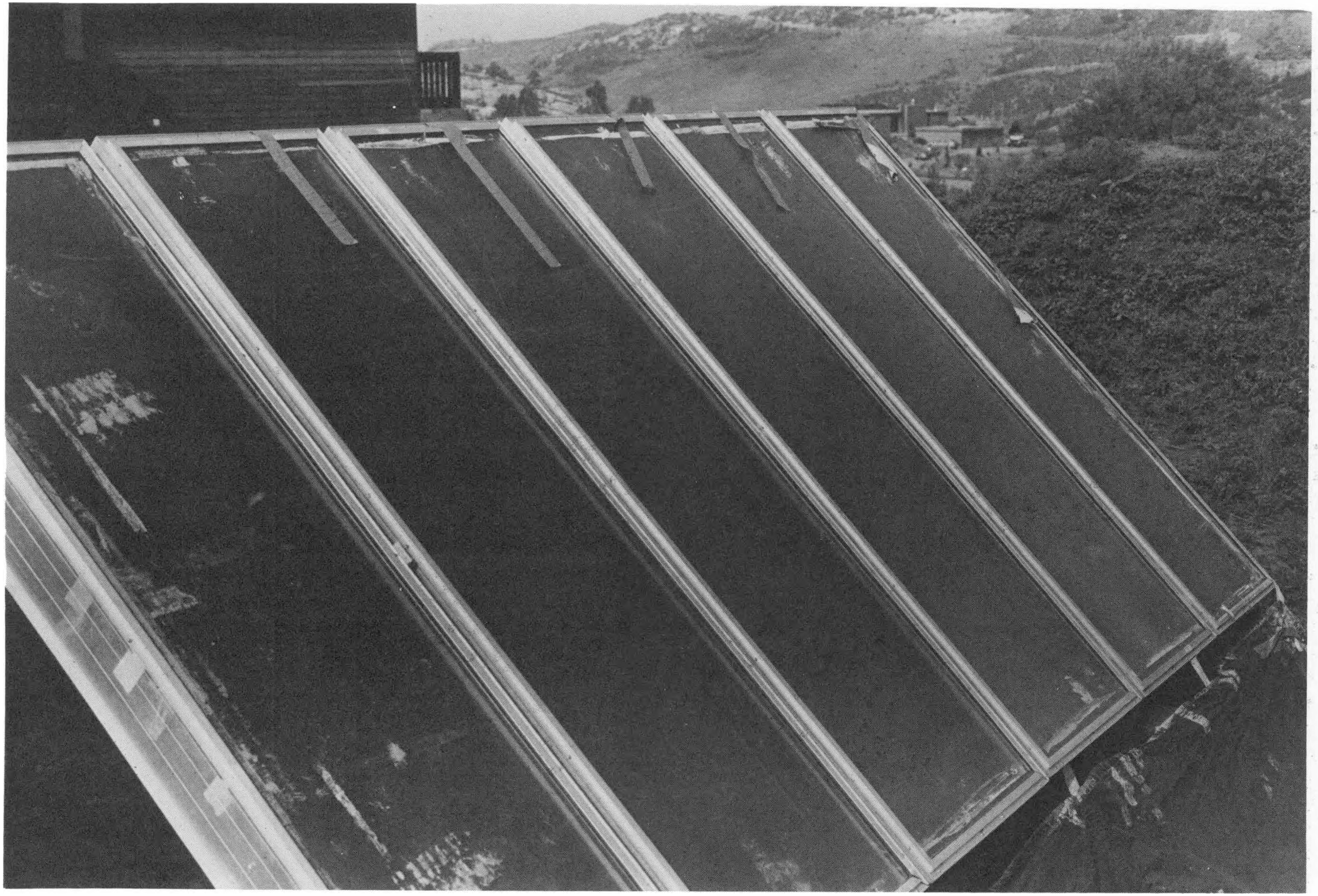


FIGURE 36 SUPPORT STRUCTURES IN DETAIL OF COLLECTORS AT DENVER HOUSE

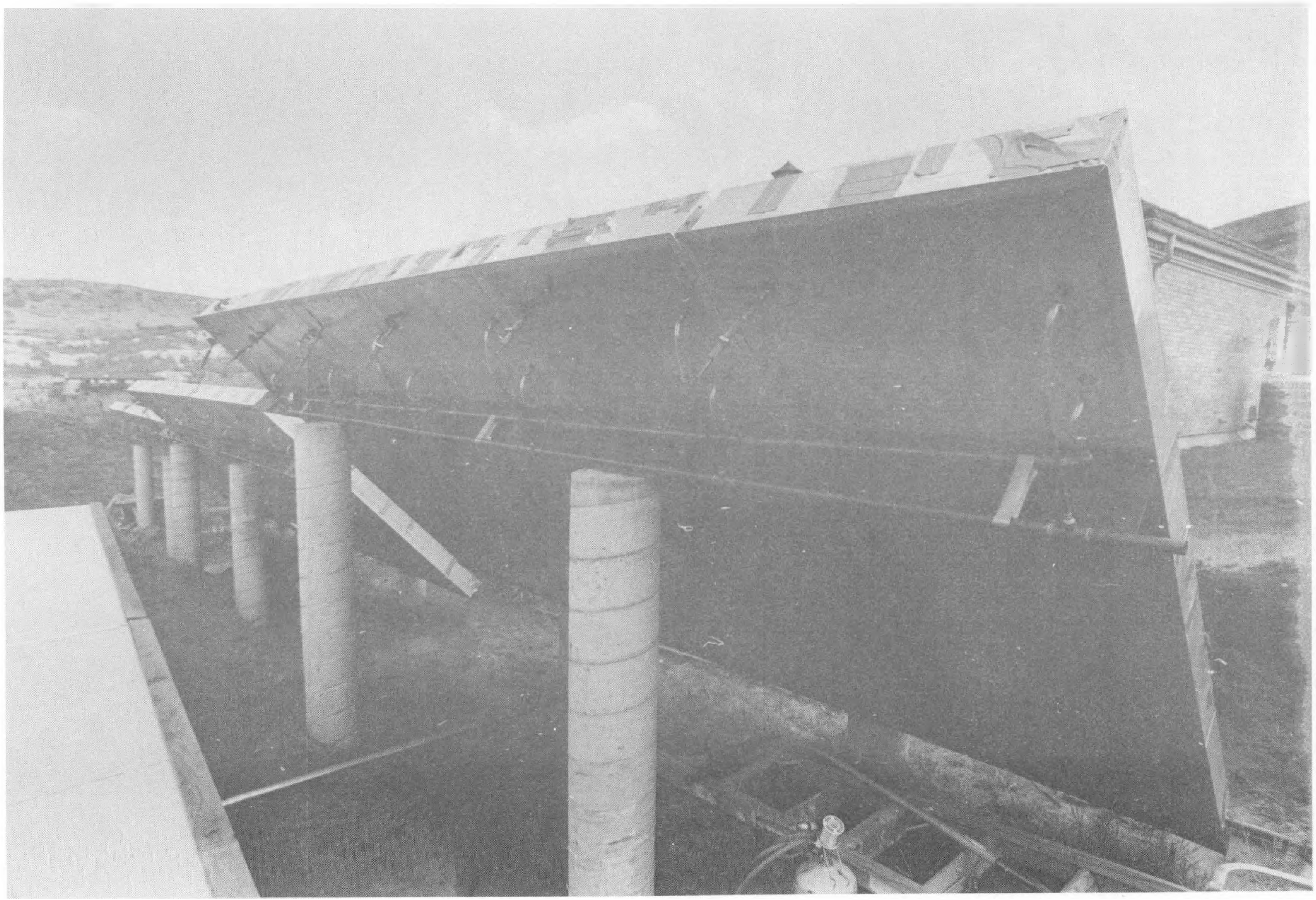
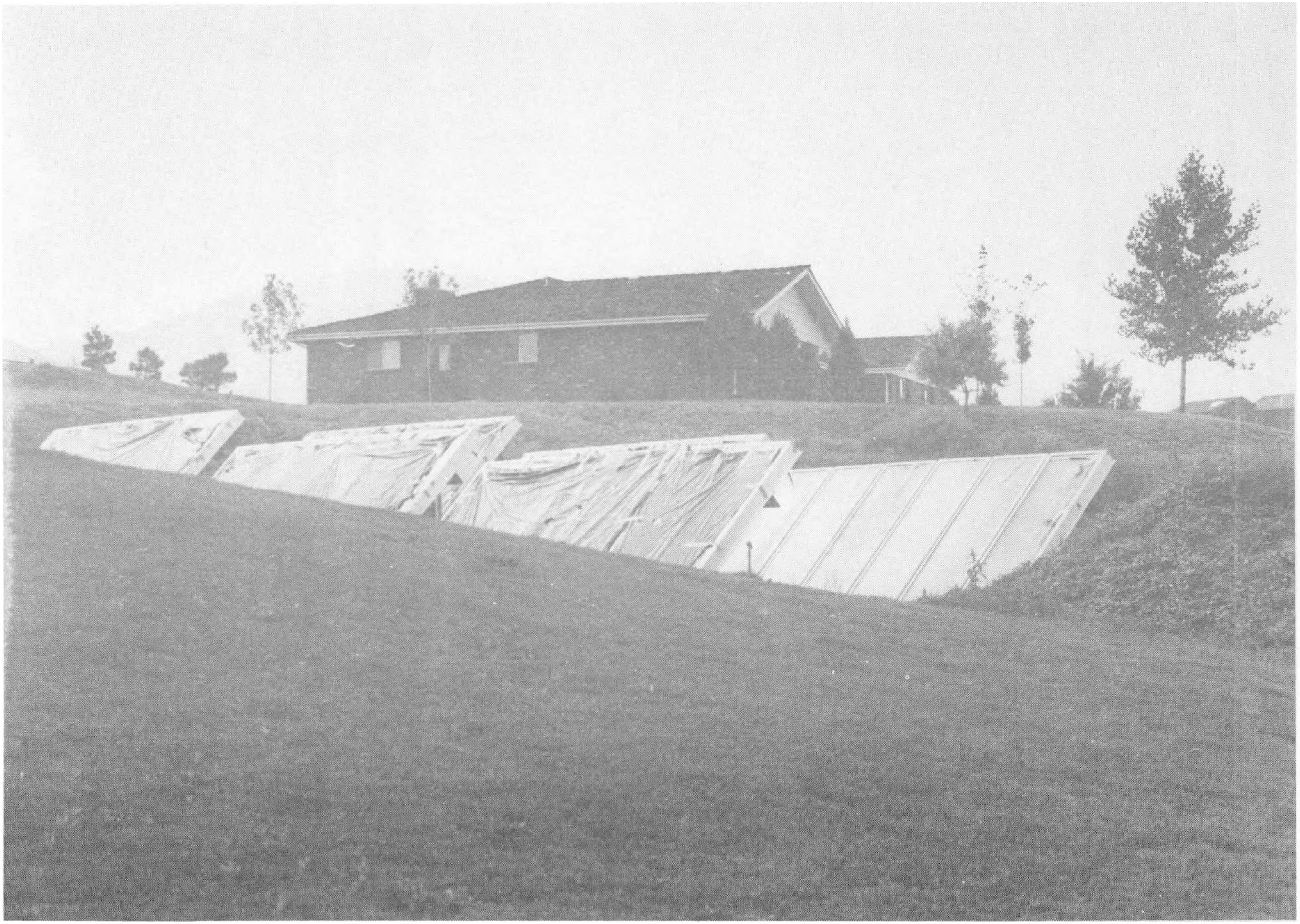


FIGURE 37 OVERALL VIEW OF COLLECTOR FIELD AT DENVER HOUSE

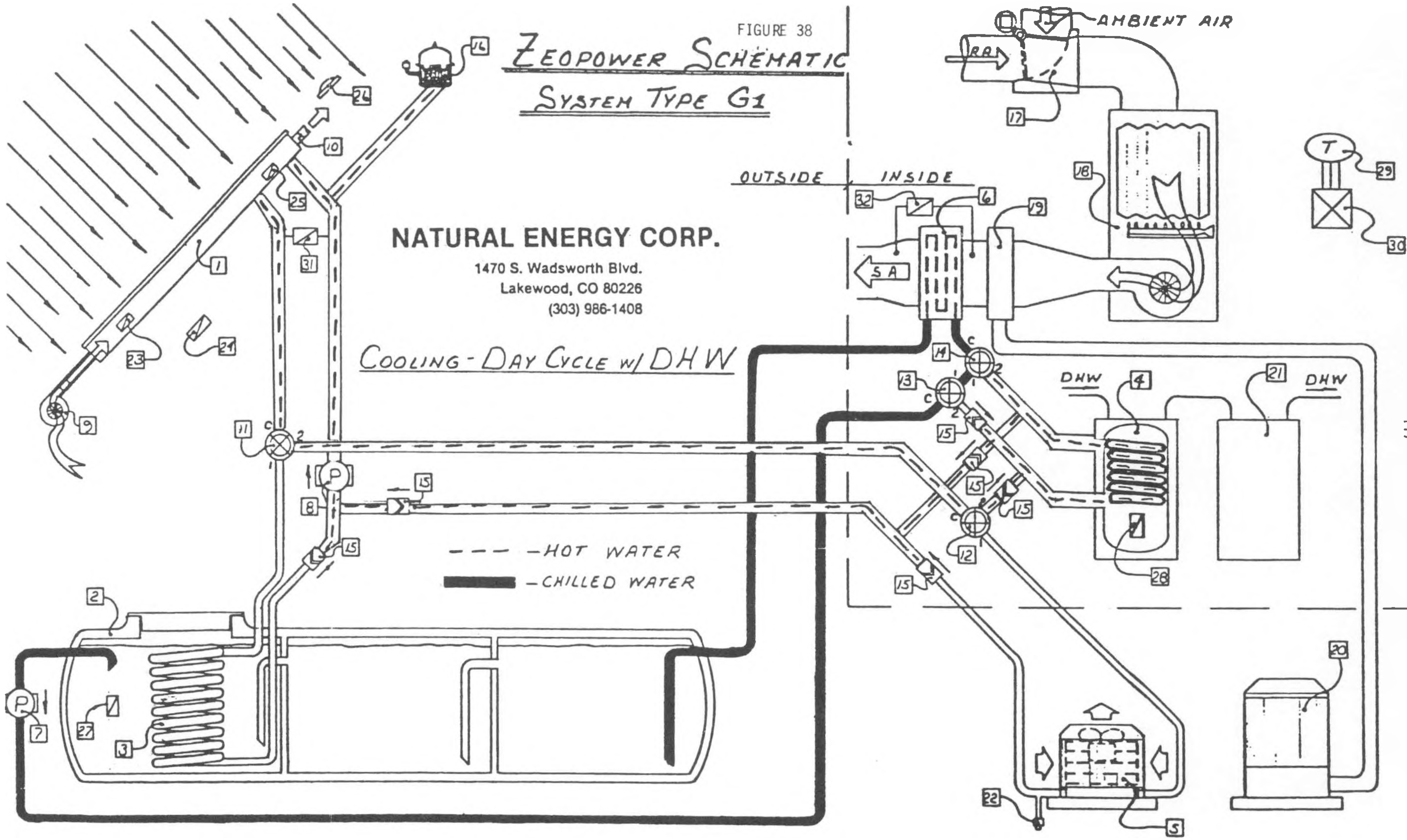


The orientation of the collectors is south at an angle of about 50^0 with the horizontal. This is done in order to match best the heating and cooling loads of the building to the solar input available. Denver has a heating season of over 4,000 Degree Days and a cooling season of only 1,000 Degree Days, and therefore the angle of the collectors - latitude plus 10 degrees - emphasizes the heating season needs. The schematic of the system diagram is shown in Figure 38. Since the collector field produces hot water year round, during the heating season the output of the collectors is fed to the storage tanks and to the domestic hot water systems via two heat exchangers. In this way the loop through the collectors is filled with glycol-water mixture while the storage tank and the DHW system use ordinary tap water. During the cooling season, only the DHW needs are satisfied before the excess heat is rejected through a fin-coil to the atmosphere. The chilled water of the collectors at night is stored in the storage tank during the cooling season. During the heating season there is no chilled water output since the automatic temperature controlled valves in the collector drain the evaporator into the zeolite panel every time its temperature reaches 35^0F.

The needs of the forced air system of the residence for either heating or cooling are met by circulating water from the storage tank through a separate loop to a duct heat exchanger. The change from heating to cooling season is done by changing the temperature of the liquid in the storage tank while the loop to the house remains always the same. Back-up is provided by the existing systems in this retrofit situation: a forced air gas fired furnace and an electrical central air conditioning unit operating with refrigerant R12.

The complete system is controlled by a microprocessor with a wide variety of programs for different control strategies. Since this is the first full-scale system utilizing the unique features of the integrated zeolite collector, it is contemplated that some experimentation with control strategy will be necessary in order to determine the optimum system control characteristics.

FIGURE 38


ZEOPOWER SCHEMATIC
SYSTEM TYPE G1
NATURAL ENERGY CORP.
1470 S. Wadsworth Blvd.
Lakewood, CO 80226
(303) 986-1408
COOLING-DAY CYCLE W/ DHW
AMBIENT AIR
RA
SA
OUTSIDE
INSIDE
DHW
DHW
T
--- -HOT WATER
-CHILLED WATER

The system of the Denver house was completed in August 1982 and some preliminary cooling performance data was obtained during the week of August 26 to September 1, 1982. Since the instrumentation for the solar input was not installed at that time, the actual solar daily input on a horizontal surface was obtained from the local station of the NOAA and was recalculated for a surface at an angle of 50^0 with the horizontal facing south using the standard solar equation. The actual data is given in Table IV.1. During this particular week only 24 of the 36 collectors were manifolded and the cooling output during the night was delivered to the storage tank and measured by the BTU meter installed in the loop. The total cooling delivered per night varied from 97,000 to 170,000 BTUs, approximately in accordance with the solar input. Normalized per unit area the cooling output was between 247 BTU/ft^2 day for a 1598 BTU/ft^2 day input for an overall efficiency of 15.5% and 435 BTU/ft^2 day for a 1976 BTU/ft^2 day input and an overall efficiency of 22%. The heating output during the daytime was simply rejected to the ambient air by the heat rejection coil without being measured.

The data from Table IV.1 is shown in graphical form in Figure 39. While there are only seven points on the graph, the general tendency is in good agreement with the rest of the data presented previously from the three different test sites. As a matter of fact, a straight line starting at about 300 to 400 BTU/ft^2 day input with a slope of 0.2 passes below most experimental points. A better fit will be given by a slope of 0.25. This seems to indicate that if the preliminary cooling data from the Denver house could be trusted, the performance of a large system is better than that of only a pair of collectors. We believe this to be due to experimental errors. In the four years of our experience, we have found it almost impossible, despite constantly improving instrumentation technology, to measure accurately the output of a single collector. If the flow rate is decreased below 0.3 gallon/minute in order to increase the input-output temperature difference,

TABLE IV.1

DENVER HOUSE

AUGUST / SEPTEMBER 1982

DATE	INPUT BTU/FT^2 DAY	COOLING OUTPUT TOTAL 24 COLLECTORS	BTU/FT^2 DAY	% EFFICIENCY
8/26/82	1598	97300	247.2	15.5
8/27/82	1813	136200	346.0	19.1
8/28/82	1833	157500	400.1	21.8
8/29/82	1976	171100	434.7	22.0
8/30/82	1549	132300	336.1	21.7
8/31/82	2032	108900	276.7	13.6
9/01/82	1912	101100	256.9	13.4

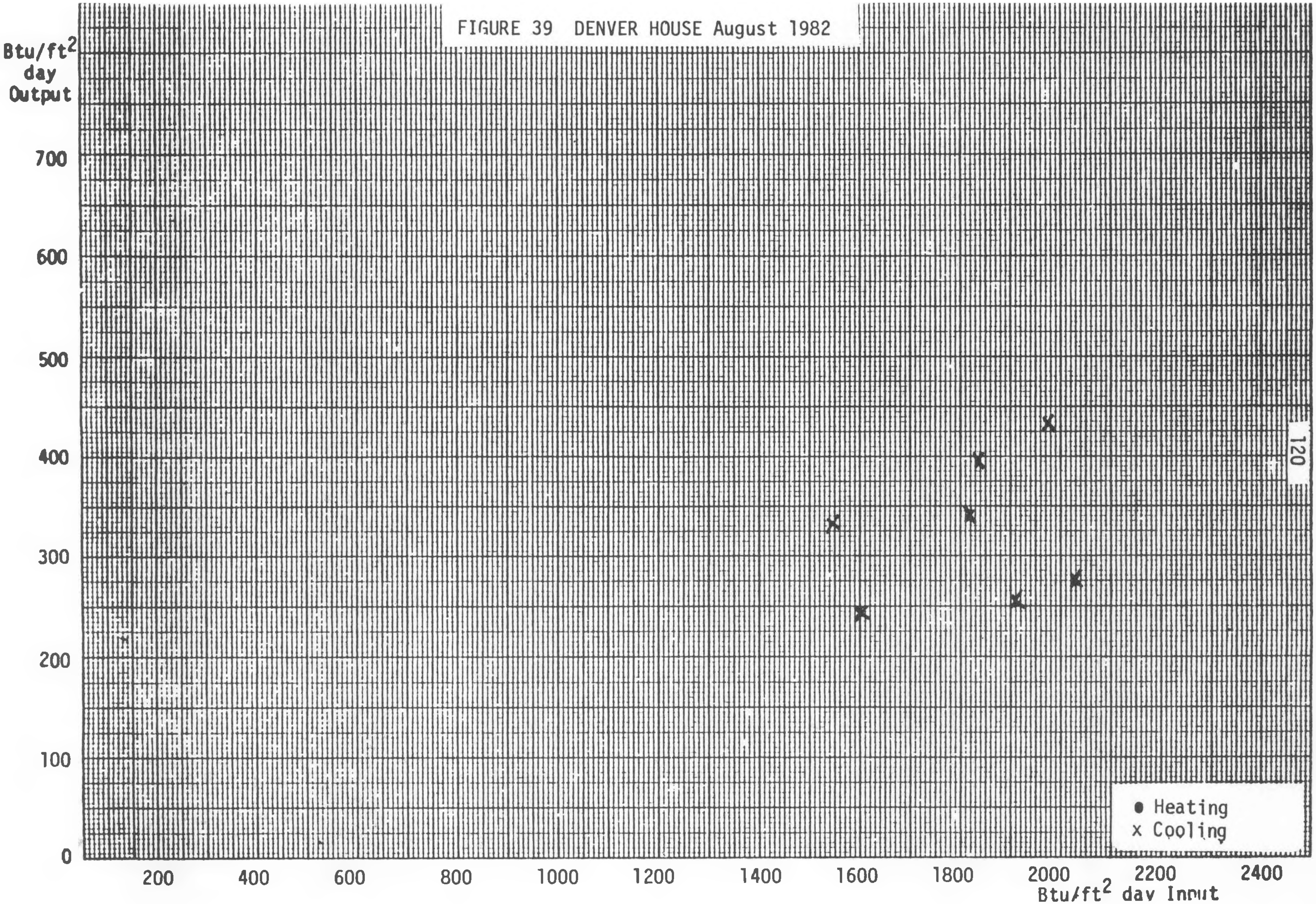


FIGURE 39 DENVER HOUSE August 1982
Btu/ft2 day Output
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Btu/ft2 day Input
● Heating
x Cooling

the error of the flow meters available on the market becomes intolerably large. If, on the other hand, the flow is increased to the accurate range of most flow meters, i.e. above 0.5 gallon/minute, the temperature difference between input and output is reduced to less than $3^{o}F$ and, despite manufacturer's claims to the contrary, most thermistors or thermocouples used in BTU meters give errors of over 25% even when carefully calibrated and matched in pairs. With the typical cooling output rate between 100 and 200 BTU/hr for a single collector during the night hours, even the experimental data of a pair of carefully instrumented collectors should be used with extreme care and constant calibration of all instruments. With a large system of 24 or 36 collectors, on the other hand, both flow rates and temperature differences can be kept within the accuracy limits of the instrumentation.

In conclusion, it can be stated that the full-scale system test results, while obtained only during a limited time period, equal or exceed the design specifications. Only further testing of the heating and cooling performance of the system, which is being continued now, will provide sufficient data to determine reliability and accuracy of the design data and economic predictions.

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