GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: 11/13/79

Project Title: Monitoring the Shenandoah (Georgia) Community Recreation Center Solar Cooling, Heating & Hot Water System

Project No: E-25-624 (Sub-projects are E-16-658/Craig/AE; A-2517/Jeter/ERL

Co-Project DirectorS: Dr. J.R. Williams & Dr. J.I. Craig

Sponsor: U.S. Department of Energy

Agreement Period: From 9/30/79 Until 4/30/81 ~~Feb. 28, 81~~ ~~9/29/80~~

Type Agreement: Contract No. DE-AS05-79CS30397

Amount:

$12,521	E-25-624
11,194	E-16-658
8,594	A-2517
$32,310	TOTAL

Reports Required: Monthly Progress Reports; Solar System Problem Reports; Updated O & M Instructions; Final Technical Report

Sponsor Contact Person (s):

Technical Matters

Contractual Matters
(thru OCA)

Oak Ridge Operations Office
U.S. Dept. of Energy
Attn: A.H. Frost, Jr.
Contract Division
P.O. Box E
Oak Ridge, Tennessee 37830

Defense Priority Rating: n/a

Assigned to: Mechanical Engineering (School/Laboratory)

COPIES TO:

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- Project File (OCA)
- Project Code (GTRI)
- Other C.E. Smith
  S.M. Jeter

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date January 20, 1984

Project No. E-25-624

School/~~Lab~~ ME

Includes Subproject No.(s) E-16-658 & A-2517

Project Director(s) Drs. J.I. Craig and Sheldon M. Jeter GTRI / ~~GIT~~

Sponsor U.S. Department of Energy, Oak Ridge Operations

Title "Monitoring the Shenandoah (Georgia) Community Recreation Center Solar Cooling, Heating & Hot Water System"

Effective Completion Date: 4/30/81 (Performance) 4/30/81 (Reports)

Grant/Contract Closeout Actions Remaining:

☐ None

☒ Final Invoice or Final Fiscal Report

☒ Closing Documents

☒ Final Report of Inventions

☐ Govt. Property Inventory & Related Certificate

☐ Classified Material Certificate

☐ Other ____________

Continues Project No. ____________ Continued by Project No. ____________

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Form OCA 60:1028

E-25-624

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

November 8, 1979

Mr. Carl Conner
US DOE
Solar Applications, CSD-PRO
Washington, D. C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79CS30397

Gentlemen:

Administrative:

Georgia Tech was advised on 27 September 1979 that the contract on this project would be awarded with an effective date of on or about 1 October 1979.

The contract was not in hand by early October but we proceeded with preliminary technical work and liaison tasks. A meeting with Mr. Dieter Franz, CEO, Shenandoah Development, Inc. was held on 12 October 1979. General agreement prevailed that the Shenandoah Corporation will undertake essentially all of the operational and maintenance responsibilities in the future leaving Georgia Tech unencumbered to carry out the data acquisition and evaluation tasks. We were pleased to learn that Mr. Leonard Bohannan, owner of Bohannan Conditioning in Moreland, Georgia, had been retained to operate and maintain the solar heating and cooling system. Mr. Bohannan is an experienced HVAC engineer and contractor and has already proved to be a significant asset to this program.

Later in October, the project budget was established with a minor alteration to allow for a change in the retirement fund anticipation which occurred since the February 1979 submission of the proposal. Budgets are established in the Engineering Experiment Station for the undersigned and the School of Aerospace Engineering for Dr. J. I. Craig. Student research assistants will be employed from the School of Mechanical Engineering. At present we are evaluating students for employment on this project, and we expect to employ a Ph.D. or M.S. candidate in Mechanical Engineering.

Mechanical Systems:

During the week ending 19 October, the system was changed to the winter operating mode, and the array was isolated. With water in the array, the system was operated for several days to check for defficiencies or problems before the glycol solution was installed.

On Tuesday and Wednesday, 23-24 October, we proceeded with filling the system with glycol solution. About 200 gallons of solution (about 40 gals of glycol) were lost during this installation when a valve was inadvertently left open. The change-over procedure will be clarified to prevent a recuurance of this. In all about 1100 gallons of solution were required which is about twice the volume of the system as calculated by the engineering consultant. The solution contains approximately 300 gallons of glycol and the indicated freeze protection is to 5° F. It was extremely difficult to obtain this volume of glycol during the season, but Mr. Bohannan was able to locate a sufficient quantity locally. During check out a problem was discovered in the function and location of the low solution level switch which is provided to inhibit pumping if the system loses solution. This was corrected. Also, a float valve was installed on the glycol holding tank to prevent wasting glycol if the array is drained because of excessive collector temperature.

Prior to installing glycol a leaking PRV in row five was replaced. This left only one known remaining leak (module 7, row 9). After installing glycol that remaining leak was pinpointed and corrected; however, a number of minor leaks appeared. All in rows 8 and 9 were corrected on 30 October by the undersigned with the assistance of Mr. Bohannan and his crew who proved expert in such repairs. None of these leaks appear to be caused by freeze damage as all were very small cracks at the panel inlet or outlet elbows or at the connections between absorber tubes and headers. These cracks appear to be caused by overheating and/or excessive thermal expansion. These cracks are wasting only a small amount of solution and should be sealed by the maintenance crew shortly.

Data Acquisition System

The data acquisition system was checked out by Dr. J. I. Craig on 30 October with the calculater, clock, and precision voltmeter installed along with the previously installed and wired transducers. Three temperature probes and flow meter F4, in the boiler loop, were found to be non-functional. This is not an excessive number of failed transducers considering how long they had been in place. We intend to replace F4 with F11, in the pool loop which is used currently, and to return F4 for factory repair. The temperature sensors (TT8, TT11, T2) appeared to be out of range due to moisture shorting the cable terminations (repairable).

The software for data acquisition appears to perform acceptably. One anticipated change is an alphanumeric indication of transducer definitions in the printed output to aid the operator in finding faults and deficiencies during daily visits.

Respectfully submitted,

Sheldon M. Jeter
Project Coordinator

jw

cc: Oak Ridge Operations Office, US DOE, Attn: A. H. Frost, Jr.
Contract Division, P. O. Box E, Oak Ridge, Tenn. 37830 - 4 cc

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program, FA33,
Marshall Space Flight Center, Alabama 35812 - 1 cc

Mr. Dieter Franz, Shennandoah Development, Inc.
P. O. Box 1157, Snenandoah, GA 30265

Mr. Otis Rodgers, Georgia Tech, PPC

A2517

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

December 5, 1979

Mr. Carl Conner
US DOE
Solar Applications, CSD-PRO
Washington, D. C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79CS30397
Monitoring the Shenandoah (Georgia) Community Recreation Center
Solar Cooling, Heating and Hot Water System, November 1979

Gentlemen:

Administrative

No particular administrative difficulties have developed during this month.

Mr. Tyronne Duffey, a technician in the School of Mechanical Engineering, has been assigned to assist in routine operation and maintenance of the data acquisition system. Since Mr. Duffey is a resident of Coweta County and is primarily assigned to other solar energy research projects in Shenandoah, this assignment is particularly convenient. He will be able to visit the building several times weekly without the expense and time of a trip from Atlanta.

Two excellent candidates have been interviewed for possible employment as graduate assistant on this project. Since data is now being recorded, a qualified person is needed soon to assist in the numerical data reduction and analysis tasks.

Data Acquisition System

The building data system has been completely checked out and all sensors have been verified to function properly. Calibration checks have been made for selected critical sensors. As of this report one temperature sensor was found damaged due to water absorption from a well leak and one Ramapo flow meter was found to be open-circuited. Both units have been returned for repair and in the interim are being replaced with backup instruments.

The data logger system was installed on 14 November and began shakedown operation on 16 November. We have encountered the usual minor problems with the equipment and the data acquisition programs, but as of 26 November the system has been working properly. Additional modifications are being made to improve the reliability of the system under the various situations we have encountered or identified. Arrangements have been finalized to insure on-site visits at least three times per week and cartridge retrieval on a weekly basis.

Data reduction and analysis programs are under development. These will be the subject of the bulk of the forthcoming effort. Results for each month will be provided in the report one month later. No data were taken for October and thus there is no summary report this month.

Mechanical Systems

Mr. Bohannan and his crew continued to eliminate the remaining leaks in the array. As discussed in the October report, evidence is that the remaining leaks resulted from overheating or thermal expansion rather than freezing.

Respectfully submitted,

Sheldon M. Jeter
Project Coordinator

jw

cc: Oak Ridge Operations Office, US DOE, Attn: A. H. Frost, Jr.
Contract Division, P. O. Box E, Oak Ridge, Tenn. 37830 - 4 cc

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program, FA33,
Marshall Space Flight Center, Alabama 35812 - 1 cc

Mr. Dieter Franz, Shennandoah Development, Inc.
P. O. Box 1157, Shenandoah, GA 30265

Mr. Otis Rodgers, Georgia Tech, PPC

A-2517
under E25-624

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

January 7, 1980

Mr. Carl Conner
U.S. DOE
Solar Applications, CSD-PRO
Washington, D.C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79CS30397
Monitoring the Shenandoah (Georgia) Community Recreation Center
Solar Cooling, Heating and Hot Water System, December 1979.

Gentlemen:

Administrative:

No particular administrative difficulties have developed during this month.

Mr. Duffey was assigned to the project throughout the month and it is already apparent that having more nearly daily attention to the station is a genuine improvement. Elimination of the many trips from Atlanta to the site for operational checks and tape replacement is also conservative in time, funds, and fuel. Tapes are being mailed from the site to Georgia Tech taking about two days.

Data Acquisition System:

Data reduction programs have been under development and testing and we should have results from at least a simple version of the program during January. Plans are to continually upgrade data reduction and quality control in stages as the project proceeds.

Data reduction will be conducted on the HP1000 computer in the Aerospace School. All peripherals are available for this mini-computer to provide rapid processing of the data. Data read from the cassette tapes will be placed in a random access disc file, and at weekly intervals will be dumped on one of two larger tape reels to provide for secure back-up data storage. Data will always exist in three forms-cassette, disc file, and at lease one tape file.

One transducer was found to be out of place. This error was apparently caused by a discrepancy between two system schematics. The problem was immediately corrected by project personnel.

Mechanical Systems:

All systems continue to operate well. Shenandoah personnel have been encouraged to fix any residual leaks as quickly as possible to avoid further loss of glycol solution. We have also emphasized that periodic checks are necessary to insure that freeze protection remains adequate.

Respectfully submitted,

Sheldon M. Øeter
Project Coordinator

SMJ:maw

cc: Oak Ridge Operations Office, U.S. DOE, Attn: A. H. Frost, Jr.
Contract Division, P.O. Box E, Oak Ridge, Tenn. 37830 - 4 cc

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program, FA33,
Marshall Space Flight Center, Alabama 35812 - 1 cc

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265

Mr. Otis Rodgers, Georgia Tech, PPC

Dr. S. Peter Kezios, Director
School of Mechanical Engineering, Georgia Tech.

F25-624

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

February 19, 1980

Mr. Carl Conner
U.S. DOE
Solar Applications, CSD-PRO
Washington, DC 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79CS30397
Monitoring the Shenandoah (Georgia) Community Recreation
Center Solar Cooling, Heating and Hot Water System, January 1980.

Gentlemen:

Administrative:

No administrative difficulties have arisen during the period covered by this report (1 Jan. 1980 to 17 Feb. 1980).

Data Acquisition System:

As mentioned in the December report (dated 7 January 1980) primary emphasis during January was placed on development of software for organizing our data files and reduction of the performance data. This effort is now sufficiently complete for preliminary purposes; however, we intend to continually upgrade our data organization, quality control, and data reduction programs throughout the course of this project.

This monthly report had been deferred until now in the hope that the preliminary analysis of the December and January data could be included; however, some occurrances, described below, have made this goal impossible.

As noted in our report for November, (dated 5 December 1979) we checked out all sensors in the system early in this project. Nearly all the sensors were working well, and those found malfunctioning were replaced or repaired. In view of the fact that the transducers were functional more than two years after installation, it seemed prudent at that time to divert our efforts to implementing software and accumulate data routinely.

In early February as the data-reduction software was being developed, some discreprencies in the transducer outputs were noticed. Initially there were found to exist significant offsets (voltages at zero flow) in the flowmeter outputs.

It was assumed that these offsets resulted from deformation of the impact sensors of the drag-based flow meters. Such deformation can result from transient overloading this is not an unusual occurrance and does not effect the relative accuracy of the meter. A considerable effort was expanded modifying the data reduction program to compensate for these offsets, and plans were made to alter the data-logging program to correct the offsets. Once this work was accomplished, the preliminary data reduction program was run, and the results were completely ambiguous and unphysical.

In view of the invalid data which were found to exist, an immediate site visit to the building was made on Saturday, 16 February. After thorough inspection and testing of the system, we determined that interaction with the diactivated SDAS was causing the erroneous signals. The SDAS units were disconnected, and it was verified that the transducer signals returned to apparently correct values. Further analysis of this situation is underway, but it appears likely that none of the data collected before the SDAS was disconnected will be useful.

In retrospect, it may have been possible for us to deduce that the SDAS was degrading out data; however, since the faults that were obvious (such as the flow meter offsets and the high temperatures observed on a couple of the RTD's) could have resulted from normal problems (such as deformation of the impact sensors or loose connections to the RTD's), our failure to discover this problem earlier should be understadable. Nonetheless, we are chagrined that this problem persisted while we were envolved in other aspects of the work, but are relieved that once detected it could be quickly corrected.

The current status is that the SDAS is disconnected and our signals now appear to be correct. We can now monitor the sensor preformance more closely since software exists to inspect and reduce the data expediciously. It does not appear that any useful data will be available from prior to 16 February. The initial good data from the balance of February will be summarized in the next monthly report.

Mechanical Systems:

All systems continue to operate well. Shenandoah personnel continue to repair the remaining residual leask. As present the array seem very tight, and hopefully all the leaks (resulting primarily from overheating and thermal expansion while the array was drained) are now sealed. Mr. Bohannan and his crew are to be complemented on their continued diligent performance of this difficult work.

It appears that pump P-14 continues to operate occasionally in its recirculation mode. This is not hazardous but does waste power and will be corrected.

Respectfully submitted,

Sheldon M. Jeter
Project Coordinator

SMJ:maw

cc: Oak Ridge Operations Office, U.S. DOE, Attn: A. H. Frost, Jr.
Contract Division, P.O. Box E, Oak Ridge, Tenn. 37830 - 4 cc.

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program,
FA33, Marshall Space Flight Center, Alabama 35813 - 1 cc.

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265.

✓ Mr. Otis Rodgers, Georgia Tech, PPC

Dr. S. Peter Kezios, Director
School of Mechanical Engineering

E-25-624

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

April 18, 1980

Mr. Carl Conner
U.S. DOE
Solar Applications CSD-PRO
Washington, D.C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79S30397
Monitoring the Shenandoah (Georgia) Community Recreation
Center Solar Cooling, Heating and Hot Water System, March 1980.

Gentlemen:

Administrative: No difficulties have arisen

Data Acquisition System: Since the deactiation of the SDAS on 16 February our system has been providing data which appears to be basically valid. Inspection of the first data tapes indicated some anomolies in the calculated heat transport rates which were traced to offsets in some differential temperature measurements. These measurements (along with the fluid flow rates) are the most important and critical in the entire system. We spent the day of 8 March calibrating these offsets by imersing the differential temperature probes together in a flask of heated water. Further and continual attention to this problem seems warrented. It should be noted that required corrections such as their are only modifications to the calibration procedure and do not effect the usefulness of previously-gathered data.

A preliminary data reduction reveals the following performance for the period 1 Marcy - 27 March:

	(10^6 Btu)
inadiance on collectors	366.92
collected heat	80.21
heating load	39.63
DHW load	19.75
auxiliary heat	17.84

This indicates a collection efficiency of 22% and a solar contribution of 70% to the combined heating requirements.

A daily record of performance is attached. Also attached are graphical output for days of particular interest. The graphics on our HP 1000 system have significantly enhanced our ability to inspect the performance data and we plan to expand these capabilities during the project. The data displayed on the graphs are identified as follows:

HT = irradiance on collector plane (Btu/in/ft/ft)

F1 = flow rate thru collectors (Gal/min)

TD1 = temperature difference across collectors (F°)

T1 = collector inlet temperature (°F)

Some pertinent characterization are:

1. Note the negative collected energy on 2 March. This results from running the collector loop during the night as a futher safeguard against freezing. Since freeze-suppresant solution is weak, this action by Mr. Bohnannon seems quite appropriate. We don't want to risk any more freeze damage.

2. The negative collected energy on 7 March resulted from intermittant operation of the array during an overcast day. Warm water from the array was apparently not reaching the sensors during pumping. This sort of operation will be difficult to monitor precisely.

3. March 9 and March 18 show operation on high-performance days. The collector flow starts reasonably early and continues at a steady rate thru the day.

Mechanical Systems: The array remains reasonably tight but a few new leaks and creeps have developed. These are likely due to thermal motion and are expected in view of the numerous repairs in the system.

Respectfully Submitted,

Sheldon M. Jeter
Project Coordinator

SMJ:maw

cc: Oak Ridge Operations Office, U.S. DOE, Attn: A. H. Frost, Jr.
Contract Divison, P.O. Box E, Oak Ridge, Tenn. 37830 - 4 cc.

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program,
FA33, Marshall Space Flight Center, Alabama 35813 - 1 cc.

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265.

Mr. Otis Rodgers, Georgia Tech, PPC

Dr. S. Peter Kezios, Director
School of Mechanical Engineering

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  16480               2
AR1 .

ATE     QCOL      QIN       STORED    T-HEAT    T-HOT W   A-HEAT    S-HOT W  EPWR
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FINAL AVERAGE STORAGE TANK TEMPERATURE= 131.46DEG-F
AR2
2      -2.71060  7.68909 -3.14264  7.72223   .93380  7.51976   .37011 3.06E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 106.07DEG-F
AR3
3       1.95793 24.16215  2.59659  4.89707   .70695  7.37433   .44127 6.05E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 127.29DEG-F
AR4
4       7.50522 22.39465  1.29993  3.84149   .20929  0.00000   .47682 2.99E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 138.00DEG-F
AR5
NTERPOLATED BETWEEN 50,  65
5        .63150  5.71382 -1.92503  1.67357   .66691  0.00000   .43200 1.41E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 122.28DEG-F
AR6
5       8.76550 23.41608  3.31623  2.47560   .66915  0.00000   .79148 3.14E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 149.42DEG-F
AR7
7       -.22273  5.03671 -2.63408  1.76139   .35475  0.00000   .35575 1.11E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 127.82DEG-F
AR8
3       3.62977  8.28826  -.66545 -4.08249   .90442  0.00000  3.09621 1.23E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 122.50DEG-F
R9
        6.53932 20.28086  3.08355  0.00000   .75492  0.00000   .77314 2.14E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 147.73DEG-F
R10
        4.95726 18.66945  1.72658  0.00000   .64066  0.00000   .76821 2.05E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 161.86DEG-F
R11
        3.21911 19.21187   .45192  0.00000   .20378  0.00000   .62021 1.72E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 165.56DEG-F
R12
2       0.00000  1.10488 -2.18216  1.21572   .87794  -.00267   .89317 1.20E+02
INAL AVERAGE STORAGE TANK TEMPERATURE= 147.61DEG-F
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        0.00000  2.25482 -2.79382  3.69753   .28341   .11510   .39446 1.26E+02
INAL AVERAGE STORAGE TANK TEMPERATURE= 124.48DEG-F
R14
        6.89369 22.33957  2.25389  2.30840   .38467  0.00000   .67154 2.62E+02
INAL AVERAGE STORAGE TANK TEMPERATURE= 143.14DEG-F
R15
        6.63318 23.44444  1.90832  1.56031   .49449  0.00000   .78754 2.61E+02
INAL AVERAGE STORAGE TANK TEMPERATURE= 158.88DEG-F
R16
        2.32013 14.74896  -.70008   .93280   .46978  0.00000   .67532 1.55E+02
INAL AVERAGE STORAGE TANK TEMPERATURE= 153.08DEG-F
R17
        0.00000  1.55050 -1.41810   .29021   .57024   .46614   .35079 9.96E+01
INAL AVERAGE STORAGE TANK TEMPERATURE= 141.42DEG-F
R18
        6.34546 24.39411  2.72088   .14030   .49251  0.00000   .88651 2.88E+02
INAL AVERAGE STORAGE TANK TEMPERATURE= 163.77DEG-F
R19
        1.41155 11.64879 -1.97434  2.27083   .37828  0.00000   .52377 1.48E+02
INAL AVERAGE STORAGE TANK TEMPERATURE= 147.58DEG-F
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1       6.27989 21.16710  2.92055  0.00000    .64593   -.02075    .89682 2.30E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 155.46DEG-F
AR22
2       6.35069 23.92762  1.61574  1.22950    .93379  0.00000   1.26107 2.57E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 168.69DEG-F
AR23
3       1.38559 14.79652 -1.47189  1.25123    .22840  0.00000    .51705 1.53E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 156.43DEG-F
AR24
4        .61597  7.61315 -1.25958   .13631    .34047  0.00000    .49503 1.14E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 146.06DEG-F
AR25
5       4.89039 18.86304  1.62593   .56878    .51136   -.00019    .72310 2.31E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 159.46DEG-F
AR26
6      -.16902  3.79781 -1.90302   .50364    .34972  0.00000    .51083 1.02E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 143.80DEG-F
AR27
7       3.18373 14.90751   .69764   .39075    .40303  0.00000    .69537 1.97E+02
FINAL AVERAGE STORAGE TANK TEMPERATURE= 149.55DEG-F
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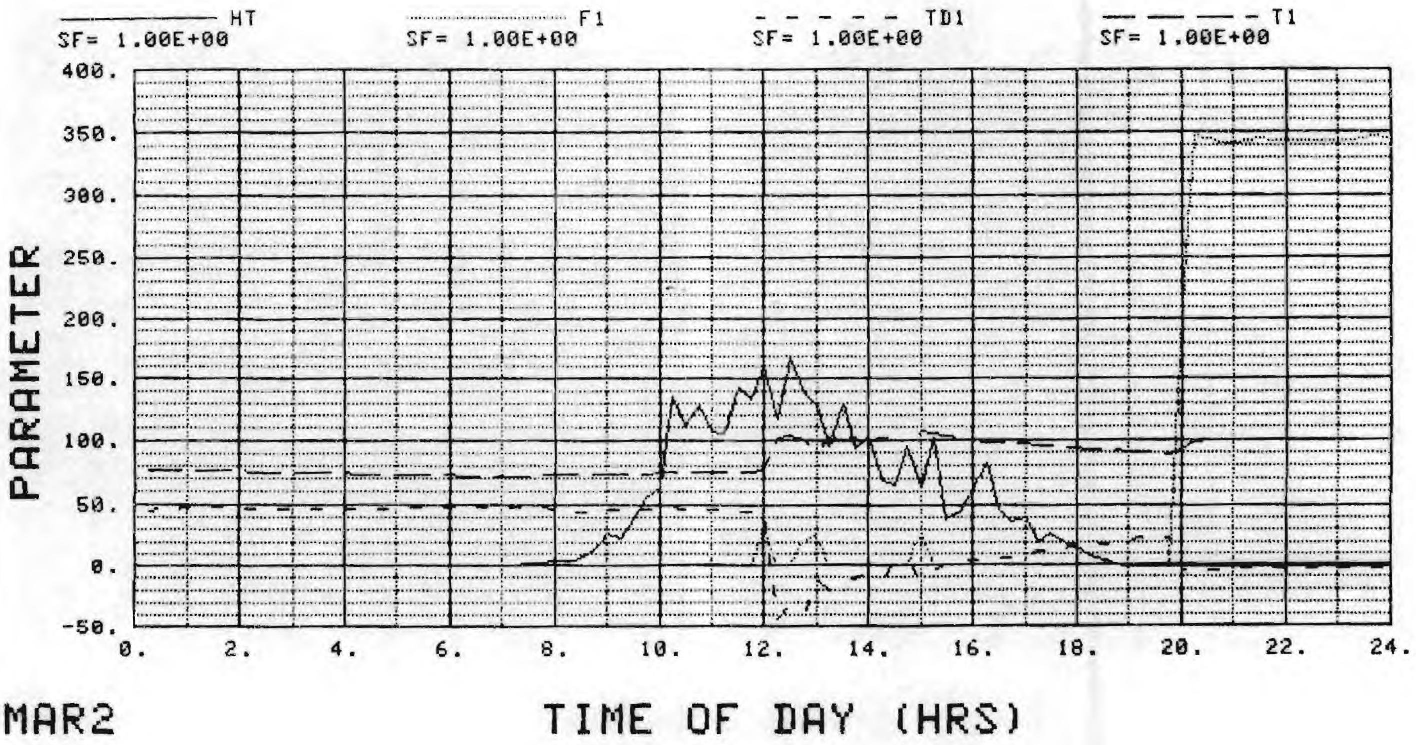
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F1
SF= 1.00E+00
TD1
SF= 1.00E+00
T1
SF= 1.00E+00
PARAMETER
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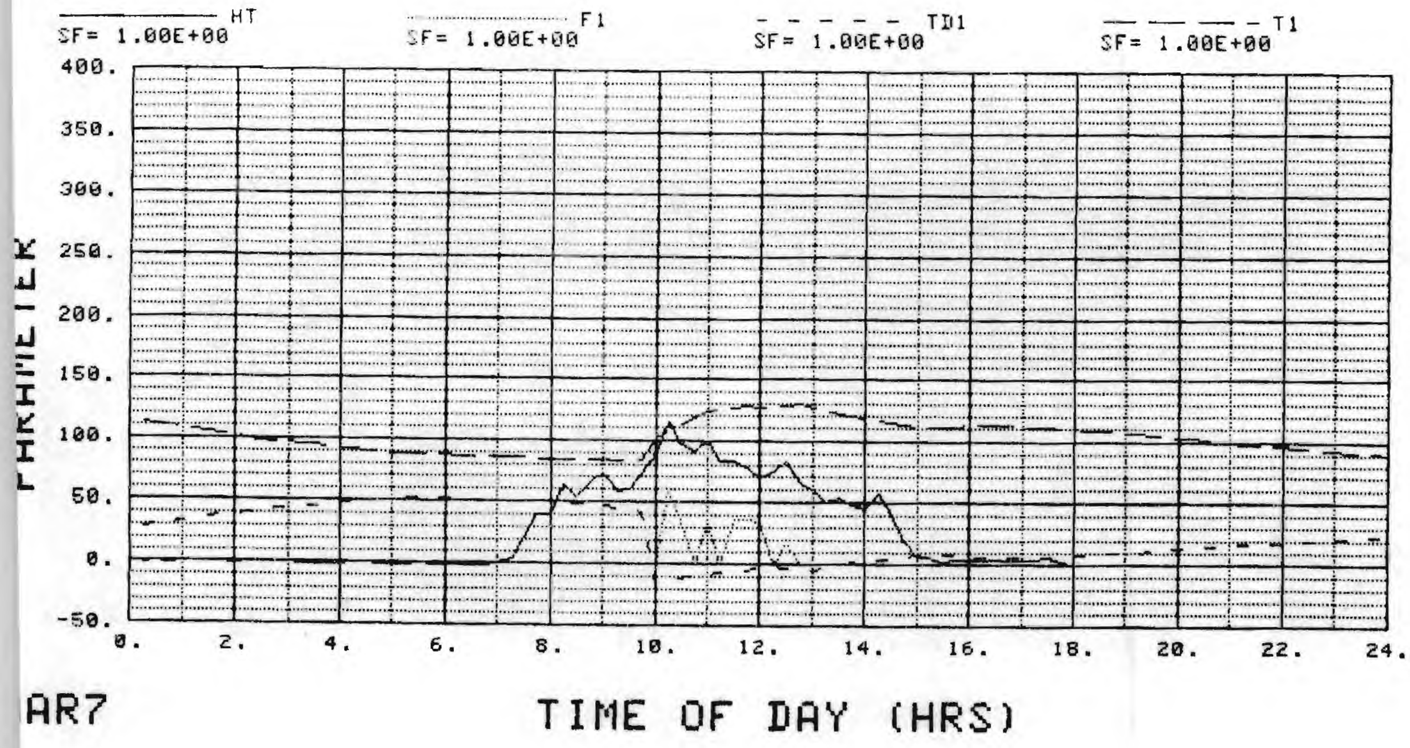
MAR2
TIME OF DAY (HRS)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F1
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TD1
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PARAMETER
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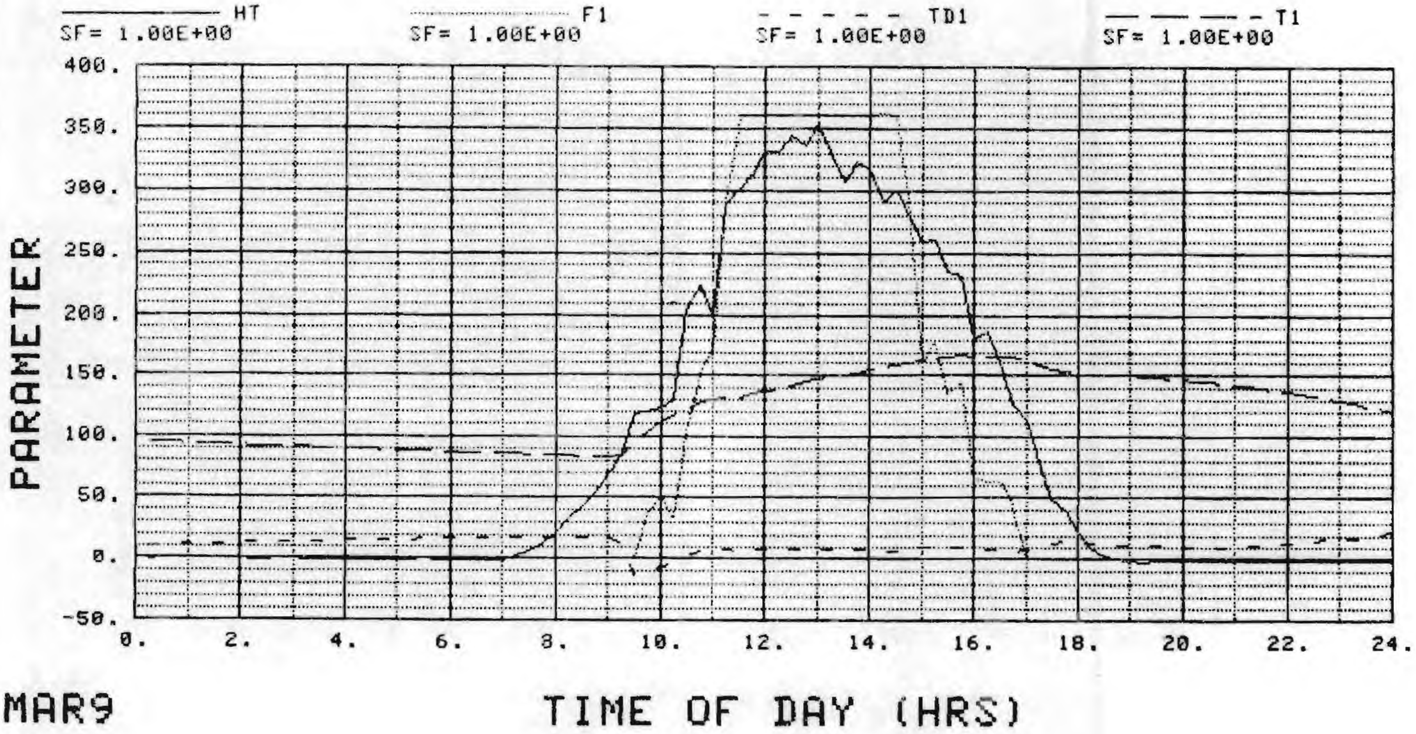
AR7
TIME OF DAY (HRS)



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F1 SF= 1.00E+00
TD1 SF= 1.00E+00
T1 SF= 1.00E+00
PARAMETER
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50.
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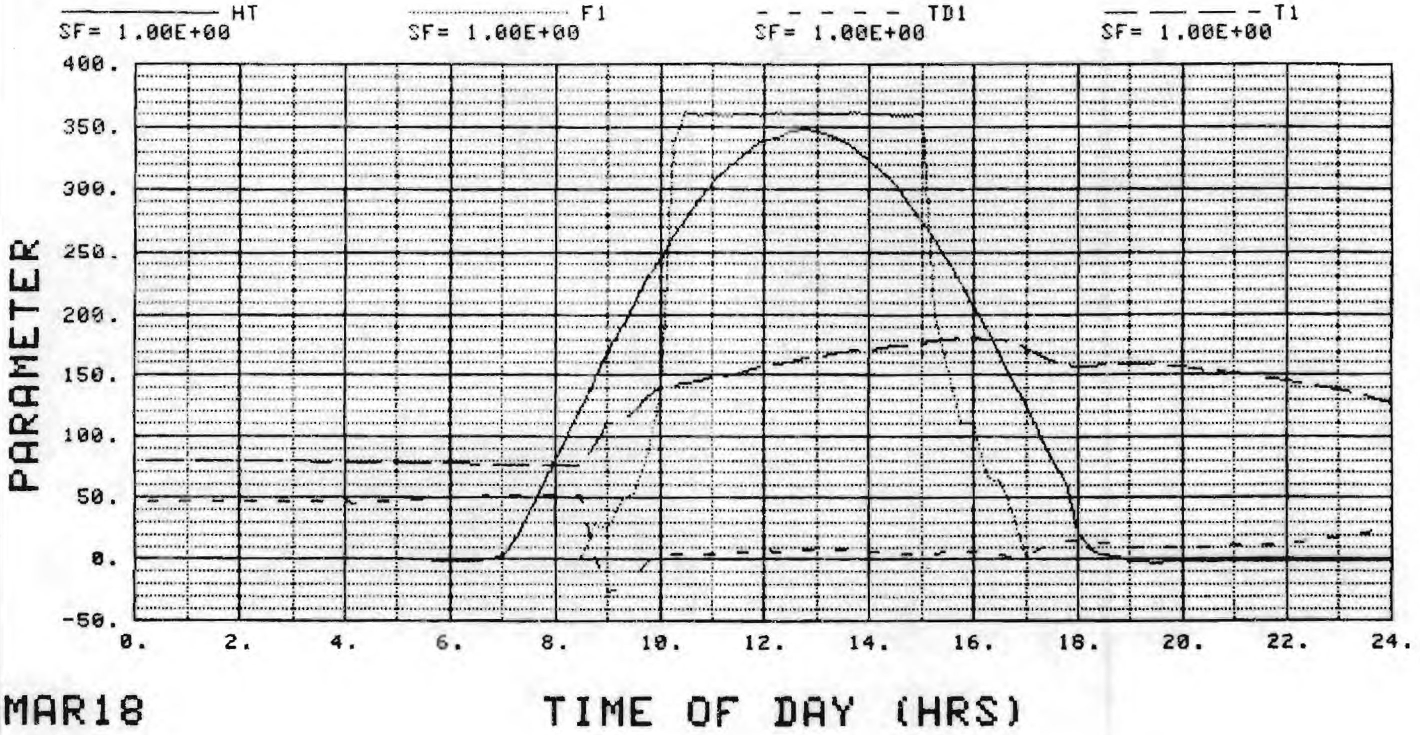
TIME OF DAY (HRS)

MAR9



HT SF= 1.00E+00
F1 SF= 1.00E+00
TD1 SF= 1.00E+00
T1 SF= 1.00E+00
PARAMETER
400.
350.
300.
250.
200.
150.
100.
50.
0.
-50.
0.
2.
4.
6.
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10.
12.
14.
16.
18.
20.
22.
24.
TIME OF DAY (HRS)

MAR18

E 25-624 or (under F16-658, A2517 ?) (E16-658 ? (under E25-624)

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

September 3, 1980

Mr. Carl Conner
U.S. DOE
Solar Applications CSD-PRO
Washington, D.C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79S30397 Monitoring the Shenandoah (Georgia) Community Recreation Center Solar Cooling, Heating and Hot Water System, May 1980.

Gentlemen:

Administrative: No difficulties have arisen. Because of some delay in initiation of this project and because of the failure of the SDAS after 5 December, more time than previously scheduled will be necessary to gather a year's data. A request for 6-month's no-cost extension has been initiated.

Data Acquisition System: This system continued to work rather well through May. One data gap appeared. This may have been caused by a nonreproducible fault in the interface buss.

Preliminary Data Reduction (in 10^6 Btu):

	April	May
Irradiance on Collectors	444	396
Collected Heat	93.5	56.5
Heating Load	14.8	*
DHW Load	55.4	7.7
Auxiliary Heat	33	266
Collection Efficiency	21%	14.3%
Solar Participation	53%	*

*Cooling season began 29 April. Software incomplete for this Analysis.

Respectfully submitted,

Sheldon M. Jeter
Project Coordinator

SMF:ew

cc: Oak Ridge Operations Office, U.S. DOE, Attn: A.H. Frost, Jr.
Contract Division, P.O. Box E, Oak Ridge, Tenn. 37830 - 4 cc.

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program,
FA33, Marshall Space Flight Center, Alabama 35813 - 1 cc.

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265

✓ Mr. Otis Rodgers, Georgia Tech, PPC

Mr. S. Peter Kezios, Director
School of Mechanical Engineering

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      829                         15
MAY1

                                     SPACE         WTR HEAT        AUXL   ELET TNK   UNBALANCE
DAY QIN   QCLT Q-TNK DU-TNK HEAT   COOL   TOTL SOLR AUX     ENRG   POWR TMP   HEAT COOL

 1 15.7   1.97  0.00    .07    .49  1.17   .40  .66  .01     4.7   177. 162  5.68   0.00
 2 17.6   4.39  0.00   1.86    .02  2.26   .47  .29 -.03     9.1   224. 169 11.18   0.00
 3 10.6    .30  0.00   -.84    .12  4.93   .06  .00  .00    17.2   188. 174 18.17   0.00
 4 16.9   2.53  0.00   -.52    .13  4.89   .03  .00  .00    15.2   259. 169 18.07   0.00
 5 16.9   2.65  0.00   -.08    .22  2.48   .08  .44  .15     6.6   212. 167  8.97   0.00
 6 17.8   4.53  0.00   1.53    .13  1.96   .25  .21 -.02     6.2   206. 169  8.83   0.00
 7 15.4   1.51  0.00    .32    .21  3.41   .24  .20  .08    12.3   202. 182 13.01   0.00
 8 11.2    .22  0.00    .07    .22  3.18   .18  .28  .09    13.7   173. 184 13.41   0.00
 9 20.0   4.59  0.00   -.43    .29  2.56   .26  .24  .12     5.3   226. 186  9.81   0.00
10 19.7   5.21  0.00   -.58    .32  1.27   .72  .37  .35     -.0   218. 175  4.74   0.00
11 19.2   5.53  0.00   -.01    .30  1.51   .41  .43  .12     0.0   219. 173  4.83   0.00
12 15.5   2.40  0.00   1.40    .32  2.87   .22  .39  .05     9.6   171. 174 10.07   0.00
13  5.2   0.00  0.00    .34    .21  4.11   .08  .08  .05    17.3   161. 187 16.70   0.00
14  3.2   0.00  0.00  -1.21    .47  2.25   .38  .78  .02     4.9    93. 188  5.29   0.00
15 15.5   2.07  0.00   -.13    .03  4.16   .23  .17  .00    10.2   164. 176 12.12   0.00
16  5.8   -.38  0.00   -.25    .25  3.20   .25  .20  .22     7.2   164. 176  6.59   0.00
17  2.7   0.00  0.00   -.55    .11  3.18   .26  .28  .16    12.8   160. 172 13.03   0.00
18 13.5   1.17  0.00   -.42    .18  4.21   .27  .36  .07    13.4   201. 168 14.55   0.00
19  8.9   -.15  0.00   -.35    .26  4.21   .26  .41  .00    14.2   168. 165 13.88   0.00
20 10.8    .19  0.00   -.33    .26  3.54   .35  .74  .04    10.8   151. 163 10.75   0.00
21  -.0   0.00  0.00-19.77    .06  0.00   .02  .11 -.01     0.0    27.  40 19.68   0.00
INITIAL DATA MISSING
22  1.5   0.00  0.00 18.90    .11   .51   .13  .09  .00     1.7    46.  61-17.47   0.00
23  6.6   -.19  0.00   -.36    .18  1.63   .34  .48  .05     6.6   126. 153  6.26   0.00
24 15.9   1.84  0.00   -.39    .02  3.44   .43  .48  .07    10.9   143. 150 12.67   0.00
25 15.9   2.21  0.00   -.37    .06  2.66   .25  .46 -.01     6.8   140. 146  9.04   0.00
26 17.2   3.00  0.00   -.30    .22  3.41   .17  .20  .03     7.3   210. 144 10.20   0.00
27 16.2   1.65  0.00   -.24    .20  3.25   .11  .13  .04     8.9   183. 142 10.48   0.00
28 12.1   1.06  0.00   -.21    .24  3.20   .27  .18  .17     9.7   174. 140 10.46   0.00
29 16.4   2.31  0.00   -.18    .26  3.54   .15  .22  .04     8.4   195. 138 10.51   0.00
 0 17.1   3.19  0.00   -.16    .26  3.76   .22  .18  .10     6.6   204. 137  9.51   0.00
 1 15.5   2.81  0.00   -.15    .07  4.70   .15  .16  .08     8.3   169. 135 11.03   0.00


 5 39.6   5.66  0.00   -.33    .62   .00   .77  .92  .20    26.6   535. 157 31.21   0.00
FINAL AVERAGE STORAGE TANK TEMPERATURE= 135.40DEG-F
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      829                           16
PR1

                                    SPACE        WTR HEAT        AUXL   ELET TNK   UNBALANCE
AY QIN   QCLT Q-TNK DU-TNK HEAT    COOL   TOTL SOLR AUX      ENRG   POWR TMP   HEAT COOL

1 22.5   6.99  2.75  1.82    .64   0.00 2.75 2.46   .76       .8   240. 154   2.62  0.00
2  5.1   -.23 -2.61 -2.56    .31    .01 1.43 1.34   .52       .1   115. 152    .68  0.00
3  7.0    .66   .23   .07   0.00   0.00 6.06 1.51 4.45       6.2   182. 140    .78  0.00
4 21.1   6.70  2.48  1.85   0.00   0.00 8.45 2.65 5.95       5.7   309. 154   2.07  0.00
5 22.9   6.99  -.08  -.45    .60   0.0011.21 5.20 5.99       4.7   345. 157    .36  0.00
6 21.8   6.70   .73   .36   1.45    .0310.40 4.46 5.94       6.1   331. 153    .55  0.00
7  6.9   -.24 -2.02 -1.84   0.00   0.00 4.45  .44 4.08       4.2   123. 150   1.34  0.00
8  7.1   -.04  1.93  1.45   0.00   0.00  .25  .00  .00       4.5   139. 154   2.76  0.00
9 21.9   5.75  3.19  2.43    .69   0.00  .24  .00  .00       0.0   216. 164   2.39  0.00
0 22.2   5.55  2.12  1.16   1.86   0.00  .05  .00  .00       0.0   231. 177   2.48  0.00
1 18.5   4.04 -1.71  -.46   1.28   0.00 1.23 1.49  .11       -.1   204. 181   1.92  0.00
2  2.0   0.00 -2.21 -2.34   0.00   0.00  .82  .61  .35       0.0    93. 171   1.52  0.00
3  1.6   0.00 -1.92 -1.76   0.00   0.00  .60  .19  .54       0.0    91. 154   1.16  0.00
4  7.3    .10 -2.17 -1.74    .25   0.00  .21  .32  .17       0.0   100. 139   1.38  0.00
5 21.7   6.31  3.01  2.64   1.46   0.00  .36  .62  .01       0.0   177. 141   1.85  0.00
6 22.0   6.90  2.90  2.19   1.31   0.00  .68  .91 -.03       0.0   282. 162   2.75  0.00
7 19.2   4.68  1.37   .51   1.34   0.00  .32  .64 -.05       0.0   230. 172   2.52  0.00
8 10.4    .35 -1.95 -2.02    .61   0.00  .55  .65 -.01       0.0   116. 166   1.20  0.00
9  8.1    .56 -1.82 -1.63    .20   0.00  .71  .68  .12       0.0   120. 152   1.29  0.00
0 17.9   6.08  2.56  2.27    .97    .03  .55  .86 -.01       0.0   256. 155   2.28  0.00
1 16.8   2.96  1.26   .61    .39   0.00  .33  .59 -.05       0.0   246. 166   1.63  0.00
2 20.8   6.10  3.44  2.53   0.00   0.00  .47  .66 -.07       0.0   279. 181   3.10  0.00
3 19.7   4.18  1.89   .68   0.00   0.00  .35  .57 -.07       0.0   219. 194   3.15  0.00
4 17.7   1.83  -.38 -1.04   0.00   0.00  .37  .49 -.10       0.0   159. 191   2.51  0.00
5 16.9    .55 -2.63 -2.83    .65    .04  .54  .55 -.05        .7   162. 175   2.86  0.00
6  7.0   -.09 -1.45 -1.30   0.00   0.00  .86  .72 -.02       0.0   100. 159    .36  0.00
7 12.0   -.17 -1.27 -1.02   0.00   0.00  .37  .38  .04       0.0   109. 150    .48  0.00
8 14.9   2.77  -.80< -.02    .50   0.00  .32  .61  .02       0.0   179. 144   1.97  0.00
9 14.2   2.92  0.00   .46   0.00   0.00  .28  .50 -.00       0.0   135. 148   2.18  0.00
0 17.3   4.54  0.00  1.58    .33    .04  .21  .49 -.03       0.0   183. 156   2.42  0.00


4 44.4   9.35   .69   .16   1.48   0.00 5.54 3.06 2.86       3.3   565. 160   5.45  0.00
FINAL AVERAGE STORAGE TANK TEMPERATURE= 162.73DEG-F
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E-16-658

under
E 25-624

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

October 1, 1980

Mr. Carl Conner
U.S. DOE
Solar Applications CSD-PRO
Washington, D. C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79S30397 Monitoring the Shenandoah (Georgia) Community Recreation Center Solar Cooling, Heating and Hot Water Systems, June 1980.

Administrative: A request for no-cost extension of this project was forwardedto Mr. A. H. Frost, Jr., on 3 September 1980. The extension is required primarily because our data was contaminated by a failure of the IBM Site Data Acquisition System prior to mid-February 1980.

Data Acquisition System: The system continued to operate basically well during June except for two distinct problems:

(1) Data gaps have appeared for two reasons. One reason is apparently hardware related and is an intermittent failure in communication between the HP9825A (the calculator) and the HP3455 (the DVM) along the HP-IB buss. Some data gaps have appeared because execution is halted when an excessive number of faults are encountered (to protect the equipment). This problem has not been solved because to identify and rectify the cause would involve removal of the HP3455 for service by the manufacturer; consequently, the cure would be worse than the disease. We have alleviated this problem by increasing the limit on the error counter before halting and by having the operator reset the error counter periodically.

The second reason is now known to be an obscure software problem. When the operator installs a new tape, the calculator should record the next data on track 0 file 10 and proceed through track 0 and switch to track 1 during the week. This reversion to the first data file is signified by a programmed key on the calculator. At some time during the early summer an erroneous program was loaded into the calculator. It is unknown how this program was generated or why it may have been loaded. (Program copies reside in the first 9 files of each data tape.) This program did <u>not</u> include the statement to switch to track 0; therefore, the first file used would be track 1 file 10. During the week, track 1 would be exhausted and the program on schedule would switch to track 1 file 0. This occurred because a program variable (not the actual system state) contained the track identifier. The result is that some previous data is overwritten causing a data gap. This problem now is seen to have a simple logical explanation; however, we spent much time searching for hardware or operational errors before discovering the cause. This problem has been solved by reloading the correct program into the calculator and copying correct versions onto all data tapes. Further, the program now accesses the track identifier directly rather than reporting the inreliable program variable when file status is requested.

(2) The second data system problem is in transducer accuracy, especially the critical temperature differences. The "high-quality" Rosemount differential transducers have not given high-quality results. A particular problem is a significant offset voltage at null temperature difference. We are attempting to recalibrate all temperature difference transducers. The excessive energy unbalances on the absorption chiller are thought to be caused by this problem.

Preliminary Data Reduction (in 10^6Btu):

	June*
Irradiance on Collectors	321
Collected Heat	61.3
DHW Load	5.2
Cooling Load	(Analysis incomplete)

*Missing: 7, 11, 21-26 June

Respectfully submitted,

SHELDON M. JETER
Project Coordinator

SMJ:ew

cc: Oak Ridge Operations Office, U.S. DOE, Attn: A.H. Frost, Jr.
Contract Division, P.O. Box E, Oak Ridge, Tenn. 37830 - 4 cc.

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program.
FA33, Marshall Space Flight Center, Alabama 35813 - 1 cc.

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265

Mr. Otis Rodgers, Georgia Tech, PPC

Dr. S. Peter Kezios, Director
School of Mechanical Engineering

E25-624

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

October 9, 1980

Mr. Carl Conner
U.S. DOE
Solar Applications CSD-PRO
Washington, D.C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79S30397
Monitoring the Shenandoah (Georgia) Community Recreation
Center Solar Cooling, Heating and Hot Water System,
July, 1980.

Administrative: No difficulties have arisen.

Data Acquisition System:

(a) Data gaps appear in the record for July. Those caused by the invalid control program predominate. This problem is solved effective September, as noted previously. One gap from the unresponsiveness of the voltmeter appeared. This problem cannot be solved without major maintenance; however, since it is apparently temperature related, this problem may disappear as colder weather arrives.

(b) Flow meter F6 was removed by maintenance personnel because it had begun to leak and was likely to fail. Fortunately, the data analysis program can be modified to correct for the absence of this sensor by correlating flow in this circuit with power to the pump motor. The defective flowmeter body was replaced by a similar body on hand at Georgia Tech. This is apparently a general defect in the RAMPO bronze-body flowmeter because the bond between the steel sensor mount and bronze body is very weak.

Preliminary Data Reduction: Deferred pending program modifications.

Respectfully submitted,

S. M. JETER
Project Coordinator

SMJ:ew

cc: Oak Ridge Operations Office, U.S. Doe, Attn: A.H. Frost, Jr.
Contract Division, P.O. Box E, Oak Ridge, Tenn. 37830 - 4 cc.

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program,
FA33, Marshall Space Flight Center, Alabama 35813 - 1 cc.

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265

Mr. Otis Rodgers, Georgia Tech, PPC

Dr. S. Peter Kezios, Director
School of Mechanical Engineering

Otis Rodgers

E25-642

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

October 16, 1980

Mr. Carl Conner
U.S. DOE
Solar Applications CSD-PRO
Washington, D.C. 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79S30397 Monitoring the Shenandoah (Georgia) Community Recreation Center Solar Cooling, Heating and Hot Water System, August 1980.

Administrative: No difficulties have arisen. We are proceeding on the assumption that our request for no-cost extension will be granted to allow collection of at least one year's data.

Data Acquisition System:

(a) For the reasons discussed previously, data gaps appear in the record for August.

(b) The "READ" errors reported by the data system controller were thought to be temperature-related as noted in the report for July. Further investigation indicates instances of obviously spurious data during late evenings and early mornings. At these times the cooling system is disabled, and it seems that the record high ambient temperatures combined with heat loss from the piping and vessels to produce excessive temperatures around the data system. The digital voltmeter was apparently susceptible to this high temperature resulting in error responses and spurious data. We plan to add a ventilating fan to alleviate this problem in the future.

(c) We are very nearly current with data processing having recovered time lost in maintenance, trouble-shooting, and loss from service of the HP1000.

Mechanical Systems: A pipe cap in a collector module came off during collector operation causing a loss of expensive glycol solution. Our provision of a low water-level shut-off prevented complete loss of solution and consequent damage to the main circulation pump. This failure was apparently not related to either the history of freeze-damage or overheating but was the result of poor workmanship in assembling the module.

Data Reduction:

(a) Preliminary results are deferred pending the completion of program modifications.

(b) Modifications include multiple redundant heat balances and comparison with model results.

(c) An enhanced data quality control algorithm may now be necessary to screen for spurious data resulting from temperature-induced erratic reading from the voltmeter.

Respectfully submitted,

SHELDON M. JETER
Project Coordinator

SMF:ew

cc: Oak Ridge Operations Office, U.S. DOE, Attn: A.H. Frost, Jr.
Contract Division, P.O. Box E, Oak Ridge, Tenn. 37830 - 4 cc.

Mr. D. W. Westrope, NASA/MSFC, Solar Heating and Cooling Program,
FA33, Marshall Space Flight Center, Alabama 35813 - 1 cc.

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265

Mr. Otis Rodgers, Georgia Tech, PPC

Dr. S. Peter Kezios, Director
School of Mechanical Engineering

E25-624
E16-6[illegible]

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

December 12, 1980

Mr. Carl Conner
U.S. Department of Energy
Solar Applications CSD-PRO
Washington, DC 20585

Subject: Monthly Progress Report, Contract No. DE-AS05-79S30397
Monitoring the Shenandoah (Georgia) Community Recreation
Center Solar Colling, Heating and Hot Water System,
September-October 1980.

Administrative: No response has been received formalizing our request for a no-cost extension on this project. We would appreciate early action on this request which will allow our completion of the technical tasks.

Data Acquisition System: After considerable effort toward data reduction and analysis, we are convinced that significant hardware problems exist which will prevent adequate analysis of the building performance unless corrected. This problem is evidenced by considerable errors in the energy accounting of the building. The primary problem appears to be innaccurate temperature-difference measurements. These are necessary to calculate the energy transfer rates. We have attempted to compensate for these errors by measurements of the null temperature-difference voltage offsets in the fluid. These efforts appear to be unsuccessful and laboratory measurements will be necessary. We plan to begin these measurements just after the holiday break.

Laboratory measurement of the voltage offsets should allow the correction of nearly all recorded data. We remain confident that the building performance can be adequately accessed from the results of this project.

Respectfully submitted,

Sheldon M. Jeter
Project Coordinator

SMJ/rc

cc: Oak Ridge Operations Office, U.S. DOE, Attn: A.H. Frost, Jr.
Contract Division, P.O. Box E, Oak Ridge, TN 37830 - 4 cc.

Mr. Lance L. Leonaitis, Southern Solar Energy Center,
61 Perimeter Park, Atlanta, GA 30341

Mr. Dieter Franz, Shenandoah Development, Inc.
P.O. Box 1157, Shenandoah, GA 30265

Mr. Otis Rodgers, Georgia Tech, PPC

Dr. S. Peter Kezios, Director
School of Mechanical Engineering

FINAL REPORT

PERFORMANCE EVALUATION
OF THE
SHENANDOAH COMMUNITY SOLAR RECREATIONAL CENTER
FOR THE YEAR 1980

Submitted to the

U.S. Department of Energy
Contract DE-AS05-79C-30397

by

J. I. Craig
S. M. Jeter

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering
School of Aerospace Engineering

December 1983

ABSTRACT

The Shenandoah Solar Recreational Center, when completed in early 1977, was the largest building to have most of its heating, air conditioning, and hot water needs met by solar energy. Principal components of the building solar energy system are a 1,121 sq-m array of modularized flat plate collectors with 2,300 sq-m of aluminum foreground reflectors integrated into a sawtooth wood truss roof, a 15.1 cu-m collector loop buffer tank, a 56.8 cu-m hot water storage tank, two 113.6 cu-m chilled water storage tanks, and a nominal 100 ton single stage absorption chiller. The system is interconnected by means of primary-secondary loops and was designed for simultaneous operation of all subsystems in either the heating or cooling modes. Control is by means of conventional HVAC pneumatic and electric control equipment.

Transient thermal simulation studies were used to design the solar energy system. The collector array size was fixed so as to provide a significant fraction of the building annual thermal load, and the hot and chilled water storage volumes and other system functions were sized to maximize economic benefit. On this basis the predicted solar fractions were 95% space heating, 64% space cooling and 50% hot water.

The building operation was monitored for a period on one year (February 1980 through February 1981) using a calculator-based data acquisition system with 80 sensors located throughout the building. This report presents an analysis of this data and an evaluation of the building performance over the year. The annual collector efficiency was found to be 19% and the overall annual solar fraction (combined thermal loads met from solar) was determined to be 39%. It is felt that this level of performance for a demonstration system is quite acceptable.

TABLE OF CONTENTS

APPENDIX

1.0 INTRODUCTION

1.1 Background

The Shenandoah Solar Recreational Center, when completed in early 1977, was the largest building to have most of its heating, air conditioning, and domestic hot water needs met by solar energy. Principal components of the building solar energy system are the 5017 sq-m of flat plate solar collectors facing south at a 45 deg tilt and the 2415 sq-m of highly polished aluminum foreground reflectors facing north at 36 deg so as to reflect additional solar radiation during the summer months onto the collectors. The collectors were installed in 63 large modules, each 6.3 m wide and 2.62 m high. The collectors are double-glazed with low-iron glass and the copper absorber plate is coated with electroplated black chrome (a=0.95, e=0.07) and insulated on the back to a K value of 0.28 W/sq-m-C. The large modules were factory assembled for low cost installation on the building and the collectors are rated for a 260C dead-end temperature. Thermal storage is provided by a 56.8 cu-m hot water storage tank and two 113.6 cu-m chilled water storage tanks. In addition a 15.1 cu-m tank in the primary collector flow loop is used as a buffer to prevent excessive cycling of the system. The main storage tanks are all buried underground in earth berms around the building.

The Recreation Center was first designed as a conventionally heated and cooled building, but was completely redesigned as a solar building when a solar energy design grant was received from the Energy Research and Development Administration (ERDA) [1]. As a consequence, the building as it now exists was designed and built from the outset to include solar energy utilization systems as an integral part of the mechanical and architectural design. The building has been operating in all its modes since its opening in early April 1977.

The initial solar design contract was awarded to the Shenandoah Development Corporation and Georgia Tech in July 1975 [1]. Following successful completion of this design contract and acceptance of the proposed building and solar design by the funding agency, a grant was made to the developer to cover the added cost of installing the solar energy utilization equipment [2]. Construction was begun in April 1976 and completed in the spring of 1977. The building was first occupied in April 1977.

While all parts of the solar energy system were tested prior to completion of the building, a number of minor and a few serious problems were encountered during the first year of operation. Many of these problems were directly due to the inability to thoroughly test the mechanical system for prolonged periods of operation in each of the major modes. For example, most of the initial testing work was done during the winter of 1976-77 and it was not possible to completely test all aspects of summertime operation with a fully loaded absorption chiller driven directly by the solar collector system. As a result, it was necessary during the first year of operation to closely monitor the operation of the system and carefully diagnose any apparent malfunctions or unexpected behavior. These efforts were seriously hampered by the lack of any type of performance monitoring instrumentation system.

The most serious problem to occur involved freeze damage that occurred to the collectors during the winter of 1977-78. The damage involved extensive freeze rupture of manifold piping within the 63 large collector modules that occurred when the collector array was drained. Water remained trapped behind unguided expansion joints and caused freeze rupture of the associated piping. This damage was repaired during the summer of 1978 by Georgia Tech personnel. The collector manufacturer replaced the original expansion loops with a concentric pipe expansion joint that should not trap water in the modules.

Continuing problems with the reliable operation of the collector recirculation freeze protection system originally designed into the solar energy system forced a detailed reevaluation of this approach during 1978. Much of the difficulty involved the reliability of the electric power to the building, especially during severe wintertime weather conditions, and the overall reliability of the very complex control system used to operate the building. Under a contract from the Department of Energy (DoE) in 1979 [3], the collector loop subsystem was redesigned to incorporate a separate primary glycol loop through the collectors. This approach isolates the collectors in a small hydronic loop that can be economically filled with a glycol antifreeze solution to protect the collectors and mechanical components from freeze damage. The heat is extracted from this loop by a large tube-and-shell heat exchanger that was added to the system for this purpose. Details of this work are included in the final report [4].

During the 1978-1979 time period, provisions were made to incorporate the Recreation Center building system into the national data acquisition network so that performance evaluation studies could be carried out on this and numerous other solar assisted buildings in the US [5]. Under terms of the original equipment grant, approximately 80 different temperature, flow, power, solar radiation and control state sensors were installed in the building system. In addition, a small compact computer-based data acquisition system was designed and the components acquired [6]. With the advent of the national data network, no continuing funds were provided to actually operate this system. Instead, it was directed that the already installed sensors be modified and connected to a new data acquisition system to be installed by the national data network contractor (IBM). This was accomplished and the system was operated in this way for a period of roughly one year. Since the IBM system was operated remotely, none of the site personnel or Georgia Tech staff were ever aware of the precise status of the equipment or the beginning and ending dates of operation.

Problems with this manner of operation, especially in a hybrid system in which the complete sensor and data acquisition system was not designed by one organization, resulted in numerous instances of questionable sensor performance or system operation. Such difficulties eventually resulted in the decommissioning of the IBM data acquisition system and the award of a contract to Georgia Tech to reactivate the original data acquisition system, recalibrate the sensors and operate the equipment for a period of one year from January 1980 to January 1981. This report presents a summary of that work and the performance analysis carried out using the data collected.

1.2 Present Status

As of the data of this report, the Recreation Center has been in continuous operation for a little over 6 years. With the exception of the periods of time following the freeze rupture damage to the collectors (1978) and during the mechanical modifications to the collector loop, the solar energy system has continued to operate. It was shut down during the above periods so that repair and modification work could be carried out. The mechanical system is attended to on a regular basis and periodic seasonal testing and adjustments are performed as appropriate. There have been the expected number of small problems associated with mechanical component failures, occasional leaks, etc.

The Georgia Tech data acquisition system used to carry out the studies reported on here was installed at the site and operated for a little over one year (1980). At the completion of the measurement phase of the study in early 1981, the principal data acquisition components were removed and returned to the campus for use in the performance evaluation and analysis studies that followed. At the present time, there is no data acquisition system at the site, although the lobby system status display board that was connected to the data system still remains. It still indicates the status of all pumps but no longer reports any of the data system measurements. All of the thermal, flow, and electric power sensors and their associated cabling are still in place. The pyranometers were returned to the campus for repair and recalibration. The IBM data acquisition system installed prior to 1980 was disconnected in February 1980 and was removed from the site later and returned to IBM.

1.3 Scope of the Evaluation Study

The performance evaluation study reported here is based on measurements of the solar energy system performance carried out at the site from December 1979 to March 1981. The original contract specifications were for a period of measurement and study from September 1979 to September 1980 but due to delays in transferring the contract to Georgia Tech, the actual work was not begun until November 1979. A number of problems associated with the simultaneous connection of the IBM data acquisition system to the sensors were not fully diagnosed until mid-February

1980. Consequently, all the data obtained prior to that point were discovered to be irreparably corrupted by interaction effects with the IBM data system. Valid data were taken from February 16, 1980 through March 11, 1981.

This report presents the results of extensive analyses of this performance data. No attempt is made to describe in detail the actual solar energy system design study, nor to relate the experience with the construction and initial checkout of the system. Finally no discussion will be presented concerning the continuing operation of the system outside the period of operation of the site data acquisition system. These matters have been covered elsewhere [6,7].

The analysis of the system performance has involved far more effort that originally estimated for a number of reasons to be described in following sections. One of the most troublesome aspects of the study has been the presence of inconsistencies in the various heat flow calculations. This involves both subsystem and total system energy balance calculations. Numerous attempts have been made to rectify these difficulties, but in the absence of redundant measurements, it has not been possible to make much sense out of many of the subsystem performance calculations. The major purpose of the report is to outline the attempted calculations and to present a drastically simplified model for performance analysis. The key results of the study are reasonably accurate figures for the overall fraction of thermal load carried by the solar energy system, efficiency measurements of the conventional fuel boiler (natural gas fired), and efficiency measurements for the collector array.

2.0 BUILDING DESIGN

2.1 Objectives

The function of the Shenandoah Recreation Center was to act as the nucleus of a new town to be built some 45 miles southwest of Atlanta. The town was to include a wide range of housing types, recreation facilities, parks and natural spaces along with an industrial and office park to provide attractive employment opportunities for the residents. Within the Center are facilities such as a professional sized ice hockey rink, a gymnatorium, athletic support facilities, community meeting rooms, and sales, exhibition and office areas for the developer.

The solar energy utilization system was designed to reliably supply the largest practicable fraction of the building thermal loads (which consist of space heating, space cooling and domestic water heating). Reliability and conservation in design were stressed and extensive use was made of experience gained from participation with Westinghouse in the design, construction and operation of the Towns Elementary School solar energy system in Atlanta.

2.2 Architectural Design

The building itself is basically a 59,000 sq-ft square two-story structure approximately 210 ft to a side. Earth is bermed up against the exterior walls to the full height to provide a high level of insulation. The only window area is on the north side and around the entrance on the west side. The solar collectors are integrated into the roof in a novel manner to incorporate foreground reflectors for collector augmentation during the summer months. This is accomplished by using a wooden truss, folded plate roof structure. These features are shown in Figures 1 and 2. The roof material itself is aluminum, with mill finish aluminum being used on the south-facing slopes to which the collectors are mounted and with anodically polished aluminum (Coilzak) being used on the north-facing slopes which serve as the collector foreground reflector surfaces.

The mechanical system incorporates numerous energy conservation features that together with the unusual architectural design served to make the building one of the most energy conservative structures of its kind at its completion. Careful design of the building and the conventional HVAC system makes the contribution of solar heating and cooling appear less significant on a cursory examination. However, the first principle of solar energy utilization is reduction of energy demands. In this respect, the Shenandoah Recreation Center is a blend of solar technology, energy conservative building design, and efficient HVAC system design.

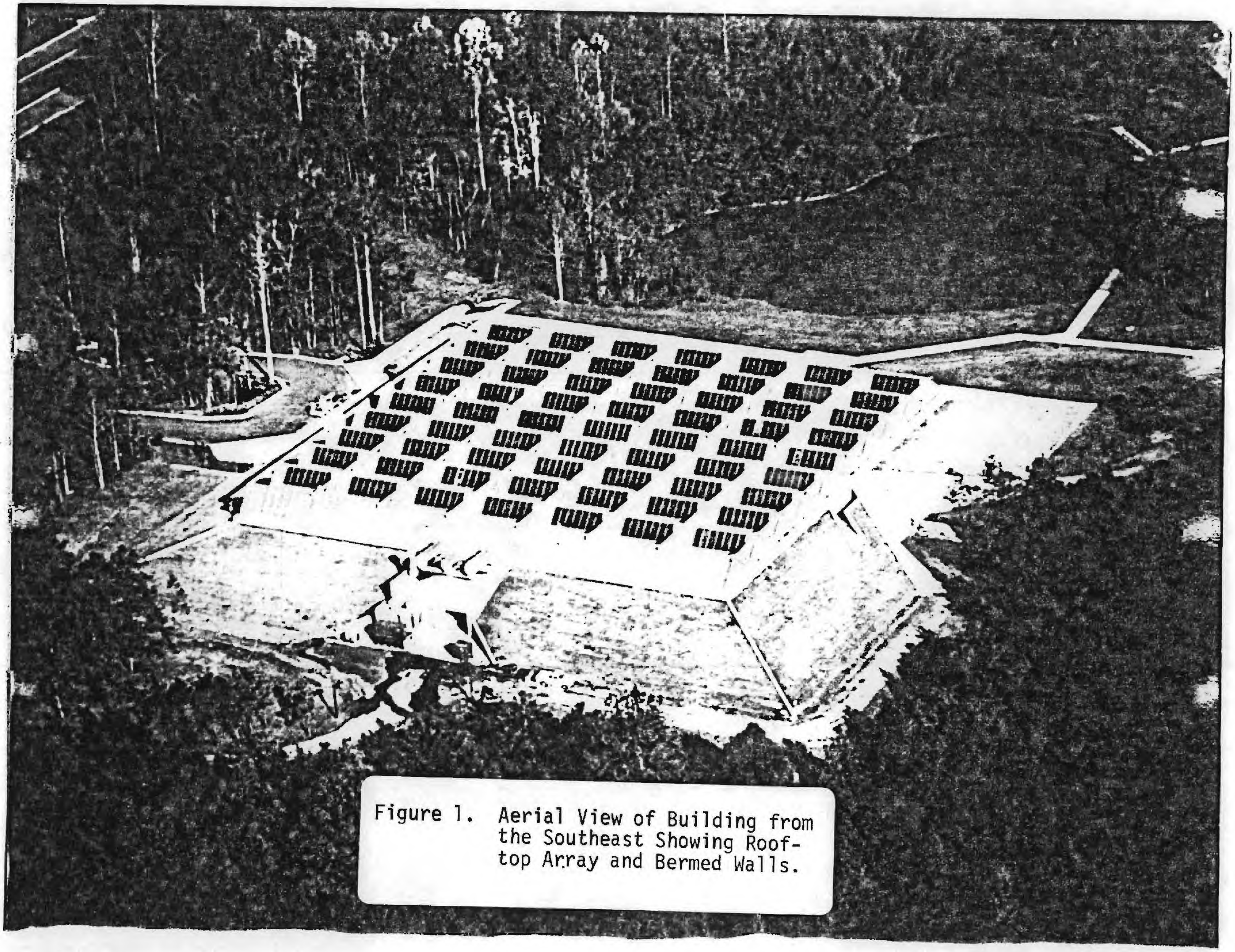


Figure 1. Aerial View of Building from the Southeast Showing Rooftop Array and Bermed Walls.

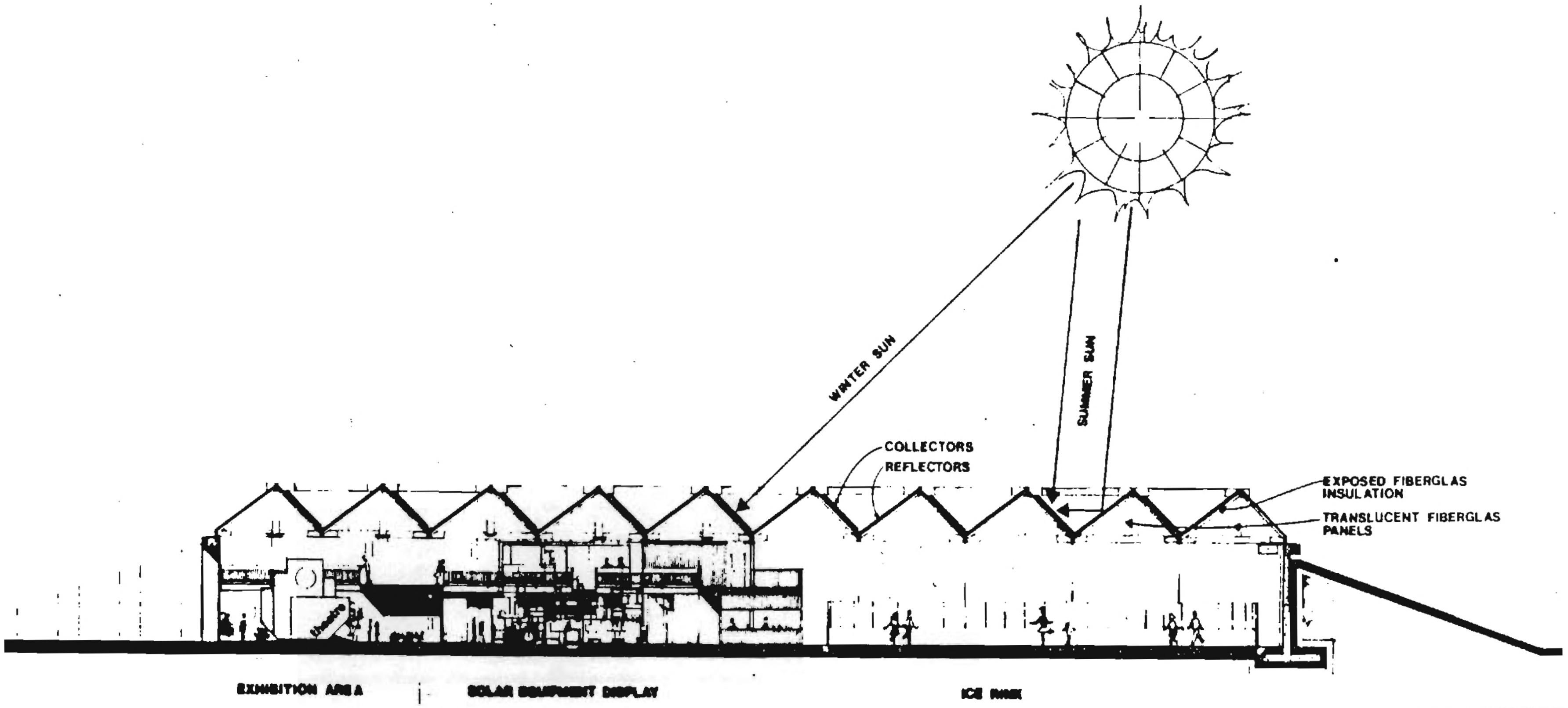


Figure 2. Architectural Cross Section of Building Showing Integrated Collector/Reflector System.

2.3 Solar Energy System Design

The solar energy utilization system was designed almost eight years ago, and during the intervening years, the technology has matured in many ways. Many of the approaches taken in the design have since proven to be of questionable or no use. New HVAC components specifically designed for solar energy utilization have been developed. New collectors more suitable for medium temperature operation with air conditioning systems have been produced. Nonetheless, there are features of the Shenandoah design that have proven extremely useful and innovative, even by today's standards.

Overall, however, the single biggest difficulty with the system design is simply its sheer complexity which is a consequence of the design decision to attempt to extract as much useful solar energy as possible for all of the thermal loads within the building. The result is a system of such complexity, with numerous operational modes, dozens of pumps and valves, and a intricate control system, that it has been extremely difficult to insure that it is fully functional at all times. Experience has shown that even slight misadjustments or small malfunctions in the system can result in drastic losses in performance or downright waste of both solar and conventional energy.

The actual solar energy utilization system design has been thoroughly covered in an ASME paper [8] that is included as Appendix I to this report. Only the key assumptions made, the overall design approach, and the final design specifications are included in this section.

The principal assumptions made at the outset of the design study were as follows:

1. A high performance flat plate, double-glazed collector factory assembled into large modules would be used,
2. Water would be used as the working fluid and the thermal storage medium,
3. Chilled water would be used as the principal energy storage subsystem for cooling mode operation (as opposed to large volume hot water storage),
4. A primary-secondary loop pumping system using constant speed pumps and modulating control valves would be used to allow simultaneous operation of the collector, storage, and boiler subsystems to meet a given load.

The assumptions were heavily based on experience that the designers gained working with Westinghouse on the earlier Towns School solar energy system. Several specific choices were made as a result of this experience:

1. Use all copper plumbing with copper collectors, rather

than the aluminum collectors with iron piping,

2. Use warm water recirculation rather than drain-down for collector freeze protection to minimize complexity and problems in refilling and restarting following cold nights,

3. Avoid use of variable speed pumps,

4. Use rigid metallic foreground reflectors rather than the aluminized mylar film employed at Towns.

The design approach involved developing a detailed computer-based model for the solar energy utilization system and then using this model to calculate annual system performance for a typical year for various combinations of parameters and configurations. The inputs to any solar simulation are the insolation, weather, and the building internal loads such as occupancy and lighting. These inputs are not deterministic in general, but include a significant random component, so that a rational simulation of the system should be based on a stochastic model for the solar components. For a number of reasons, including the lack of an adequate statistical solar input model, this approach was not followed. The approach taken was to employ transient simulations using deterministic models for all components and a basic time step of one hour. Certain subsystem performance calculations were based on quasi-steady state computations using monthly averaged daily solar data and did not include daily variations due to random weather patterns. Where possible, a subsystem was designed based on these simpler conditions, but if not, the parameters were left to be determined in the full system simulation studies.

The approach taken was to design what is basically an experimental solar energy system using available commercial components and typical construction methods wherever possible. Conventional energy costs in 1976 were low enough so that it was not economically practical to design a solar powered cooling system for operation in the Atlanta region. That is, it was not possible to design a system that would provide a net life-cycle cost savings compared to a conventional fueled system over an assumed lifetime (25 years) using commonly accepted inflation and fuel escalation rates. While on these terms an economically superior system was not realized, a minimum-cost design was made. Cost engineering methods using an iterative design procedure involving analytical mechanics, architectural design, mechanical design, and building construction experience were used to design most major components except for the collector array size. Since the major emphasis of the project was to design a research/demonstration system capable of supplying roughly 50% of the building energy demands, a collector area of approximately 1,000 sq-m was fixed at the outset.

The design procedure consisted of two phases:

(a) determine the collector area and tilt in order to meet a desired solar augmentation for average conditions over a one year period, and

(b) determine storage volumes for both hot and chilled water in to handle daily variations in the solar radiation input.

Average daily and hourly insolation for Atlanta were used in the first phase to compute average monthly and yearly collector heat production for various areas and tilt angles. The combination of a high annual hot water load and a large cooling load placed incompatible requirements on the tilt angle since a relatively flat (10 to 20 deg) tilt is desirable for maximum summertime heat production while a larger (40 to 50 deg) angle is required for maximum annual heat production. The solution used was to employ foreground planar reflectors to augment the collector array. In this approach which was first used at the Towns School [9], the collectors are set to a high tilt to handle wintertime or annual load requirements and foreground reflectors are installed to provide additional solar radiation during the summer. This approach was studied in detail during the design contract and is reported on in [8]. Other studies have since been made of this method [10].

Phase (b) involved carrying out detailed transient simulations of the solar energy system and building in order to estimate the effect of daily variations in insolation and usage patterns. Thermal energy storage is required to meet loads which do not coincide with the diurnal variation in insolation or the random daily changes in weather conditions. No storage means that loads not coincident with insolation cannot be met, but too large a storage results in excessive thermal inertia and heat loss. Simulations of short-term transient performance were carried out to determine the fraction of load met by the system for various hot and chilled storage volumes. Sizes were selected to minimize transient auxiliary energy usage over typical summer and winter days.

The building thermal loads were estimated from detailed hourly calculations carried out with the aid of computer programs developed by APEC and the American Gas Association [11,12]. In order to keep computer costs within reason, these computations were handled separately from the solar energy system simulation studies. In other words, no attempt was made to couple the simulation of the solar energy system with the building load calculations. This drastically simplifies the problem since it is not necessary to recalculate building loads for each simulation run. On the other hand, it assumes that the building and the mechanical HVAC system are uncoupled, that is, the HVAC system must, either through solar or conventional means, provide the necessary heating or cooling.

A schematic diagram of the mechanical system is shown in Figure 3. The basic design is a primary-secondary loop configuration in which the system is constructed from a series of

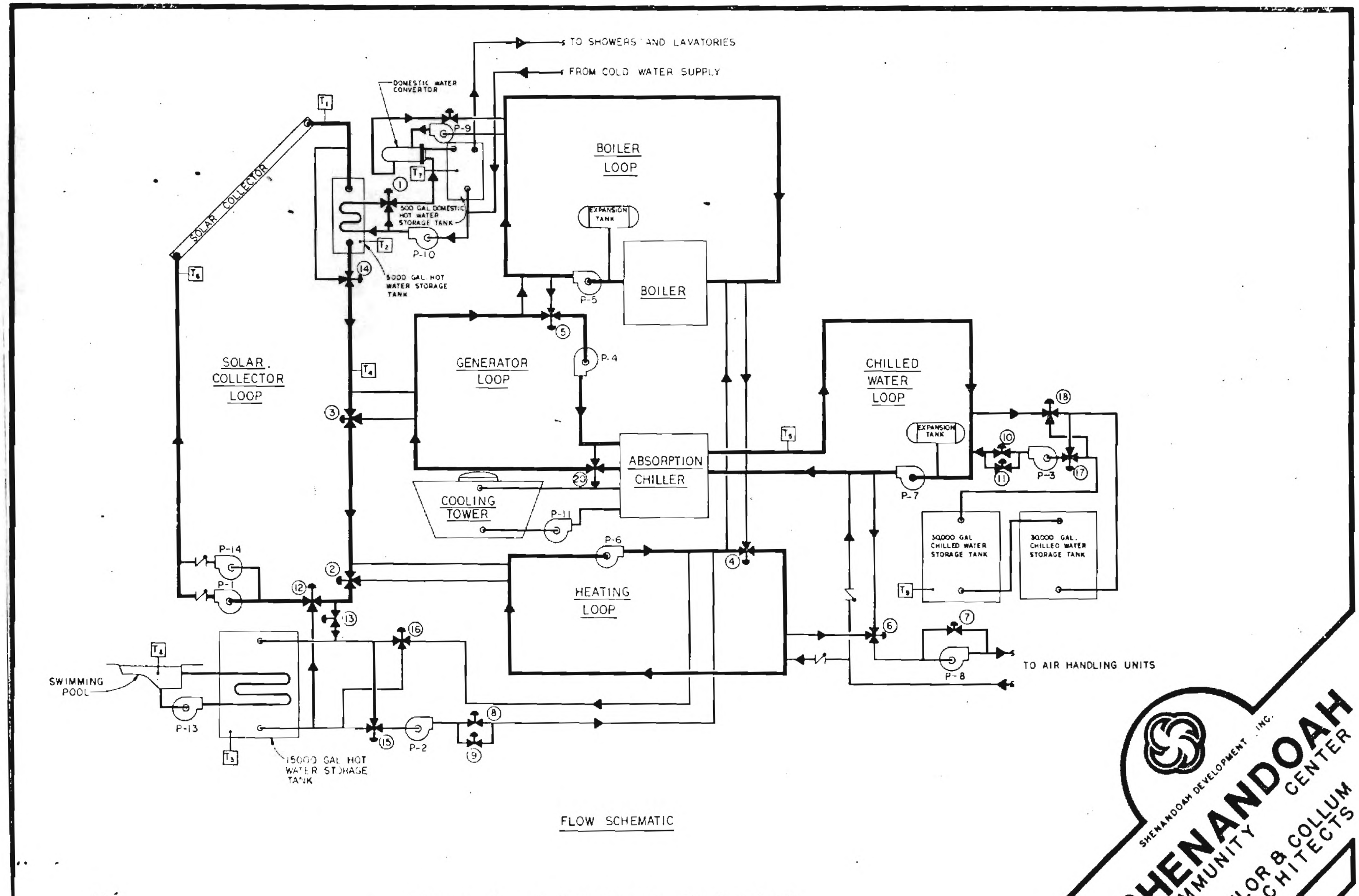


Figure 3. Solar Energy Mechanical System Schematic Diagram.

interconnected pumping loops. Modulating valves are used to control the amount of fluid, and therefore energy, transferred between loops. One or more loops are used to control energy transfer to or from a component and each of these subsystems operates somewhat independently of the others.

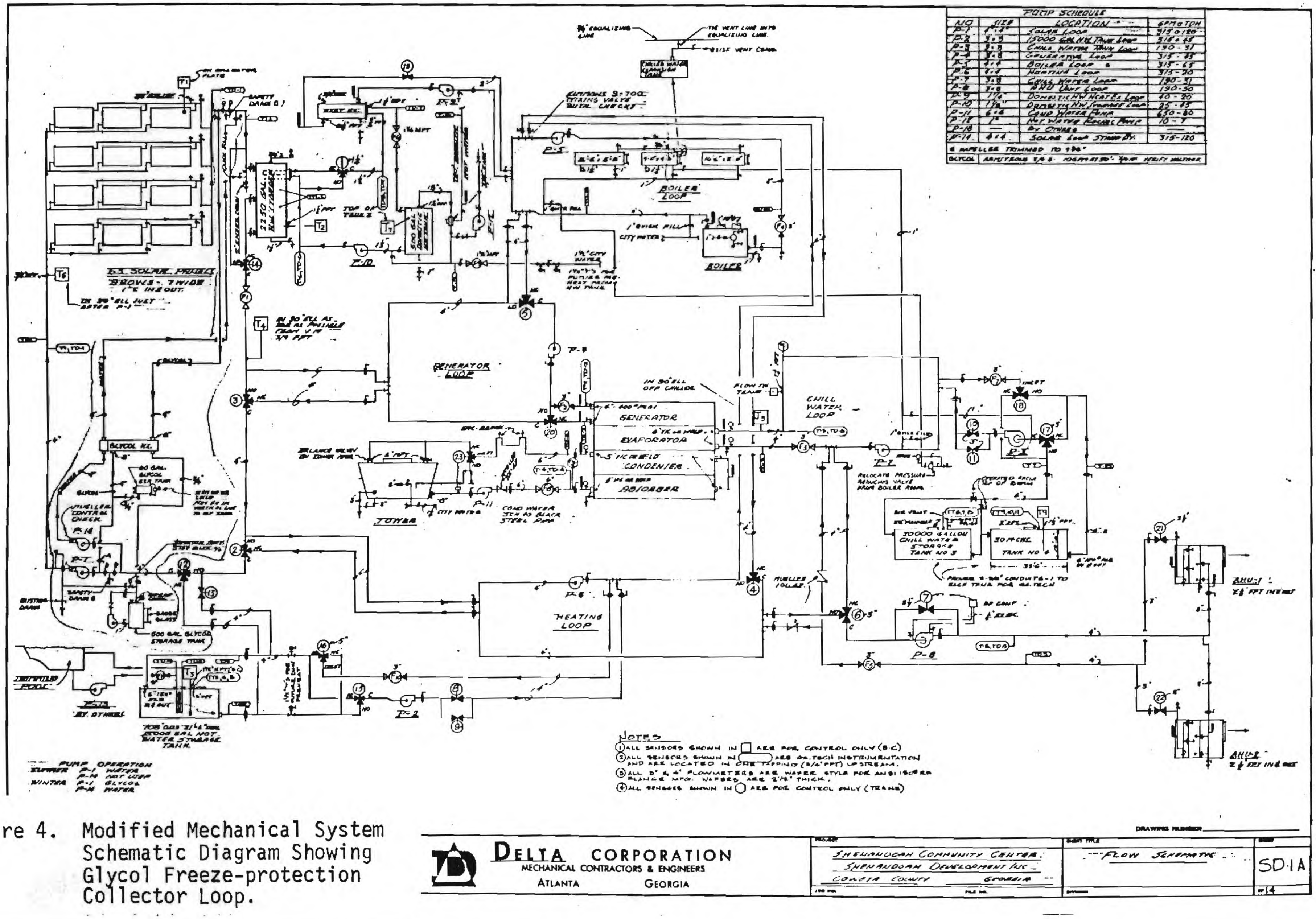
For example, the collector loop consists of pump P1, the collectors, a buffer tank, and the valves 14, 3 and 2. Fluid is circulated in this loop at a constant rate until the temperature is raised enough to match the load, at which point valves 2 or 3 are modulated to divert energy (flow) to the heating or generator loops. The small buffer tank is used to avoid unnecessary cycling of the control system. Similar operation for the other loops can be deduced from the figure or from a more detailed description included in Appendix I..

One aspect that deserves further comment is the relative ease with which auxiliary energy can be added from the boiler, either to the chiller or to the building heating loop, simultaneously with collector operation. The hot and chilled storage systems function similarly. While these concepts look good in theory, one of the big disappointments of the evaluation study was the relatively difficulty experienced in trying to made the rather complex control system handle these simultaneous demands. Small errors or component malfunctions often caused the system to operate well off of design conditions and at drastically reduced effectiveness. Additional problems associated with instrumenting this highly interconnected system contributed to difficulties in properly evaluating the overall system performance.

It should be pointed out that the collector loop was extensively modified just prior to the study reported here in order to remedy problems encountered earlier with operation of the freeze protection subsystem. As noted earlier, failure of the recirculation freeze protection system coupled with the inability to totally drain the array of water in an emergency resulted in extensive damage to collector module piping. An exhaustive study was made of possible solutions and the recommendation was made to modify the collector loop to isolate it from the rest of the system and then operate the collectors with an antifreeze solution [4]. The isolation was accomplished by introduction of a large tube-and-shell heat exchanger and a schematic of the resulting configuration is shown in Figure 4. Note that no additional pumps or modifications to the collector array or data acquisition system were required. The freeze protection pump, P14, was used to power the collector-heat exchanger loop and the original collector loop pump, P1, was used to couple the heat exchanger to the rest of the system.

2.4 Predicted Performance

The design and modeling techniques outlined in the previous sections were used iteratively to arrive at the final design parameter values which are summarized below. The predicted annual performance can then be obtained from a final simulation



POMP SCHEDULE			
NO	SIZE	LOCATION	GPM @ TDH
P-1	4"x4"	Solar Loop	315 @ 180
P-2	3x3	15000 Gal HW Tank Loop	315 @ 45
P-3	3x3	Chill Water Tank Loop	190 - 31
P-4	3x8	Generator Loop	315 - 85
P-5	4x4	Boiler Loop *	315 - 65
P-6	4x4	Heating Loop	315 - 20
P-7	3x8	Chill Water Loop	190 - 31
P-8	3x8	AHU Unit Loop	190 - 50
P-9	1¼"	Domestic HW Heat Ex Loop	40 - 20
P-10	1½"	Domestic HW Storage Loop	25 - 35
P-11	6x6	Cond Water Pump	650 - 80
P-12	1"	Hot Water Recirc Pump	10 - 7
P-13	—	By Others	—
P-14	4x4	Solar Loop Standby	315 - 180
* IMPELLER TRIMMED TO 9¾"			
GLYCOL	ARMSTRONG 3/4 B - 10 GPM AT 30' - 3/4 HP VERIFY VOLTAGE		

NOTES

① ALL SENSORS SHOWN IN ☐ ARE FOR CONTROL ONLY (B-C)

② ALL SENSORS SHOWN IN ⬭ ARE OA. TECH INSTRUMENTATION AND ARE LOCATED IN ONE TAPPING (3/4" FPT) UPSTREAM.

③ ALL 3" & 4" FLOWMETERS ARE WAFER STYLE FOR ANSI 150# RF FLANGE MTG. WAFERS ARE 2½" THICK.

④ ALL SENSORS SHOWN IN ⬡ ARE FOR CONTROL ONLY (TRANE)

DRAWING NUMBER

DELTA CORPORATION
MECHANICAL CONTRACTORS & ENGINEERS
ATLANTA GEORGIA

PROJECT
SHENANDOAH COMMUNITY CENTER
SHENANDOAH DEVELOPMENT INC
COWETA COUNTY GEORGIA

SHEET TITLE
FLOW SCHEMATIC

SHEET
SD-1A
OF 14

Figure 4. Modified Mechanical System Schematic Diagram Showing Glycol Freeze-protection Collector Loop.

run using these parameters and the reference design inputs.

Loads: The building loads computed for 1964 test reference year (TRY) data were based on the following assumptions:

Building Area:	2,800	sq-m
Building Volume:	17,000	cu-m
Extreme Temperatures:	-12C	winter
	33C/25C	summer
Night Setback:	-/+ 2.8C	winter/summer
System Shutoff:	9PM-5AM	weekdays
	10PM-5AM	weekends
Ventilation:	0.76	liter/sec-sq-m
	7.6	liter/person
Peak Cooling:	143/176	tons (100/400 persons)

The load was recorded as hourly heating, cooling and hot water loads in computer files and retained for use in the solar studies. Key results from the calculations are listed below:

Max transmission load	10.89	btuh/sq-ft
Max O/A sensible load	9.58	btuh/sq-ft
Max O/A latent load	0.0	
Max balance heat	0.0	
Installed heating cap	21.51	btuh/sq-ft
Design heating load	20.47	btuh/sq-ft
Annual heating peak	13.74	btuh/sq-ft
Hours at installed peak	27	

Max transmission load	3.09	btuh/sq-ft
Max O/A sensible load	2.76	btuh/sq-ft
Max O/A latent load	5.92	btuh/sq-ft
Annual cooling peak	338.26	sq-ft/ton
Installed cooling cap	38.38	btuh/sq-ft
Design cooling load	36.32	btuh/sq-ft
Annual cooling peak	35.48	btuh/sq-ft
Hours at installed peak	55	

The ice rink was not included as a space conditioning load since the ice-making equipment itself provides this function for its zone, however, the large hot water requirement for resurfacing the ice was included.

Solar Fractions: The solar energy system design studies yielded the following key parameter values as those that would maximize the life-cycle cost savings for a baseline collector area that would supply roughly 50% of the building energy demands:

Collector area:	982 sq-m
Collector tilt:	45 deg
Reflector tilt:	36 deg (full slope coverage)
Collector type:	2-cover, selective coated, as described in the text
Hot water storage:	56.7 cu-m (15,000 gal)

Chilled water storage: 226.8 cu-m (60,000 gal)
Buffer tank: 15.0 cu-m (4,000 gal)

On this basis, the predicted annual performance for heating, cooling and hot water were:

Space heating: 95%
Space cooling: 64%
Hot water: 50%

The performance values were based on assumed equipment that did not entirely agree with what was ultimately installed. However, the differences in heating and cooling fractions were estimated to be small and no further simulation studies were carried out. The hot water fraction is questionable because of changes in equipment selection and in system operation.

3.0 INSTRUMENTATION SYSTEM

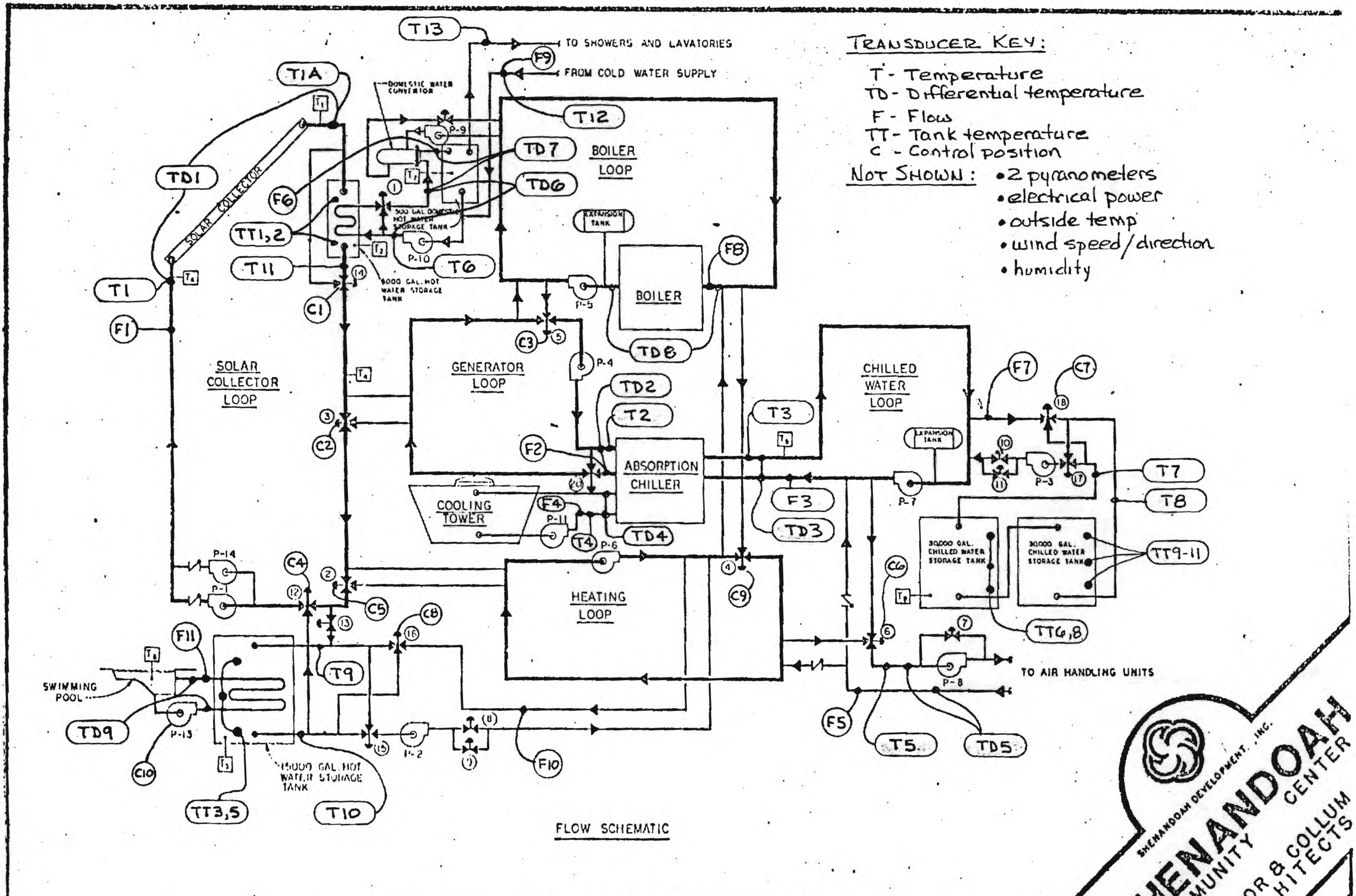
3.1 Objectives

The Georgia Tech data acquisition system at the site was included in the initial design and in the construction grant. All the sensors and wiring were installed and the data recording equipment was acquired. However, before the equipment was put into operation, a dual IBM data system was installed to replace the Georgia Tech equipment. This system connected directly to the installed sensors so that the IBM and Georgia Tech systems could be operated in parallel if desired. The systems were both designed to be operated in an unattended mode. The IBM system transferred data nightly via telephone connections to a remote processing, archiving, and analysis facility. The Georgia Tech system stored data on small magnetic tape cartridges that were retrieved at weekly intervals in connection with a site visit and system inspection. The sensor selection and placement and the measurement procedures were designed to provide sufficient data to allow complete determination of the energy flow and utilization within the system on an hourly, daily and monthly basis.

A schematic diagram of the HVAC system showing the locations of all sensors is presented in Figure 5. Table 1 lists the characteristics and identification of each of the sensors. With modulating control valves in primary-secondary loops, it becomes rather difficult to accurately sense energy flow between various subsystems. Instead, the approach taken in this system was to monitor the energy flow to or from each subsystem rather than between subsystems. This requires a single flow sensor and a differential temperature measurement for the collector loop, but it requires three such measurements for the chiller (generator-absorber, condenser, and evaporator circuits). In the case of the thermal storage tanks, both the energy transfer (to and from) and the stored energy were sensed, the first by a heat flow circuit similar to that for the collectors and the latter simply by measurement of the temperature distribution throughout the tanks.

3.2 Sensors

Platinum resistance temperature detectors (RTD's) were used for all temperature measurements and individual bridge circuits were provided for maximum flexibility. Critical differential temperature measurements such as those associated with intercomponent heat flow were made by using a direct differential bridge circuit that avoids the errors associated with differencing readings from separate bridges. Three and four-wire sensor connections were used for maximum accuracy. Pipe mounted sensors were installed in accordance with ISA and NBS recommendations. Thermocouples, while considerably cheaper on a per sensor basis, were not used for two reasons: (1) accuracies obtainable in standard industrial or commercial configurations



TRANSDUCER KEY:

T - Temperature
TD - Differential temperature
F - Flow
TT - Tank temperature
C - Control position

NOT SHOWN:
- 2 pyranometers
- electrical power
- outside temp
- wind speed/direction
- humidity

Figure 5. Mechanical System Schematic Diagram Showing Sensor Locations and Designations.

TABLE 1
BUILDING SENSOR CHARACTERISTICS

ID	Description	Type	ID	Description	Type
HT	Tilted Global	Eppley PSP	F1	Collector Flow	Impact
T1	Collector In	RTD	F2	Generator Flow	Impact
T2	Generator In	RTD	F3	Evaporator Flow	Impact
T3	Evaporator Out	RTD	F4	Condenser Flow	Impact
T4	Condenser In	RTD	F5	Building Flow	Impact
T5	Building In	RTD	F6	DHW Solar Flow	Impact
T6	DHW In	RTD	F7	CWT Store FLow	Impact
T7	To CWT Top	RTD	F8	Boiler Flow	Impact
T8	To CWT Bot	RTD	F9	CW Input Flow	Impact
T9	To HWT Top	RTD	F10	HWT Store Flow	Impact
T10	To HWT Bot	RTD	F11	Swim Pool Flow	Impact
T11	Buffer Out	RTD	EP1	P1/P14 Power	Wattmeter
T12	CW Input	RTD	EP2	P4/7/15 Chiller	Wattmeter
T13	DHW Out	RTD	EP3	P3 CWT Power	Wattmeter
T14	Zone 1 Temp	RTD	EP4	P11 Cond Power	Wattmeter
T15	Zone 2 Temp	RTD	EP5	P5 Boiler Power	Wattmeter
T16	Outside Temp	RTD	EP6	P6 Bldg Loop	Wattmeter
T1A	Collector Out	RTD	EP7	P2 HW Store	Wattmeter
TT1	Buffer Tank T	RTD	EP8	P8 AHU Loop	Wattmeter
TT2	Buffer Tank B	RTD	EP9	P9 DHW Boiler	Wattmeter
TT3	HWT Top	RTD	EP10	P10 DHW Solar	Wattmeter
TT4	HWT Mid	RTD	EP11	AHU-1 Power	Wattmeter
TT5	HWT Bot	RTD	EP12	AHU-2 Power	Wattmeter
TT6	CWT-1 Top	RTD	EP13	Cooling Tower	Wattmeter
TT7	CWT-1 Mid	RTD	CV1	CV-1 State	PE Switch
TT8	CWT-1 Bot	RTD	CV2	CV-2 State	PE Switch
TT9	CWT-2 Top	RTD	CV3	CV-3 State	PE Switch
TT10	CWT_2 Mid	RTD	CV4	CV-4 State	PE Switch
TT11	CWT-2 Bot	RTD	CV9	CV-9/15/16	PE Switch
CV5	CV-5 State	PE Switch	CV11	CV-11/17/18	PE Switch
HT0	Global Irr.	Eppley PSP	QCOL	Col Heat Prod	Calc.
TD1	Col. Rise	Dual RTD	QC2	Col Heat Prod	Calc.
TD2	Gen. Drop	Dual RTD	QHAB	Abs HW Store	Calc.
TD3	Evap. Drop	Dual RTD	QHST	HW Store	Calc.
TD4	Cond. Rise	Dual RTD	QCAB	Abs CW Store	Calc.
TD5	Bldg. Drop	Dual RTD	QCST	CW Stored	Calc.
TD6	DHW Sol Rise	Dual RTD	QBLD	Bldg. Heat	Calc.
TD7	DHW Boiler	Dual RTD	QDWS	DHW Sol Heat	Calc.
TD8	Boiler Rise	Dual RTD	QDW	DHW Heat Tot	Calc.
TD9	Pool Rise	Dual RTD	QAUX	Boiler Heat	Calc.

NOTES:
1. Eppley PSP = precision spectral pyranometer
2. RTD = platinumn resistance temperature detector - 100 Ohm
3. Dual RTD = differential bridge RTD (temp. difference)
4. PE Switch = pneumatic-operated electric switch
5. Wattmeter = Hall-effect power (watt) transducer
6. Calc. = quantities calculated by data system and saved
7. Impact = impact-type flowmeter (Ramapo Co.)

are about +/-1C over 0-100C as compared to +/-0.5C for the RTD units, and (2) signal conditioning is simpler and less costly for the resistance sensors. It was found that the hardware, signal conditioning and installation costs for either type of sensor averaged out to about the same on a per channel basis. The increased performance and flexibility for use in direct differential measurements favored use of the RTD's. It might be noted that linearized thermistor sensors, while similar in principal to RTD's generally provide accuracies comparable to thermocouples but at RTD costs.

Impact (or drag) type flowmeters were used to sense the flow of water in the various circuits. These units (Ramapo wafer and pipe threaded models) employ a small cantilever mounted target located directly on the fluid flow centerline. The fluid drag created by the target is sensed as a bending strain in the cantilever. Conventional strain gages in a bridge circuit are used to sense the strain. This has the advantage in the present system of appearing much like the bridge circuit used for the RTD circuits and simplified the data acquisition system. On the other hand, since the flowmeters are drag type devices, they respond in a square-law fashion to flowrate. This yields a smaller usable dynamic range since flowrate is proportional to the square root of the output signal. As with the RTD's, the flowmeters were installed in strict accordance with upstream and downstream piping requirements specified by ISA and the manufacturer.

Conventional electric power, meteorological, and radiometric transducers were used to sense other variables. Electric power sensors (wattmeters) were used for all pumps in the HVAC system but not for the air handling equipment. Epply solar pyranometers located on a horizontal as well as on a collector tilt plane were used to sense the insolation at the site. Pneumatically activated SPST switches were used to sense control system states.

All sensors were wired via 18 AWG wire in rigid conduit to a central junction panel which included all signal conditioning equipment. Connection to the IBM and Georgia Tech data acquisition equipment was made at this point.

3.3 Acquisition Instruments

The Georgia Tech data acquisition system was based around a small desktop calculator/computer (Hewlett-Packard 9825) with associated peripheral instruments. This approach provides a system of modest cost that due to its programmability is quite flexible and adaptable to a range of data acquisition requirements. Details of this system design were presented at a DoE conference [13]. Principal features of the calculator system are:

1. Fully automatic and unattended operation. The only operator intervention required was a weekly change of the tape data cartridge which was conveniently done

during the weekly site visit and inspection.

2. Automatic power failure recovery with a battery backup for the system clock. On power-up, the data acquisition programs are reloaded from tape and data acquisition resumes.

3. Up to 12 days storage of data when logged at 15 minute intervals using the built-in cartridge data tape. Actual sensor measurements were made a one minute intervals and were suitably averaged and recorded at the 15 minute intervals.

4. Interactive display of data and system function using the calculator live keyboard and display. In addition, 8 data values were displayed on LED readouts located in a system display panel in the lobby.

The basic measurement was a DC voltage from the various sensors and signal conditioning bridges. The system voltmeter was capable of making 6-digit readings to microvolt resolution at 25 samples per second. Consequently, it was not necessary to employ separate signal conditioning amplifiers that can often be major sources of measurement error. The system was configured to accept 80 3-wire channels via an Acurex reed relay low level analog scanner (expandable to 100 channels). A calender/clock with battery backup was provided to synchronize readings.

The calculator-based system proved to be both powerful and highly adaptable to the requirements presented. The live keyboard feature of the HP9825 allows on-line examination and modification of variables in a program currently being executed. This capability provided a powerful interactive means for dynamically examining the data and assessing present HVAC system performance without disrupting the primary data acquisition functions.

4.0 DATA_SYSTEM_OPERATION

4.1 Objectives

The data acquisition system described in the previous sections was operated for 15 months from December 1979 to March 1981. The system remained in continuous operation except for occasional brief disruptions for either data system maintenance or for solar energy system repair and adjustment. The objective of this effort was to acquire performance data from the system that covered a period of at least one year and therefore encompassed all seasons and modes of operation. The monitoring contract specified a period from September 1979 to September 1980, but due to bureaucratic delays, work did not begin until November 1979. Of the 15 months of data acquired, roughly three months of data were corrupted by interaction with the IBM data system units and another month of data was found to be useless as a result of data system malfunctions. The balance of 11 months of useable data was the subject of the analysis and performance evaluation work described in this report.

This section describes the operation of the data system and the procedures that were developed to insure that reliable data were acquired.

4.2 Operation

One of the principal difficulties that must be dealt with in carrying out a project such as this to monitor the performance of a large HVAC system is the matter of insuring that the system is operating correctly and is properly maintained. It was appealing to consider installing a site data MODEM and connecting the data system directly to a host computer at Georgia Tech. In this way the site system could be called by telephone each day and instructed to dump the acquired data back to the host. While this provides data in a very rapid manner, it does not inherently insure that the system will be properly operated. Even though immediate analysis of the data will quickly spot problems and allow for timely repair, it does not necessarily reveal all malfunctions and therefore can be very misleading. In a complex system such as the present, there are many observations of system operation that are not practicable to include within the scope of the data system. Tank levels, leaks, all control system states, condition of the mechanical equipment, etc. are such observations. Also, it is not possible to take redundant manual measurements to back up the data system and guard against small, consistent and largely undetectable measurement errors.

Given these considerations and the relative proximity of the site to Georgia Tech, it was decided at the outset to operate the data system with scheduled weekly site visits and inspections. Once this decision was made, it was only logical to use the tape data cartridges for storage and to retrieve them during the weekly visit.

A site visit plan and an HVAC and data system inspection procedure were developed and implemented by use of a detailed check list to be completed by the inspector. A copy of the form is shown in Figure 6. It incorporates checks of the HVAC system itself, the data acquisition system, and finally, the collector array and outside piping. Noteworthy items on the list include a walk-through inspection of the collector array to check for leaks, recording of various fluid levels and control valve states in the HVAC system, and redundant measurement and recording of several key sensor readings. Finally, space is provided for comments to cover observations not otherwise handled on the log form.

At the outset, the visits were conducted by driving the 45 miles each way to the site. This required a half day at the least and it quickly became apparent that the effort would exceed budgeted personal services. For the last 6 months, this procedure was modified to make use of personnel already near the site and being employed on other research projects. This arrangement allowed the site visits to be made on a three per week basis, typically Monday, Wednesday, and Friday. A log sheet was completed for each visit and the sheets for each week were mailed along with the data cartridge to Georgia Tech.

4.3 Data Archiving

When the data and site visit log sheets were returned to Georgia Tech, the log sheets were examined and filed in a master logbook, and the tape cartridges were transcribed. At the outset the data transcription task consumed excessive time because of the particular interface required to copy data to a large minicomputer system. This caused an unacceptable delay in examining the data which was remedied later in the study by installation of a faster interface.

The transcription procedure consisted of using a second HP9825 calculator to read the data cartridges and then reformat the data into standard ASCII line image form. The transcribing program then transferred the ASCII data over a 2400 baud serial line (and later over a much faster IEEE-488 (HPIB) bus) to an HP1000 minicomputer system. Here the data was stored in disk files each containing one day's data. The disk files in turn were saved in archival format on standard 800 bpi 9-track magnetic tapes. For efficiency, only the compacted binary form of the data was saved to tape (as opposed to the original ASCII text format). As needed, various copies of selected data were transferred via a remote job entry (RJE) link from the HP1000 to the campus mainframe CDC CYBER computer facility.

Initially, all of the analysis and performance evaluation studies were carried out on the HP1000. This proved to be satisfactory in terms of ease of use and speed of operation. However, severe disk space constraints would not allow more than one or two months of data to be present on-line in files. If other data were needed, they could only be accessed by retrieving

Serial No.______
Key: (W)=weekly

OPERATION AND MAINTENANCE LOG
SHENANDOAH COMMUNITY RECREATION CENTER SOLAR HEATING AND COOLING SYSTEM

DATE:__________ TIME:__________ OPERATOR:__________

MECHANICAL SYSTEMS CHECK

P-1 suction pressure__________
Glycol exp. tank level__________
Antifreeze protection to______(W)
Zone t'stat setting_____&_____(W)

P-3 suction pressure__________
Make up line pressure__________
Summer-Winter sel.___SUM,___WIN
Water exp. tank level________(W)

CONTROL SYSTEM STATUS CHECK

Date_____ Time_____

Weather__________
Array output T1 (T1A)__________
Buffer tank T2 (TT1)__________
HW storage T3 (TT4)__________
Chilled water T5 (T5)__________
Array input T6 (T1)__________

DHW temperature (T7)__________
CW storage T9 (TT7)__________
Outdoor temperature__________
Indoor temperature__________
Collector rise: T1-T6 __________
P1 pump status__________

CALCULATOR DATA SYSTEM CHECK

Date_____ Time_____

RUN light ok?__________
Clock: date__________
time__________
Address light blinking?__________

Tape position: track____ file____
Filter cleaned__________(W)
Panel status__________
General check__________

Compare current INSTANT PRINT with inspection:
Defficiencies:

Inform Georgia Tech person:__________ Date______ Time______
Tape changed?____: Old SN____, New SN_____, Dispatched__________

PUMP CONDITIONS

Time__________

P-1___	________	P-4___	________	P-7___	________	P-11___	________
P-2___	________	P-5___	________	P-8___	________	P-12___	________
P-3___	________	P-6___	________	P-9___	________	P-13___	________
				P-10___	________	P-14___	________

Key: (1-on, 0-off)(remarks)
Note any leaks or damage.

VALVE CONDITIONS

Time__________

CV-1____	CV-3____	CV-5____	CV-7____	CV-9____	CV-11____	CV-13____
CV-2____	CV-4____	CV-6____	CV-8____	CV-10____	CV-12____	CV-14____

(G=open, R=close, or pressure) Note leaks or damage.

ARRAY INSPECTION

Date:________(W)

North End of Array

	Row	1	2	3	4	5	6	7
	1	________					__	________
	2	________					__	________
	3	________					__	________
W	4	________					__	________
e	5	________					__	________
s	6	________					__	________
t	7	________					__	________
	8	________					__	________
	9	________					__	________

Note leaking or damaged collectors or disconnected modules.

Figure 6. Site Log Used to Monitor Operation and Maintenance of Solar Energy System.

daily disk files from tape archival storage. Ultimately, this proved to be too inconvenient and instead a selected subset of the data was transferred to the CYBER mainframe system for extensive analysis. In this way, the entire length of data could be kept on-line at one time.

5.0 EVALUATION AND ANALYSIS

5.1 Objectives

The evaluation and analysis task evolved in response to problems encountered during the project. Initially, a sustained effort was made to reduce all collected data. As inconsistencies and errors were detected, the data reduction program was modified extensively to include redundant calculations, error detection and transducer corrections where possible. Minor difficulties with individual transducers and problems in the data acquisition system compounded to make this approach infeasible with such a complex system. An attempt to use parameter identification techniques to isolate the sources of error and to develop a detailed model of the collector subsystem were abandoned because of time constraints. It was finally determined that much of the data would not be useful but that a concentrated review of the most pertinent data (e.g., collector and boiler heat rates and fuel gas consumption) could yield useful results.

The original concept was to employ all the available data to compute the pertinent heat rates from the collector array, among the various energy conversion and storage components, and to or from the conditioned space. Immediately after the Georgia Tech data system was activated, an intense effort was begun to develop an elementary data reduction program. Our plan was to begin observing the data as soon as possible to detect any problems in the data system or mechanical system. This would allow us to avoid collecting an undue amount of contaminated data. The value and validity of this approach were demonstrated as extensive problems were quickly discovered. Considerable time and effort were expended before cross-coupling from the IBM site data acquisition system was identified as the source of the problem.

Once the IBM system was disconnected, we began to record data that was of better quality but not devoid of inconsistencies and apparent errors. A most troublesome problem was persistent offsets in the temperature difference measurements. Several attempts were made to evaluate the magnitude of this offset. Another problem area was accurate calculation of heat rates in loops where the flow is discontinuous or modulated. This seemed to be a special problem in the air-handlers and the absorption chiller. As experience dictated and time permitted, the original data reduction software was greatly augmented. Features were included to detect errors and make such corrections in the temperature and flow measurements as were possible.

It was finally determined that further efforts to upgrade the entire data set would be nonproductive, and efforts were concentrated on the most important data pertinent to the collector and boiler heat rates. A reasonably accurate reduction of these data would provide the energy collected by the solar array and the net output of the boiler. This result would allow the calculation of the solar fraction which is a popular and useful performance indicator. An additional reason for concentrating interest on these data is that some redundancy in measurements was available. At the collectors, both a direct temperature difference measurement and independent measurements of inlet and outlet temperatures were made. For the boiler, the absorbed energy as indicated by flow and temperature difference measurements can be compared with the fuel input from utility bills or direct reading of the gas meter.

The adopted procedure was to sift the pertinent data from the archived data records and assemble this reduced set of information into files corresponding to utility billing periods. The required data were at 15 minute periods and consisted of:

I - solar irradiation on collector plane for the period
F1 - average flow in the collector loop
EP1 - energy consumed by the collector loop circulators
TD1 - average temperature difference across collector array
T1A - average collector outlet temperature
T1 - average collector inlet temperature
T16 - average ambient temperature
F8 - average flow in the boiler loop
EP5 - energy consumed by the boiler loop circulator
TD8 - average temperature difference across the boiler

After assembling the data, each billing period data set was scanned for missing or bad records and such records were flagged to exclude them from further computation. This was done by both programmatic and manual inspection. The data reduction program was then exercised. The important calculations were:

(a) Solar irradiation on the array aperture,
(b) Collector heat rate using both TD1 and T1A-T1,
(c) Boiler heat rate

This program also makes two model calculations which are used to detect erroneous data. A clear day irradiance is calculated [14]. This value is used as a gage of the measured irradiance and in graphical output, helps to outline the expected operating time for the collector array. A simple Hottel-Whiller-Bliss collector equation was used to model the collector output as a rough gage of these data.

As described above, a number of attempts were made to compensate for some perceived defficiencies in the operation of the direct differential temperature sensors (e.g., TD1). The most alarming perceived problem was an apparent offset signal from the differential temperature bridges when an attempt was made to hold both RTD's at the same temperature. It was never determined if this problem had any practical significance or was an artifact of our verification technique. Since there is little difference between the results for collector performance when the uncompensated differential temperature sensor (TD1) was used compared to calculating the difference from independent sensors (T1A-T1), it was decided to rely upon the calculated difference rather than the more complicated differential temperature circuit.

The data reduction program was then run for each billing period and the output inspected. A sample output is shown in Table 2. Note how the line printer plots of the important heat rates can be easily scanned for consistency and note that erroneous data (e.g., from isolated malfunctions of the data acquisition system or equipment) would stand out clearly. A very few clearly erroneous records were identified and flagged, and after final modification the program was run again for all the billing periods.

5.2 Results

The overall performance of the solar heating and cooling system has two components - the energy collection performance of the collector array and the contribution of the solar energy system to the overall heating, cooling, and hot water needs of the building.

In Figure 7 is shown the average daily solar irradiation on the collector array, the average daily energy collection, and the monthly overall collection efficiency. To account for missing data both the solar irradiation and the energy collection values were scaled upward by a correction factor. In this case the correction factor was based on modeled clear day irradiation. Specifically, the correction factor is unity plus the ratio of modeled clear day irradiation during periods of missing data to the modeled clear day irradiation during periods when data was successfully collected.

Overall, Figure 7 and Table 3 indicate that the reflector augmented collector design was generally successful. The steep collector angle (45 deg) promoted good performance during winter while the high temperatures required for summertime cooling were accommodated by reflector augmentation. The low energy requirement during mild periods (e.g., October and November) can cause high storage temperatures further reducing the collector performance near the equinoctals. Collector array efficiency reached a monthly high of 20% in March and averaged 19% for the year. One should bear in mind that this efficiency includes array piping losses and, further, is based on the total irradiation including periods of low intensity when the collectors are not even operating. Instantaneous efficiencies exceeding 50% were observed on clear days both during summer and winter.

The solar fraction, SF, is a convenient expression for the portion of the building heat requirements (for heating and cooling) provided by the solar energy system:

$$SF = Q(solar)/[Q(conv) - Q(solar)]$$

where

Q(solar)= heat to building from solar (assumed equal to the solar heat collected.

Q(conv) = heat to building from boiler.

TABLE 2. Typical Data Output from Performance Analysis Programs.

```
1MN DY PD OPAR  EFF  AIT QCP1 QCP2  QBP   CLEAR DAY I    MEASURED I       QC-MODEL        QC-BY DELT      QC BY TO-TI      BOILER HEAT
  8 10  1 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  2 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  3 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  4 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  5 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  6 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  7 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  8 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10  9 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 10 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 11 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 12 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 13 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 14 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 15 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 16 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 17 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 18 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 19 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 20 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 21 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 22 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 23 **** 0.00   0.   0.   0.   0.0.00 +           0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 24 **** 0.00   2.   0.   0. 153. .02 +            .00 +           0.00 +           0.00 +           0.00 +            .15 ++
  8 10 25 **** 0.00   6.   0.   0.  71. .09 +            .01 +           0.00 +           0.00 +           0.00 +            .07 +
  8 10 26 3.73 0.00  21.   0.   0.  32. .16 ++           .02 +           0.00 +           0.00 +           0.00 +            .03 +
  8 10 27 1.90 0.00  39.   0.   0.  24. .24 +++          .04 +           0.00 +           0.00 +           0.00 +            .02 +
  8 10 28 1.17 0.00  61.   0.   0.   5. .28 +++          .06 +           0.00 +           0.00 +           0.00 +            .01 +
  8 10 29  .77 0.00  88.   0.   0.   1. .32 ++++         .09 +           0.00 +           0.00 +           0.00 +            .00 +
  8 10 30  .54 0.00 120.   0.   0.   3. .35 ++++         .12 ++          0.00 +           0.00 +           0.00 +            .00 +
  8 10 31  .40 0.00 386.   0.   0.   0. .39 ++++         .39 ++++        0.00 +           0.00 +           0.00 +           0.00 +
  8 10 32 0.00 0.00   0.   0.   0.   0. .44 +++++       0.00 +           0.00 +           0.00 +           0.00 +           0.00 +
  8 10 33  .22 0.00 241.   0.   0.   0. .48 +++++        .24 +++         0.00 +           0.00 +           0.00 +           0.00 +
  8 10 34  .19 0.00 272.   0.   0.  32. .52 ++++++       .27 +++         0.00 +           0.00 +           0.00 +            .03 +
  8 10 35  .30 0.00 321.   0.   0. 411. .54 ++++++       .32 ++++        0.00 +           0.00 +           0.00 +            .41 +++++
  8 10 36  .47 -.64 370.-235.-227. 309. .57 ++++++       .37 ++++         .06 +            .24 ---          .23 ---          .31 ++++
  8 10 37  .45 -.27 409.-110.-103. 227. .60 +++++++      .41 +++++        .08 +            .11 --           .10 --           .23 +++
  8 10 38  .42 -.16 451. -73. -67.   0. .63 +++++++      .45 +++++        .10 +            .07 -            .07 -           0.00 +
  8 10 39  .45 -.09 475. -41. -33.   0. .66 +++++++      .48 +++++        .09 +            .04 -            .03 -           0.00 +
  8 10 40  .50 -.01 455.  -6.   2.   0. .69 +++++++      .45 +++++        .06 +            .01 -            .00 +           0.00 +
  8 10 41  .43  .10 569.  57.  72. 233. .71 ++++++++     .57 ++++++       .12 ++           .06 +            .07 +            .23 +++
  8 10 42  .43  .13 608.  77.  86. 295. .74 ++++++++     .61 +++++++      .13 ++           .08 +            .09 +            .29 +++
  8 10 43  .42  .18 654. 116. 131. 269. .76 ++++++++     .65 +++++++      .15 ++           .12 ++           .13 ++           .27 +++
  8 10 44  .41  .26 690. 182. 207. 219. .78 ++++++++     .69 +++++++      .16 ++           .18 ++           .21 +++          .22 +++
  8 10 45  .40  .19 710. 132. 152.   0. .80 +++++++++    .71 ++++++++     .17 ++           .13 ++           .15 ++          0.00 +
  8 10 46  .43  .22 700. 151. 166.   0. .82 +++++++++    .70 ++++++++     .15 ++           .15 ++           .17 ++          0.00 +
  8 10 47  .47  .20 669. 134. 148.   0. .83 +++++++++    .67 +++++++      .11 ++           .13 ++           .15 ++          0.00 +
  8 10 48  .48  .49 657. 325. 351. 101. .84 +++++++++    .66 +++++++      .11 ++           .32 ++++         .35 ++++         .10 ++
  8 10 49  .45  .51 653. 334. 369. 119. .85 +++++++++    .65 +++++++      .12 ++           .33 ++++         .37 ++++         .12 ++
  8 10 50  .45  .48 648. 309. 345. 137. .85 +++++++++    .65 +++++++      .12 ++           .31 ++++         .35 ++++         .14 ++
  8 10 51  .48  .45 603. 271. 303. 134. .86 +++++++++    .60 +++++++      .10 +            .27 +++          .30 ++++         .13 ++
  8 10 52  .43  .18 670. 123. 137. 151. .85 +++++++++    .67 +++++++      .14 ++           .12 ++           .14 ++           .15 ++
  8 10 53  .62  .14 491.  69.  80.   0. .85 +++++++++    .49 +++++        .01 +            .07 +            .08 +           0.00 +
  8 10 54  .48  .18 649. 117. 130.   0. .84 +++++++++    .65 +++++++      .10 ++           .12 ++           .13 ++          0.00 +
  8 10 55  .51  .23 638. 145. 155.  93. .83 +++++++++    .64 +++++++      .09 +            .15 ++           .16 ++           .09 +
  8 10 56  .60  .33 519. 170. 185. 237. .82 +++++++++    .52 ++++++       .02 +            .17 ++           .19 ++           .24 +++
```

TABLE 2. (Continued)

```
8 10 57  .53  .28 567. 159. 174. 221. .80 ++++++++    .57 ++++++      .07 +        .16 ++       .17 ++       .22 +++
8 10 58  .44  .24 661. 161. 178. 180. .78 ++++++++    .66 +++++++     .13 ++       .16 ++       .18 ++       .18 ++
8 10 59  .76  .21 375.  78.  85. 272. .76 ++++++++    .38 ++++       0.00 +        .08 +        .08 +        .27 +++
8 10 60  .48  .26 586. 151. 171. 176. .74 ++++++++    .59 ++++++      .10 +        .15 ++       .17 ++       .18 ++
8 10 61  .58  .19 479.  90. 101. 237. .71 ++++++++    .48 +++++       .03 +        .09 +        .10 ++       .24 +++
8 10 62  .55  .24 503. 123. 132. 233. .69 +++++++     .50 ++++++      .05 +        .12 ++       .13 ++       .23 +++
8 10 63  .60  .17 451.  76.  84. 233. .66 +++++++     .45 +++++       .02 +        .08 +        .08 +        .23 +++
8 10 64 1.03 0.00 256.   0.   0. 280. .63 +++++++     .26 +++        0.00 +       0.00 +       0.00 +        .28 +++
8 10 65  .65  .22 402.  90.  99. 234. .60 ++++++      .40 +++++      0.00 +        .09 +        .10 +        .23 +++
8 10 66  .75  .08 348.  27.  31. 279. .57 ++++++      .35 ++++       0.00 +        .03 +        .03 +        .28 +++
8 10 67  .84  .10 303.  31.  37. 265. .54 ++++++      .30 ++++       0.00 +        .03 +        .04 +        .27 +++
8 10 68 1.06 0.00 235.   0.   0. 297. .51 ++++++      .24 +++        0.00 +       0.00 +       0.00 +        .30 +++
8 10 69 1.18 0.00 200.   0.   0. 276. .47 +++++       .20 ++         0.00 +       0.00 +       0.00 +        .28 +++
8 10 70 1.40 0.00 186.   0.   0. 336. .43 +++++       .19 ++         0.00 +       0.00 +       0.00 +        .34 ++++
8 10 71 1.71 0.00 127.   0.   0. 307. .39 ++++        .13 ++         0.00 +       0.00 +       0.00 +        .31 ++++
8 10 72 2.42 0.00  88.   0.   0. 262. .35 ++++        .09 +          0.00 +       0.00 +       0.00 +        .26 +++
8 10 73 3.64 0.00  58.   0.   0. 261. .31 ++++        .06 +          0.00 +       0.00 +       0.00 +        .26 +++
8 10 74 6.25 0.00  34.   0.   0. 305. .28 +++         .03 +          0.00 +       0.00 +       0.00 +        .31 ++++
8 10 75 0.00 0.00   0.   0.   0.   0. .23 +++        0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 76 **** 0.00  18.   0.   0. 237. .16 ++          .02 +          0.00 +       0.00 +       0.00 +        .24 +++
8 10 77 **** 0.00   5.   0.   0.   0. .08 +           .00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 78 **** 0.00   0.   0.   0.   0. .01 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 79 **** 0.00   0.   0.   0. 136.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +        .14 ++
8 10 80 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 81 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 82 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 83 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 84 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 85 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 86 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 87 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 88 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 89 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 90 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 91 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 92 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 93 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 94 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 95 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +
8 10 96 **** 0.00   0.   0.   0.   0.0.00 +          0.00 +          0.00 +       0.00 +       0.00 +       0.00 +


DAILY TOTALS AND EFFICIENCIES:

     AITD=   19723.
     QC1D=    3234.,  EFFY=  .16
     QC2D=    3679.,  EFFY=  .19
     QCMD=    2574.,  EFFY=  .13
     QBD=     8284.


     AVERAGE AMBIENT TEMPERATURE  85.43

         HEATING DEGREE DAYS...   0.0
         COOLING DEGREE DAYS...  57.1
```

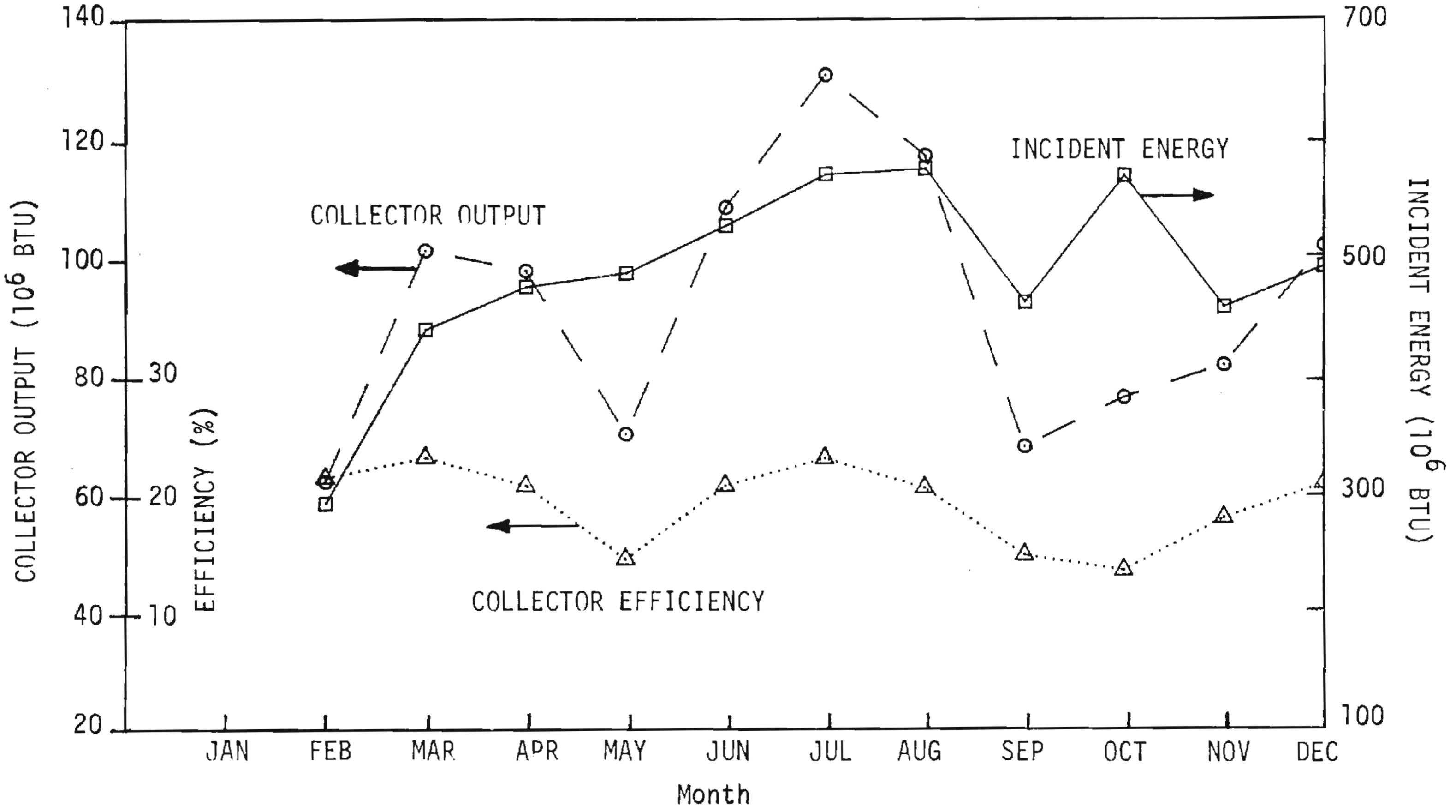


Figure 7. Collector Array Performance.

TABLE 3
COLLECTOR PERFORMANCE SUMMARY

Billing Period		Days in	Ht	Qc	Effy
No.	Dates	Period	(million BTU)		(%)
2	2/16-3/3	17	17.77	3.78	21.3
3	3/4 -4/1	29	15.33	3.53	23.0
4	4/2 -4/30	29	16.37	3.37	20.6
5	5/1 -6/1	32	15.36	2.21	14.4
6	6/2 -6/30	29	17.97	3.70	20.6
7	7/1 -7/31	31	18.14	4.16	22.6
8	8/1 -9/2	33	17.19	3.50	20.4
9	9/3 -10/2	30	15.54	2.29	14.7
10	10/3-11/3	32	17.78	2.38	13.4
11	11/4-12/3	30	15.11	2.70	17.8
12	12/4-1/4	32	15.45	3.20	20.8

Annual Efficiency: 19.0%

Ht = daily average irradiation on collector array
Qc = daily average collected energy

TABLE 4
ENERGY COLLECTION AND CONSUMPTION SUMMARY

Billing	Ht	Qc	Gas	Qb	Boiler	SF-1	SF-2
Period	(----million BTU -----)				Effy (%)	(%)	(%)
2	291.5	61.9	12.4	47.6	-	83.3	55.9
3	438.8	101.1	2.0	2.4	-	98.1	97.7
4	474.8	97.7	54.0	26.8	49.6	64.4	78.5
5	486.3	69.9	412.0	240.8	61.1	14.5	21.7
6	526.1	108.3	405.0	167.5	60.7	21.1	30.6
7	568.9	130.6	532.0	314.9	69.4	19.7	26.1
8	573.7	116.9	440.0	238.9	68.2	21.0	28.0
9	461.3	67.8	422.1	236.6	56.6	13.8	22.1
10	567.8	76.1	59.2	39.5	67.4	56.3	65.6
11	457.4	81.6	46.0	31.1	70.8	63.9	71.5
12	491.9	101.8	169.8	42.3	27.7	37.5	68.4
Total:	5338.6	1013.8	2554.5	1603.7	62.8%	28.4%	38.7%

Ht = total irradiation on collector array for period
Qc = total energy collected for billing period
GAS = energy consumed from computed from gas billing
Boiler Effy = (Qb/GAS)x100 = average boiler efficiency
SF-1 = Qc/(Qc+GAS) x100 = solar fraction #1
SF-2 = Qc/(Qc+Qb) x100 = solar fraction #2

As stated above, Q(solar) is calculated from measurements in the collector loop. Determination of Q(conv) is more complicated. One method is to base Q(conv) on conventional energy input. According to this calculation the annual average SF was 28.4%. The monthly trends for this SF are plotted in Figure 8 as SF-1 and are tabulated in Table 4.

A more revealing SF is one based on gross energy demands rather than inputs. For this the amount of energy absorbed in the boiler and transferred to the HVAC system is required. Table 4 compares the gas billings with the measured energy absorbed. The calculated boiler efficiency is as low as 27.7% and approximates 70% for the month of greatest demand. The lower efficiencies are explanable as occurring during periods of low demand. The energy lost due to intermittent cooling of the boiler loop during cyclic operation reduces the efficiency. This loss is accentuated by the very long piping ,passing through an unheated space, that connects the boiler with the balance of the energy plant. The boiler efficiency calculations thus indicate that the gass billings are consistent with and support the measurements of boiler heat ultimately supplied to the building. The only inconsistent data are for the two months with very small gas billings. Slight inaccuracies could yield the unrealistically high efficiencies.

Basing the SF on gross demand gives the values for SF-2 plotted in Figure 8 and listed in Table 4. It is seen that the annual solar fraction on this basis is nearly 39% which is close to the design goal of roughly 50%.

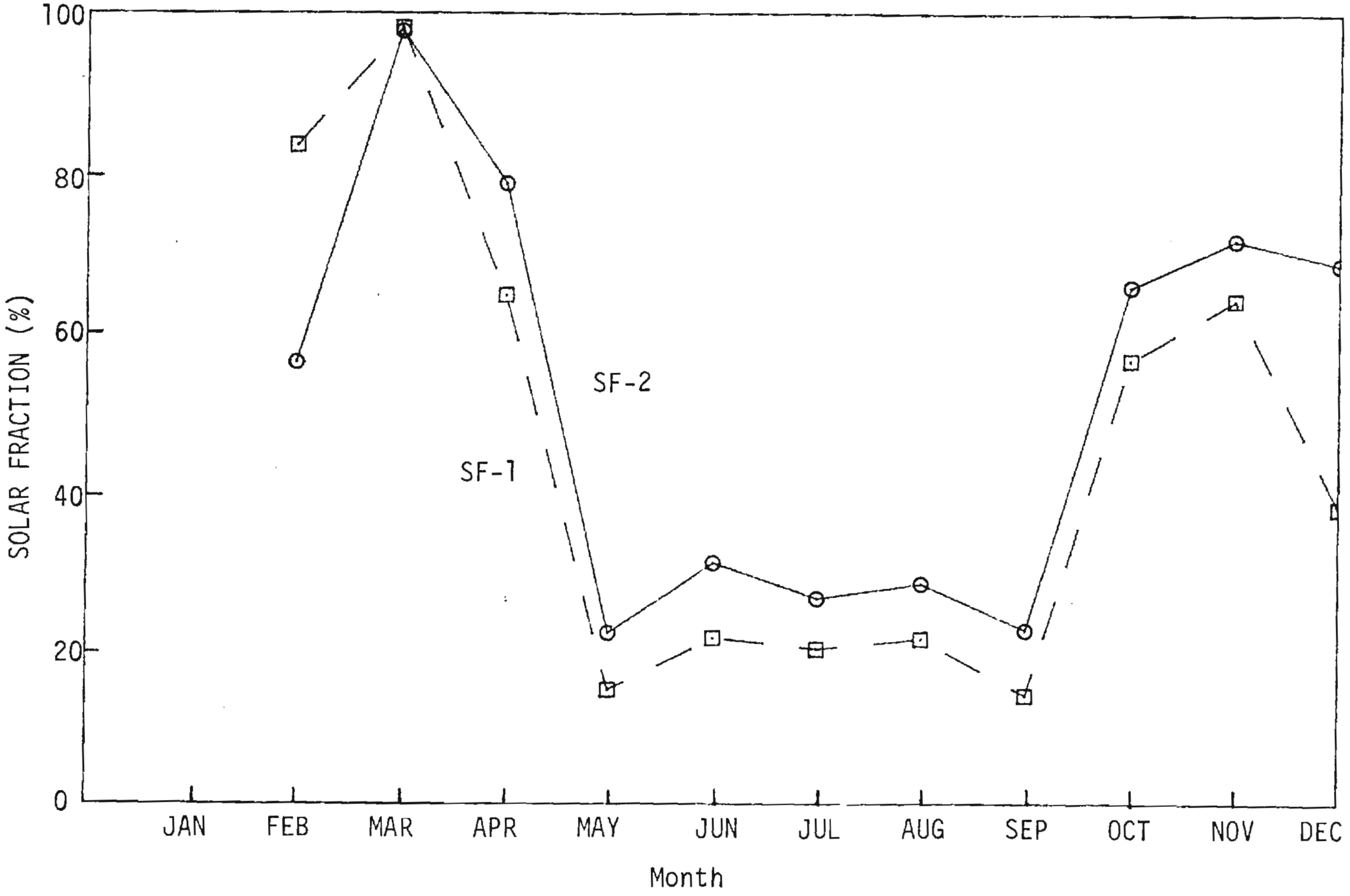


Figure 8. Solar Fractions, SF-1 and SF-2.

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APPENDIX

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Design and Simulation Studies for the Shenandoah Community Center Large-Scale Solar Cooling Demonstration

J. I. CRAIG

Associate Professor,
Aerospace Engineering

J. R. WILLIAMS

Associate Dean,
Engineering

Georgia Institute of Technology,
Atlanta, Ga.

S. F. BRUNING

Newcomb and Boyd,
Consulting Engineers,
Atlanta, Ga.

T. HARTMAN

Graduate Research Assistant,
Georgia Institute of Technology,
Atlanta, Ga.

The design for the Shenandoah Community Center integrated solar cooling project is presented. Major emphasis is placed on the mathematical model and simulation procedures used. The results of extensive modeling of the 983-m^2 reflector-augmented collector to optimize tilt angles and reflector areas are described, and the effects of collector location and area relative to the reflector are discussed. Transient simulations were conducted over periods of from several days to months using measured meteorlogical inputs and synthesized insolation data. It is shown that a solar system with hot and chilled storage capability can compete in life-cycle cost with conventional systems when fuel escalation rates in excess of 12 percent are assumed. Finally, a unique mechanical system configuration that can simultaneously operate from solar and auxiliary inputs while also using energy from storage to meet a load described.

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Design and Simulation Studies for the Shenandoah Community Center Large-Scale Solar Cooling Demonstration

J. I. CRAIG **J. R. WILLIAMS** **S. F. BRUNING** **T. HARTMAN**

ABSTRACT

The design for the Shenandoah Community Center integrated solar cooling project is presented. Major emphasis is placed on the mathematical modeling and simulation procedures used. The results of extensive modeling of the 983m^2 reflector-augmented collector to optimize tilt angles and reflector areas are described, and the effects of collector location and area relative to the reflector are discussed. Transient simulations were conducted over periods of from several days to months using measured meteorological inputs and synthesized insolation data. It is shown that a solar system with hot and chilled storage capability can compete in life-cycle cost with conventional systems when fuel escalation rates in excess of 12% are assumed. Finally, a unique mechanical system configuration that can simultaneously operate from solar and auxiliary inputs while also using energy from storage to meet a load is described.

INTRODUCTION

Sunshine has been a bountiful commodity over many regions of the earth since the beginning of time. Yet, the controlled use of the sun as a source of energy for practical applications has not been seriously undertaken until quite recently. There are many reasons for this - interruptions in availability, presence of cheaper alternate sources, low heat flux - to name a few. The simple fact is, however, that up until the present century, the world demand for energy has been insignificant compared to the present and projected breakneck consumption rates that will exhaust most known sources within a few hundred years. In this situation, the relatively higher cost but essentially unlimited supply of solar energy appears to offer great promise for a number of present and future energy needs.

Solar energy is by no means useful for all applications. It is generally of rather low thermodynamic quality, and consequently is not easily converted to other forms for use or storage. Some of the more attractive uses, however, are for water heating, space heating and space cooling where the manner of collection is most effeciently matched to the load.

The Shenandoah Community Center project described in this paper represents a step in the development of a practical low temperature technology. The design work, supported by the Energy Research and Development Administration, was begun in July 1975 and actual construction work was initiated in April 1976. The objectives of this project are to identify design approaches and define construction methods that will substantially reduce the cost of of solar systems when used in new construction. The solar system has been designed to provide about 60% of the cooling, 70% of the hot water, and essentially the entire heating requirement for all but the ice rink section of a 5,016 m^2 community center located 32 km south of Atlanta. The system is designed around a 983 m^2 array of doubly-glazed, selectively coated flat plate collectors. Principal features are:

1. A collector-reflector array integrated into the chord structure of a 71.6 m by 71.6 m long-span roof truss,
2. Chilled water as the principal energy storage subsystem for cooling mode operation (minimum hot storage),

3. A primary-secondary loop pumping system using constant-speed pumps and modulating valves that will allow simultaneous operation of the collector, storage and boiler subsystem to meet a given load.

SOLAR SYSTEM DESIGN

Design Philosophy

Over the past 40 years there have been a number of significant research reports which describe in detail the mechanical and thermodynamic operation of major solar components. The performance of hypothetical solar systems has been simulated, but presently there are a limited number of large experimental systems that have actually been constructed and operated for several years. Consequently, while it is possible to use general rules of design for sizing small solar heating systems, it is usually necessary to make detailed calculations of performance in order to properly design large systems.

The inputs to any solar system are the insolation, environmental variables and the building internal loads. These inputs are not all deterministic, but rather, include a significant random component due to variations in the weather, so that a rational simulation of the system should be based on a stochastic model for the solar components. For a number of reasons, including the lack of an adequate statistical model for the solar input, this approach has not been fully explored. As a result, the only reliable design approach at present is a combination of steady-state and transient simulations using deterministic models for the various components. The steady-state computations are based on average values for insolation, temperatures and loads calculated at hourly or daily intervals from monthly averages. These do not include the daily variations due to random weather patterns. The transient computations are based on either actual hourly measured values for the input variables or synthesized values when measurements are not available.

The approach taken in the present study has been to design what is basically an experimental solar system using first a simple steady-state model for system performance followed later in the design process by detailed transient modeling. There are three major parameters that must be adjusted:

(a) fraction of solar augmentation
(b) area of solar collectors
(c) volume of thermal storage

As noted in several previous studies (1, 2) a local minimum for the life-cycle cost function exists so long as the conventional auxiliary fuel cost is above a minimum value. If the fuel costs are below this value, the minimum cost system will not include any solar components. It has been amply demonstrated in numerous studies to date (2,3,4,5) that at least for the next few years it is not economically feasible to design solar assisted cooling systems in most regions of the country using current fuel prices. At present prices for natural gas, the auxiliary fuel for this project, it has not been possible to design a cost-competitive solar system in Atlanta at this time.

While in these terms an economically superior system has not been realized, a minimum-cost design has been made. Cost engineering methods have been used to size most components except for the collector array. In this case, the major emphasis for the project has been to design a research-demonstration system, and consequently, in order to furnish a reasonable (50% or more) fraction of the building energy demand, a collector area of roughly 1,000 m^2 was decided upon. It will be shown in later sections that such a configuration with appropriate thermal storage has a 25 year life-cycle cost that is superior to a conventional system, provided however, that present fuel prices with a greater than 10% escalation rate are assumed (discounted at 7%).

The design procedure consisted of two phases:

(a) determine collector area and tilt in order to meet the desired solar augmentation for average conditions over a one year period.
(b) determine storage volumes for both hot and chilled water in order to handle daily variations in the solar radiation input.

In the first phase, average daily and hourly insolation data for Atlanta, Georgia were used and average monthly and yearly heat production computed for various collector tilt angles. The combination of a relatively high annual hot water load (ice rink resurfacing) and a large cooling load placed incompatible requirements on the tilt angle since a relatively flat (10-25°) tilt is desirable for maximum summertime heat production while a larger tilt (40-50°) is required for maximum annual heat production. A reflector-augmented collector array similar in concept to that used in the Towns School design (6) has been used to overcome this problem and allow use of a large tilt angle for winter heat production while augmenting summer production. Phase (a) of the design procedure included computation of both the collector angle and the reflector angle required to maximize the annual heat production. This, coupled with building load data, allowed determination of the collector/reflector areas needed to meet the augmentation level desired.

Phase (b) of the design involved carrying out a detailed transient simulation of the solar system and building in order to estimate the effect of daily variation in insolation. Thermal energy storage is required in a solar system to meet loads which do not coincide with the diurnal variation in insolation or the random daily changes in meterological conditions. No storage means that loads not coincident with insolation cannot be met but too large a storage size results in excessive thermal inertia and heat loss.

Solar Data

Both the steady-state and transient simulations require solar and meteorological inputs. For the steady state computations, average values for insolation and daily temperatures are required. Liu and Jordan (7,8) have compiled long term monthly average daily insolation data, and this data, for the Atlanta area, was used to compute the average daily heat production for each month of the year for various collector and reflector orientations.

The transient simulations require point rather than average values for insolation and temperature at hourly or more frequent intervals. This type of data is not available for the Atlanta area, and consequently, hourly insolation values had to be estimated from other meteorological data. Boeing (9) and later Kimura and Stephenson (10) developed correlations between the type and amount of clouds in several layers and the measured insolation. Admittedly, this approach is crude and has not been generalized for different regions of the country. However, it appears to be the most rational method for synthesizing insolation values in the absence of measured data. For the present design, the 1964 Weather Service cloud cover data for Atlanta were used to compute estimated hourly horizontal insolation figures. Figure 1 shows typical clear and cloudy day insolation records for a winter and a summer day. Figure 2 compares the monthly average daily insolation computed from the 1964 data with the long term ASHRAE averages from Ref. 7. Insufficient information is available to make a quantitative statistical comparison, however the averages generally agree within 15% which seems reasonable for a single year, especially given the notorious poor reliability of solar observations.

Building Loads

It is generally recognized that in order to realistically calculate building heating and cooling loads, the dynamic thermal behavior of the building, including storage effects, must be considered. While this is straightforward in concept, the practical details of considering construction methods, multiple rooms and zone zones, occupancy and lighting schedules, and variable meteorological input for a large building requires the use of computer programs. When coupled with the models necessary to represent the solar assisted heating and cooling system, the result is a large program that is relatively expensive to run, especially in a parametric-type study.

It has been assumed in this study that the load calculation portion can be uncoupled from the HVAC system simulation. That is, it is assumed that building loads, including storage effects, can be calculated separately for each operating schedule desired and the results saved for input to the HVAC system simulation program. In this way a few load calculation runs can be made and the results used for many solar system simulations with various combinations of collector areas, storage volumes and control strategies.

The implicit assumptions for this approach are, first that the heating and cooling system will always meet the building load, and second, that the control system will eliminate any dynamic interaction of the solar assisted HVAC system with the building. It is felt that this is warranted for the large majority of conditions. For those extreme instances, such as system failure or fuel interruption conditions, separate short-term coupled simulations can be investigated.

The building loads were calculated at hourly intervals for a complete year for several operating schedules. In calculating the hourly load values two computer programs were utilized, one for calculation of the peak design load and another to distribute this load over each hour of the year according to weather conditions, input building usage profiles, and input system operation schedules. The peak heating and cooling loads were calculated using the APEC HCC III computer program which utilizes design oriented ASHRAE algorithms for its calculations (12). The E-CUBE program was then used to estimate the hourly energy requirements for the building (13). The calculated loads were stored in files for subsequent input to the solar-HVAC simulation programs.

Solar System Components

Modeling the solar assisted HVAC system involved both the use of currently available simulation models as well as the development of two specialized models to, (a) describe the behavior of a reflector augmented flat plate collector array, and (b) represent the performance of a commercial-sized water-fired absorption chiller.

It has been shown in the Towns School solar system design (6) that a simple, nonadjustable, reflector augmented flat plate collector array can collect energy during the summertime at rates greater than the optimally oriented collector alone while providing maximum collection rates during the winter. This is important for systems which require large amounts of energy to drive absorption chillers when approximately equal annual heating and cooling loads exist. Collector and reflector geometries were fixed by structural considerations in the Towns retrofit experiment and therefore optimal orientations were not studied. For the present design a complete analytical description of the collector-reflector system was developed and used to study the effect of variations in the size, location, and tilt of reflector surfaces on the collector heat production.

The assumptions made in constructing the reflector-collector model are:

(a) the reflector is a specular surface,
(b) the collector receives beam components of solar radiation directly from the sun and, depending upon solar altitude and azimuth, indirectly from the reflector,
(c) the collector receives diffuse radiation as if the reflector surface were not present,
(d) solar azimuth and the relative sizes of the collector and reflector are considered.

In (a) the reflectivity is assumed independent of wavelength. In (c) the reflector is assumed to reflect diffuse radiation equivalent to that which would be seen by the collector if the reflector did not reduce the sky vault view angle. This is a conservative assumption since much of the reflected diffuse radiation originates from the region around the sun during hours of substantial heat production. In (d) the end effects as well as the effect of varying the reflector width or collector location on the slant are included. In (b) the incidence angle for the reflected beam on the collector is computed so that the angular dependence of the cover plate transmissivity can be evaluated.

The first step in describing the reflector performance is to determine the amount and direction of beam radiation. The latter can be computed in a straightforward manner using well-known solar and terrestrial geometry formulas. Since transient performance is not required at this point, long term monthly averaged daily total insolation data were used (7). This is the most reliable data for the Atlanta-North Georgia region; however, the information does not include separate beam and diffuse components.

The most logical procedure for separating beam and diffuse components appears to be that due to Liu and Jordan (8). The method was developed from averaged daily insolation data and its application to instantaneous insolation values is therefore subject to question. The method assumes the diffuse component is uniformly distributed over the sky vault so that on clear days when the reflector is most effective, the method may yield conservative results. Nonetheless, it has been used here.

The assumed collector-reflector geometry is shown in Figure 3 where A and B are the tilt angles for the collector and reflector, respectively. The collector (height, X_C) is located X_{CB} above the "V" apex, while X_R and X_{RB} are similarly defined for the reflector surface. For a given solar angle the direct rays striking the upper and the lower reflector edges define an illuminated strip on the collector slope. Since the strip dimensions along the row are unaffected by A or B, the component of reflected insolation falling on the collector can be determined as a function of the illuminated strip dimensions parallel to X_C and X_R. The results can be conveniently represented in a modified form of the Liu and Jordan expression for the insolation on the collector:

$$I_C = I_{BO} R_C \left(1 + \frac{R_R}{R_C}\,\frac{X_R}{X_C}\,\rho f\right) + \frac{1}{2}(1+\cos A) I_{DO}$$

$$+ 1/2\,(1 - \cos A)\,\rho\, I_{TO}$$

where I_{BO}, I_{DO}, I_{TO} = beam, diffuse and total insolation on the horizontal

R_C, R_R = beam correction factors for the collector and reflector surfaces
ρ = reflector reflectivity
f = fraction of the illuminated strip from the reflector that falls on the collector
A, B, X_R, X_C = as defined previously

It is important to note that the reflected component is effectively assumed to act uniformly over the entire collector, and not in a band as actually happens. This is acceptable since spatial variations in insolation are not considered in the collector model at this time. Additional geometric relations have also been developed to provide the angle of incidence of reflected beam on the collector (17).

The collector model used for the design study is basically that due to Hottel and Woertz (15) and is thoroughly described in Ref. 14. Two levels of modeling were used at different stages in the design:

(a) the flow efficiency factor, transmissivity-absorptivity factor and overall loss coefficient were computed analytically
(b) equivalent values for the above parameters were estimated from test data furnished by collector manufacturers.

The angular dependence of the cover plate transmissivity for both the direct and reflected beams was initially considered but later dropped.

The absorption refrigeration machine is the most difficult component in the system to model. This is true not only because of the complicated thermodynamic cycle used but also because the equipment usually must be operated well below design capacity when solar-driven. There have been a few attempts made at modeling such machines, the most accessible perhaps, being that incorporated in the University of Wisconsin TRNSYS program (16). In all cases, a quasi-steady state approach has been followed in which empirically determined steady-state performance data are used to estimate instantaneous operation. In addition, the work noted dealt with relatively small machines which use the refrigerant directly to cool air, rather than chillers which cool an intermediate fluid. This destinction can have a significant effect on the modeling.

For the present study a quasi-steady state chiller model was developed using measured performance data supplied by a chiller manufacturer. An absorption chiller is inherently nonlinear, especially when the load ratio is varied, so initially, a nonlinear analytical approximation for the performance curves was sought. Computational problems with the solution of these equations forced consideration of a linear model, however. A number of fairly severe restrictions were made: in particular, a chilled water flow rate of 2 GPM/TON, hot water flow rate of 4 GPM/TON,

and a condenser water flow rate of 6 GPM/TON were assumed. Further, it was assumed that the machine would operate at a load ratio in the neighborhood of 0.5. With these restrictions, explicit linear equations were developed to predict the performanc
and an average error of no more than 1.5%. Additional constraints were placed on the model to represent the physical limitations of the actual machine. For example, the chilled water outlet temperature was constrained to remain above 5.6 °C while generator temperatures were not allowed below a crystallization limit.

Simulation Programs

A schematic outline of the overall simulation plan is shown in Figure 4. The schematic starts with the raw meteorological and building occupancy data and proceeds through to the final computation of hourly temperatures, flow rates and percent auxiliary energy requirements. Three different simulation programs were used at successively more refined stages in the design process. In increasing order of complexity they are:

(a) an average daily collector heat production program
(b) a simple heat balance program for simulating the overall heating and cooling operation using transient input data and calculated building loads
(c) a partial simulation using the TRNSYS program.

In the first program, average daily collector heat production was computed for the 15th of each month in order to determine the most efficient combination of collector and reflector areas and tilts. Constant inlet and ambient temperatures were used for each month.

The second program was used to study the long-term effects of chilled and hot water storage volumes on system performance. In addition, the effect of different chiller control strategies was explored. The system was simulated for a complete year of operation using hourly transient input data. A simple heat balance simulation at hourly intervals was used principally because of its computational simplicity over extended simulation periods. The technique is essentially a rectangular integration scheme with single node storage tanks.

The last simulation work consisted of using the TRNSYS program for modeling transient behavior in thermal systems (16). The same models from (b) were incorporated in the program but intervals no longer than weekly were considered. The major emphasis was to determine the short term effect of mode switching, control strategy, and collector loop storage on system efficiencies. Integration steps as short as 0.25 hours were required for some runs which together with the greater complexity of the integration technique resulted in relatively large computer run times.

System Configuration

Several current solar heating and cooling systems, particularly the Towns School project (6), were examined to determine problem areas in their construction and operation. This indicated that three aspects: (1) collector freeze-up protection, (2) variable-speed collector loops with or without a heat exchanger, and (3) the presence of large liquid volumes, could be potential problems. Fortunately, during winter some excess capacity is available so that the possibility exists for using stored heat to maintain nighttime collector fluid temperatures just above freezing without resorting to drain-down or use of antifreeze solutions. An advantage of this over drain-and-fill designs is that the collectors are always full and the loop can therefore begin operation as soon as radiation is present, without the risk of freeze-up as the collectors are filled on clear but cold days.

The system schematic is shown in Figure 5. The basic design is a primary-secondary loop concept in which the system is constructed from a series of interconnected pumping loops. Modulating valves are used to control the amount of fluid, and therefore energy, transferred between loops. Basically, one or more loops are used to control energy transfer to or from a component and each of these subsystems operates somewhat independently of the others. For example, the collector loop consists of pump P-1, the collectors, a buffer tank, and valves 14, 3 and 2.

Fluid is circulated in this loop at a constant rate until the temperature is raised enough to match the load, at which point valves 2 or 3 are modulated to divert energy (flow) to the heating or generator loops, respectively. The small buffer tank is used to avoid unnecessary cycling of the control system. Similar operation for the other loops can be deduced from the figure. One aspect that deserves further comment is the relative ease with which auxiliary energy can be added from the boiler, either to the chiller (generator) or to the building heating loop, simultaneously with collector operation. The hot and chilled storage systems function similarly, so that for example, chiller evaporator output can be fed to the building with any excess capacity diverted to the storage tanks. Appropriate control interlocks are included so that this would only occur during conditions of 100% solar operation. At other times the tanks could be used with the chiller or boiler to meet the load. Further details of the system operation are available in references 17 and 18.

SOLAR SYSTEM PERFORMANCE

The design and modeling techniques outlined in the previous sections have been applied in an iterative approach. At each cycle in the design, construction costs estimates were compared with projected operating costs. As a general rule it was found that the construction costs, at this stage of solar technology, were such a large portion of the life-cycle cost that a realistic minimum cost configuration could not always be determined. Nonetheless, this approach was pursued, but with the constraint when necessary of minimum value for certain parameters (i.e., collector area).

Load Calculation

The APEC HCC III and E-CUBE programs were used to compute the heating and cooling loads for the 1964 weather data. Parameters for these calculations are given in Figure 6. The building was zoned but the ice rink was not included as a space conditioning load since the ice-making equipment itself provides this function for its zone. However, the large hot water requirements for resurfacing the ice were included.

The monthly total heating, cooling and hot water loads calculated on the basis of typical usage schedules are shown in Figure 6. It should be noted that the heating load is plotted on an expanded scale and actually amounts to about 4% of the cooling load. On the other hand, the hot water load is 81% of the cooling load and is due primarily to the ice rink requirements.

Collector-Reflector Design

The performance of the collector-reflector system was studied with average hourly insolation assumed as input and constant temperature inlet water supplied. The calculated heat production represents, therefore, a long-term average performance without regard to storage effects and is useful for estimating the average reflector augmentation per unit collector area.

The use of a single, fixed collector tilt cannot provide maximum heat collection at all times of the year. Tilt values can be chosen to maximize the annual collection or to minimize the variation between winter and summer. For a space heating and cooling system, the most effective arrangement would be to provide a pattern of energy collection which most nearly matches the load, especially during peak periods. As shown in the following figures, a feature of the reflector augmented array is that by the appropriate adjustment of the geometry, the heat production can not only be maximized for a specified period but can also be somewhat tailored to follow the load. The overall performance can be significantly improved since the higher heat production achieved with a relatively inexpensive reflector can lead to reduced collector areas. For the present system, the use of an aluminium roofing material that can serve also as a reflector system provides further benefit.

The effect of collector and reflector tilt on the "summer" and "winter" heat production (6 month periods) is shown in Figure 7. A high performance flat plate design with selective coating has been modeled, and it is assumed that the collector and reflector completely cover their respective slopes. Three features are apparent:

(a) a particular choice of collector-reflector tilts (60° - 38°) will yield maximum summer heat production
(b) increasing collector tilts for a fixed reflector tilt increases heat production during the summer months
(c) shallower reflector angles improve winter heat production.

The curves can, however, be misleading since the sensitivity to the reflector angles below 40° and collector angles above 40° is relatively small. The overall conclusion is that any reflector angle between 35° and 40° substantially increases heat production (up to 30%) over the nonaugmented configuration.

When, on the other hand, the performance is considered over 12 consecutive months, the effect of reflector augmentation on the annual distribution of heat collection is apparent as is shown in Figure 8. Here, the heat production for a single 45° collector tilt is plotted for various reflector angles. Three conclusions can be drawn:

(a) lower reflector angles tend to peak heat production during the spring and fall (important in school design for example)
(b) higher reflector angles tend to peak heat production during midsummer.
(c) mid-winter heat production is essentially unaffected.

Finally, the effect of collector and reflector relative areas and their locations on the array surface must be considered. Figure 9a shows the effect of varying the collector position below the ridgeline and Figure 9b shows the result of varying the location and area of reflector. Both plots were constructed for a 45° collector slope and 36° reflector slope with a 274 cm peak-to-valley height. The collector location curve was calculated for a 243 cm long collector module and a 426 cm reflector, and it indicates that the best location is not up at the ridge but rather about 60 cm below. Figure 9b shows that, as expected, decreasing the reflector width significantly decreases heat production. The two curves show the relative effect of removing reflector material from either the lower (left curve) or upper (right) sections of the reflector's slope. It is apparent that the most effective portion of the reflector is the region near the ridge since removing area near the valley produces less of a decrease in heat production. The intersection is the reference for both cases and represents a centered reflector surface covering 88% of the slope.

The 45° collector/36° reflector angles and 365 cm reflector width ultimately selected for the present design were based upon structural and roofing considerations. While not the optimum choices for overall heat production, the differences are negligible for all practical purposes.

Transient Simulation

The previous calculations resulted in selection of a collector and reflector geometry. Initially, a 983 m^2 collector area was assumed in order to meet, on an average annual basis, 50% or more of the cooling load, 90% of the heating load, and 40% of the hot water load. The computations described next were done in order to determine the hot and cold water storage volumes required to maintain these performance levels in the face of varying solar input and weather conditions.

Cooling. Transient simulations of system performance computed at hourly intervals were made for selected periods from April through October. In addition, a transient heat balance model was run for the complete cooling season. Performance of the system with 227 kℓ of chilled water storage for a typical summer day and a spring day are shown in Figure 10. The August data represents worst case conditions and shows the solar system meeting less than 25% of the load (the shaded portion is auxiliary energy). The April data shows the opposite case in the springtime. The cooling load is that at the input to the chiller. Note in both cases the presence of a large load during the first hour of operation as a result of cooling shut-off at night.

Figure 11 shows the result of carrying out the simulation for the entire cooling season using various chilled water volumes and collector areas. The efficiencies shown are the fraction of cooling provided by the solar system. It is apparent from this data that for the summer period the system performance is worst and the usefulness of the storage a minimum. This is due directly to the fact that during this period the system is operating at near capacity for loads that are essentially coincident with the insolation. In this situation storage is of little help since no excess energy is collected. Storage would be more effective if the collector area was increased or if the building usage was discontinuous over periods of days (i.e., like a school with no weekend load). On the other hand, storage is obviously more useful in the spring and fall when the load is reduced more than the insolation.

When the cooling efficiency is computed over the complete cooling season, the effect of storage is more obvious. Figure 12 shows the yearly efficiency (augmentation) for air conditioning as a function of chilled storage volume. The curves show that provision for storage can reduce the auxiliary requirements by more than 20% depending upon the collector area used. The upper two curves show the performance for a 983 m^2 array with or without the reflector surfaces, while the bottom two curves show the effect of increasing the collector area (with reflectors). It is apparent in all cases that the first few kiloliters of storage added are the most useful and that subsequent additions have much less effect. The curves also indicate that as the collector area is increased, the same amount of storage is more useful - that is, the system is better able to use the storage on "good" days to produce excess chilled water for future use. Finally, the use of larger collector areas requires larger tank volumes to achieve the minimum auxiliary energy usage.

Heating. Transient simulation of the heating system over typical days and the entire season were also carried out. The performance for a good and bad day is shown in Figure 13. Note that while there is a large load at the start of the day, it disappears before noon. This is due to the large heat input provided by the lights, etc., in a well-insulated building; during the afternoons, outside air is often required to provide cooling.

When considered over a complete year, the portion of the heating load met by the solar system is shown in Figure 14 as a function of hot water storage for two collector areas. Again, as with the cooling performance, the first few kiloliters of storage are more useful than subsequent ones. In contrast, however, the storage volume for minimum auxiliary energy usage does not increase with increasing collector area. This is due to the fact that the major part of the load is from hot water needed for the ice rink, and consequently, is relatively constant and unaffected by weather conditions.

ECONOMIC ANALYSIS

The previous simulation results can be used to identify a collector area and storage volume that will provide a specified level of performance for given environmental conditions. For a collector area, a storage volume can be chosen that will minimize the auxiliary energy; however, increasing the area will progressively reduce the auxiliary energy so that essentially any level of performance can be attained.

The design objective is, of course, to provide solar assistance at a cost that is less than that for a conventional system alone. Consequently, it is necessary to consider not the annual auxiliary energy required, but rather, the overall cost of owning the system as compared to an equivalent conventional system. Since the two systems are not directly comparable - the solar system requiring a larger initial investment but lower operating costs - it is necessary to compare their costs over an estimated lifetime of operation.

One method of comparing costs over a period of time is to project these costs to a net present value at the outset. In this way, variable future costs such as for fuel or maintenance, including anticipated escalation rates, can be compared as a single value at one point in time. For example, future costs are "discounted" to a present value that takes into account the interest that the funds would accrue until they are spent (for fuel or maintenance). For a given control strategy, this process can be visualized as seeking the minimum point on a "cost" surface defined by collector area and storage volume. While steepest descent or other analytical methods can be used, a purely graphical approach has been employed here. Figure 15 shows a "cost-above-base" versus storage volume for several collector areas considered. A 25 year life has been assumed for the systems and periodic maintenance costs have been considered. Several assumptions have been made for variable costs associated with the systems:

Collector & reflector cost: $\$160/m^2$
Storage tank cost: $160/kℓ
Conventional fuel cost (nat'l gas):
0.11C per MJ (12¢ per therm)

Two families of curves are shown in Figure 15. Group A charts the cost for various collector areas assuming a fuel escalation rate of 7% and a 10% discount rate. These numbers are representative of present rate structures; however, when projecting forward 25 years using natural gas as a fuel source, the 7% rate may be too optimistic. As a result, a second family of curves, Group B, has been included to show the costs assuming a 12% escalation rate and a 7% discount rate. In both cases the cost curves show a minimum for a particular storage volume, and as the collector area is made smaller, this volume is correspondingly reduced (dotten lines connect minima).

For Group A, the cost for a conventional system is shown as the dashed line, "A", representing the fuel and maintenance costs. It is well below the solar system curves indicating that under assumption A, the conventional system would be the least-cost approach. For Group B, the conventional system cost is the dashed line, "B", but now the corresponding curve for a 933 m^2 solar system falls below for storage volumes of from 75 kℓ to 265 kℓ to 265 kℓ. This indicates that under these assumptions, the solar system offers a cost advantage. Other "B" curves, not shown in the figure, could be constructed for smaller collector areas and would indicate still even lower costs. However, below about 450 m^2 area, the relatively fixed cost for plumbing and pumps will cause the cost to rise with decreasing area. The relatively flat character of the curves indicates that, in contrast to collector area, the storage volume has a smaller effect on cost.

ACKNOWLEDGMENTS

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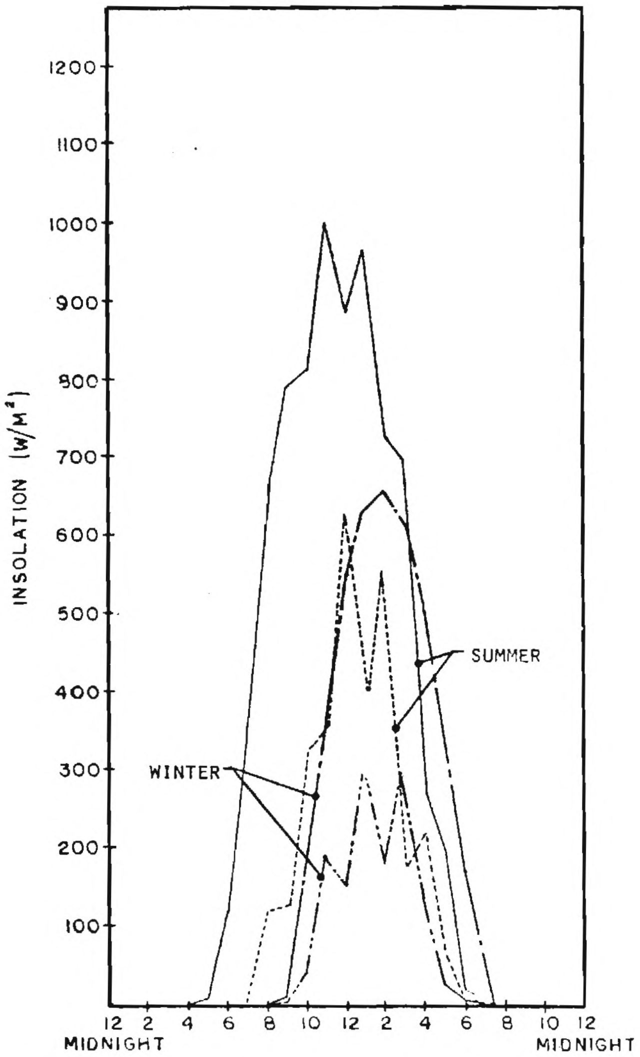


FIGURE 1. SYNTHESIZED HOURLY SOLAR RADIATION

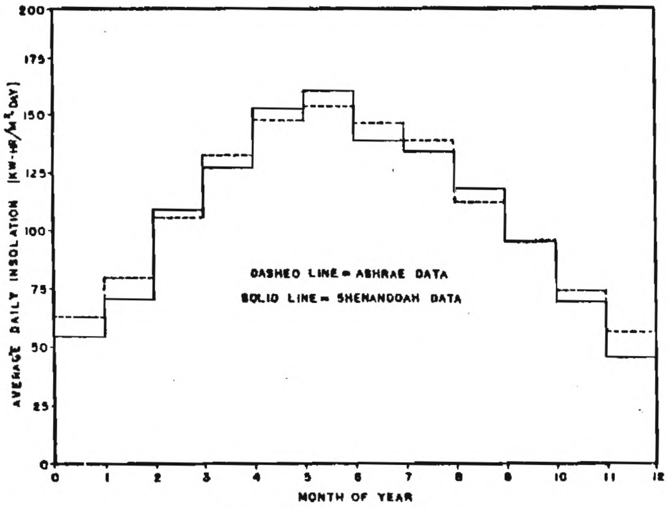


FIGURE 2. COMPARISON OF MEASURED AND SYNTHESIZED INSOLATION

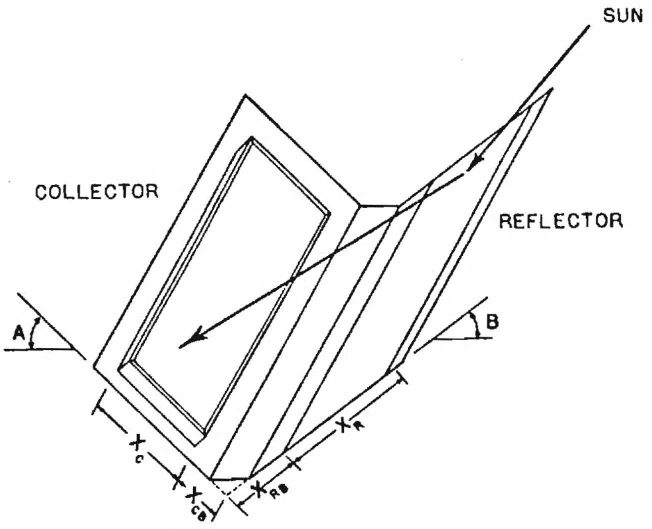


FIGURE 3. COLLECTOR-REFLECTOR GEOMETRY

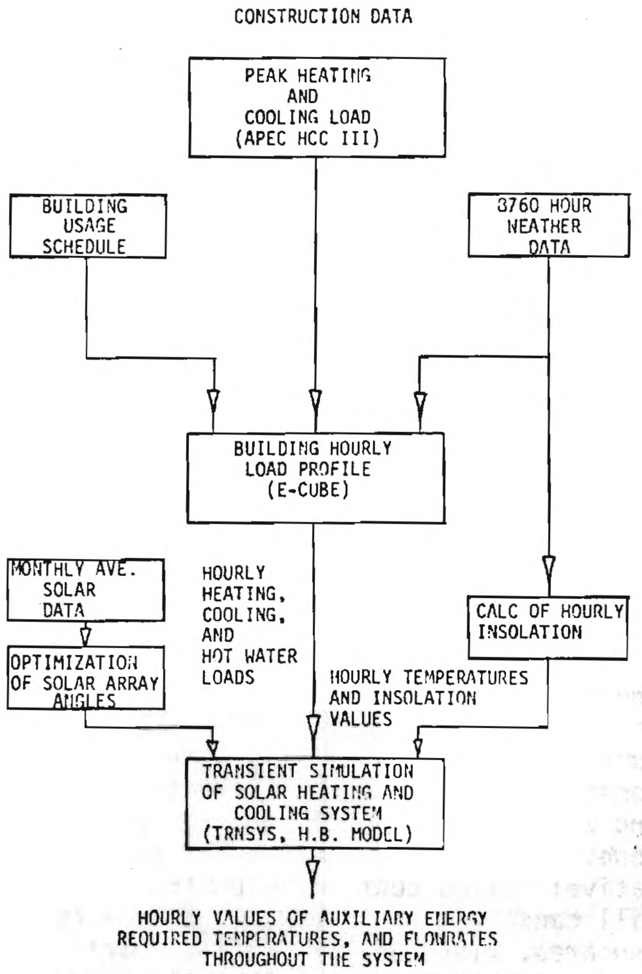
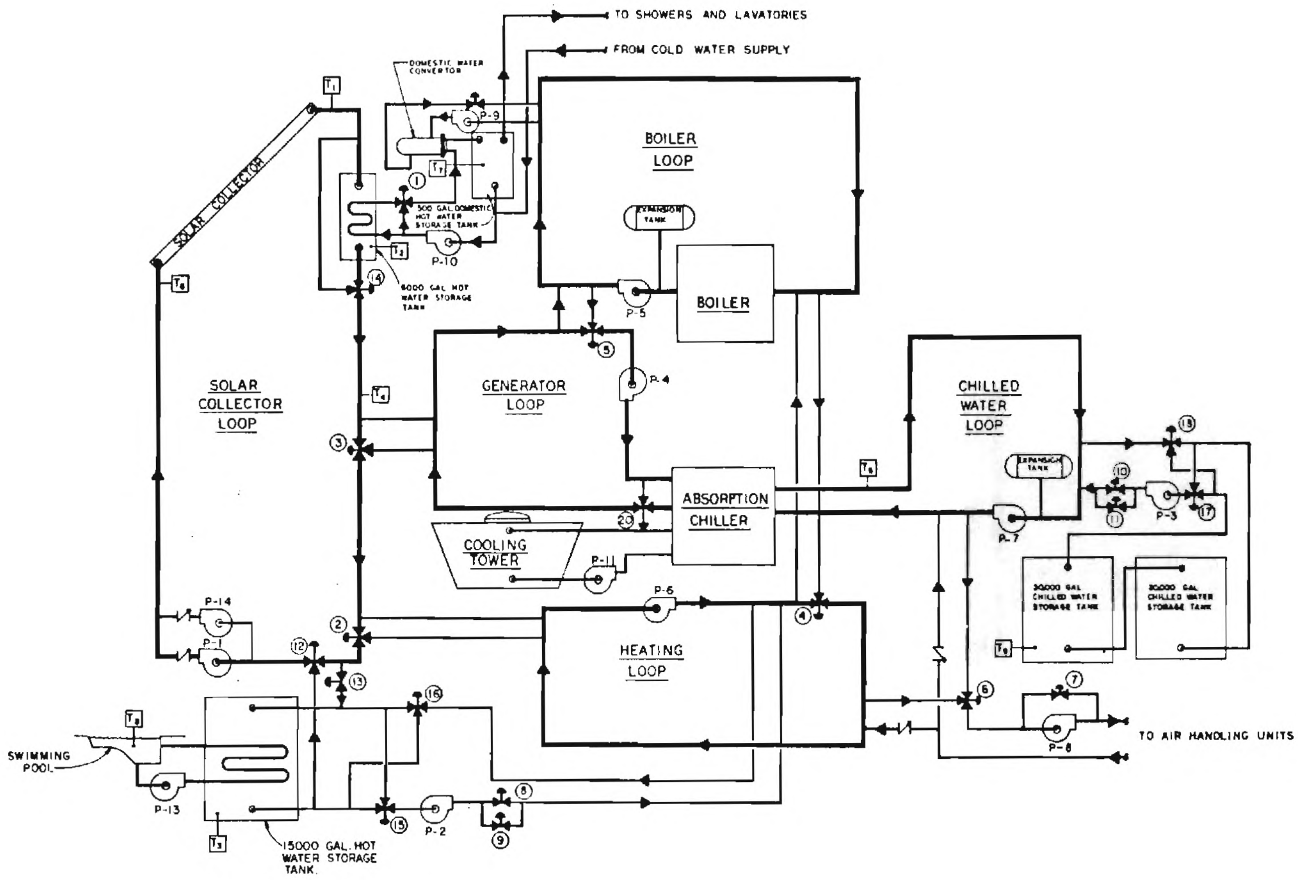


FIGURE 4. SCHEMATIC OF SIMULATION PROCEDURES



FLOW SCHEMATIC

FIGURE 5. SOLAR SYSTEM SCHEMATIC

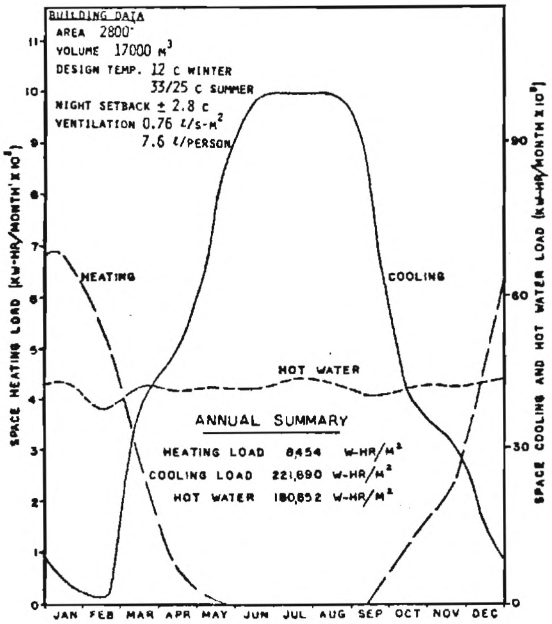


FIGURE 6. CALCULATED BUILDING LOADS

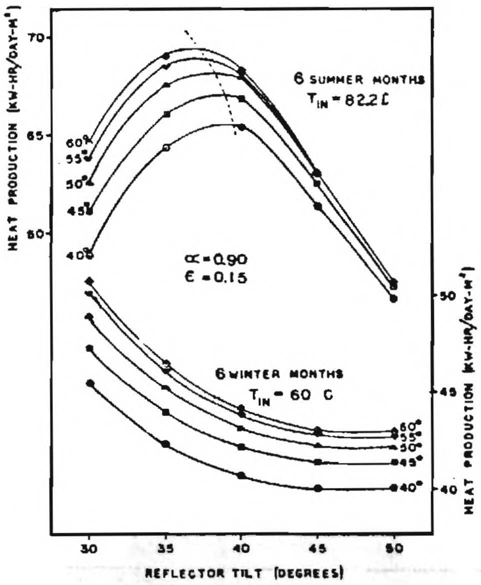


FIGURE 7. AVERAGE DAILY HEAT PRODUCTION FOR VARIOUS COLLECTOR AND REFLECTOR ANGLES

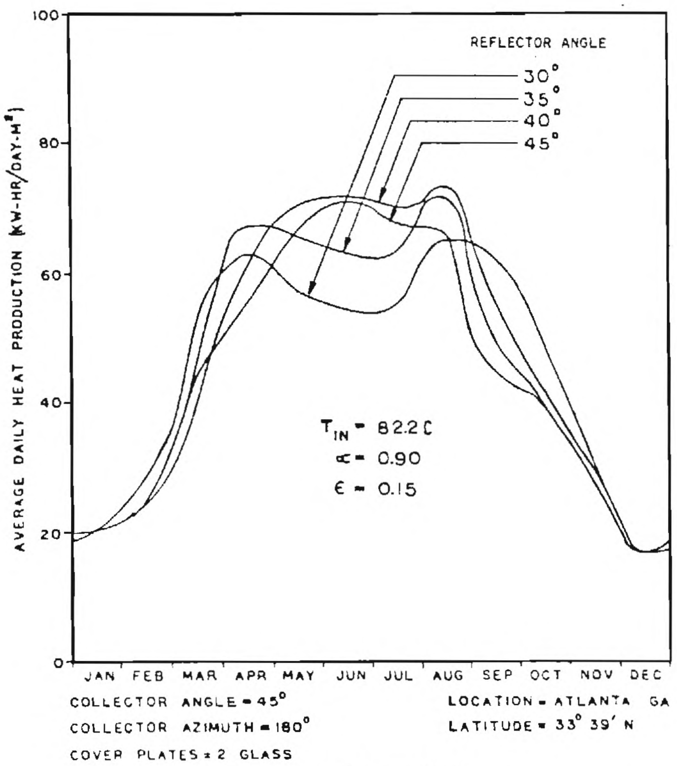


FIGURE 8. ANNUAL DISTRIBUTION OF COLLECTED ENERGY

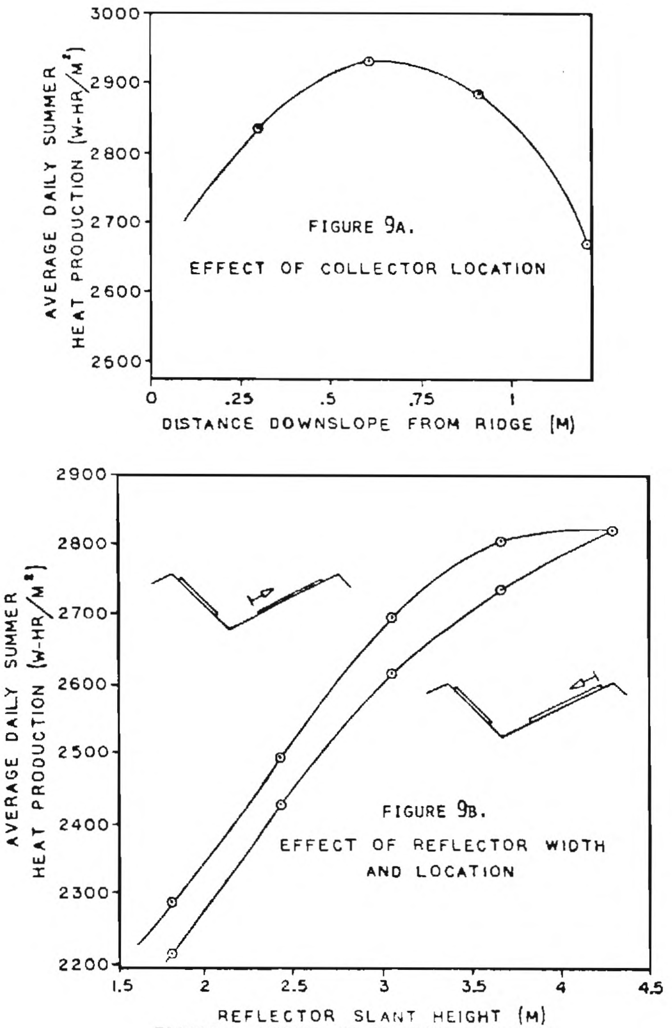


FIGURE 9. EFFECT OF RELATIVE LOCATION OF REFLECTOR AND COLLECTOR ON ANNUAL HEAT COLLECTION

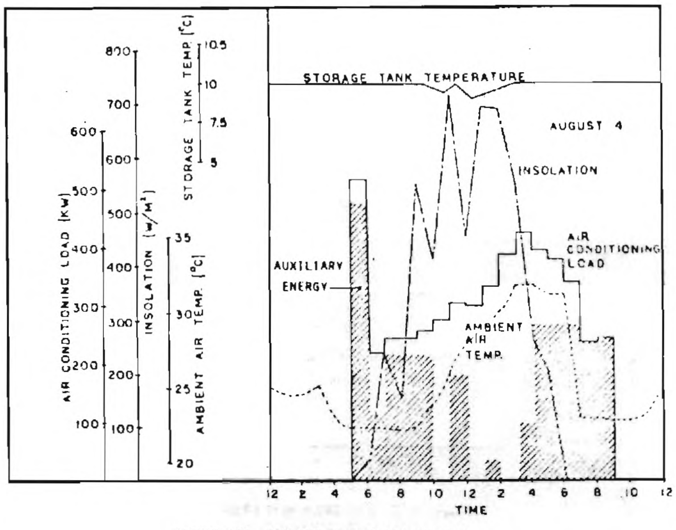


FIGURE 10A. COOLING SIMULATION-HOT DAY

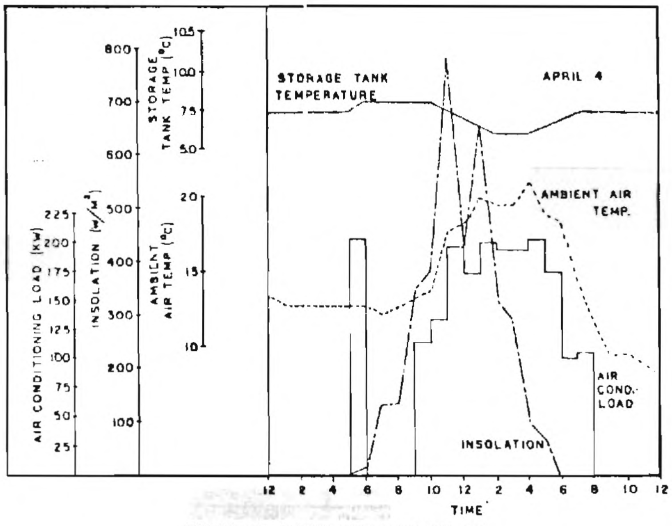


FIGURE 10B. COOLING SIMULATION-COOL DAY

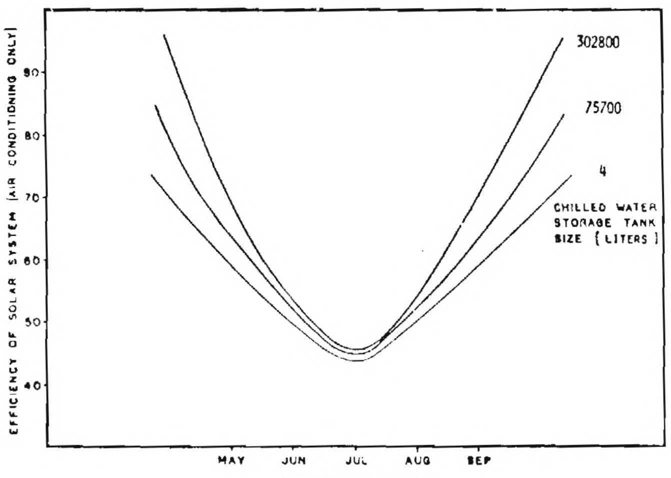


FIGURE 11. EFFECT OF CHILLED WATER STORAGE IN SUMMER

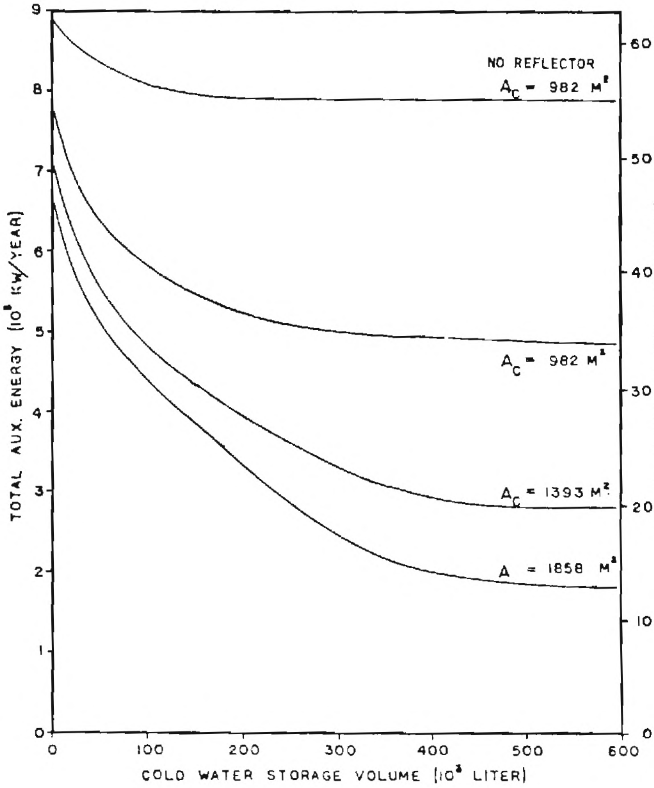


FIGURE 12. EFFECT OF CHILLED WATER STORAGE ON ANNUAL EFFICIENCY

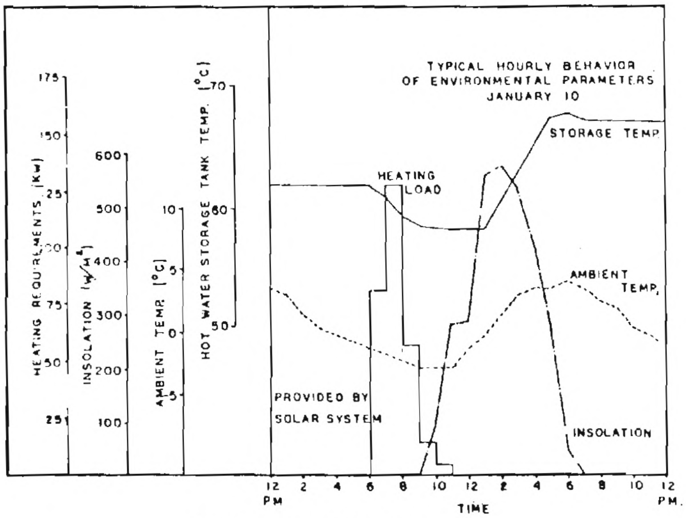


FIGURE 13A. HEATING SIMULATION - WARM DAY

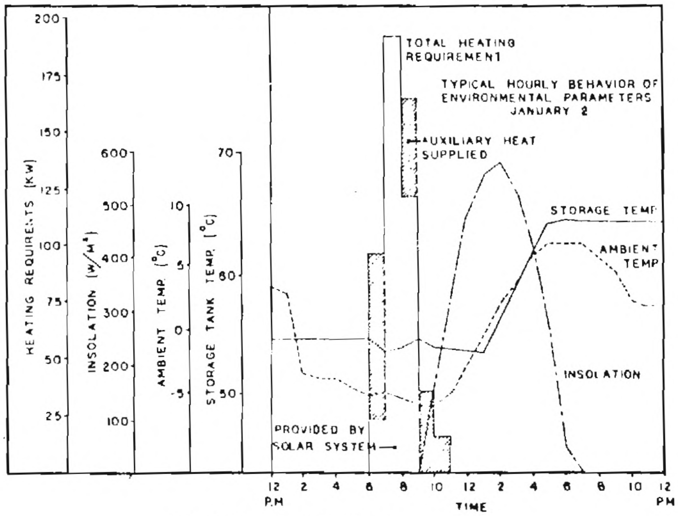


FIGURE 13B. HEATING SIMULATION COLD DAY

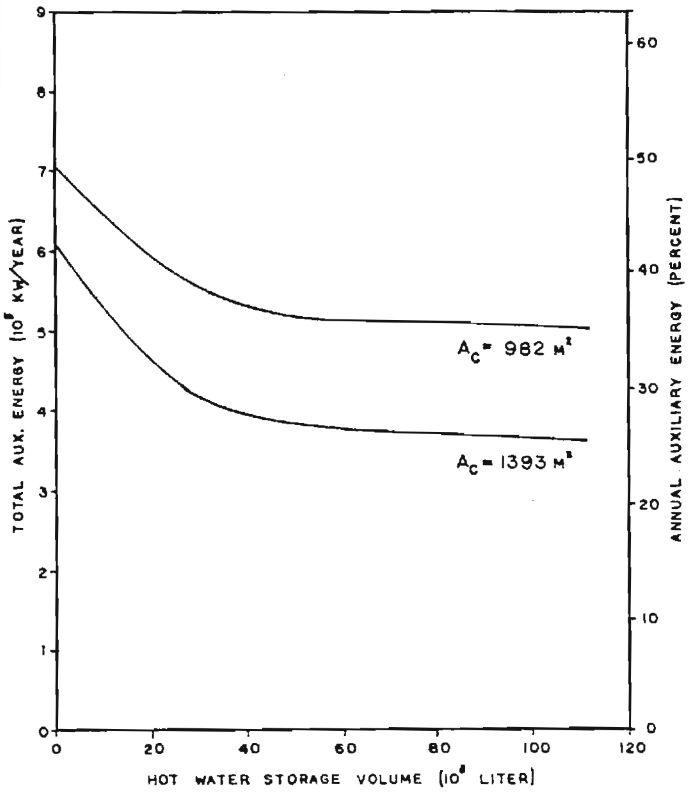


FIGURE 14. EFFECT OF HOT WATER STORAGE ON ANNUAL EFFICIENCY-HEATING ONLY

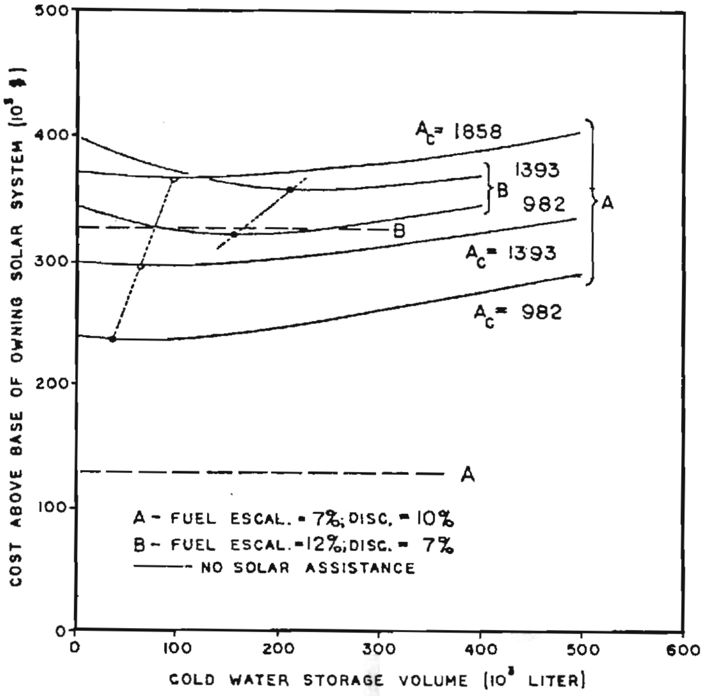
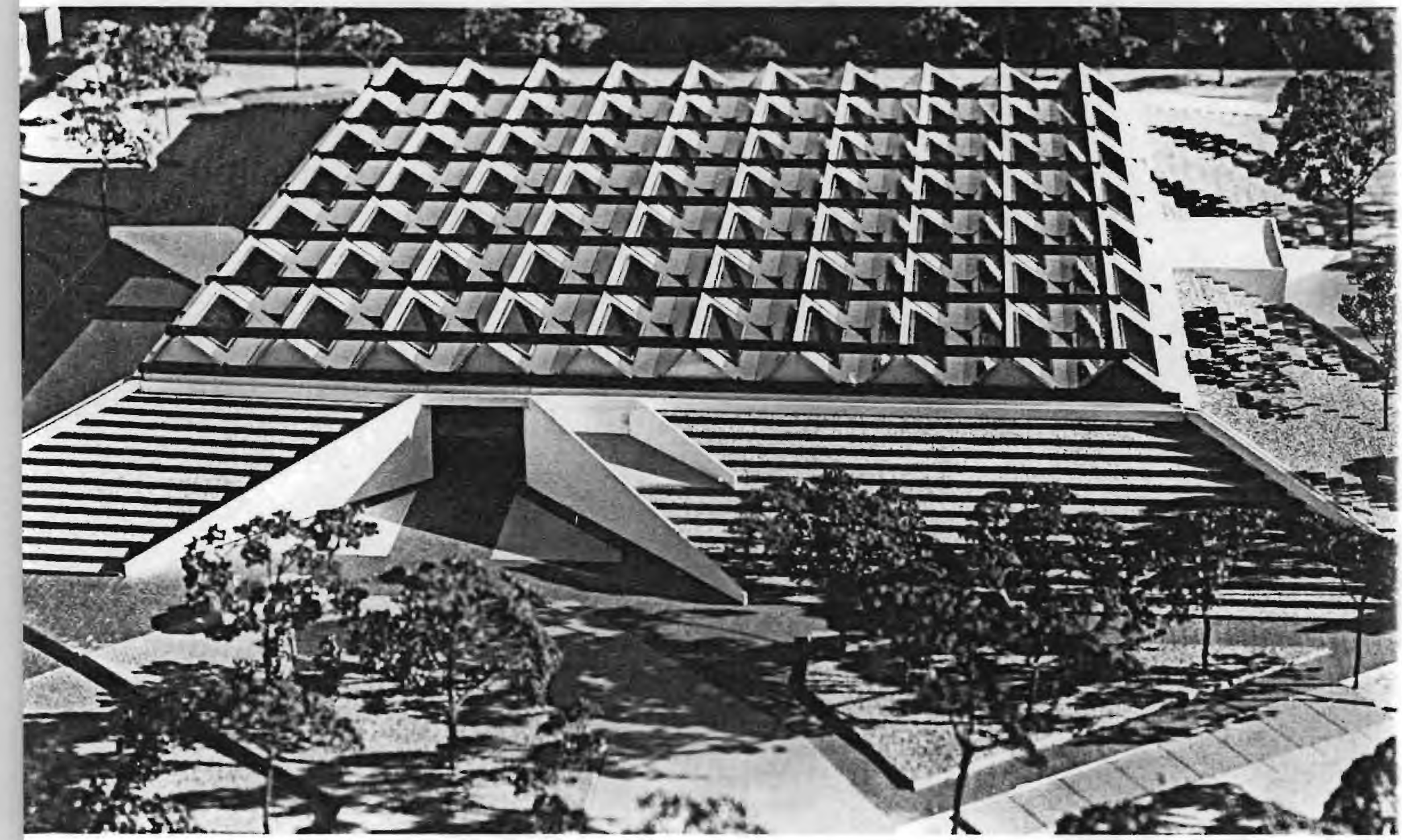


FIGURE 15. LIFE-CYLCE COSTS FOR SOLAR SYSTEM FOR TWO ESCALATION/ DISCOUNT RATES

Reprinted from November, 1976 issue of ASHRAE JOURNAL

The Shenandoah Community Center: A total solar design concept



Late this year, the Shenandoah, Georgia Community Center will be dedicated and opened to the public as one of the first commercial solar demonstration projects designed from the beginning with solar energy in mind. When completed, it will be one of the largest solar heating and cooling installations in the world.

STEVEN F. BRUNING
Associate Member ASHRAE

MARTIN S. GEORGE
Associate Member Ashrae

THE solar heating and cooling system of the Shenandoah Community Center consists of 10,584 sq. ft. of reflector augmented flat plate collectors, a nominal two hundred ton lithium bromide absorption chiller, 20,000 gallons of hot water storage and 60,000 gallons of chilled water storage. The system is designed to provide space heating and cooling for the building as well as domestic water heating.

The building will serve as the Community Center for the new town of Shenandoah, GA, 25 miles southwest of Atlanta. The town is projected to have a population of 40,000 residents on 7,200 acres. The center includes an ice rink, combination auditorium/gymnasium, meeting and exhibition rooms, and offices. The basic architectural design of the building emphasizes energy conservation in all aspects. The main floor building is approximately 4 ft. below normal grade with the excavated earth used to form berms on all sides of the building. The small glass area located at the office and exhibit areas faces north to minimize the resulting cooling load. While the earth berm provides excellent insulating characteristics for heat transfer into and out of the building, it also offers a convenient solution to the problem of burying the large water storage tanks used by the solar system. Because of the proximity of the tanks to the building and the design features of the piping system, all automatic switching and shutoff valves are located inside building rather than in valve pits at the tanks where they are more or less exposed to the elements. The problem of supporting the solar collector panels was solved by utilizing a sawtooth roof structure supported by a long span open web wood truss system. The actual angles of the sawtooth were chosen to coincide with the optimum angles for collector and reflector mounting as determined by extensive computer modeling. The reflector panel was utilized to increase the solar intensity on the collector surface. This is particularly important during the summer months when the collectors are required to heat water to as high as 200F to drive the absorption chiller.

COLLECTORS

The solar collection array consists of 63 8ft. x 21ft. flat plate solar collector panels. The large panel size was

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S. F. Bruning and M.S. George are with the consulting engineering firm of Newcomb & Boyd, Atlanta, GA.

chosen for ease and speed of installation. Once in place, only 63 supply and 63 return piping connections need be made by hand instead of a total of 1176 connections which would be required if the more conventional 6ft. x 3ft. panel size were used.

The collectors are constructed of a copper absorber plate with internally bonded fluid flow tubes of the "tube-in-sheet" type. The tubes are spaced approximately 5-1/2 in. apart and are designed for a working pressure of 40 psig. The absorber plate is coated with an electroplated black chrome selective coating with an absorptivity of 0.95 and an emissivity of 0.07. The collector is double glazed with low iron, tempered, double weight glass. The rear of the collector is insulated. The overall coefficient of heat transfer from the absorber plate to the ambient air at the rear of the collector is 0.05 Btuh/ft.^{2}/°F. The collectors are actually supported above the roof surface by angle frames. Originally it was thought to be more economical to integrate the collectors into the roof structure and have them actually act as the waterproof surface. However this did not prove to be true because of difficulties which would be encountered in waterproofing the joints between the collectors and conventional roof surface. The method adopted was to support the collectors with the roof structure, but to provide a conventional roofing surface below them for waterproofing purposes.

DESIGN

The solar system was designed with two primary criteria in mind: **(1)** provide a system to efficiently utilize the available solar energy for heating, cooling, and domestic water heating and **(2)** to accomplish this goal using the simplest, most maintenance-free system available. The basic system design incorporates several unique features which both simplify the overall design of the system, as well as improve the operating efficiency.

The initial step taken to insure that these goals were met was to study several current solar heating and cooling projects to determine problem areas in the construction and operation of the systems. This survey indicated that the majority of the problems occur in three basic areas: **(I)** collector freeze protection, **(II)** expansion and contraction of the large liquid volumes, and **(III)** flow characteristics in the complex piping systems. To avoid these problems, the following steps were taken:

- Primarily due to the construction of the building, the summer cooling load is much larger than the winter heating load. Consequently, during winter some excess heat is available from the solar system. This helps use of stored heat to maintain night-time collector fluid temperatures above freezing without resorting to drainage of the collectors or use of antifreeze solutions. One advantage of this over drain-and-fill designs is that the collectors are always full and the loop can therefore begin operation as soon as radiation is present, without the risk of freeze-up as the collectors are filled on a clear but cold day. By not using antifreeze, the reduced heat transfer ability associated with that type of system is avoided.
- The expansion of the working fluids was carefully studied to insure that sufficient allowances were made for the excessive expansion resulting from the large volumes of fluid. The compression tanks were located as high as possible in the building to minimize their size. However, their total volume still was over 5900 gals.
- The basic piping system was designed utilizing the primary/secondary loop concept to avoid the problems sometimes associated with piping systems having very complex flow patterns. A schematic of the system is shown in Fig. 1. Modulating valves are used to control energy transfer to or from a component and each of these subsystems operates somewhat independently of the others. For example, the collector loop consists of pump P-1, the collectors, a buffer tank, and valves 14, 3 and 2. Fluid is circulated in this loop at a constant rate until the temperature is raised enough to contribute to the load, at which point valves 2 or 3 are modulated to divert energy (flow) to the heating or generator loops, respectively. The small buffer tank is used to avoid unnecessary cycling of the control system. Similar operation for the other loops can be deduced from Fig. 1. One aspect that deserves further comment is the relative ease with which auxiliary energy can be added from the boiler, either to the chiller (generator) or to the building heating loop, simultaneously with collector operation. The hot and chilled water storage systems function similarily, so that for example chiller evaporator output can be fed to the building with any excess capacity diverted to the storage tanks. Appropriate control interlocks are included so that this would only occur during conditions of 100% solar operation. At other times the tanks could be used with the chiller or boiler to meet the load.

An additonal design feature is the use of a 15,000 gal. tank purely for hot water storage. Orginally this tank was intended to operate as a chilled.water storage tank during the summer and a hot water storage tank during the winter in order to reduce the cost of the project. Further investigation revealed this was not the case. With this particular system design, the cost of the additional piping, pumps, and control interlocks to accomplish the automatic switchover of the tank almost exceeded the cost of the tank itself. This is one reason it was decided to use this tank for hot water storage only and eliminate switching it to chilled water storage. Another reason for not switching the tank is the limitation on the chilled water temperature entering the chiller. This temperature cannot exceed approximately 90F. If the tank is switched from hot water to chilled water storage it will take several days for the tank to cool down to 90F. This time period would make automatic and efficient operation of the system extremely difficult, especially in the Georgia climate where the intermediate seasons are usually quite extensive. Once the tank has cooled to 90F, the chiller must still cool the water down to approximately 54F before normal operation of the system can resume. This load amounts to 6.4 million Btu of additional energy which must be input to the absorption chiller, assuming an average cop of the chiller of 0.7. In some systems, switching chilled and hot water storage tanks may well be worthwhile, however, for the above reasons, this was not used on the Shenandoah project.

OPERATION

In order to thoroughly describe the system's operation, sequences under various conditions have been included. These sequences represent different phases, although the system basically has only two modes of operation: Summer (above 55F) and winter (below 55F).

- **Summer Mode With Sufficient or Excess Insolation**—Pump P-1 provides flow through the collector array whenever the outlet temperature of the collector, T-1, is greater than the temperature in the buffer tank, T-2. When the temperature in the collector loop exceeds 180F, valve #3 is energized, diverting water into the generator loop of the absorption

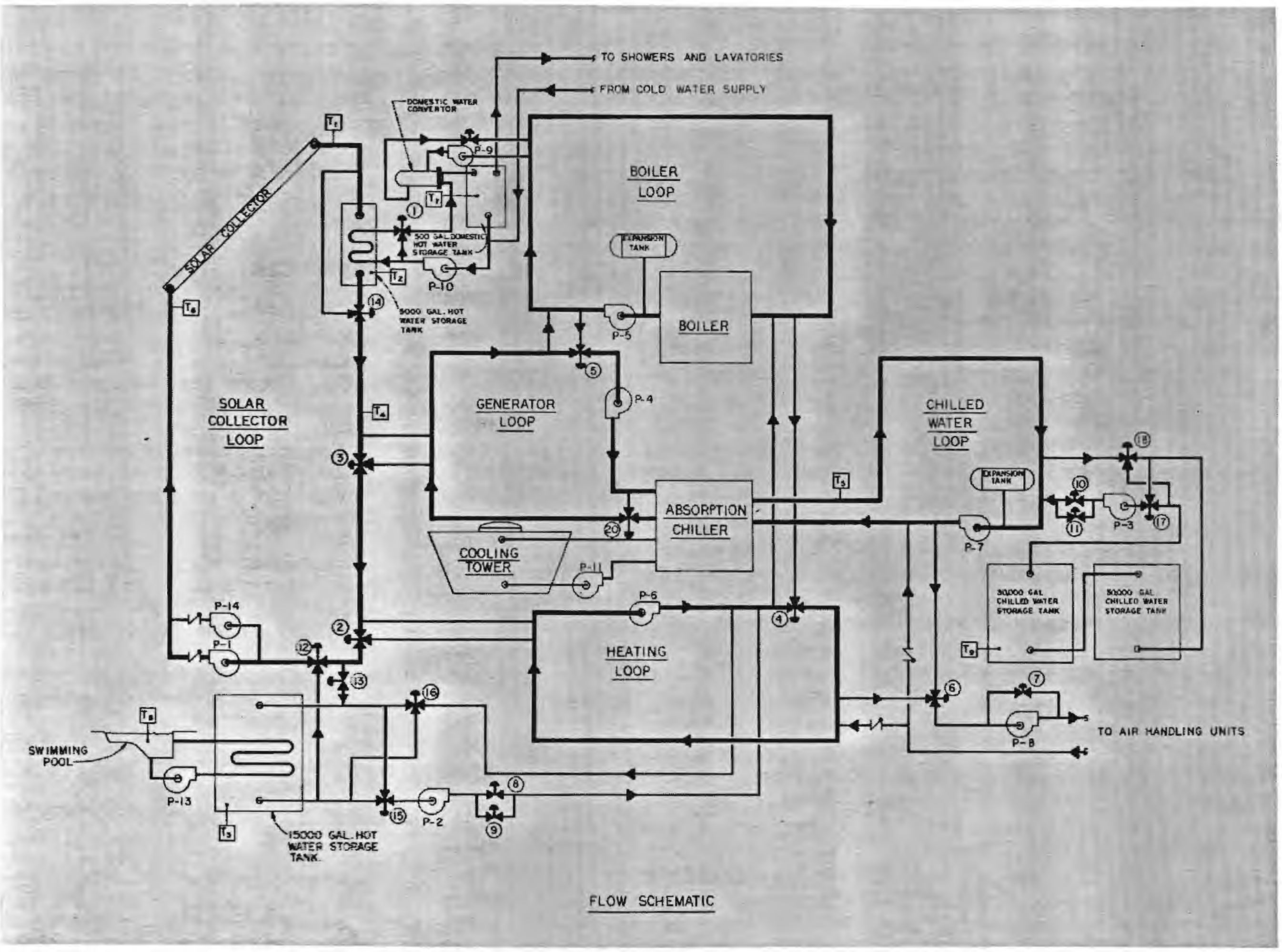

Fig. 1

chiller. *(As mentioned earlier, the buffer thank prevents rapid temperature fluctuations from reaching the absorption machine.)* Pump P-8, which supplies water to the air handling units for space conditioning, draws chilled water from the primary evaporator loop. If the absorption machine is providing more cooling than is required to satisfy the space conditions, the air handling unit valves will begin to close. As this occurs, a pneumatic signal activates valve #10 and pump P-3 to begin storing the excess chilled water. As valve #10 begins to open, warmer water from the top of the chilled water storaged tank is blended with the colder water coming from the evaporator to provide only that temperture which is necessary to maintain the space conditions. Therefore, an equal amount of chilled water from the evaporator is stored in the bottom of the chilled water storage tank. In this way, the absorption machine is utilized to convert all available heat from the solar system to chilled water. This eliminates the need for storing the high temperature water from the collectors. It should be noted at this point that the solar system is not used to heat domestic water while the absorption refrigeration machine is in use and utilizing energy from the solar system.

● **Summer Mode With Insufficient Insolation**—If the temperature of the chilled water rises above a certain point, or if the space temperature rises above the set point, the air handling unit valves will open to the maximum position. When this occurs, indicating a need for more cooling, a pneumatic signal energizes valve #11 and pump P-3 if the temperature of the water in the storage tank, T-9, is lower than the temperature of the water in the chilled water loop, T-5. Chilled water is then pumped from the storage tanks to the load and back through the chiller to pick up whatever cooling is available before being returned to the storage tank.

If space conditions rise above the set point and the water temperature in the chilled water storage tanks is not sufficient to maintain conditions, the boiler is activated to provide auxiliary heat to the generator of the absorption refrigeration machine. Valve #5 is modulated to blend only enough water from the boiler loop to operate the absorption machine at a level sufficient to maintain space conditions. The solar system is still used to provide whatever energy is available to the generator loop. Valve #3 remains open to the generator loop as long as there is a temperature rise across the collectors. When there is no solar energy available the boiler provides all the energy necessary to drive the absorption machine. Whenever the boiler is activated the storage system is locked out so that the boiler is not used to store chilled water.

● **Winter Mode With Sufficient or Excess Insolation**—Pump P-1 provides flow through the collectors whenever the temperature at the collector outlet exceeds 110F or is higher than the temperature in any of the hot water storage tanks. Valve #2 is energized to provide collector water to the primary heating loop. As in the summer mode, whenever more heat is provided than is necessary to maintain the space conditions, the air handling unit valves begin to close. When this happens, a pneumatic signal energizes valve #8 and pump P-2 and blends cooler water from the bottom of the hot water storage tank to provide only that temperature which is necessary to maintain space conditions. The hotter water from the collectors is thereby stored in the top of the hot water storage tank. Pump P-10 pumps domestic water through a heat exchanger located in the buffer tank whenever the temperature of the water in the buffer tank is higher than the temperature of the water in the domestic water storage tank. The boiler is used to supplement this energy whenever the temperature of the water in the domestic water storage tank drops below 140F. Any excess energy that is collected but is not used for either domestic water heating or space conditioning is used to heat the swimming pool.

When the insolation is insufficient to maintain space conditions, the following control operations occur: If the air handling unit valves are in a maximum open position and the space temperature continues to drop, a pneumatic signal energizes valve #9 and pump P-2 to pump hot water from the storage tank to the system, assuming the water in the storage tank is hotter than the water coming from the collectors. The water is pumped from the storage tank to the system and back to the collectors to pick up whatever energy is available before being returned to the storage tank. If the temperature of the water in the storage tank is not greater than that coming from the collectors, or if the space temperature continues to fall, the boiler is activated to provide additional heating.

When the boiler is activated, valve #4 is modulated to blend water from the boiler loop with water coming from the collectors to provide only that amount of heating which is necessary to maintain the space conditions. Valve #2 remains open to provide to the heating loop with whatever energy is available from the collectors.

When no solar energy is available the boiler is used to provide all the heat necessary to maintain space conditions. Again, valve #4 is modulated to blend water from the boiler loop with water in the heating loop to maintain space conditions. Water is also pumped from the boiler loop to heat the domestic water. If the temperature in the collectors drops below 40F, pump P-l4 is energized to circulate a minimal amount of water through a closed loop to prevent freeze up. Although it is acknowledged that some energy will be lost with this method of freeze protection, the heating load for this particular building is so small that this extra energy should be available.

ANALYSIS

Under the leadership of Dr. J. I. Craig of Georgia Tech, a team composed of our engineers and Georgia Tech graduate students performed detailed computerized simulation studies. The building load and solar system performance were modeled using a variety of computer programs. The peak heating and cooling loads were calculated using the APEC HCC III program. These peak loads were combined with a year of hourly weather data and occupancy profiles as input to the E-CUBE program. E-CUBE then produced an hourly file of heating, cooling, and domestic water heating loads, which was used as input to the actual solar system simulation using a combination of heat balance type programs written specifically for this project and a modified TRNSYS program from the University of Wisconsin. The results of the methods used in the simulation and analysis are too extensive to report here, but are described in Ref.[1]. The Shenandoah Community Center is one of the first of the second generation of large scale solar heating and cooling demonstration projects funded by ERDA. Its award-winning* design has benefited greatly from knowledge gained on previous projects. This increasing accumulation of information is necessary if the use of solar energy is to become a practical and economical source of energy.

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*Recipient of the Owens-Corning Fiberglas 1976 Energy Conservation Award—Commercial Category. The design and installation team was composed of: Dr. J. Richard Williams, GIT; Taylor & Collum, Architects; Newcomb & Boyd, Solar System Engineers; Wright Engineering Assocs., Mechanical Engineers; Adams & Roberts, Electrical Engineers; Jack Lynch & Assocs., Structural Engineers; Batson Cook, Inc., General Contractors; and Delta Corp., Mechanical and Solar contractor.