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DEFINITION STUDY FOR PHOTOVOLTAIC RESIDENTIAL PROTOTYPE SYSTEM

By

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16. Abstract

A definition study, including conceptual design, performance and sensitivity analysis as well as experiment planning and test equipment definition, was performed in support of a program to deploy experimental photovoltaic powered single family residences at selected locations throughout the Continental United States.

As the first step in this program, a site evaluation was performed to assess the relative merits of different regions of the country in terms of the suitability for experimental photovoltaic powered residences. Eight sites were selected based on evaluation criteria which included population, photovoltaic systems performance and the cost of electrical energy.

A parametric sensitivity analysis was performed for four selected site locations. Analytical models were developed for four different power system implementation approaches. Using the model which represents a direct (or float) charge system implementation the performance sensitivity to the following parameter variations is reported: (1) solar roof slope angle, (2) ratio of the number of series cells in the solar array to the number of series cells in the lead-acid battery, and (3) battery size. For a Cleveland site location, a system with no on-site energy storage and with a maximum power tracking inverter which feeds back excess power to the utility was shown to have 19 percent greater net system output than the second place system.

Based on the results of this parametric analysis, the recommended conceptual design of the experiment emphasizes an evolutionary development of the power system which allows the evaluation of different basic system implementations. As a first stage in the recommended experiment evolution, a maximum power tracking inverter with no on-site energy storage and with feedback of excess power to the utility was proposed. During the second stage, on-site energy storage would be added to the residence by connecting the battery directly to the solar array bus and using a digital partial shunt regulator to limit the battery terminal voltage.

The experiment test plan is described. The load control and data acquisition system and the data display panel for the residence are discussed.

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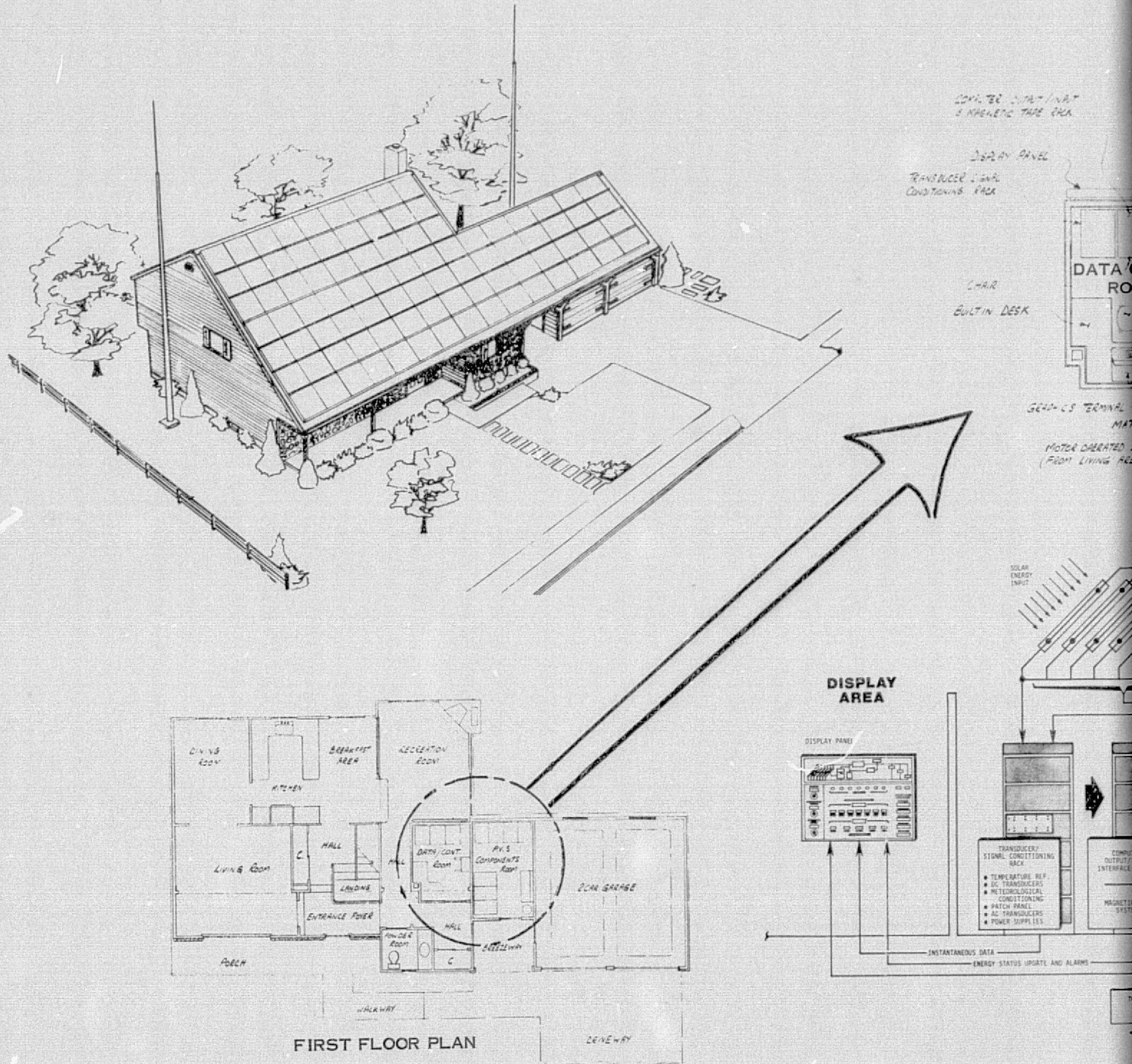
SECTION 1

SUMMARY

The definition study for Residential Prototype System Test (RPST) installations has resulted in a recommended conceptual design which is depicted in Figure 1-1. The architectural design at this residence provides 169 m^2 of living area in a contemporary design, which meets the energy conservation guidelines established by ASHRAE Standard 90-75. No attempt was made to investigate other architectural concepts since this was considered to be beyond the scope of this study. The photovoltaic power system components, as well as the data acquisition and control system required to monitor the experiment, can be easily integrated into a residential structure of this type. The south facing roof can accommodate up to 87 subarrays (each 1.219 x 1.219 m) for a total gross array area of 129.3 m^2. The solar cell modules are mounted above the conventional roof structure to facilitate the integration and test of various module designs. The other functional elements which are not found in a conventionally-powered residence include a Photovoltaic System (PVS) Components Room and a Data/Control Room. The latter houses the data acquisition and control equipment which is necessary for the operation of the RPST experiment. A display panel is also provided as a visual aid to graphically represent the operation and performance of the system under test. The PVS Components Room houses all other equipment such as batteries and power conditioning equipment.

Two power system configurations were proposed as the basis for a two stage experiment design evolution. The results of a performance sensitivity analysis have shown that a system approach with no on-site energy storage achieves the highest system output. With this approach the excess power from the solar array is fed back to the utility, which in effect acts as an infinite source and sink for power. A system of this type, which includes a solar array maximum power tracking controller to force inverter operation at the solar array maximum power point, is proposed as the first stage in the experiment implementation. Following a 12 month operational evaluation period with this PVS configuration, a lead-acid battery is added to the system by connecting it directly across the solar array bus. A digitally switched partial shunt voltage limiter is also added to provide the necessary battery charge voltage limit control. This system constitutes the second evolutionary stage of the experiment. The size of the battery and the number of series connected battery cells relative to the number of series connected solar cell modules are selected based on an analysis using a mathematical model of this system option. An important objective of this experimental program is the verification of terrestrial photovoltaic power system analytical models. The experimental house has been adequately instrumented (with 53 analog data channels) to permit the accurate measurement of system performance. An on-site minicomputer, with associated peripherals including a line printer and graphics CRT terminal, provides the capability for on-site data reduction and display in tabular and graphical form. Experiment control flexibility will enable the periodic in-situ measurement of solar cell circuit I-V characteristics and the control of house loads to effect energy saving load management options.



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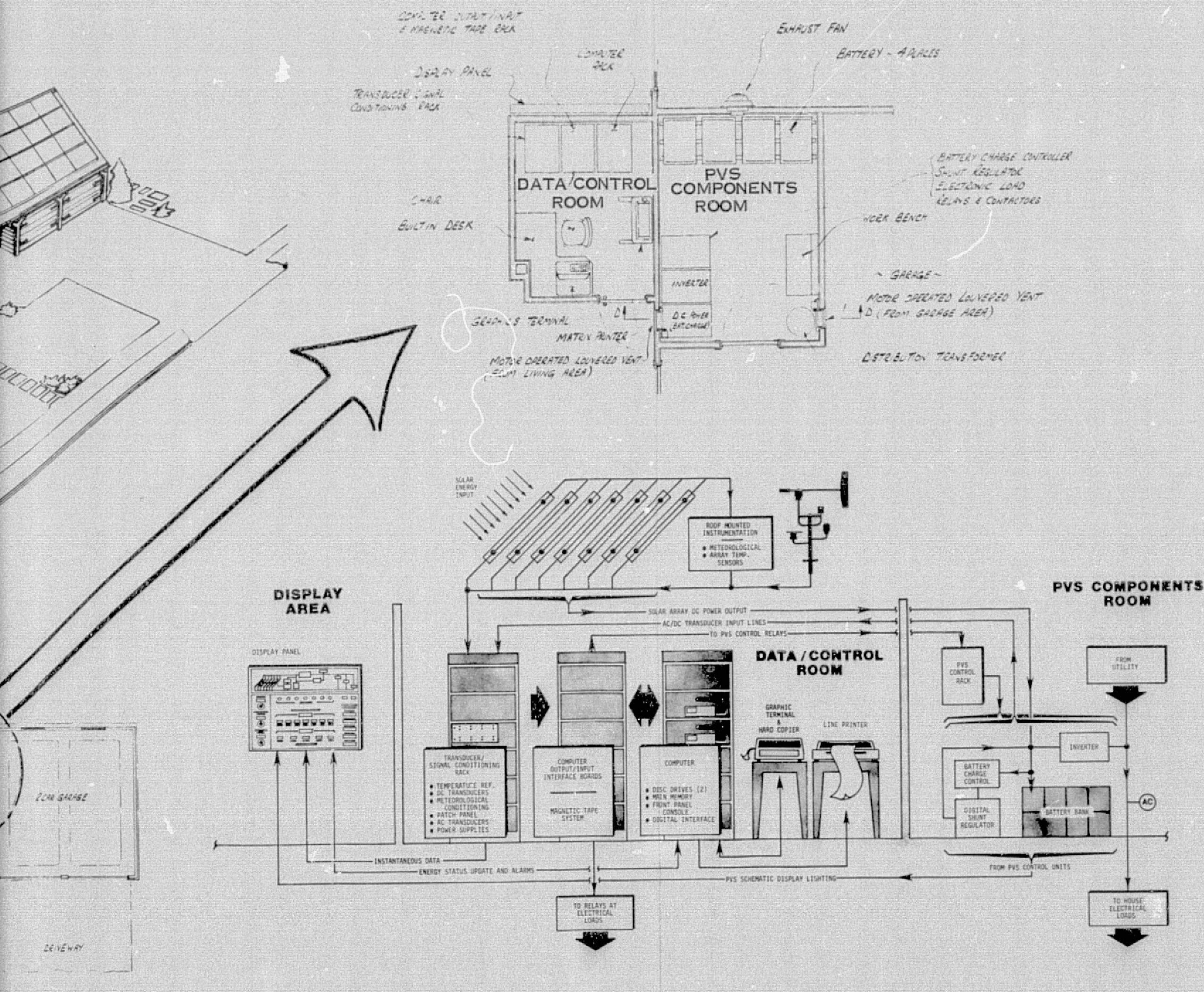

Figure 1-1. RPST Experiment Design Scenario

SECTION 2

INTRODUCTION

The Residential Prototype System Test (RPST) is defined as a prototype experimental photovoltaic power system which is integrated into a conventional single-family residential structure. This six month definition study was intended to analyze the performance, conduct the conceptual design, plan the testing program and specify the test equipment requirements for such an experimental residence. Since RPST installations are currently planned for several regional site locations, this program also included a site selection evaluation.

The development of these regional RPST's is a logical extension of the system studies and mission analyses reported in References 1 and 2 of Section 5.

The study program activity was subdivided into six major work tasks as defined in Table 2-1.

Table 2-1. Study Tasks

Task No.	Description	Report Section No.
I	Site Selection	3.1
II	Parametric Sensitivity Analysis	3.2
III	Conceptual Design	3.3
IV	Test Planning	3.4
V	Test Equipment Requirements and Procedures	3.5
VI	Institutional Problems	3.6

The main body of this report has been organized to discuss these subjects along the lines of this work task structure as originally defined by the contract statement of work.

The Site Selection Task, as discussed in Section 3.1, consisted of the identification of twelve geographical regions within the continential U.S. Each of these regions was evaluated in terms of photovoltaic power system performance. Eight sites were recommended from a list of 41 potential locations by applying an evaluation process which included three criteria: (1) population, (2) photovoltaic system performance, and (3) cost of electrical fuel.

The Parametric Sensitivity Analysis, as discussed in Section 3.2, was an extension of the analysis effort reported in Reference 1. Four different terrestrial photovoltaic power system analytical models were developed for use in this task. These models were applied to the analysis of site locations in Cleveland, Ohio; Los Angeles, California; Phoenix, Arizona; and Washington, D.C. These site locations were selected by the LeRC Project Manager for analysis purposes only and do not necessarily represent possible sites for RPST's.

Section 3.3 describes the results of the Conceptual Design task which recommends and defines a two stage experiment design evolution. This approach to RPST design will enable the experimental evaluation of the most promising power system configurations, the first of which employs no on-site energy storage and uses the utility grid as an infinite source and sink for energy. The analytical evaluations under Task II have shown this approach to be superior in terms of net system output. As the second stage of this design evolution a lead-acid battery is added to the system and no feedback of power to the utility is allowed.

The Test Planning activity, as discussed in Section 3.4, establishes a proposed testing sequence and schedule to achieve the specified design and test objectives. The data requirements are defined to allow the subsequent specification of the test equipment requirements.

Section 3.5 discusses these test equipment requirements and recommends specific instrumentation and minicomputer hardware to achieve the desired overall test objectives for the RPST project. The costs for this equipment and the recommended servicing and maintenance are included in this discussion.

The potential institutional problems associated with the RPST project are discussed in Section 3.6. Two major issues were considered in this investigation: (1) legal liability during and after installation, and (2) labor practices, building restrictions, and architectural design guides.

SECTION 3

TECHNICAL DISCUSSION

3.1 SITE SELECTION (TASK I)

3.1.1 INTRODUCTION

This section presents the results of the Task I - Site Selection activity. This task was organized and accomplished in the following steps:

1. Identification of twelve geographical regions within the continental U. S. (based on solar energy related factors).

2. The evaluation of these twelve regions in terms of photovoltaic power system performance.

3. The selection and identification of at least three potential site locations for each region.

4. The recommendation of eight locations as possible construction sites for a residential prototype system test (RPST). One of these site locations shall be Lewis Research Center, Cleveland, OH.

The selection of 12 geographical regions was based on previous work performed during the Phase 0 "Solar Heating and Cooling of Buildings" contract. The identification of these regions and the approach used to establish the climatological data for each region is discussed in Section 3.1.2.

Section 3.1.3 contains a discussion of the procedure used to evaluate the expected performance of a residential photovoltaic power system in each of the twelve selected regions. Each region is evaluated using the insolation/weather data base tape associated with the "climatic designator" for each region. These 12 tapes are first processed to establish the hourly heating/cooling load demands for the residence. These load demands along with the insolation/weather data are then used by the photovoltaic system analysis program to calculate the performance of the power system in terms of annual available solar array energy and annual energy displacement factor.

Section 3.1.4 lists 41 potential site locations and describes the rationale used in the selection of these sites.

The final objective of this task is the recommendation of eight locations as possible construction sites for the RPSTs. These recommended sites are listed and discussed in Section 3.1.5.

3.1.2 SELECTION OF GEOGRAPHICAL REGIONS

Figure 3-1 shows the recommended division of the continental U.S. into 12 geographical regions based on solar energy related factors such as insolation and heating and cooling degree days. This regional division was evolved during the course of the Phase 0 ERDA sponsored study entitled, "Solar Heating and Cooling of Buildings" (SHACOB). The delineation of the various regions in Figure 3-1 was made to follow the outlines of Bureau of Economic Analysis Economic Areas (BEA). BEA's are a designation of the Department of Commerce and are used for reporting economic activity and forecasts of economic activity for the entire United States. Table 3-1 lists each BEA with the associated geographical identification and region number corresponding to the division shown in Figure 3-1. Table 3-2 lists the specific location within each region which was selected as the "climatic designator (CD)" for the region. These specific locations represent weather stations for which a combined insolation/weather data base magnetic tape exists in the GE library. These tapes permit the hourly analysis of photovoltaic system output using measured insolation, ambient temperature and wind speed to accurately determine solar cell output.

Table 3-2 also gives the specific year which is represented by each data base tape. The integrated total yearly insolation on a horizontal surface, as obtained from the specified tape, is listed in the table for comparison with the corresponding value obtained from the Climatic Atlas (Reference 3, Section 5). The Climatic Atlas value represents a multiple year average. The percent deviation of the value obtained from the tape, when compared with the multiple year average, is given in Table 3-2 for each CD considered. The greatest deviation is 17.3 percent for the Madison, Wisconsin tape.

The yearly average normal daily maximum temperature as obtained from the data base tape and from the Climatic Atlas are given for each CD. This maximum ambient temperature value is significant because of its affect on the resultant solar array energy output at the maximum power point. These temperature and insolation values will be used later to develop a generalized expression for solar array energy output based on calculated system performance from the twelve data base tapes.

3.1.3 EVALUATION OF REGIONS

The 12 selected regions were evaluated in terms of the expected performance of a residential photovoltaic power system. In each case the insolation/weather data base tape was used as the input to a program called Building Transient Thermal Loads (BTTL). This program calculates the hourly total building heating/cooling load demand as described in Appendix B of Reference 1. The building characteristics for a single family residence with 169 m^2 of living area were used as described in the referenced report. The hourly heating/cooling load demands obtained from this program are written on another tape along with the insolation and weather data which is transcribed from the data base tape. This loads tape is subsequently used as the input to the

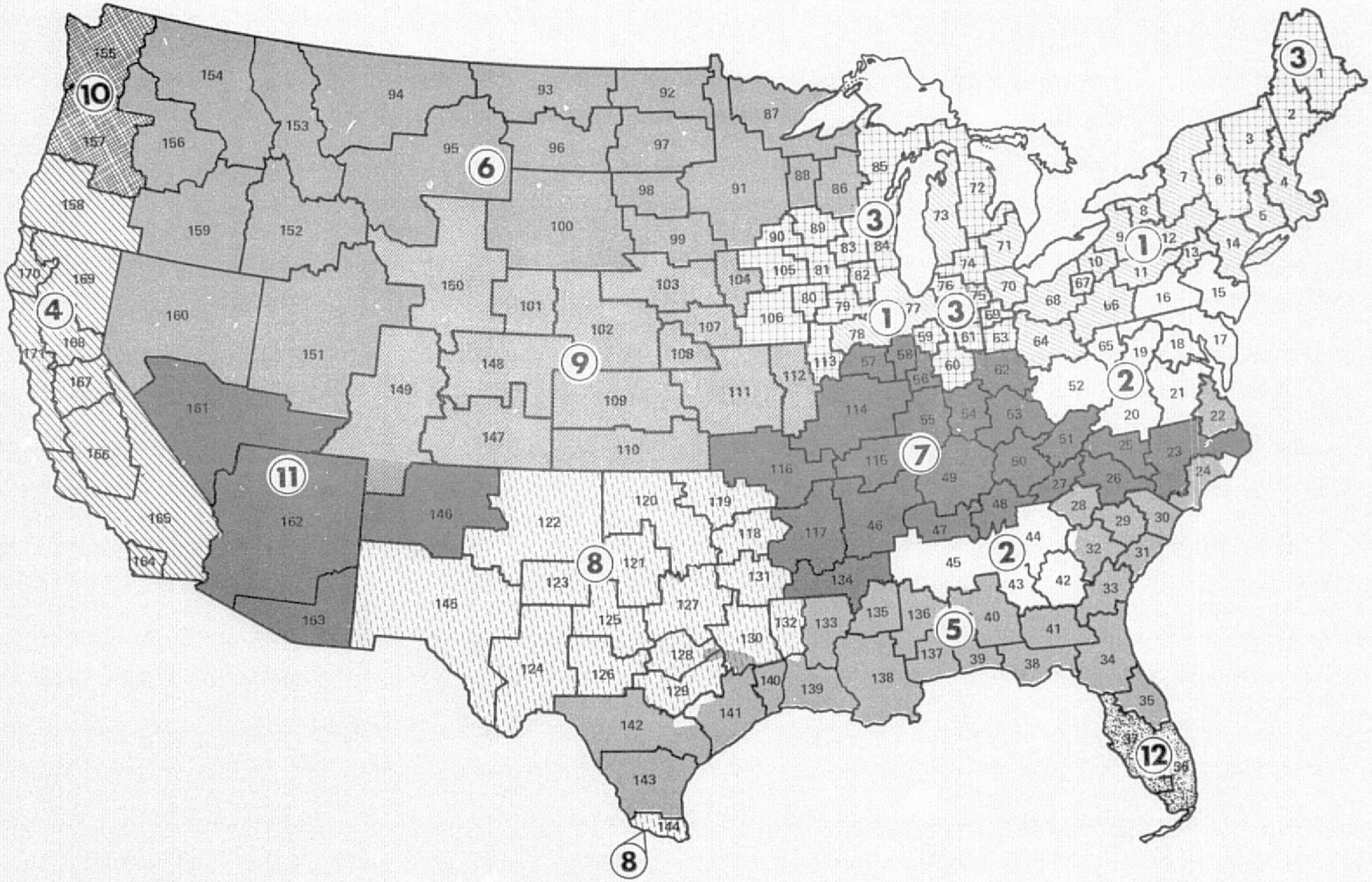

Figure 3-1. Climatic Scenario for Solar Energy

Table 3-1. Identification of BEA's

BEA No.	Location	Region No.
1	Bangor, ME	3
2	Portland, ME	3
3	Burlington, VT	3
4	Boston, MA	1
5	Hartford, CT	1
6	Schenectady, NY	3
7	Syracuse, NY	1
8	Rochester, NY	1
9	Buffalo, NY	1
10	Erie, PA	1
11	Williamsport, PA	1
12	Binghamton, NY	1
13	Wilkes Barre, PA	1
14	New York, NY	1
15	Philadelphia, PA	2
16	Harrisburg, PA	2
17	Baltimore, MD	2
18	Washington, DC	2
19	Stanton, VA	2
20	Roanoke, VA	2
21	Richmond, VA	2
22	Norfolk, VA	5
23	Raleigh, VA	7
24	Wilmington, NC	5
25	Winston Salem, NC	7
26	Charlotte, NC	7
27	Asheville, NC	7
28	Greenville, SC	5
29	Columbia, SC	5
30	Florence, SC	5
31	Charleston, SC	5
32	Augusta, GA	5
33	Savannah, GA	5
44	Atlanta, GA	2
45	Birmingham, AL	2
46	Memphis, TN	7
47	Huntsville, AL	7
48	Chattanooga, TN	7
49	Nashville, TN	7
50	Knoxville, TN	7
51	Bristol, VA	7
52	Huntington, WV	2
53	Lexington, KY	7
54	Louisville, KY	7
55	Evansville, IN	7
56	Terre Haute, IN	7
57	Springfield, IL	7
58	Champaigne, IL	7
59	Lafayette, IN	3
60	Indianapolis, IN	3
61	Anderson, IN	3
62	Cincinnati, OH	7
63	Dayton, OH	3
64	Columbus, OH	1
65	Clarksburg, WV	2
66	Pittsburgh, PA	1
67	Youngstown, OH	1
68	Cleveland, OH	1
69	Lima, OH	3
70	Toledo, OH	1
71	Detroit, MI	1
72	Saginaw, MI	3
73	Grand Rapids, MI	1
74	Lansing, MI	3
75	Fort Wayne, IN	3
76	South Bend, IN	3

34	Jacksonville, FL	5
35	Orlando, FL	5
36	Miami, FL	12
37	Tampa, FL	12
38	Tallahassee, FL	5
39	Pensacola, FL	5
40	Montgomery, AL	5
41	Albany, GA	5
42	Macon, GA	2
43	Columbus, GA	2

77	Chicago, IL	1
78	Peoria, IL	1
79	Davenport, IA	3
80	Cedar Rapids, IA	3
81	Dubuque, IA	3
82	Rockford, IL	3
83	Madison, WI	3
84	Milwaukee, WI	3
85	Appleton, WI	3
86	Wausau, WI	6

BEA No.	Location	Region No.
87	Duluth, MN	6
88	Eau Claire, WI	6
89	LaCrossee, WI	3
90	Rochester, MN	3
91	Minneapolis, MN	6
92	Grand Forks, ND	6
93	Minot, ND	6
94	Great Falls, ND	6
95	Billings, MT	6
96	Bismarck, ND	6
97	Fargo, ND	6
98	Aberdeen, SD	6
99	Sioux Falls, SD	6
100	Rapid City, SD	6
101	Scottsbluff, NB	9
102	Grand Island, NB	9
103	Sioux City, IA	9
104	Fort Dodge, IA	9
105	Waterloo, IA	3
106	DeMoines, IA	3
107	Omaha, NB	9
108	Lincoln, NB	9
109	Salina, KS	9
110	Wichita, KS	9
111	Kansas City, MO	9
112	Columbia, MO	9

BEA No.	Location	Region No.
130	Tyler, TX	8
131	Texarkana, TX/AR	8
132	Shreveport, LA	8
133	Monroe, LA	5
134	Greenville, MS	7
135	Jackson, MS	5
136	Meridian, MS	5
137	Mobile, AL	5
138	New Orleans, LA	5
139	Lake Charles, LA	5
140	Beaumont, TX	5
141	Houston, TX	5
142	San Antonio, TX	5
143	Corpus Christi, TX	5
144	McAllen, TX	8
145	El Paso, TX	8
146	Albuquerque, NM	11
147	Colorado Springs, CO	9
148	Denver, CO	9
149	Grand Junction, CO	9
150	Cheyenne, WY	9
151	Salt Lake City, UT	6
152	Idaho Falls, ID	6
153	Butte, MT	6
154	Spokane, WA	6
155	Seattle, WA	10

94	Great Falls, ND	6	137	Mobile, AL	5
95	Billings, MT	6	138	New Orleans, LA	5
96	Bismarck, ND	6	139	Lake Charles, LA	5
97	Fargo, ND	6	140	Beaumont, TX	5
98	Aberdeen, SD	6	141	Houston, TX	5
99	Sioux Falls, SD	6	142	San Antonio, TX	5
100	Rapid City, SD	6	143	Corpus Christi, TX	5
101	Scottsbluff, NB	9	144	McAllen, TX	8
102	Grand Island, NB	9	145	El Paso, TX	8
103	Sioux City, IA	9	146	Albuquerque, NM	11
104	Fort Dodge, IA	9	147	Colorado Springs, CO	9
105	Waterloo, IA	3	148	Denver, CO	9
106	DeMoines, IA	3	149	Grand Junction, CO	9
107	Omaha, NB	9	150	Cheyenne, WY	9
108	Lincoln, NB	9	151	Salt Lake City, UT	6
109	Salina, KS	9	152	Idaho Falls, ID	6
110	Wichita, KS	9	153	Butte, MT	6
111	Kansas City, MO	9	154	Spokane, WA	6
112	Columbia, MO	9	155	Seattle, WA	10
113	Quincy, IL	3	156	Yakima, WA	6
114	St. Louis, MO	7	157	Portland, OR	10
115	Paducah, KY	7	158	Eugene, OR	4
116	Springfield, MO	7	159	Boise City, ID	6
117	Little Rock, AR	7	160	Reno, NB	6
118	Fort Smith, AR	8	161	Las Vegas, NV	11
119	Tulsa, OK	8	162	Phoenix, Az	11
120	Oklahoma City, OK	8	163	Tuscon, AZ	11
121	Wichita Falls, TX	8	164	San Diego, CA	4
122	Amarillo, TX	8	165	Los Angeles, CA	4
123	Lubbock, TX	8	166	Fresno, CA	4
124	Odessa, TX	8	167	Stockton, CA	4
125	Abilene, TX	8	168	Sacramento, CA	4
126	San Angelo, TX	8	169	Redding, CA	4
127	Dallas, TX	8	170	Eureka, CA	4
128	Killeen, TX	8	171	San Francisco, CA	4
129	Austin, TX	8			

Table 3-2. Climatological Data Base for Each Region

Region No.	Climatic Designator Location	Year	Yearly Insolation on a Horizontal Surface: From Data Base Tape (kw-hr/m^2)	Yearly Insolation on a Horizontal Surface: From Climatic Atlas (Ref. 3) (kw-hr/m^2)	Percent Deviation of Selected Yearl, Insolation from Climatic Atlas Average	Yearly Average Normal Daily Maximum Ambient Temperature (°C): From Data Base Tape	Yearly Average Normal Daily Maximum Ambient Temperature (°C): From Climatic Atlas (Ref. 3)	Percent Deviation of Yearly Average Daily Maximum Temperature from Climatic Atlas Value
1	Cleveland, OH	1962	1264	1423	-11.2	13.3	13.1	+1.5
2	Washington, DC	1963	1689	1513	+11.6	17.7	18.8	-5.9
3	Madison, WI	1961	1615	1377	+17.3	12.7	12.0	+5.8
4	Los Angeles, CA	1963	1844	1852	- 0.4	21.2	21.0	+1.0
5	Charleston, SC	1963	1744	1716	+1.6	23.4	24.4	-4.1
6	Bismarck, ND	1962	1498	1568	- 4.5	12.1	12.1	0
7	Nashville, TN	1959	1549	1508	+2.7	20.4	21.4	-4.7
8	Fort Worth, TX	1962	1830	1891	-3.2	24.1	24.7	-2.4
9	Omaha, NB	1963	1645	1610	+2.2	16.5	23.1	-28.6
10	Seattle-Tacoma, WA	1960	1261	1275	- 1.1	14.1	15.2	- 7.2
11	Phoenix, AZ	1962	2119	2209	-4.1	28.8	31.8	-9.4
12	Miami, FL	1963	1950	1916	+1.8	27.3	28.4	-3.9

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Table 3-2. Climatological Data Base for Each Region

Region No.	Climatic Designator Location	Year	Yearly Insolation on a Horizontal Surface: From Data Base Tape (kw-hr/m^2)	Yearly Insolation on a Horizontal Surface: From Climatic Atlas (Ref. 3) (kw-hr/m^2)	Percent Deviation of Selected Yearly Insolation from Climatic Atlas Average	Yearly Average Normal Daily Maximum Ambient Temperature (°C): From Data Base Tape	Yearly Average Normal Daily Maximum Ambient Temperature (°C): From Climatic Atlas (Ref. 3)	Percent Deviation of Yearly Average Daily Maximum Temperature from Climatic Atlas Value
1	Cleveland, OH	1962	1264	1423	-11.2	13.3	13.1	+1.5
2	Washington, DC	1963	1689	1513	+11.6	17.7	18.8	-5.9
3	Madison, WI	1961	1615	1377	+17.3	12.7	12.0	+5.8
4	Los Angeles, CA	1963	1844	1852	- 0.4	21.2	21.0	+1.0
5	Charleston, SC	1963	1744	1716	+1.6	23.4	24.4	-4.1
6	Bismarck, ND	1962	1498	1568	- 4.5	12.1	12.1	0
7	Nashville, TN	1959	1549	1508	+2.7	20.4	21.4	-4.7
8	Fort Worth, TX	1962	1830	1891	-3.2	24.1	24.7	-2.4
9	Omaha, NB	1963	1645	1610	+2.2	16.5	23.1	-28.6
10	Seattle-Tacoma, WA	1960	1261	1275	- 1.1	14.1	15.2	- 7.2
11	Phoenix, AZ	1962	2119	2209	-4.1	28.8	31.8	-9.4
12	Miami, FL	1963	1950	1916	+1.8	27.3	28.4	-3.9

photovoltaic system analysis program which was developed under the ERDA definition study (Reference 1). A system implementation with no energy storage was selected for this regional comparison. In this system approach the inverter dynamically tracks the solar array maximum power operating point and feeds any excess power back to the utility. This system model, which is called NOBATRY, is described in Section 3.2.2.1. The load demand of the all-electric home consists of three constituents: (1) diversified load, (2) domestic hot water heating load, and (3) heating/cooling load. The diversified and hot water heating demand profiles are discussed in Section 3.2.2.2.4.

These profiles are identical to those used in the ERDA definition study. The heat pump electrical load required to satisfy the calculated hourly heating/cooling demand is determined based on the coefficient of performance (COP) which is treated as a function of outside ambient temperature and thermal load demand. Heating loads in excess of the heat pump capacity under a given set of conditions are handled by supplemental resistance heating. The heat pump modeling is discussed in Section 3.2.2.2.5.

Table 3-3 summarizes the results of this comparative performance evaluation of the twelve regions based on the insolation/weather data base tape for each CD as indicated. The total annual heating and cooling load in kW_t-hr are listed as derived by summing the hourly values which result from the execution of the BTTL program. Using the heat pump model described in Section 3.2.2.2.5, the corresponding electrical energy required to meet these heating and cooling load demands is also given in Columns 3 and 4 of Table 3-3. The highest heating load occurred in Region 6 (represented by Bismarck, ND) and the highest cooling load occurred in Region 12 (represented by Miami, FL). The next column gives the total annual electrical load demand of the all-electric residence including the diversified load, hot water heating load, and electrical load required to satisfy the heating/cooling requirements. This total electrical demand ranges from 15071 kW_e-hr in Region 4 (represented by Los Angeles, CA) to 33031 kW_e-hr in Region 6 (represented by Bismarck, ND).

Column 6 of Table 3-3 gives the total annual available solar array energy at the maximum power point in kW_e-hr/m^2 of cell area based on the solar array performance discussed in Section 3.2.2.2.1. This value is the summation of the calculated hourly solar array output at the maximum power point. This available solar array energy includes the influences of both insolation and solar cell temperature. The solar cell temperature is calculated by the program based on the hourly ambient temperature and wind speed assuming that the solar cell modules are mounted on a framework structure approximately 0.3m above a conventional roof which is sloped at the site latitude angle and mounted against an unventilated attic space. It should be emphasized that the values in Column 6 were derived directly from the data base tapes, which in some cases have significant deviations from the multiple year average insolation. Column 7 of the table gives the corresponding values which have been corrected to reflect the Climatic Atlas values using the expression:

1	2	3		4		5	6
Region No.	Climatic Designator Location	Annual Heating Load		Annual Cooling Load		Total Annual Residential Electrical Load Demand (kw_e-hr)	Total A… Solar A… Maximu… (kw_e-h…
		(kw_t-hr)	(kw_e-hr)	(kw_t-hr)	(kw_e-hr)		
1	Cleveland, OH	18634.	11350.	1577.	742.	24871.	
2	Wasnington, DC	12547.	7108.	3153.	1539.	21426.	
3	Madison, WI	22849.	14563.	1742.	830.	28172.	
4	Los Angeles, CA	2445.	997.	2800.	1295.	15071.	
5	Cnarleston, SC	4192.	2461.	8959.	4017.	19256.	
6	Bismarck, ND	28481.	19941.	661.	312.	33031.	
7	Nashville, TN	8959.	4945.	6362.	3091.	20814.	
8	Fort Worth, TX	4287.	2341.	12356.	6178.	21297.	
9	Omaha, NB	18321.	12452.	3392.	1682.	26912.	
10	Seattle-Tacoma, WA	15474.	7707.	721.	347.	20833.	
11	Phoenix, AZ	2364.	1076.	12888.	6837.	20692.	
12	Miami, FL	81.	33.	18268.	8754.	21566.	

Notes:

(1) Product of values from columns 7 and 9

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Table 3-3. Summary of Regional Solar Energy Related Performance Parameters

Residential ad Demand r)	(6) Total Annual Available Solar Array Energy at Maximum Power Point (kw_e-hr/m^2 cell area)	(7) Corrected Total Annual Available Solar Array Energy at Maximum Power Point (kw_e-hr/m^2 cell area)	(8) Annual Energy Displacement Factor (%)	(9) Corrected Annual Energy Displacement Factor (%)	(10) Photovoltaic System Figure-of-Merit (1)
	133.3	160.7	36.5	44.0	7071
	196.1	167.7	62.3	53.2	8922
	192.7	156.1	46.5	37.7	5885
	207.1	203.7	93.5	91.9	18720
	194.5	186.6	68.7	65.9	12297
	186.5	177.7	38.4	36.6	6504
	168.0	165.6	54.9	54.1	8959
	201.7	205.4	64.4	65.6	13474
	201.1	175.8	50.8	44.4	7806
	143.5	143.0	45.8	46.7	6678
	231.6	234.1	76.2	77.0	18026
	207.4	205.5	65.4	64.8	13316

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$$E_C = 0.1074H\,[1 - 0.00345\,(T-28)]$$

where

E_C = Total annual available solar array energy at the maximum power point for an array sloped at the site latitude angle (kW_e-hr/m^2 cell area).

T = Yearly average normal daily maximum ambient temperature (^oC)

H = Yearly total insolation on a horizontal surface (kW-hr/m^2)

This expression was derived from the calculated values of available solar array energy by first correcting these values to the standard temperature of 28°C using the coefficient -0.345 percent/°C to represent the temperature dependence of cell maximum power output. The calculated values for yearly average daily maximum ambient temperature from the data base tapes were used as the basis for this temperature correction. Figure 3-2 shows the resulting temperature corrected values of annual solar array energy plotted as a function of calculated annual insolation on a horizontal surface as obtained from the tapes. A best fit linear curve of these 12 data points forms the basis for the expression given above.

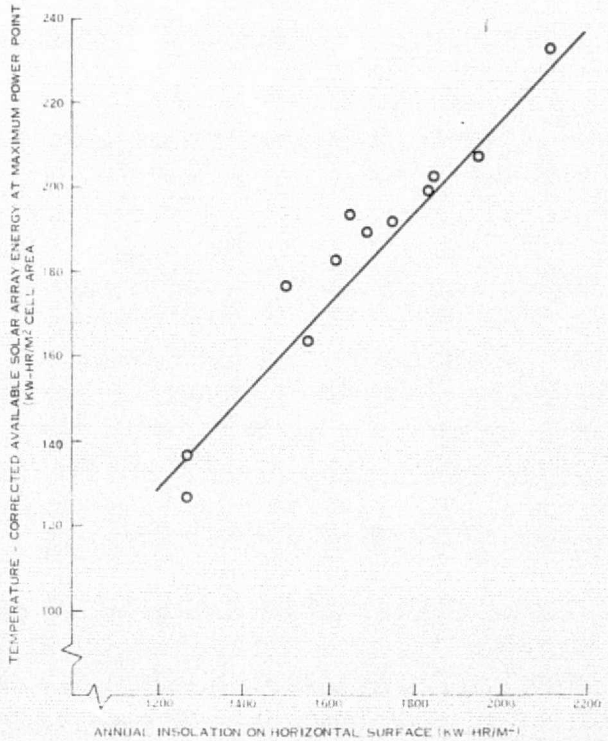

Figure 3-2. Linear Curve Fit of Temperature-Corrected Calculated Annual Solar Array Energy Output

Column 8 of Table 3-3 gives the annual energy displacement factor for the residence. This factor is defined as the ratio of the total annual electrical energy output of the photovoltaic system to the total annual electrical energy demand of the residence.

The values given in Column 8 of Table 3-3 were calculated for $78.19 m^2$ of cell area mounted above the south facing roof which is sloped at the site latitude angle in each case. An effective inverter efficiency of 87 percent was also assumed in the calculation using the hourly insolation/weather data base tape. The corrected values for annual energy displacement factor are given in Column 9. These values were derived using the following expression:

$$AED_C = \frac{0.87\ (78.19)\ E_C}{E_L}$$

where

AED_C = Corrected annual energy displacement factor.

E_L = Total annual residential electrical load demand (kW_e-hr)

This assumes that the values for E_L are independent of small changes in insolation and ambient temperature.

The last column in Table 3-3 gives the photovoltaic system figure-of-merit for each region. These values were calculated as the product of Column 7 (Corrected Total Annual Available Solar Array Energy at Maximum Power Point) and the corresponding value in Column 9 (Corrected Annual Energy Displacement Factor). Using this criterion for rating each region, Region 4 (represented by Los Angeles, CA) ranks highest in terms of overall residential photovoltaic system performance. The highest value of energy displacement factor coupled with an available solar array energy which is only 13 percent below the highest value, result in a figure-of-merit which the highest of the twelve regions considered. Region 11 (represented by Phoenix, AZ) ranks a close second with a figure-of-merit which is only 3.7 percent less than the value for Region 4.

3.1.4 SELECTION OF POTENTIAL SITE LOCATIONS

As shown in Table 3-4, 24 non-DOD government departments or agencies own a total of 730,383,036 acres of land within the U.S. This represents 32.2 percent of the total U.S. land area. The selection of at least three potential site locations for each of the twelve regions would appear to be a simple task with such a large land area from which to choose. However, the vast majority of this land is unsuitable for such an experimental installation. Table 3-5 lists 41 potential site locations within the continental U.S. The first 24 entries on this list were selected from the real property under the control of NASA, ERDA, NSF and the Department of Commerce (which includes NOAA and the

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Table 3-4. Land Owned by Non-DOD Federal Agencies in the United States (Data from Reference 8)

Agency or Department	Total Land Area (Acres)
Department of Agriculture	187,628,699.
Department of State	122,595.
ERDA (formerly AEC)	2,102,504.
Central Intelligence Agency	309.
Department of Justice	27,958.
Department of Commerce	57,976.
Department of Labor	3,760.
Department of Health, Education and Welfare	4,062.
Department of Housing and Urban Development	8.
Department of the Interior	539,153,326.
Department of Transportation	171,089.
Environmental Protection Agency	250.
Federal Communications Commission	2,646.
General Services Administration	20,236
Government Printing Office	6.
National Science Foundation	3,721
NASA	137,075.
National Capital Housing Authority	2.
Office of Economic Opportunity	60.
Tennessee Valley Authority	916,125.
Treasury Department	436.
U.S. Information Agency	8,702.
U.S. Postal Service	2,114.
Veterans Administration	19,377.
Total	730,383,036. (2.956×10^{12} m^2)

Table 3-5. List of Potential Sites

SITE NO.	BEA NO.	REGION NO.	SITE IDENTIFICATION AND LOCATION	FEDERAL DEPT. OR AGENCY	Potential Site Evaluation Criteria: 1980 POPULATION IN BEA (THOUSANDS)	POPULATION RANKING	POPULATION SCORE	PHOTOVOLTAIC FIGURE-OF-MERIT	FOM RANKING	FOM SCORE	1980 RESIDENTIAL ELECTRICAL FUEL PRICE ($/GJ)	FUEL PRICE RANKING	FUEL PRICE SCORE	TOTAL SCORE
1	171	4	Ames Research Center Moffett Field, California	NASA	5990.	3.62	3.62	18720	10.00	10.00	7.56	3.36	3.36	16.98
2	166	4	Flight Research Center Edwards, California	NASA	1064.	1.39	1.39	18720	10.00	10.00	7.95	3.46	3.46	14.85
3	18	2	Goddard Space Flight Center Greenbelt, Maryland	NASA	3507.	2.53	2.53	8922	3.13	3.13	8.35	3.89	3.89	9.55
4	47	7	George C. Marshall Space Flight Center Huntsville, Alabama	NASA	746.	1.24	1.24	8959	3.16	3.16	7.27	[illegible].71	2.71	7.11
5	165	4	Jet Propulsion Laboratory Pasadena, California	NASA	12271.	6.46	6.46	18720	10.00	10.00	7.95	3.46	3.46	19.92
6	35	5	John F. Kennedy Space Center Kennedy Space Center, Florida	NASA	1123.	1.41	1.41	12297	5.50	5.50	9.03	4.64	4.64	11.55
7	22	5	Langley Research Center Hampton Virginia	NASA	1270.	1.48	1.48	12297	5.50	5.50	9.92	5.61	5.61	12.59
8	68	1	Lewi. Research Center Cleveland, Ohio	NASA	4718.	3.04	3.04	7071	1.83	1.83	9.52	5.17	5.17	10.04
9	141	5	Lyndon B. Johnson Space Center Houston, Texas	NASA	2774.	2.16	2.16	12297	5.50	5.50	9.03	4.64	4.64	12.30
10	17	2	Wallops Flight Center Wallops Island, Virginia	NASA	851.	1.29	1.29	8922	3.13	3.13	10.70	6.46	6.46	10.88
11	137	5	National Space Technology Laboratories Bay St. Louis, Mississippi	NASA	783.	1.26	1.26	12297	5.50	5.50	8.15	3.68	3.66	10.44
12	146	11	Sandia Laboratories Albuquerque, New Mexico	ERDA	614.	1.18	1.18	18026	9.51	9.51	9.72	5.39	5.39	16.08
13	171	4	University and Visitor Center Area Lawrence Livermore Laboratory Livermore, Calif. (40 miles from Oakland)	ERDA	5998.	3.62	3.62	18720	10.00	10.00	7.86	3.36	3.36	16.98
14	77	1	Fermilab (60 miles W of downtown Chicago) Batavia, Illinois	ERDA	9016.	4.99	4.99	7071	1.83	1.83	10.51	6.25	6.25	13.07
15	77	1	Argonne National Laboratory 9700 South Cass Avenue (30 miles W of downtown Chicago Chicago, Illinois on I-55)	ERDA	9016.	4.99	4.99	7071	1.83	1.83	10.51	6.25	6.25	13.07
16	111	9	SECOM Antenna Site Adjacent to Richards-Gebaur AFB Kansas City, Missouri	ERDA	2503.	2.04	2.04	7306	2.35	2.35	6.78	2.18	2.18	6.57
17	50	7	Weather Bureau Tract Oak Ridge National Laboratory (Near Holiday Inn on Oak Ridge, Tennessee S. Illinois Ave.)	ERDA	954.	1.33	1.33	8959	3.16	3.16	6.68	2.07	2.07	6.56
18	14	1	New Brunswick Laboratory New Brunswick, New Jersey	ERDA	20090.	10.00	10.00	7071	1.83	1.83	13.94	10.00	10.00	21.83
19	14	1	Long Island Expressway Triangle Brookhaven National Laboratory Upton, New York	ERDA	20090.	10.00	10.00	7071	1.83	1.83	13.94	10.00	10.00	21.83
20	4	1	Blue Hill Observatory Blue Hill, Massachusetts	Commerce	7090.	4.11	4.11	7071	1.83	1.83	12.37	8.29	8.29	14.23

Table 3-5. List of Potential Sites (Cont'd)

SITE NO.	BEA NO.	REGION NO.	SITE IDENTIFICATION AND LOCATION	FEDERAL DEPT. OR AGENCY	Potential Site Evaluation Criteria									TOTAL SCORE
					1980 POPULATION IN BEA (THOUSANDS)	POPULATION RANKING	POPULATION SCORE	PHOTOVOLTAIC FIGURE-OF MERIT	FOM RANKING	FOM SCORE	1980 RESIDENTIAL ELECTRICAL FUEL PRICE ($/GJ)	FUEL PRICE RANKING	FUEL PRICE SCORE	
21	148	9	National Center for Atmospheric Research Boulder, Colorado	Commerce	1757.	1.70	1.70	7806	2.35	2.35	9.33	4.96	4.96	9.01
22	155	10	Coast and Geodetic Survey Pacific Marine Center Seattle, Washington	Commerce	2675.	2.11	2.11	6678	1.56	1.56	5.70	1.00	1.00	4.67
23	65	2	National Radio Astronomy Observatory Green Bank, West Virginia	NSF	341.	1.06	1.06	8922	3.13	3.13	8.35	3.89	3.89	8.08
24	163	11	Kitt Peak National Observatory Tucson, Arizona	NSF	511.	1.13	1.13	16026	9.51	9.51	9.72	5.39	5.39	16.03
25	3	3	White Mountain National Forest New Hampshire	Interior	545.	1.15	1.15	5885	1.00	1.00	12.57	8.50	8.50	10.65
26	3	3	Green Mountain National Forest Vermont	Interior	545.	1.15	1.15	5885	1.00	1.00	12.57	8.50	8.50	10.65
27	79	3	Hiawatha National Forest Michigan	Interior	629.	1.19	1.19	5835	1.00	1.00	9.43	5.07	5.07	7.26
28	95	6	Yellowstone National Park Wyoming	Interior	246.	1.01	1.01	6504	1.43	1.43	11.10	6.90	6.90	9.34
29	100	6	Mt. Rushmore National Memorial South Dakota	Interior	220.	1.00	1.00	6504	1.43	1.43	11.10	6.90	6.90	9.33
30	94	6	Glacier National Park Montana	Interior	215.	1.00	1.00	6504	1.43	1.43	11.10	6.90	6.90	9.33
31	49	7	Mammoth Cave National Park Kentucky	Interior	1579.	1.62	1.62	8959	3.16	3.16	7.27	2.71	2.71	7.49
32	145	8	Mascalero Apache Reservation New Mexico	Interior	703.	1.22	1.22	13474	6.32	6.32	8.74	4.32	4.32	11.86
33	122	8	Lake Meredith National Recreation Area Texas	Interior	400.	1.08	1.08	13474	6.32	6.32	9.13	4.75	4.75	12.15
34	130	8	Davy Crockett National Forest Texas	Interior	603.	1.18	1.18	13474	6.32	6.32	8.74	4.32	4.32	11.82
35	148	9	Rocky Mountain National Park Colorado	Interior	1757.	1.70	1.70	7806	2.35	2.35	9.33	4.96	4.96	9.01
36	157	10	Mt. Hood National Forest Oregon	Interior	1840.	1.74	1.74	6678	1.56	1.56	7.26	2.01	2.01	6.11
37	155	10	Olympic National Park Washington	Interior	2675.	2.11	2.11	6678	1.56	1.56	5.70	1.00	1.00	4.67
38	162	11	Grand Canyon National Park Arizona	Interior	1614.	1.63	1.63	16026	9.51	9.51	9.72	5.39	5.39	16.53
39	36	12	Everglades National Park Florida	Interior	2886.	2.21	2.21	13316	6.21	6.21	8.44	3.99	3.99	12.41
40	36	12	Seminole Indian Reservation Florida	Interior	1886.	2.21	2.21	13316	6.21	6.21	8.44	3.99	3.99	12.41
41	37	12	DeSoto National Memorial Florida	Interior	2037.	1.83	1.83	13316	6.21	6.21	9.82	5.50	5.50	13.54

NBS). These sites were obtained from References 4 and 5 based on the probable availability of on-site technical personnel to support the experimental residence during the operational period. The remaining 17 sites which complete the list were selected from Reference 6 to meet the requirement for at least three potential site locations for each of the twelve regions.

For each of these 41 potential site locations a numerical rating system was evaluated using three criteria. The first of these criteria is the 1980 population within the Bureau of Economic Analysis Economic Areas (BEA) containing the site (Reference 7). This criterion is generally indicative of the number of people within a short driving distance from the site location. The second criterion is the photovoltaic system figure-of-merit (FOM) as discussed in Section 3.1.3. The twelve values listed in Table 3-3 were assigned to each of the 41 sites depending on regional location. The third criterion is the 1980 residential electrical fuel price ($/Giga Joule) as obtained from Reference 9. A high cost of electrical fuel means a high cost of electrical energy. Alternative non-conventional energy sources, such as photovoltaics, become more attractive, from an economical standpoint, in areas with high electrical energy cost.

For each of these evaluation criterion the absolute values for each site were normalized on a scale from 1 to 10 with a value of one assigned to the lowest (and least attractive) value and a value of ten assigned to the highest (and most attractive) value. For each evaluation criterion, this normalized value for each site is called the ranking.

The score for each criterion is obtained by multiplying the individual ranking within each criterion by a predetermined weighting factor associated with each criterion. The weighting factor can thus be used to reflect a relative importance among the three evaluation criterion. A unity weighting factor was assigned to each criterion for the purpose of this site selection task. This implies an equal importance among the three criterion. Using this assumption for weighting factor, the score for each criterion is equal to the corresponding ranking for each site. The sum of the individual site scores in each of the three criterion yields the total site score as given in the right-hand column of Table 3-5.

3.1.5 RECOMMENDED SITE LOCATIONS

Table 3-6 lists the top 15 potential sites based on the total score given in Table 3-5. The obvious advantages or disadvantages associated with each of these sites is also indicated in Table 3-6. These comments on site suitability are necessarily general in nature due to the contractual imposed sanction against direct contact with the personnel at any potential site location. The two sites in metropolitan New York City rank highest in total score using the criteria established for this evaluation. These two sites have the same score due to the fact that they are both within the same BEA. The sites ranking second and third in terms of total score are located in the metropolitan Los Angeles and San Francisco areas, respectively.

Table 3-6. List of Top 15 Potential Site Locations

TOTAL SCORE	SITE IDENTIFICATION AND LOCATION	ADVANTAGES/DISADVANTAGES
21.83	Brookhaven National Laboratory Upton, New York	• On-site technical personnel
21.83	New Brunswick Laboratory New Brunswick, New Jersey	• On-site technical personnel
19.92	Jet Propulsion Laboraotry Pasadena, California	• On-site personnel experienced in photovoltaics • Key role in ERDA photovoltaics program
16.98	Ames Research Center Moffett Field, California	• On-site personnel experienced in photovoltaics
16.98	Lawrence Livermore Laboratory Livermore, California	• On-site personnel experienced in photovoltaics • Role in ERDA photovoltaics program
16.53	Grand Canyon National Park Arizona	• No on-site technical personnel
16.08	Sandia Laboratories Albuquerque, New Mexico	• On-site personnel experienced in photovoltaics • Key role in ERDA photovoltaics program
16.03	Kitt Peak National Observatory Tucson, Arizona	• On-site technical personnel
14.85	Flight Research Center Edwards, California	• On-site technical personnel
14.23	Blue Hill Observatory Blue Hill, Massachusetts	• On-site technical personnel
13.54	DeSoto National Memorial Florida	• No on-site technical personnel
13.07	Fermilab Batavia, Illinois	• On-site technical personnel
13.07	Argonne National Laboratory Chicago, Illinois	• Role in ERDA solar energy programs
12.59	Langley Research Center Hampton, Virginia	• On-site personnel experienced in photovoltaics
12.30	Lyndon B. Johnson Space Center Houston, Texas	• On-site personnel experienced in photovoltaics

This list of the top 15 potential sites was used as the basis for selecting the eight recommended sites listed in Table 3-7 and located on the map given in Figure 3-3. The Lewis Research Center, which is the site for the first RPST, appears first on this list of recommended sites. The New Burnswick Laboratory in New Brunswick, New Jersey was selected over Brookhaven National Laboratory to represent the metropolitan New York City area. New Brunswick, N. J. is about equidistance between New York City and Philadelphia. It is situated near the New Jersey Turnpike and on the Metroliner route between Washington, D. C., and New York City. The Jet Propulsion Laboratory, with its participation in the ERDA photovoltaic program, was selected for third place on the list. The Lawrence Livermore Laboratory was selected over Ames Research Center to represent the metropolitan San Francisco area. The Livermore Laboratories' role in the ERDA photovoltaics program was the reason for this choice. Sandia Laboratories was selected for the fifth position because of its role in the ERDA photovoltaic program. The other Southwest sites were not recommended because of their climatological similarity with Sandia. Blue Hill Observatory was selected for sixth position. The Flight Research Center in Edwards, California was not recommended because two California sites, with higher scores, were previously selected. In seventh position is the Argonne National Laboratory which was selected over Fermilab to represent the Metropolitan Chicago area. The DeSoto National Memorial was not recommended because of the absence of on-site technical personnel.

Table 3-7. Recommended Site Locations*

1.	Lewis Research Center
2.	New Brunswick Laboratory
3.	Jet Propulsion Laboratory
4.	Lawrence Livermore Laboratory
5.	Sandia Laboratories
6.	Blue Hill Observatory
7.	Argonne National Laboratory
8.	Lyndon B. Johnson Space Center

*See Figure 3-3

The Lyndon B. Johnson Space Center was recommended for the final position on the list. Langley Research Center was not selected because of the prior selection of New Brunswick Laboratory to represent the Mid-Atlantic region.

3.2 PARAMETRIC SENSITIVITY ANALYSIS (TASK II)

3.2.1 INTRODUCTION

The stated purpose of the parametric sensitivity analysis task is to: (1) delineate the range of parameters and design options of interest relative to the residential photovoltaic

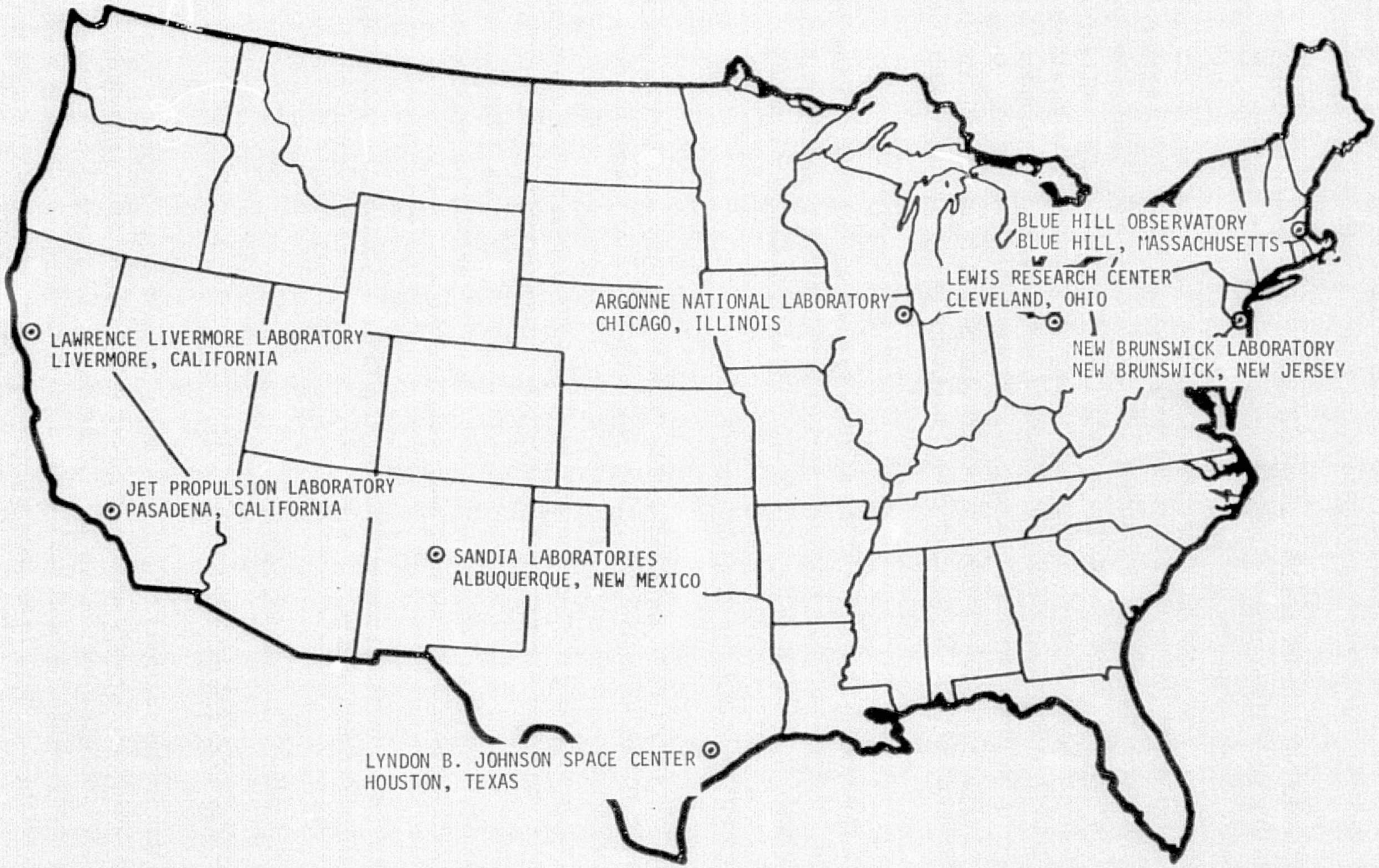


Figure 3-3. Location of Eight Recommended Sites

system, and (2) identify the parameters and options that are critical to the optimization and require systems experiments and operational experience to evaluate properly.

The analytical approach to the performance of this task relies heavily on the previous system modeling performed under ERDA Contract Number E(29-2)-3689. The results of this work are reported in Reference 1.

Section 3.2.2 describes the four different terrestrial photovoltaic power system analytical models which were used in this analysis. In Section 3.2.3 the input climatological data base is discussed. Twelve combined weather/insolation/building loads tapes are available for use in this analysis. Using this library as a source, site locations in Cleveland, Ohio; Los Angeles, California; Phoenix, Arizona; and Washington, D.C. were selected by the LeRC Project Manager for the parametric sensitivity analysis task. An additional limited performance assessment was also made for a site location in Boston, Massachusetts. These sites do not necessarily represent possible sites for RPSTs.

Section 3.2.4 discusses the results of the sensitivity analysis for each of these four site locations. In Section 3.2.5 a detailed system performance comparison is made for the Cleveland site location using each of the four system analytical models.

3.2.2 ANALYTICAL MODEL DEVELOPMENT

Analytical models for four different terrestrial photovoltaic power system concepts have been used to assess the sensitivity of system performance on an annual basis using hourly insolation and weather data tapes as the input. The analysis methodology in each case is similar in that the programs determine the instantaneous system operating point as a function of individual subsystem characteristics. This operating point of the system is determined for each discrete time increment (one hour) of the total time period (which may be up to one year long) by performing iterative numerical calculations until Kirchoff's Law is satisfied at each node within the system.

The subsystem characteristics are common among these system analysis programs and are discussed in section 3.2.2.2.

3.2.2.1 System Modeling Methodology

DIRECT CHARGE SYSTEM (UNREG)

The first system model, called UNREG, utilizes a Direct Charge System (DCS) in which the battery is connected directly across the solar array bus as shown on Figure 3-4. With this system configuration, charging is at the rate determined by the load demand and the solar array capability until such time as the battery voltage limit is reached. At this predetermined voltage level the battery charge controller (BCC) limits the voltage by shunting excess current through dissipative elements.

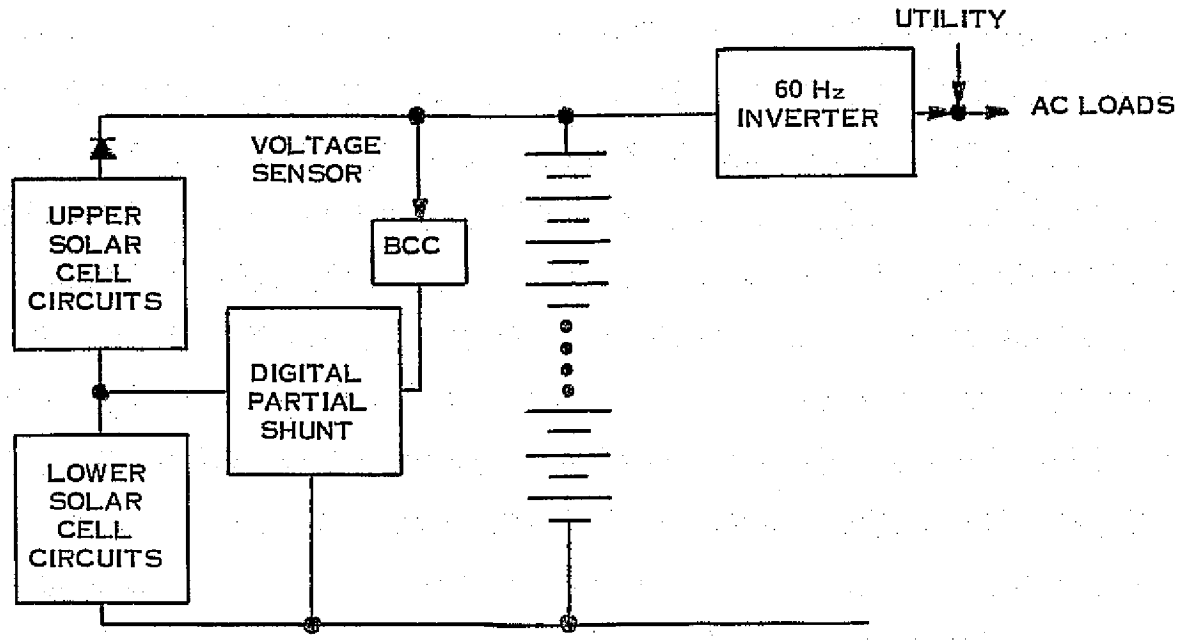


Figure 3-4. Simplified Functional Block Diagram of Direct Charge System (DCS) Approach

For each discrete time increment (each hour) the operating point of the system is determined by performing an iterative numerical calculation until Kirchoff's Law is satisfied at the node between the solar array, battery and load. The resulting instantaneous battery charge/discharge current is used to correct the battery state of charge (SOC). During battery charge, an average charge efficiency factor is used to correct the SOC to account for charging inefficiencies. At each one hour time interval the program prints out the following data:

1. Month, day and hour
2. AC load demand for the diversified load + hot water heating (kW)
3. AC load demand for heating or air conditioning (kW)
4. Solar array power output (kW)
5. Accumulative Ampere-hours discharged
6. Accumulative Ampere-hours charged
7. Battery state-of-charge

8. Battery voltage (V)

9. Battery power (kW)

10. Power required from the utility (kW)

11. Excess power dissipated in shunt voltage limiter (kW)

12. Inverter power loss (kW)

13. Total insolation of solar array panel surface (Btu/hr ft^2)

14. Ambient temperature ($^{\circ}$F)

15. Solar cell temperature ($^{\circ}$F)

16. Wind speed (mph)

17. Total building heating/cooling load (Btu/hr)

The program switches operation onto the utility when the battery voltage reaches a predetermined low threshold value. The system continues to operate on utility power with the inverter disabled until the battery voltage reaches the shunt limit value. At this point operation is switched back onto the photovoltaic/battery system by enabling the inverter.

NO BATTERY/FEEDBACK SYSTEM (NOBATRY)

The No Battery/Feedback system shown in Figure 3-5 consists of a maximum power tracking inverter which is connected directly to the solar cell circuits.

When the solar array power output capability allows the inverter output power to exceed the house load demand, the excess power flows back into the utility grid. During night time periods and when the sunlit array maximum power output is less than the load demand, power is supplied by the utility to meet the house load demand. Thus, the utility distribution system essentially becomes the storage medium for the residential photovoltaic system. When the photovoltaic power generation capacity within a given region is small compared to the utility distribution capacity, the utility grid will appear to be an "infinite" sink for power.

The performance analysis program for this configuration of power system employs an iterative calculation routine to hunt for the solar array maximum power operating point during each sunlit hour. The power tracking controller is assumed to perform this function with no error and with negligible internal power consumption.

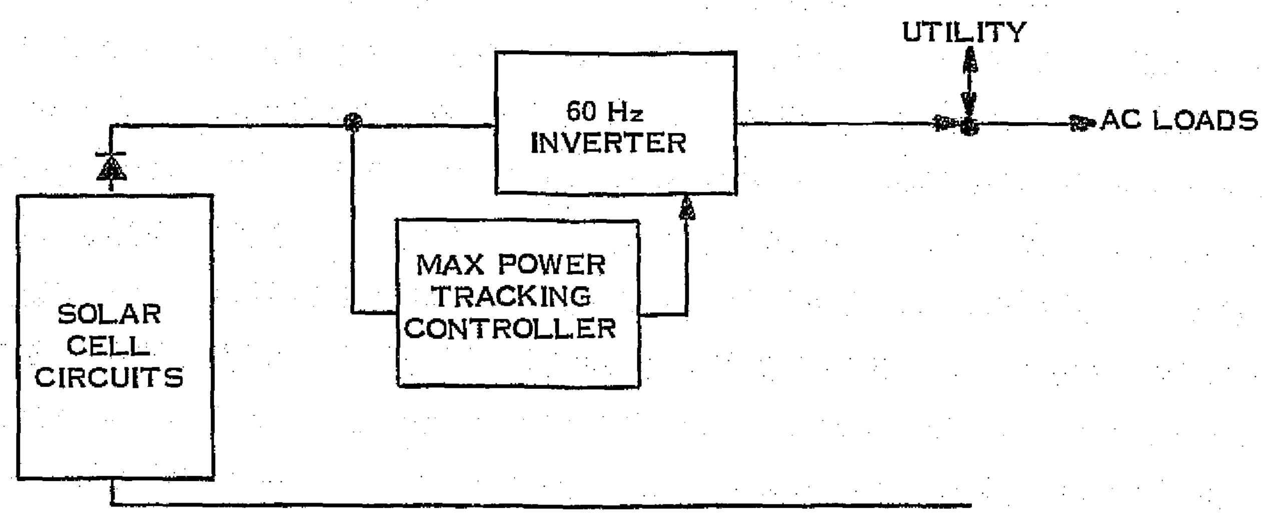


Figure 3-5. Simplified Functional Block Diagram of the No Battery/Feedback System

SERIES MAXIMUM POWER TRACKER (SMPT)

The Series Maximum Power Tracker (SMPT) shown in Figure 3-6 allows operation at the solar array maximum power voltage when the array is illuminated. The duty cycle of the pulse width modulated (PWM) down converter is controlled by the maximum power tracker to force operation at the solar array maximum power voltage. If the total available power at the solar array maximum power point is greater than what the load inverter and batteries will accept, the duty cycle of the PWM converter automatically decreases to move the system operating voltage toward the open circuit voltage of the array until the available source power is equal to the total power demand of the load and batteries.

PARALLEL MAXIMUM POWER TRACKER (PMPT)

The Parallel Maximum Power Tracker System (PMPT) shown in Figure 3-7 allows operation at the solar array maximum power voltage when the array is illuminated and the output capability exceeds the load demand. If the total available power at the array maximum power point is greater than what the inverter and batteries will accept, the duty cycle of the PWM regulator automatically decreases to move the system operating voltage toward the open circuit voltage of the array until the available source power is equal to the total power demand of the load and batteries. When the load demand exceeds

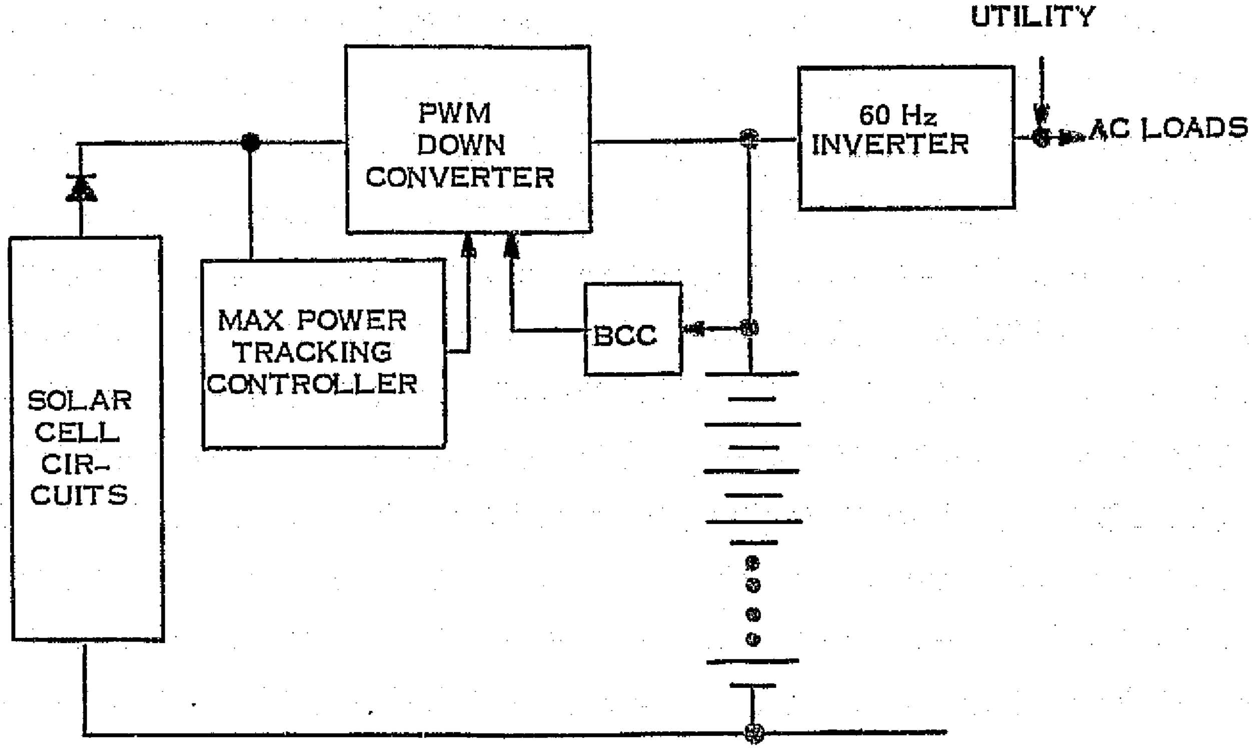


Figure 3-6. Simplified Functional Block Diagram of the Series Maximum Power Tracker System (SMPT) Approach

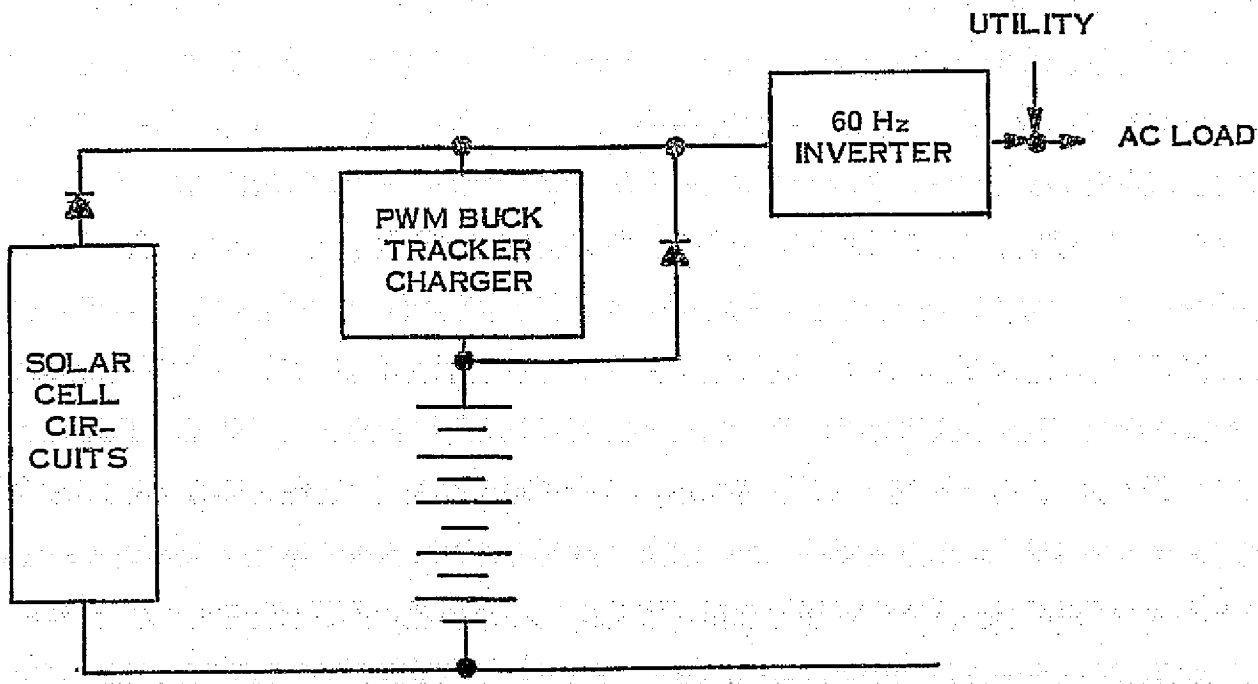


Figure 3-7. Simplified Functional Block Diagram of a Parallel Maximum Power Tracker (PMPT) System Approach

the power available from the solar array, the batteries discharge, clamping the dc bus voltage to the battery discharge voltage and forcing operation at a voltage considerably less than the solar array maximum power voltage.

3.2.2.2 Subsystem Analytical Models

3.2.2.2.1 Solar Array Electrical Model

The synthesis of solar array current-voltage characteristics is based on a set of stored cell characteristics which generates a curve which is in close agreement with the LeRC Solarex cell no. 2391 as shown in Figure 3-8. This cell curve represents the average characteristic of over 4000 Solarex cells as measured by LeRC.

The I-V curve synthesis program represents the cell characteristics by the following relationship:

$$I = CI_{sc} - \frac{V}{R_p} - I_o \left\{ \exp \left[K (V+IR_s) \right] -1 \right\}$$

where

I = cell output current (Amperes/cm^2)

V = voltage across cell terminals (Volts)

I_{sc} = illumination current (virtually equal to short-circuit current) (Amperes/cm^2)

C = ratio of the total insolation incident on the solar cells to the reference insolation for the basic cell characteristics (100mW/cm^2)

R_p = shunt resistance of the cell (Ohms$\cdot$cm^2)

I_o = reverse saturation current of the ideal diode characteristics (Amperes/cm^2)

$$= \frac{\left(I_{sc} - \frac{V_{oc}}{R_p}\right)}{\exp (K V_{oc}) - \exp (K R_s I_{sc})}$$

K = coefficient of the exponential (Volts^{-1})

R_s = series resistance of the cell (Ohms$\cdot$cm^2)

V_{oc} = cell open circuit voltage (Volts)

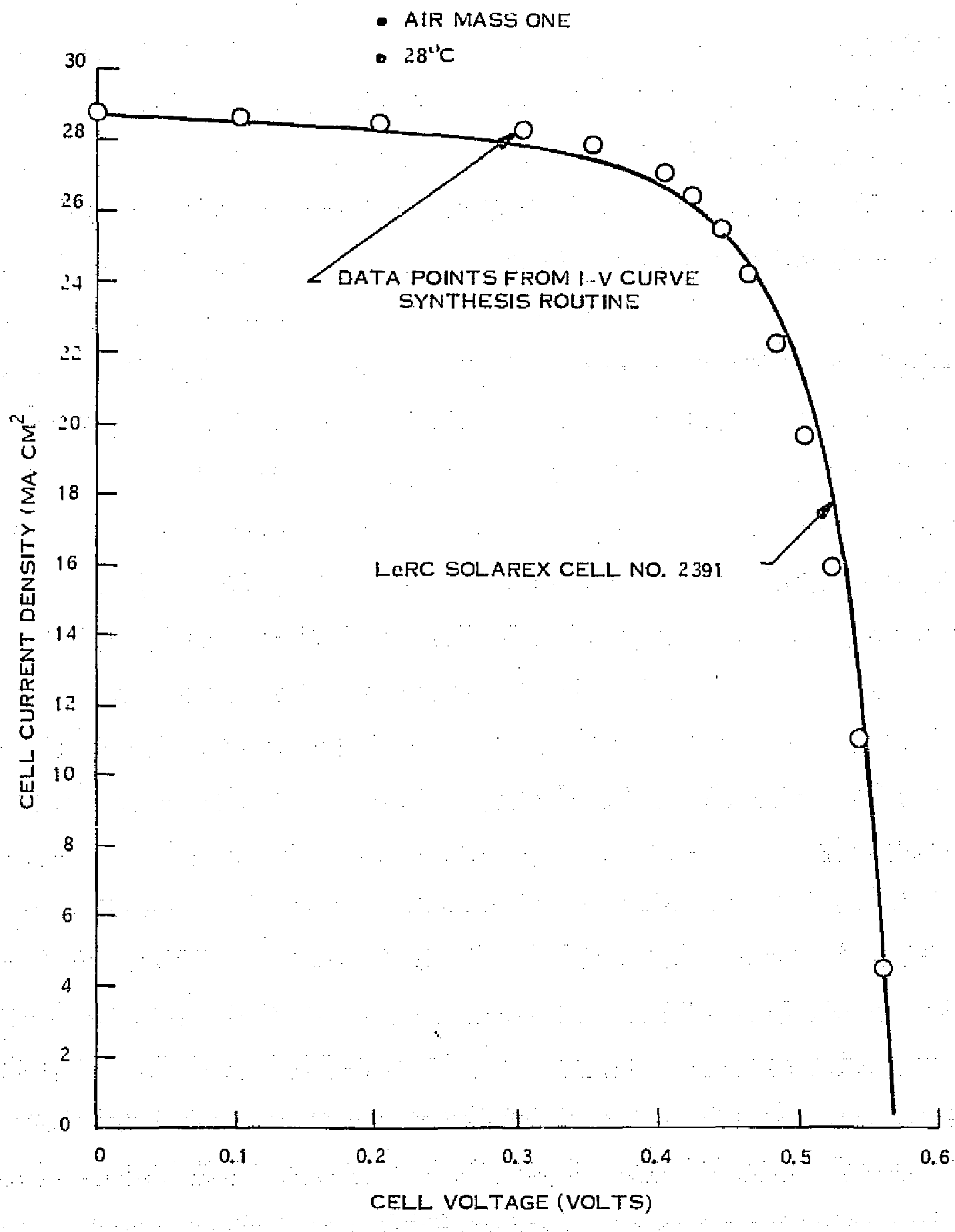


Figure 3-8. Comparison of LeRC Solarex Cell No. 2391 With Solar Array I-V Curve Synthesis Routine

I_{sc}, R_s, R_p, K, and V_{oc} are represented by polynominals of the form:

$$Y = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5 + a_6 T^6$$

where:

T = Solar cell temperature (^oF)

Y = Dependent variable (I_{sc}, R_s, R_p, K, or V_{oc})

The values of the coefficients used to represent the reference Solarex cell characteristic are given in Table 3-8.

Table 3-8. Coefficients of Solar Cell Characteristic Polynomials

	I_{sc}	R_s	R_p	K	V_{oc}
a_0	0.0281	0.5958	884.4	21.34	0.6792
a_1	0.8015E-5	-0.1024E-2	0.1919E-1	-0.1010E-1	0.1184E-2
a_2	0	0.2266E-4	-0.1689E-1	-0.4628E-4	0
a_3	0	0.3240E-7	0.5908E-4	0.1503E-6	0
a_4	0	-0.8004E-9	0.5268E-6	0.1494E-8	0
a_5	0	-0.8526E-13	-0.8224E-9	-0.1344E-11	0
a_6	0	0.1064E-13	-0.6256E-11	-0.1743E-13	0

The total solar array output characteristic is calculated based on the single cell characteristic by multiplying the voltages and currents by the number of cells in series and parallel, respectively. In addition, the isolation diode voltage drop (as a function of temperature and fraction of rated forward current) and the series resistance of panel wiring are accounted for in the array characteristic.

The value for total incident insolation (direct plus diffuse) is obtained by taking the total insolation incident on a horizontal surface, as read from the insolation data base tape, and separating it into direct and diffuse components using a curve fit of the results of Liu and Jordan (Reference 10). The total flux incident on the tilted solar array surface (H_T) is given by: (from Reference 11).

$$H_T = H_{DIR} R_{DIR} + H_{DIF} \left[\left(\frac{1 + \cos \beta}{2} \right) + \rho \left(\frac{1 - \cos \beta}{2} \right) \right]$$

where:

H_{DIF} = Diffuse component of the solar flux incident on a horizontal surface

H_{DIR} = Direct component of the solar flux incident on a horizontal surface

β = Angle between horizontal and solar array surface

ρ = The reflectance of the surrounding ground

The value of R_{DIR} is the ratio of the cosine of the solar angle of incidence (θ_i) on the tilted solar array surface to the cosine of the solar angle of incidence (θ_h) on a horizontal surface. The value of $\cos \theta_i$ is determined as a function of the day of the year, time of day and surface location and orientation in accordance with the following relationship:

$$\cos \theta_i = \sin \delta \left[\sin \phi \cos \beta - \cos \gamma \cos \phi \sin \beta \right]$$
$$+ \sin \gamma \sin \beta \cos \delta \sin \omega$$
$$+ \cos \delta \cos \omega \left[\cos \gamma \sin \phi \sin \beta + \cos \phi \cos \beta \right]$$

where:

θ_i = Angle of incidence of beam radiation measured between the beam and the normal to the solar array surface

ϕ = Site latitude (north is positive)

δ = Solar declination angle

β = Angle between horizontal and solar array surface

γ = Solar array surface azimuth angle (zero is due south, west of south is positive)

ω = Hour angle (zero is solar noon)

For a horizontal surface this expression reduces to:

$$\cos \theta_h = \sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi$$

3.2.2.2.2 Solar Array Thermal Model

The temperature of the solar cell modules was calculated with natural convective cooling from both sides. The subarrays of solar cell modules were assumed to be mounted about 0.3 m (1 ft) above a conventional roof to facilitate the testing of alternative module designs. The temperature of the attic air space is assumed to be 5.6°C above the outside ambient temperature. The area of the module not covered by solar cells was assumed to have a solar absorptance of 0.3. Under these conditions the heat balance equation for the solar cell modules is given by:

$$[\alpha_s \cdot p + 0.3\,(1-p)\,]\,H_{TOTAL} = 2h_o\,(T_{cell} - T_{amb}) + h_{r1}\,(T_{cell} - T_{sky}) + h_{r2}\,(T_{cell} - T_R)$$

and the heat balance equation for the roof is given by:

$$h_{r2}\,(T_{cell} - T_R) + h_{oi}\,(T_{attic} - T_R) = h_o\,(T_R - T_{amb})$$

where:

H_{TOTAL} = Total insolation incident on the solar array surface (W/m^2)

p = Ratio of solar cell area to total module area

= 0.688

α_s = Solar absorptance of solar cells

= 0.88

T_{amb} = Ambient temperature (°K)

T_{sky} = Sky temperature (°K)

T_{cell} = Solar cell module temperature (°K)

T_R = Temperature of roof directly under solar array (°K)

T_{attic} = Temperature of attic air space (assumed to be 5.6°K above ambient temperature)

h_{oi} = Film coefficient on interior of attic roof

= 2.84 $W/m^2\,K$

The radiation heat transfer coefficient to the sky, h_{r1}, is calculated by:

$$h_{r1} = \epsilon \sigma \left(\frac{T_{cell}^4 - T_{sky}^4}{T_{cell} - T_{sky}} \right)$$

where:

ϵ = Hemispherical emittance of front surface of the solar cell modules (=0.80)

σ = Stefan - Boltzmann constant

= 5.6697×10^{-8} W/m^2 K^4

The sky temperature, T_{sky}, is calculated, using the relationship given in Reference 12.

$$T_{sky} = 0.0552\, T_{amb}^{1.5}$$

The radiation heat transfer coefficient between the solar cell modules and the roof, h_{r2}, is given by:

$$h_{r2} = \frac{\sigma(T_{cell}^4 - T_R^4)}{(\frac{1}{\epsilon_c} + \frac{1}{\epsilon_R} - 1)(T_{cell} - T_R)}$$

where:

ϵ_c = Hemispherical emittance of the rear side of the solar cells modules

= 0.78

ϵ_R = Hemispherical emittance of the roof

= 0.78

The film coefficient, h_o, is calculated using the relationship given in Reference 13.

$$h_o = 5.7 + 3.8V$$

where:

V = Wind speed (m/s)

The two heat balance equations given above were solved using an iterative technique to yield the results shown in Figure 3-9.

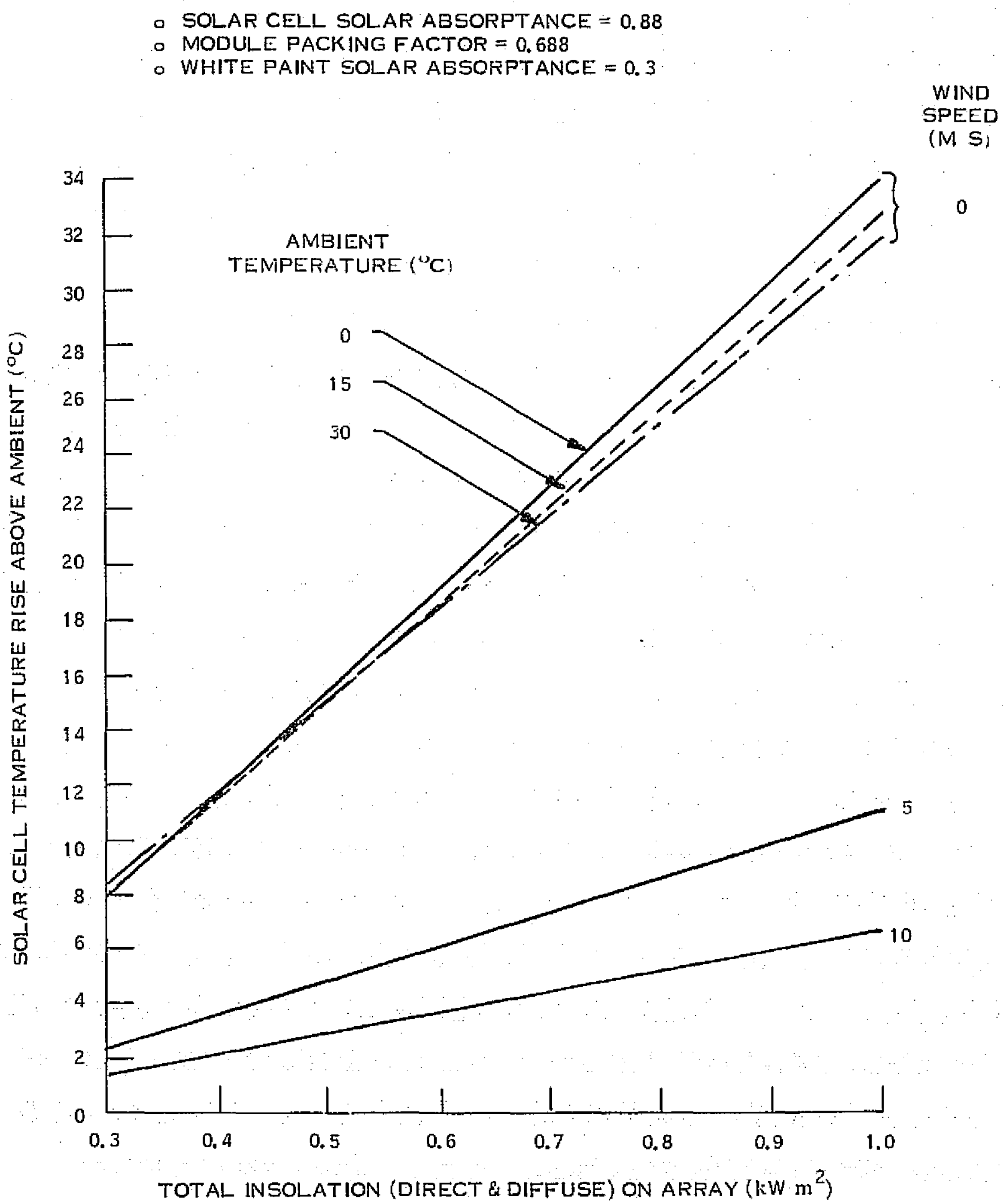


Figure 3-9. Temperature Predictions Using Analytical Model

3.2.2.2.3 Battery Model

The charge and discharge voltage of a hybrid lead-acid battery has been modeled as a function of battery state of charge (SOC) and instantaneous charge or discharge rate. Figure 3-10 shows these characteristics as modeled based on data supplied by C&D Batteries. The bottom set of curves are discharge characteristics with discharge rates varying from C/50 to C/5. The top set of curves are charge characteristics at the same rates, assuming that recharge starts from the fully discharged condition.

An average Ampere-hour charging efficiency of 0.952 was used in the simulations based on information supplied by C&D Batteries.

3.2.2.2.4 Electrical Load Demand

The electrical load demand for the diversified load and for hot water heating were assumed to be identical to those used in the ERDA systems study (Reference 1). The diversified load demand profile, shown in Figure 3-11, includes lighting and appliances and results in an accumulative daily energy requirement of 21 kW-hrs. This demand is representative of an all-electric home with the following major appliances:

Major Appliance	Average Daily Energy Consumption (kW-hr)
Frost-free Refrigerator	5.0
Color Television	1.2
Range/Oven	3.3
Dishwasher	1.0
Clothes Dryer	2.7
Washing Machine	0.3

Figure 3-12 shows the hot water heater electrical load demand profile with an accumulative daily energy requirement of 14 kW-hr.

3.2.2.2.5 Electrically Driven Heat Pump

The electrical load demand associated with space heating and air conditioning was obtained from the hourly heating or cooling load demand by accounting for the appropriate coefficient of performance (COP) for a heat pump system. The COP and the thermal capacity of each of three heat pump systems, as obtained from the General Electric

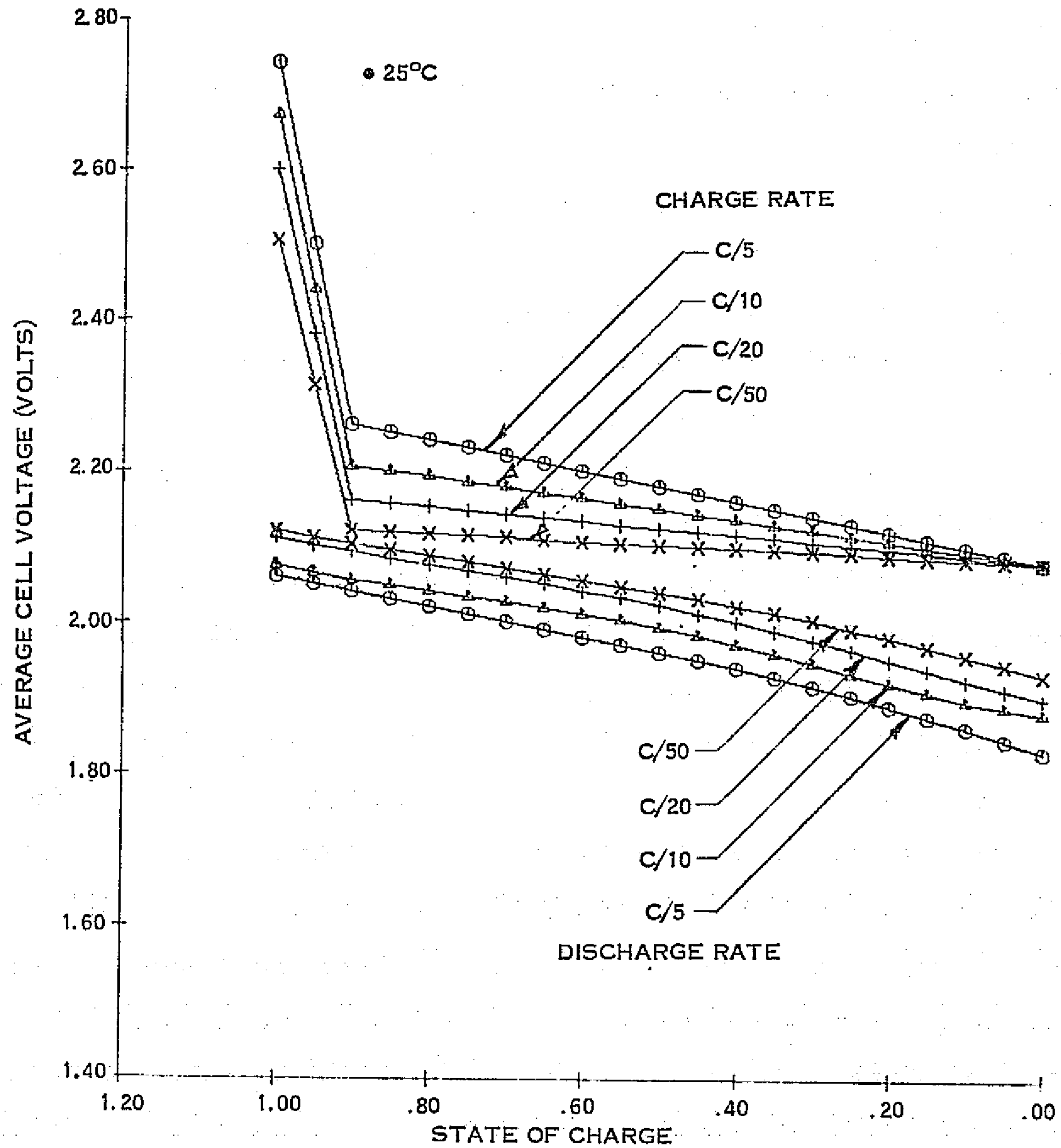


Figure 3-10. Typical Hybrid Lead-Acid Battery Charge/Discharge Characteristics

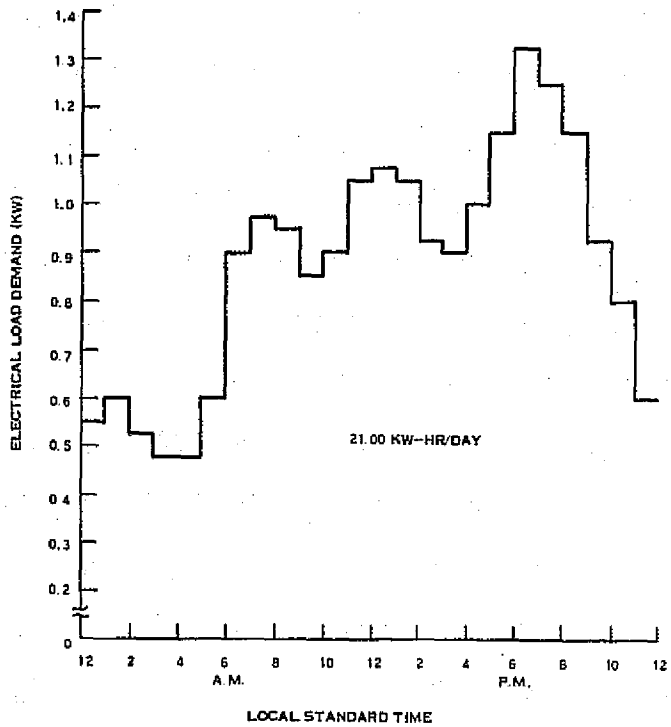


Figure 3-11. Diversified Load Demand Profile

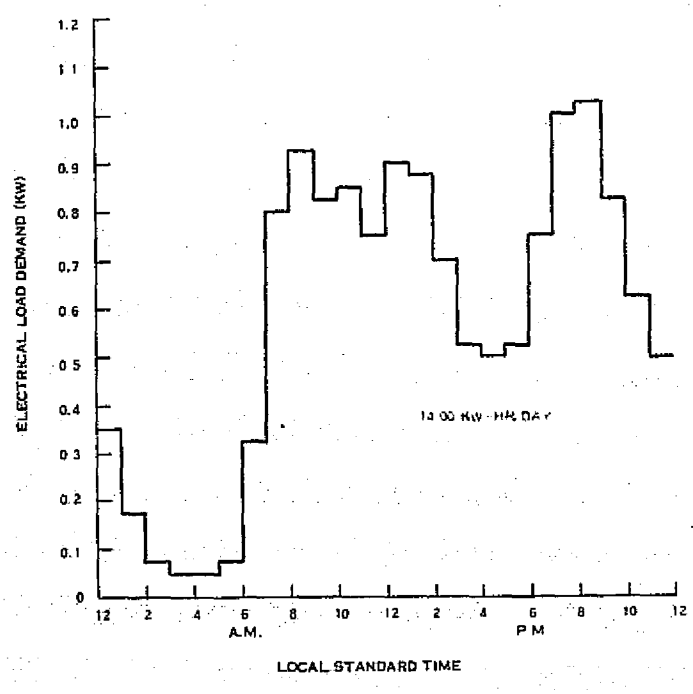


Figure 3-12. Hot Water Heater Electrical Load Demand Profile

Central Air Conditioning and Heating Product Data Guide, have been given as a function of the outside dry bulb temperature. Figure 3-13 shows this data for a 10.55 kW_t (3 ton) heat pump unit when operating in the heating mode. In the heating mode, the indoor dry bulb temperature is assumed to be 21.1°C (70°F). If a heat pump system cannot completely handle a specific hourly heating demand, supplementary electric resistance heating is provided. The resistance heating COP is assumed to be 0.995 based on the Product Data Guide referenced above. If a heat pump COP is less than 0.995 then only resistance heating is used. In the cooling mode, it has been assumed that the indoor dry bulb temperature is 25.6°C (78°F) and the indoor wet bulb temperature is 18.3°C (65°F), which corresponds to an indoor relative humidity of fifty percent.

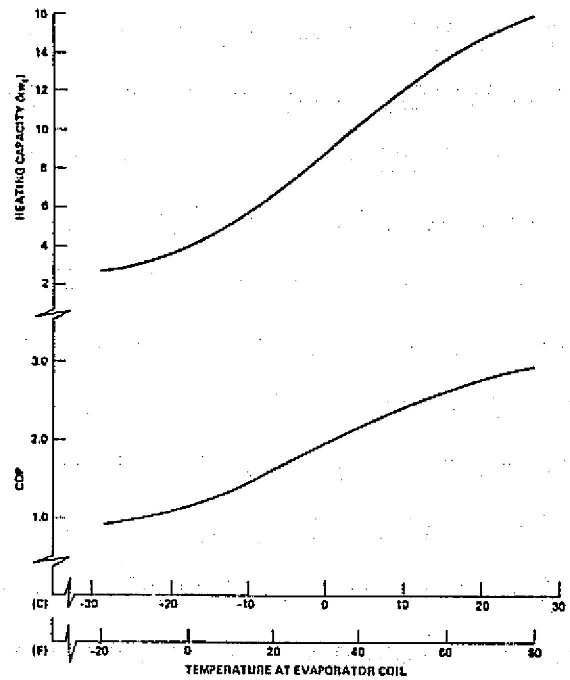


Figure 3-13. Performance of 3-Ton Heat Pump in Heating Mode Without Defrosting

In the heating mode operation some combinations of outdoor temperature and humidity will produce frost on the heat pump evaporator coil and will lower its heating performance. When this happens, the evaporator coil must be "defrosted" periodically much like household refrigerators and freezers. The most common method of defrosting is to change the heat pump operation over to the cooling mode for a few minutes so that the evaporator coil is heated and the frost is melted. During this defrost period, additional power in the form of electric resistance heating must be used to supply the heating load and to counteract the cooling caused by the reversed operation of the heat pump. The elapsed time for defrosting is about 5 percent of the regular operating time.

The input power and reversed output during defrosting is assumed to be the same as during regular operation. With that assumption, the total input power that the heat pump will need, including the defrosting power, is 1.1 P_{HP}, where P_{HP} is the electric power needed by the heat pump when no defrosting is required.

Likewise, the electric resistance heater power input, when the heat pump is defrosting, is $P_{RH} + 0.1(C_{HP}/COP_{RH})$. P_{RH} is the electric power needed by the resistance heater when the heat pump is not defrosting, C_{HP} is the heat load handled by the heat pump if it were not defrosting, and COP_{RH} is the coefficient of performance of the resistance heater.

Frost will accumulate on the heat pump outdoor coils when the temperature reaches approximately 4.4°C (40°F), but will lessen with simultaneous decrease in outdoor temperature and moisture content. It is assumed that defrosting will be necessary when both of the following temperature and humidity conditions exist:

$$-2.2^{\circ}C \leq T_{OD} \leq 3.9^{\circ}C; \quad \frac{(1.8\,T_{OD} + 72)}{100.0} \leq RH \leq 1.00$$

where:

RH = Relative humidity

T_{OD} = Outside dry bulb temperature, °C

3.2.3 CLIMATOLOGICAL DATA BASE

The climatological data base magnetic tapes required for this task were developed in connection with the Task I activity. A total of thirteen data base tapes have been processed through the Building Transient Thermal Loads (BTTL) program to yield a combined tape which includes hourly insolation and weather data as well as hourly building loads. The BTTL program determines the hourly loads by summing conduction heat losses/gains, infiltration losses/gains, internal heat gains (sensible and latent heat gain for people, electrical appliances, showers, etc) and solar heat gains through windows. In all cases the residence is assumed to have 169 m^2 of living space. The details of the building model are given in Appendix B of Reference 1. Table 3-9 lists the thirteen available data base tapes along with the year represented by the data.

Table 3-9. Available Climatological/Thermal Loads Data Base Tapes

Location	Year
Cleveland, OH	1962
Washington, DC	1963
Miami, FL	1963
Phoenix, AZ	1962
Madison, WI	1961
Los Angeles, CA	1963
Charleston, SC	1963

Location	Year
Nashville, TN	1959
Fort Worth, TX	1962
Omaha, NB	1963
Seattle, WA	1960
Bismarck, ND	1962
Boston, MA	1959

In all cases these magnetic tapes consist of 8762 records. The first record is a title which identifies the data on the tape but is not used in the system analysis program. The second record includes the following parameters:

IYEAR - Year of the weather data (last two digits only)

NZONE - Number of zones in the building model

XLON - Longitude of the building location

LATIT - Latitude of the building location

TZN - Time zone number for the location used in calculating the equation of time.

TZN	Time Zone
5	Eastern
6	Central
7	Mountain
8	Pacific

The next 8760 records have the same parameters for each hour of the year. These parameters, in the order of appearance on the tape, are listed below:

MON - Month of the year

DAY - Day of the month

HR - Hour of the day (0 - 23)

HBAR - Horizontal measured solar insolation (Btu/hr-ft^2)

HEXT - Extraterrestrial solar insolation (Btu/hr-ft^2)

TAMB - Ambient dry bulb temperature (^{o}F)

TWB - Ambient wet bulb temperature (^{o}F)

RH - Relative humidity (%)

WIND - Wind speed (miles/hour)

QL - Hourly building heating/cooling requirement, total of all zones (Btu/hr)

QLZ (I) - Hourly building heating/cooling requirements for zone (I) (Btu/hr)

QINF (I) - Hourly building infiltration heating/cooling requirement for zone (I). (Btu/hr)

QLAT (I) - Hourly latent heat requirement for zone (I). (Btu/hr)

Four of the 12 available sites were selected by the LeRC Project Manager for use as the input data base for the parametric sensitivity analysis task. Table 3-10 lists these selected sites with a summary of associated climatological and loads data. The Boston, MA site location was considered in a two point performance assessment only. These sites do not necessarily represent possible sites for RPSTs.

Table 3-10. Selected Site Locations with Pertinent Information

Site Location	Source of Weather/ Insolation Data Base Tape	Year	Station Longitude	Station Latitude	Yearly Insolation on a Horiz. Surface (kW-hr/m^2)		Percent Deviation of Selected Yearly Insolation from Climatic Atlas Average
					From Data Base Tape	From Climatic Atlas	
Cleveland, OH	Aerospace	1962	81.85°W	41.40°N	1264	1423	-11.2
Phoenix, AZ	Aerospace	1962	112.02°W	33.43°N	2119	2209	- 4.1
Los Angeles, CA	GE	1963	118.38°W	33.93°N	1844	1852	- 0.4
Washington, DC	GE	1963	77.47°W	38.98°N	1689	1513	+11.6
Boston, MA	GE	1959	71.1°W	42.4°N	1392	1279	+ 8.8

3.2.4 SENSITIVITY ANALYSIS RESULTS

3.2.4.1 Approach

The UNREG and NOBATRY Programs were used to perform the performance sensitivity analyses for the 4 selected site locations. In all cases, the solar array was modeled based on the general requirements of Reference 14. In accordance with these requirements, the specified 1.22 x 1.22 m (4x4 ft) subarrays were arranged to provide 84 subarrays on a 8.54 x 14.64 m (28 x 48 ft) array structure. Each of these subarrays was postulated to consist of six modules with each module consisting of 42 series connected circular solar cells. Table 3-11 summarizes these assumptions regarding the solar array. Using this packing arrangement it is possible to provide 78.19 m^2 of solar cell area in the roof area specified. This physical arrangement of solar cells was combined with the reference Solarex cell performance, as shown in Figure 3-8, to provide the basis for overall solar array electrical performance to be used in the parametric sensitivity analyses.

Table 3-11. Solar Array Design Characteristics

Parameter	Value
Number of subarrays	84
Number of modules/subarray	6
Number of cells/module	42
Solar cell area	36.94 cm^2
Module size	193 mm x 1168.0 mm (7.60 in. x 46.00 in.)
Total number of solar cells	21168
Total solar cell area	78.19 m^2
Module packing factor	0.688
Total array packing factor	0.626

For each of the 4 selected locations, the sensitivity analysis consisted of 5 major areas of investigation:

1. Determination of the optimum number of series solar cells for a given lead-acid battery using the UNREG Program

2. Determination of the optimum solar roof slope angle using both the UNREG and NOBATRY Programs.

3. Sensitivity of system performance to battery size using the UNREG Program

4. Sensitivity of system performance to effective inverter efficiency using both the UNREG and NOBATRY programs

5. Sensitivity of system performance to battery average Ampere-hour charging efficiency using the UNREG program

The following sections discuss the results in each of these areas of investigation. In all cases the measure of system performance is the Annual Energy Displacement Factor (EDF), which is defined as the ratio of the total annual electrical energy output of the photovoltaic system to the total annual electrical energy demand of the residence. The absolute system output can be easily obtained from EDF using the values for total annual electrical energy demand given in Table 3-12.

Table 3-12. Total Annual Electrical Energy Demand

Site Location	Total Annual Electrical Energy Demand (kW-hr)
Cleveland, OH	24871
Phoenix, AZ	20692
Los Angeles, CA	15071
Washington, DC	21426
Boston, MA	22323

3.2.4.2 Number of Series Cells

Figure 3-14 shows the annual EDF as a function of the number of series cells in the solar array circuits for a constant solar cell area of 78.19 m^2. The solar roof slope angle was set equal to the site latitude in each of the four cases, and the roof azimuth was due south. In each case, the curves show the characteristic sharp decrease as the number of series solar cells is reduced. As the number of series solar cells is reduced for a given set of insolation and temperature conditions, more and more hours of operation in the summer result in a battery charging voltage which exceeds the array maximum power voltage. On the other hand, an increase in the number of series cells above the optimum causes a gradual decrease in system output due to the reduction in array current at the average battery charging voltage. The results for these four sites are summarized in Figure 3-15, in terms of the optimum number of series connected lead-acid battery cells for a given solar array configuration. The series connection of 12 modules was used as a common electrical arrangement for all sites. The abscissa of the curve is the module maximum power voltage at AM1, 100 mW/cm^2 and 60°C. To meet the requirements of Reference 14, the range of this value is 15.8 to 17.0 Volts. The results of the analysis show that 3 of the 4 sites require the same number of series cells for optimum performance. Phoenix requires fewer series battery cells for an optimum match with the selected solar array arrangement. This is due to the high ambient temperature and high insolation which yield higher values of solar cell module temperature.

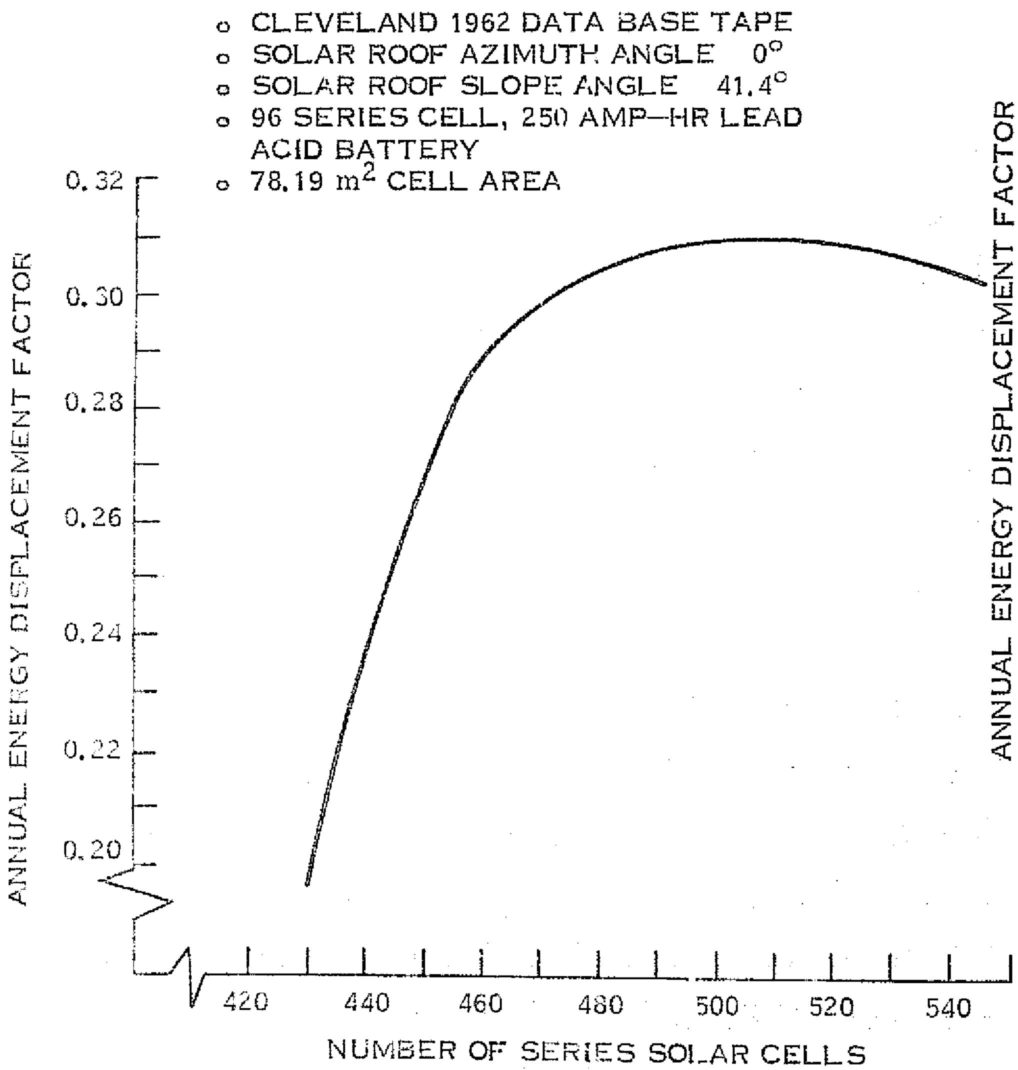
3.2.4.3 Solar Roof Slope Angle

The results of the sensitivity analysis for solar roof slope (measured from the horizontal) are given in Figure 3-16. Both the UNREG and the NOBATRY programs were used in all four cases. The roof azimuth orientation was due south in all cases, and the electrical circuit arrangement for the UNREG program was the optimum match of series solar cells and series battery cells as determined by the analysis reported in Section 3.2.4.2.

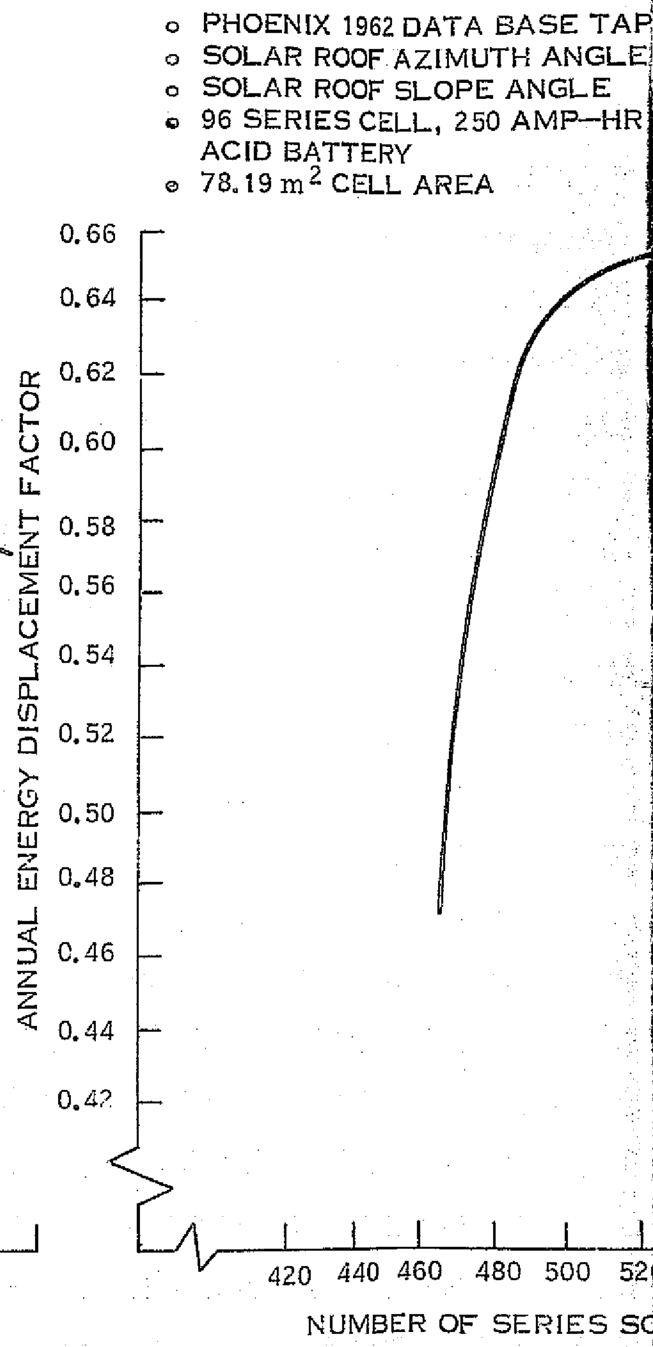
Both the UNREG and NOBATRY programs yield essentially the same result for optimum roof slope angle. These values are tabulated in Table 3-13 along with the angle selected for use in the subsequent analyses. A slightly off-optimum angle of 37 degrees was selected for the Cleveland site location. Operation at this angle will result in a two-percent reduction in annual energy displacement but will provide a more desirable slope for the self removal of snow.

3.2.4.4 Battery Size

The battery size in the UNREG program was varied with the results shown in Figure 3-17 for each of the site locations considered. The roof slope angle was varied from site-to-site to correspond to the selected value listed in Table 3-13.

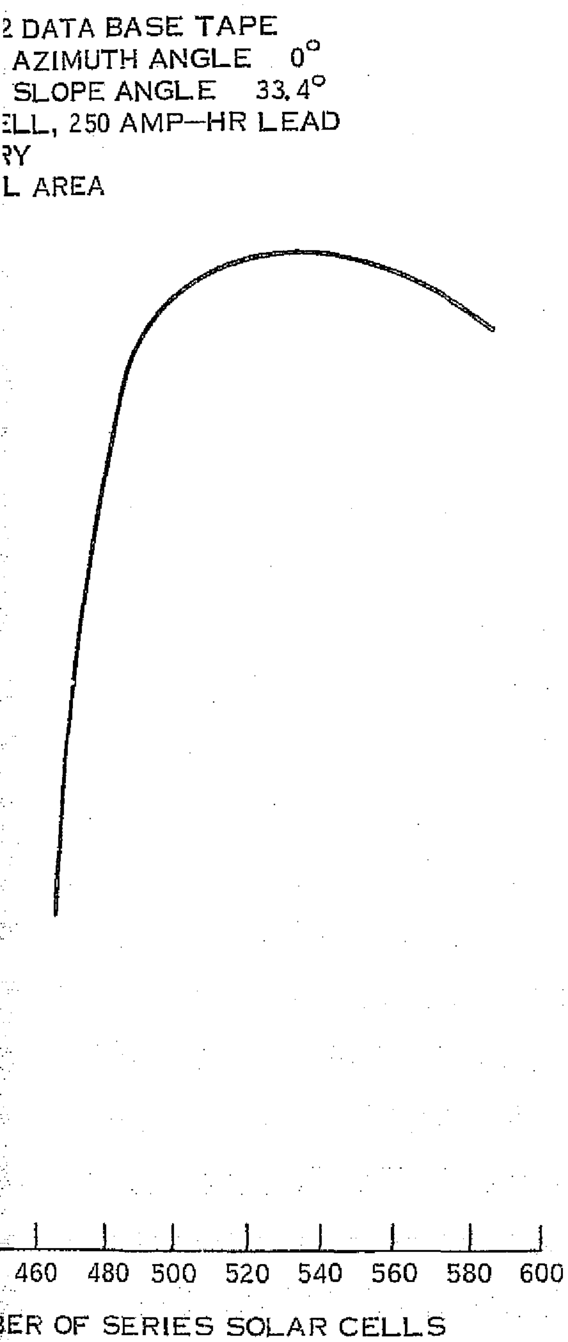


(A) CLEVELAND, OH

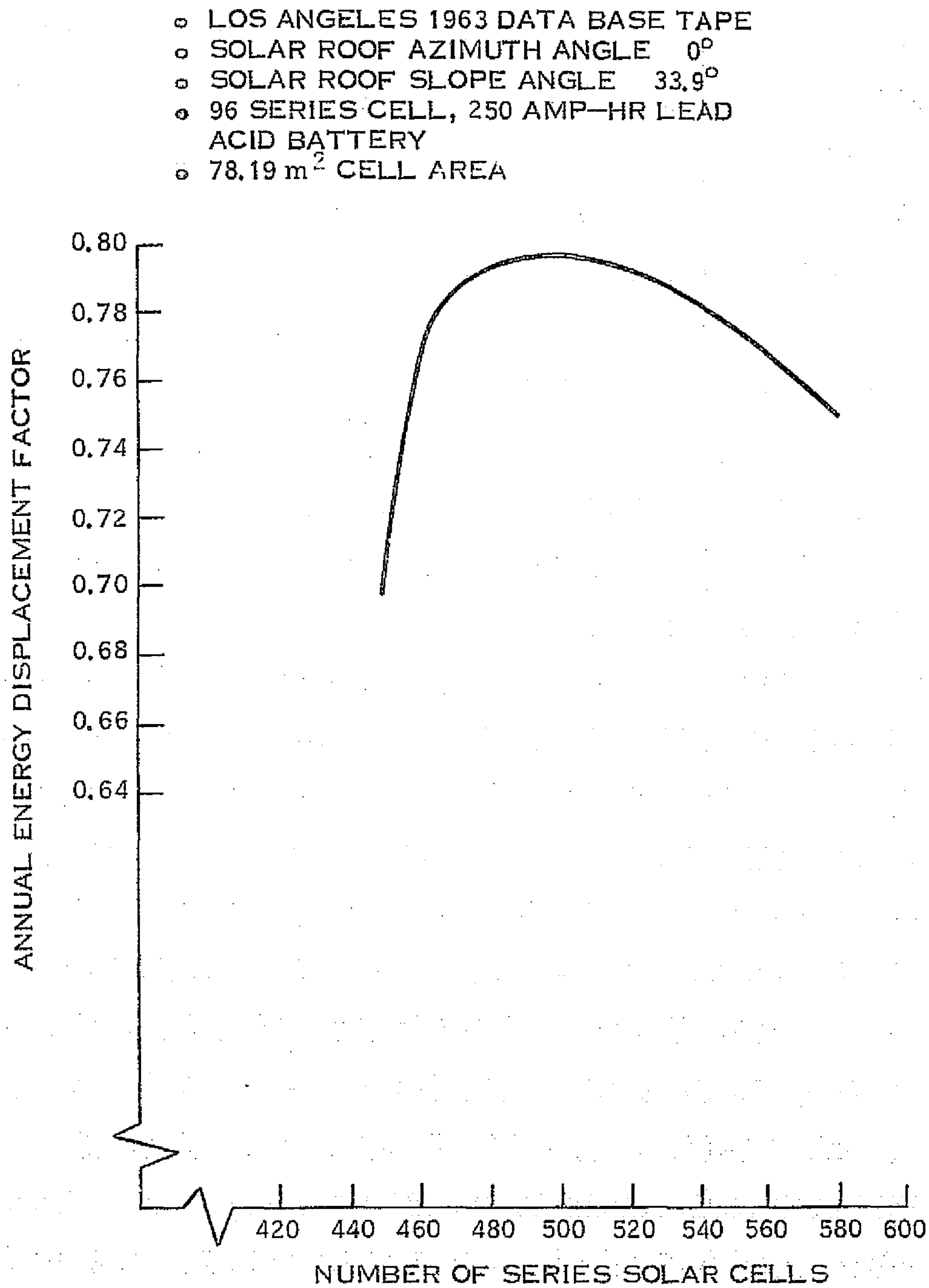


(B) PHOENIX,

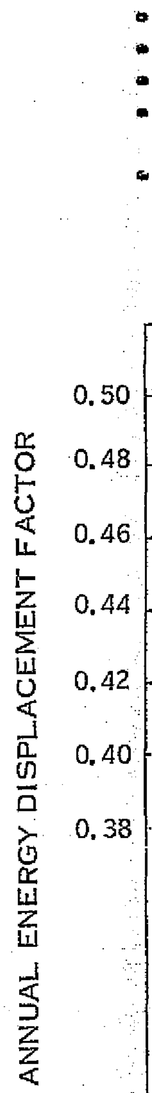
FOLDOUT FRAME 1

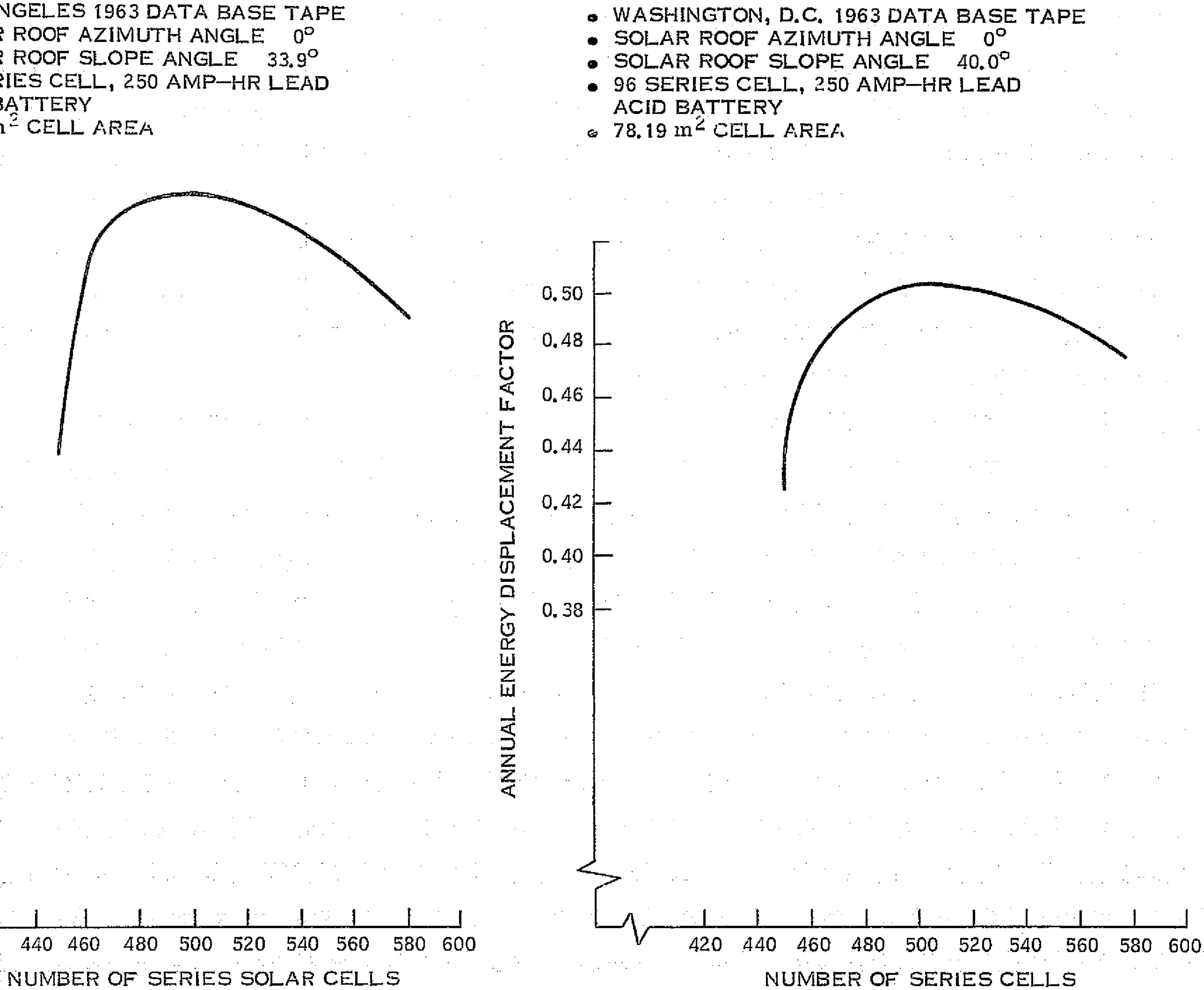


(B) PHOENIX, AZ



(C) LOS ANGELES, CA





(C) LOS ANGELES, CA

(D) WASHINGTON, D.C.

Figure 3-14. Determination of the Optimum Number of Series Cells

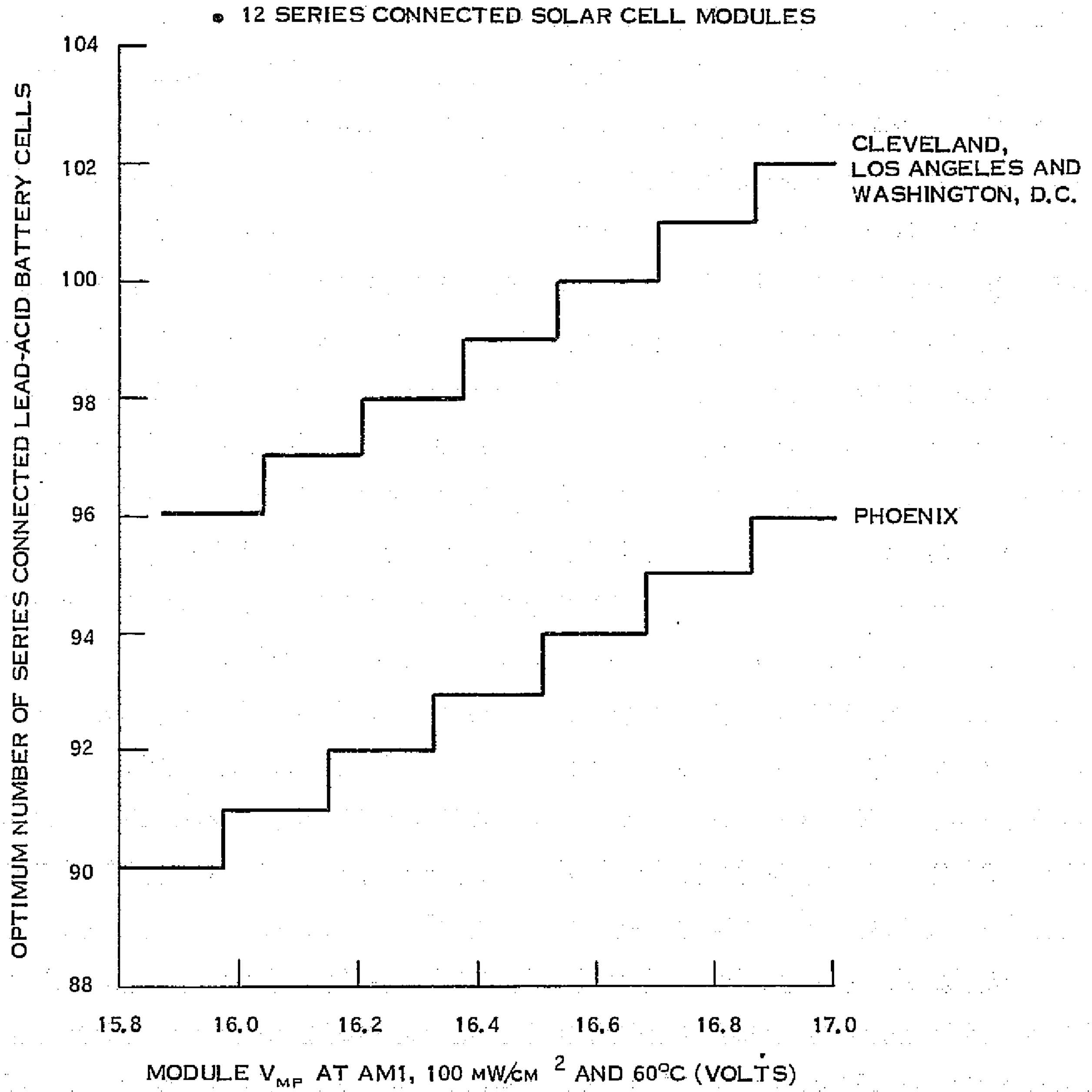
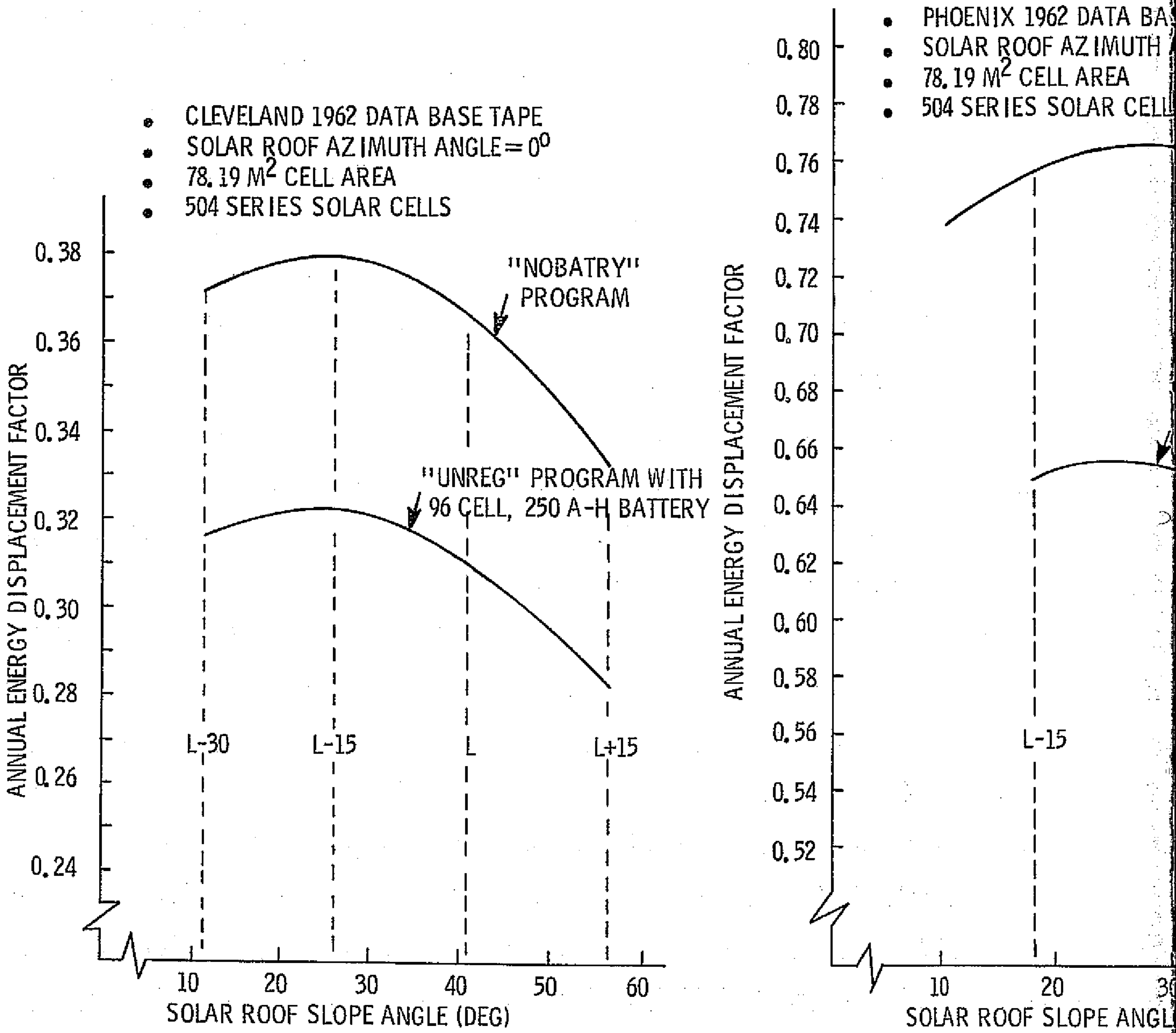
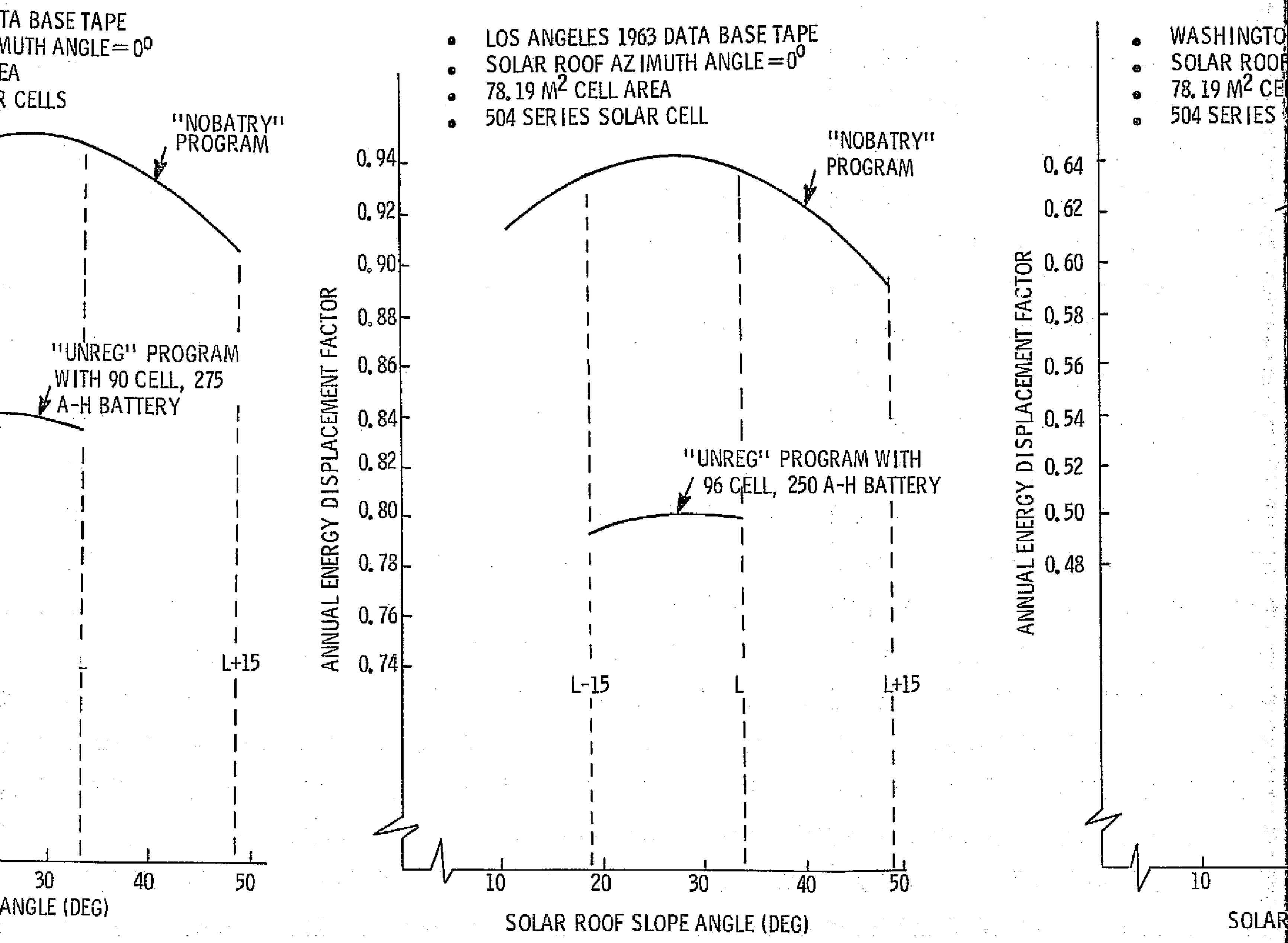


Figure 3-15. Optimum Number of Series Battery Cells for a Given Solar Array Configuration



(A) CLEVELAND, OH

(B) PHOENIX, AZ



(C) LOS ANGELES, CA

(D) WASHINGTON,

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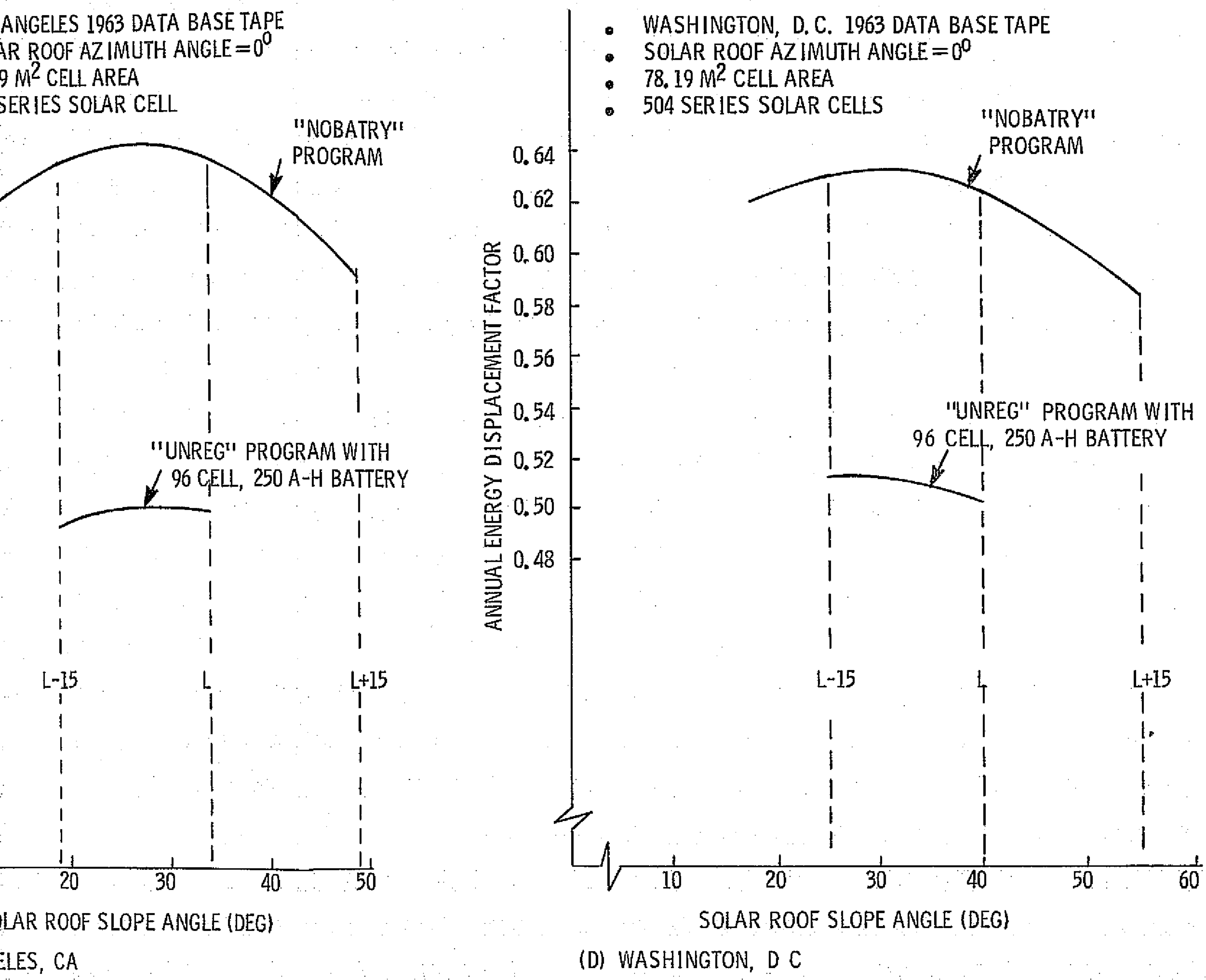
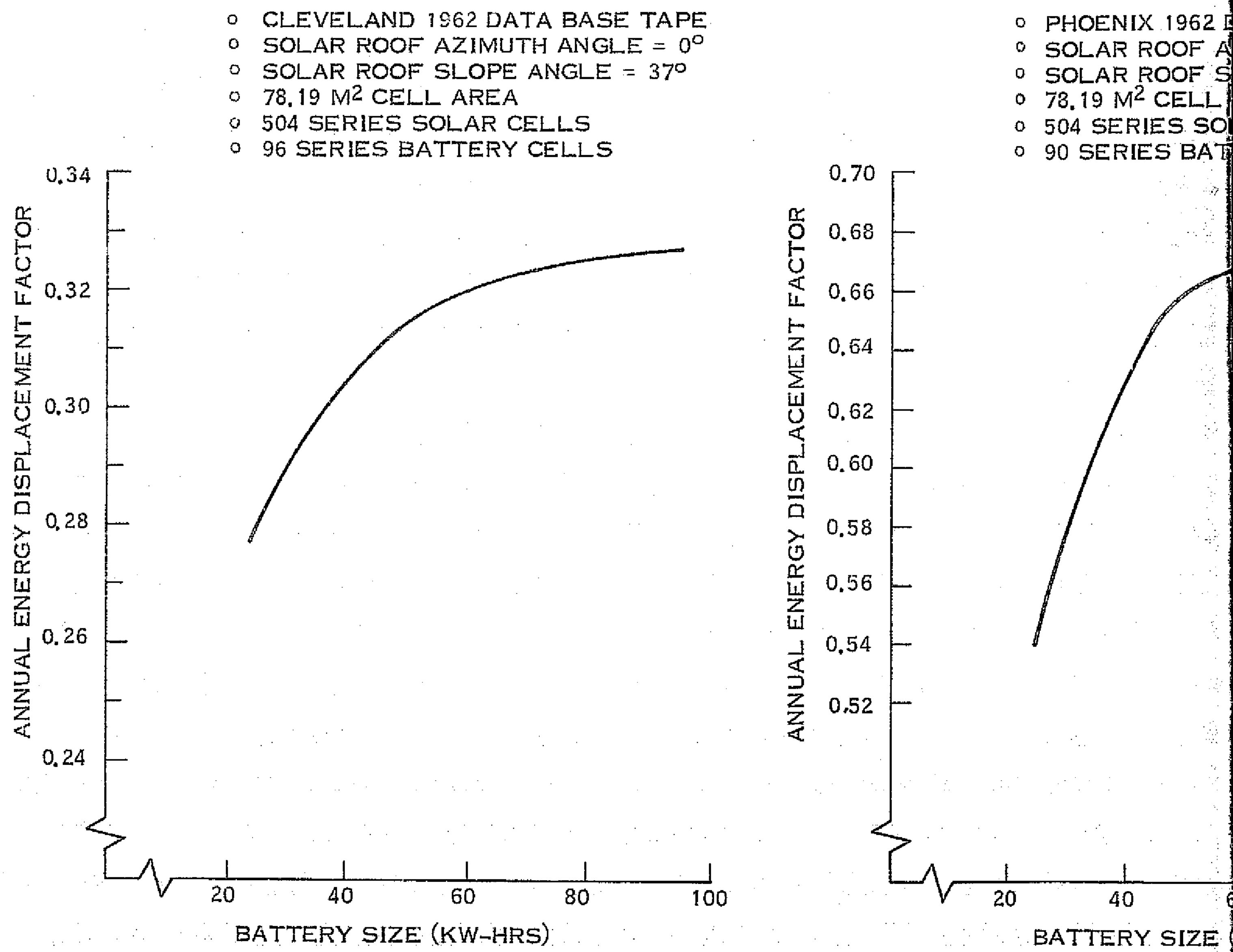


Figure 3-16. Determination of Optimum Solar Roof Slope Angle



(A) CLEVELAND, OH

(B) PHOENIX,

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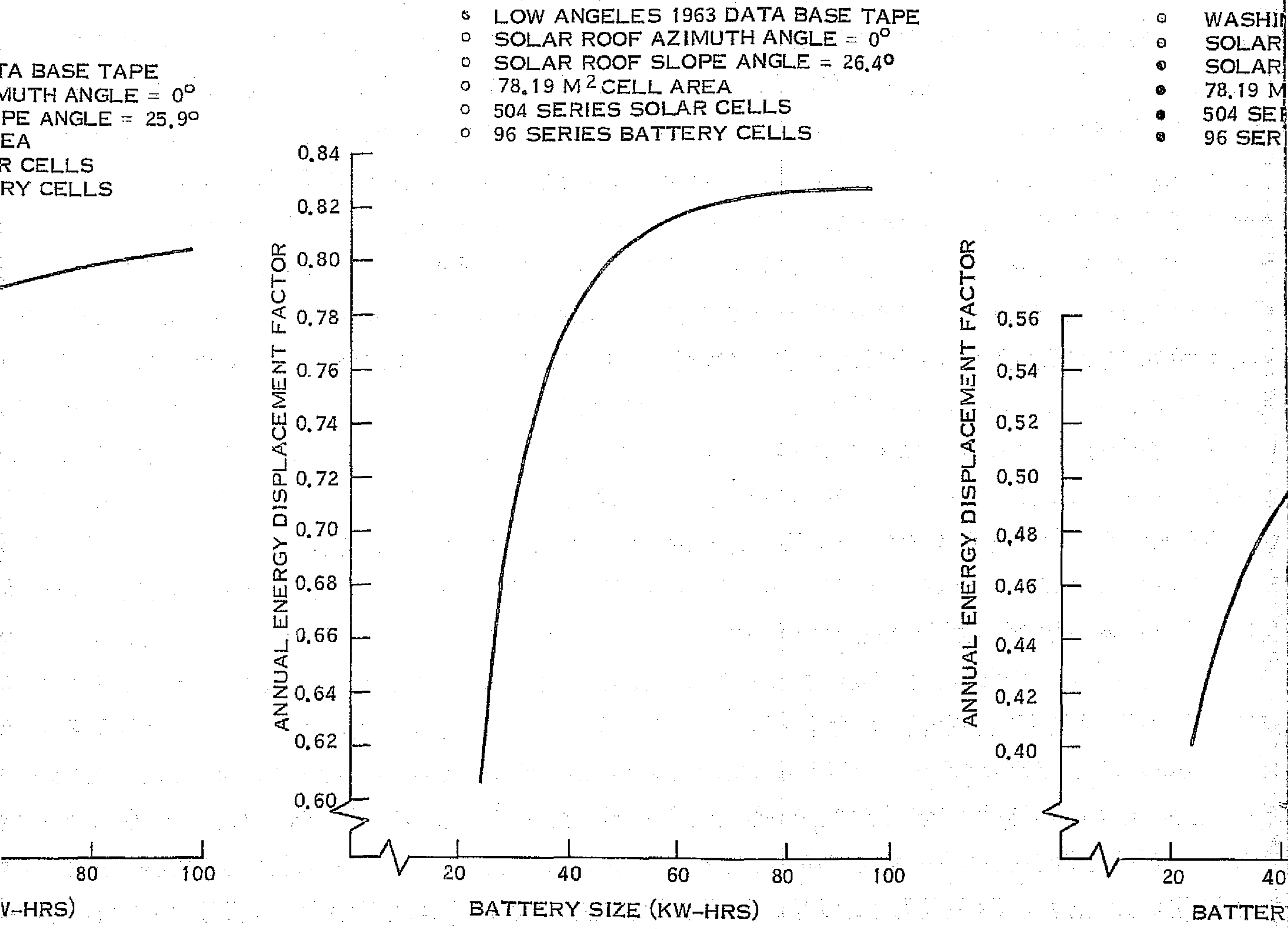

(C) LOS ANGELES, CA

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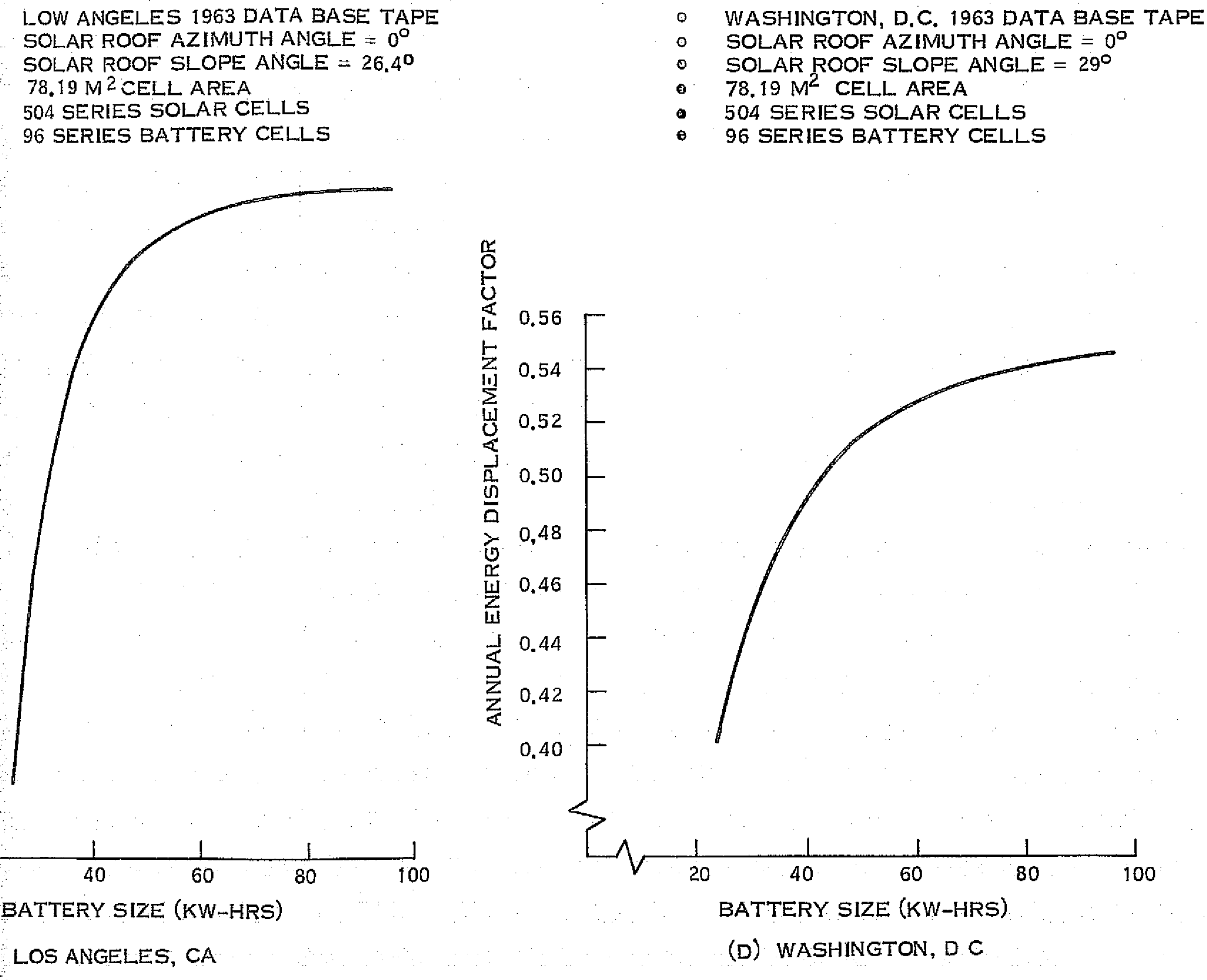

Figure 3-17. System Performance vs Battery Size

Figure 3-18 summarizes the results of these four cases in terms of the rate of change of the annual EDF expressed in percent per kW-hr of storage. Based on these results, a battery size of approximately 50 kW-hrs appears to be a reasonable choice for any of the four locations considered in the analysis.

Table 3-13. Optimum Solar Roof Slope Angle

Site Location	Optimum Roof Slope Angle (α) (deg)	Latitude (α) (deg)	Selected Roof Slope Angle (deg)
Cleveland, OH	26.4	15.0	37.0
Phoenix, AZ	25.9	7.5	25.9
Los Angeles, CA	26.4	7.5	26.4
Washington, DC	29.0	11.0	29.0

3.2.4.5 Effects of Inverter Efficiency

All previous analyses used a constant effective inverter efficiency of 87 percent. The effects on system performance due to the use of a lower efficiency, but available, inverter design were assessed by considering the use of the Model PC-16 Westinghouse inverter in both the NOBATRY and UNREG system models. This self-commutated inverter was initially developed for use with fuel cells and is representative of present day inverter technology. The internal losses for this inverter were obtained from Reference 15 and are given by:

$$P_{LOSS} = 1050 - 2.5\, V_{in} + 0.13\, P_{out}$$

where:

P_{LOSS} = Total internal inverter power losses (Watts)

V_{in} = DC input voltage ranging from 100 to 180 Vdc

P_{out} = Output power (Watts)

Using this model for inverter losses, the NOBATRY and UNREG programs were run for the Cleveland site location to obtain the system performance over an entire year. Because of the input voltage limitations of this unit it was necessary to reduce the voltage level by connecting eight modules in series for each solar cell circuit instead of 12 modules as described in the baseline circuit arrangement. The overall solar cell area was maintained at 78.19 m^2 to permit comparison with previous results which used a constant effective inverter efficiency of 87 percent. For the UNREG system model the

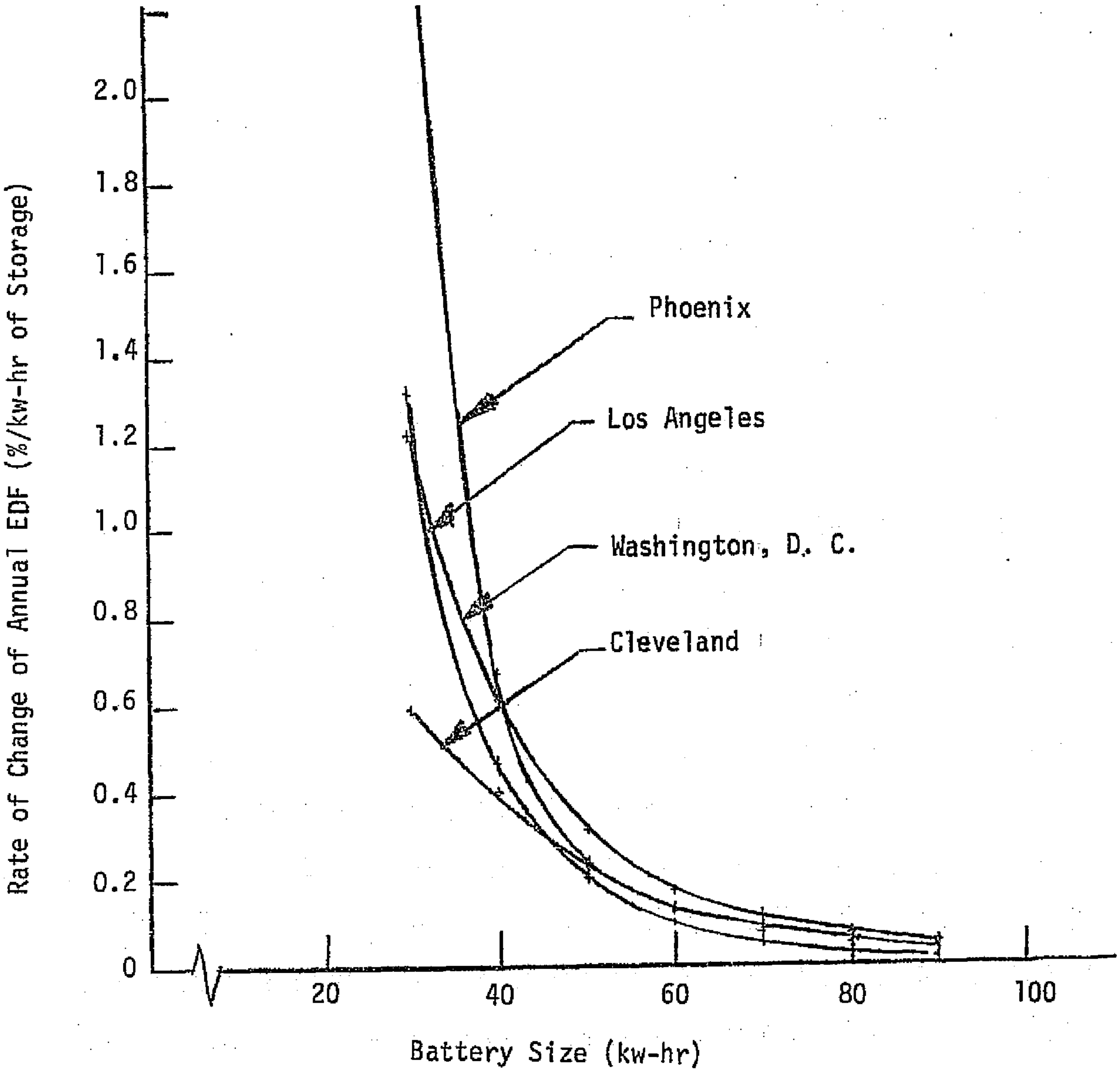

Figure 3-18. Sensitivity of System Performance to Battery Size

number of series connected battery cells was changed from 96 to 64 to correspond with the reduction in the number of series connected solar cell modules. The capacity of these battery cells was increased to 375 Ampere-hours to maintain the same total kW-hr capacity as in the previous analyses. Table 3-14 gives the annual system performance with the PC-16 inverter when used in both power system implementations - NOBATRY and UNREG. The baseline system performance, which uses a constant effective inverter efficiency of 87 percent, is shown in each case for comparison purposes. For the NOBATRY system model the use of the PC-16 inverter reduces the net system output by 21.4 percent when compared to the baseline system performance. The small difference in annual solar array energy output between the two performance calculations is attributed to the slightly higher conduction losses for the diodes which results because the lower solar array voltage required for the PC-16 inverter increases the forward current in the solar array insolation diodes.

Table 3-14. Performance of PC-16 Inverter for Cleveland Site Location

	NOBATRY		UNREG	
Annual Performance Parameter	Baseline System	With PC-16 Inverter	Baseline System	With PC-16 Inverter
House Electrical Load (kW_e-hr)	24871.	24871.	24871.	24871.
System Output (kW_e-hr)	9252.	7270.	7769.	6037
Utility Energy Required (kW_e-hr)	15619.	17601.	17102.	18834.
Solar Array Output (kW_e-hr)	10634.	10622.	10235.	10149.
Power Conditioning Losses (kW_e-hr)	1382.	3352.	1161.	2784.
Excess Energy (kW_e-hr)	-	-	295.	238.
Battery Heat Dissipation (kW-hr)	-	-	1010.	1090.
Energy Displacement Factor	0.372	0.292	0.312	0.243
Effective Inverter Efficiency	0.870	0.684	0.870	0.684

The effective inverter efficiency associated with the PC-16 inverter used in the NOBATRY system is calculated to be 68.4 percent. This value is determined by dividing the system output by the solar array output. This value represents that constant efficiency which could be used to represent the more complex PC-16 loss model and still achieve the same annual system performance.

For the UNREG system implementation, the PC-16 inverter results in 22.3 percent less system output when compared to the performance of the baseline UNREG system. The effective inverter effeciency for this case is also calculated to be 68.4 percent. This value is calculated by dividing the system output by the sum of the system output and the power conditioning losses. It is an apparent coincidence that this value of effective efficiency is numerically equal to the value obtained for use with the NOBATRY system. The inverter operating conditions are considerably different between these two cases so that the resulting effective efficiency could be generally expected to be different.

Based on these data points, Figure 3-19 shows the effect of inverter efficiency on the annual energy displacement factor for a Cleveland site location.

3.2.4.6 Effects of Ampere-Hour Charging Efficiency

The average battery Ampere-hour charging efficiency was maintained at 0.952 for all previous analyses using the UNREG program. Figure 3-20 shows the influence of this parameter on the system performance for the Cleveland site location. Under these conditions, a five percentage point change in the average battery Ampere-hour charging efficiency is reflected as a 237 kW-hr change in annual system output.

3.2.5 SYSTEM COMPARISON RESULTS

Single point system performance analyses were conducted to compare the results of the four system implementation approaches which were modeled as described in Section 3.2.2. The system performance calculated by UNREG, NOBATRY, PMPT and SMPT was compared for the Cleveland site location.

Table 3-15 gives the results of this comparative evaluation. Note that the house electrical load is the same in all cases. The solar array output for the PMPT approach is slightly less than either the NOBATRY or SMPT cases due to the fact that this system is maximum power tracking only when the batteries are charging. During the sunrise and sunset periods of the day, when some load sharing battery discharge is required, the solar array bus voltage is clamped to the battery discharge voltage and the maximum power tracking battery charge regulator is disabled. The UNREG system has the lowest solar array energy output because the system does not track the maximum power point.

The power conditioning losses associated with each system include the inverter losses as well as the maximum power tracking power conditioner, if it is required. A inverter efficiency of 87 percent was used in all cases and a tracker efficiency of 95 percent was used for both the SMPT and PMPT cases. The SMPT has the highest power conditioning losses due to the fact that all solar array power must pass through two series devices to reach the load. The losses in the PMPT case are slightly less than for the SMPT case because the tracker is in parallel with the solar array so that only the battery charging power passes through this device.

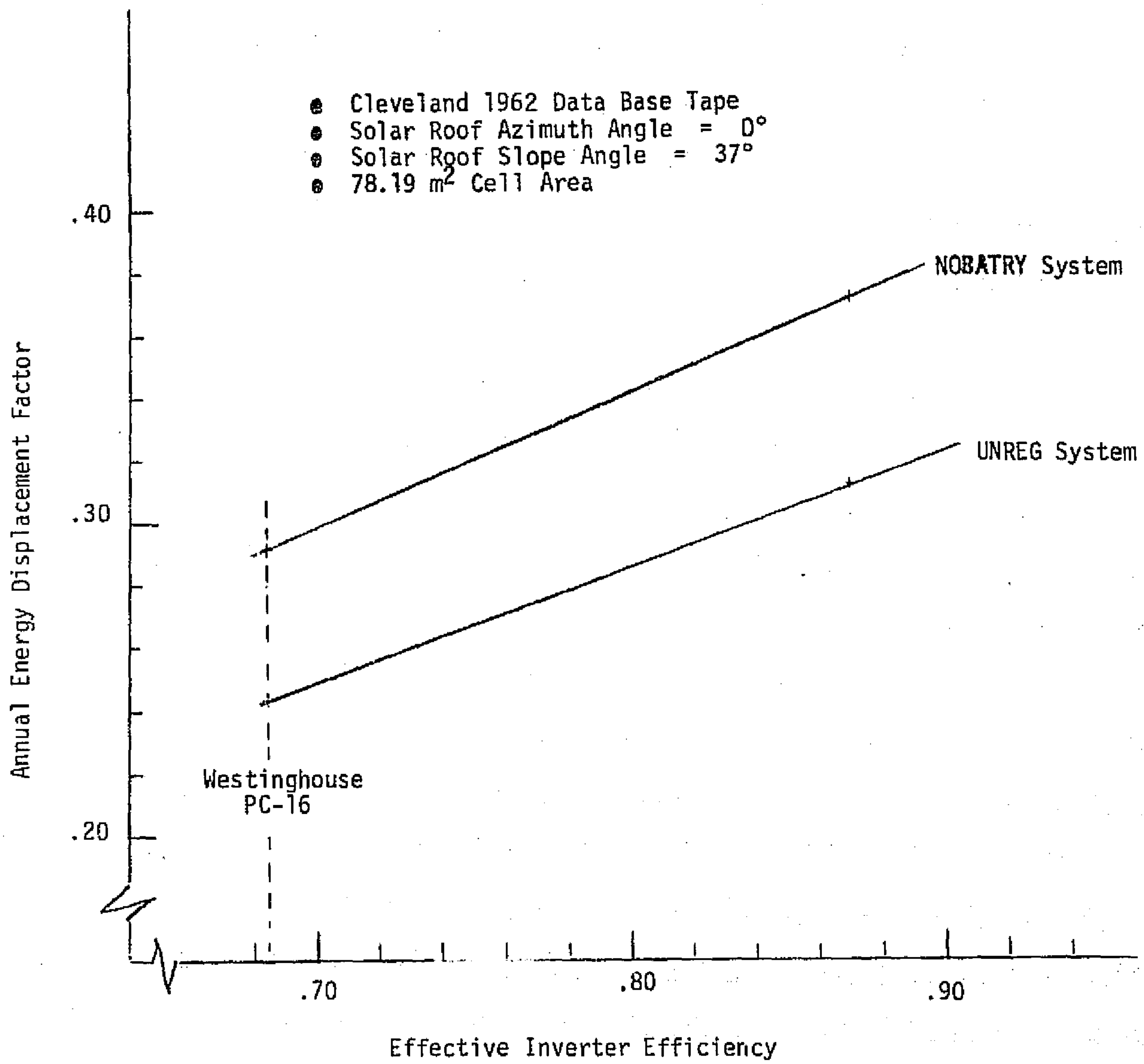

Figure 3-19. Influence of Inverter Efficiency on System Performance

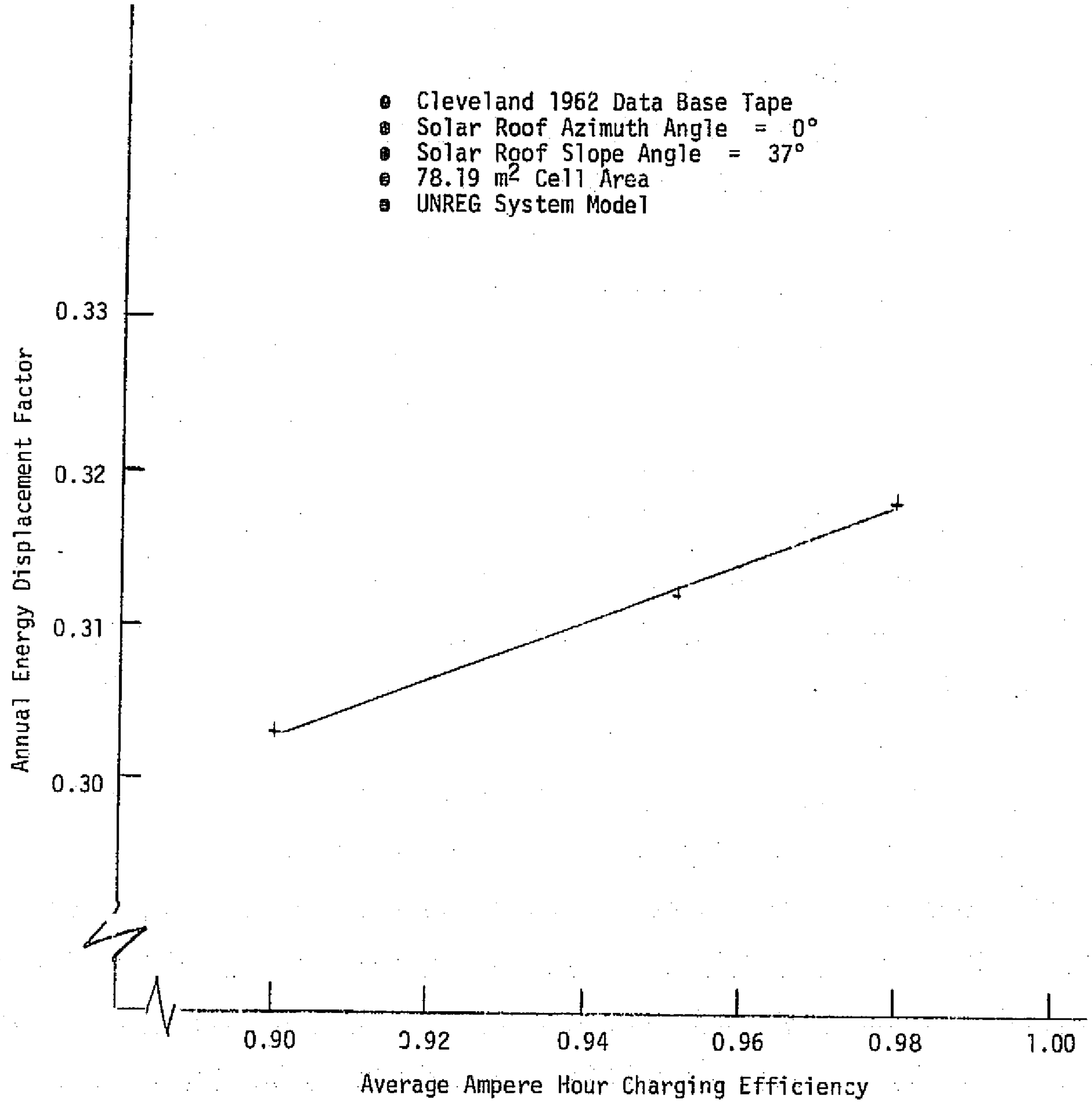

Figure 3-20. Influence of Average Battery Amper-Hour Charging Efficiency on System Performance

Table 3-15. Comparison of System Implementation Options for the Cleveland Site Location ($78.19\ m^2$ Cell Area and 48 kW_e-hr Battery Capacity)

	System Implementation			
	UNREG	NOBATRY	SMPT	PMPT
House Electrical Load (kW_e-hr)	24871.	24871.	24871.	24871.
System Output (kW_e-hr)	7769.	9252.	7683.	7691.
Utility Energy Req'd (kW_e-hr)	17102.	15619.	17188.	17180.
Solar Array Output (kW_e-hr)	10235.	10634.	10517.	10508.
Power Conditioning Losses (kW_e-hr)	1161.	1382.	1674.	1493.
Excess Energy (kW_e-hr)	295.	-	17.	28.
Battery Heat Dissipation (kW_e-hr)	1010.	-	1143.	1296.
Energy Displacement Factor	0.312	0.372	0.309	0.309

For those systems which contain energy storage (UNREG, SMPT, and PMPT) the excess energy values indicate that amount of solar array energy which is lost (not collected or dissipated in the shunt voltage regulator) by virtue of the requirement to maintain voltage limit control of the charging process.

All systems with energy storage have a loss associated with the heat dissipation in the battery. This factor is a significant contributor to making the NOBATRY system appear so attractive compared to all the other systems considered. The system output for the NOBATRY approach is 1483 kW-hr greater than the UNREG system which is in second place in terms of system output. The two maximum power tracking systems with energy storage (SMPT and PMPT) do not appear to offer performance advantages when compared to the UNREG system.

Table 3-16 compares the UNREG system with the NOBATRY system for each of the four site locations considered in the sensitivity analysis as well as for a Boston, Massachusetts location. For this additional site the roof slope angle was fixed at 37 degrees, measured from the horizontal. For the UNREG system a battery capacity of 48 kW-hr was used.

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Table 3-16. System Performance Comparison for Five Site Locations

Site Location	Cleveland		Phoenix		Los Angeles		Washington, D.C.		Boston	
System Implementation	UNREG	NOBATRY	UNREG	NOBATRY	UNREG	NOBATRY	UNREG	NOBATRY	UNREG	NOBATRY
House Electrical Load (kW_e-hr)	24871	24871	20692	20692	15071	15071	21426	21426	22323	22323
System Output (kW_e-hr)	7769	9252	13589	15829	12056	14167	10972	13520	9061	11456
Utility Energy Required (kW_e-hr)	17102	15619	7103	4863	3015	904	10454	7906	13262	10867
Solar Array Output (kW_e-hr)	10235	10634	17668	18194	15880	16284	14930	15540	12687	13168
Power Conditioning Losses (kW_e-hr)	1161	1382	2030	2365	1802	2117	1640	2020	1354	1712
Excess Energy (kW_e-hr)	295	-	524	-	689	-	823	-	872	-
Battery Heat Dissipation (kW-hr)	1010	-	1525	-	1333	-	1495	-	1400	-
Energy Displacement Factor	0.312	0.[illegible]72	0.657	0.765	0.800	0.940	0.512	0.631	0.406	0.513
% Increase in System Output with no Storage	19.1		16.5		17.5		23.2		26.4	

3.3 CONCEPTUAL DESIGN (TASK III)

3.3.1 DESIGN OBJECTIVES AND PHILOSOPHY

The conceptual design of the photovoltaic power system for the RPSTs is based on the results of the work performed under the ERDA contract "Conceptual Design and System Analysis of Photovoltaic Power Systems" (Contract No. E (29-2) - 3686) and on the results of the sensitivity analysis and performance evaluations performed as Task II of this contract. During the course of this analysis task four different power system approaches were modeled (viz., NOBATRY, UNREG, SMPT, and PMPT) as reported in Section 3.2, the system implementation called NOBATRY with no on-site energy storage and with a solar array maximum power tracking inverter which feeds excess power back onto the utility grid results in an annual system output which is 19 percent better than the second best system for a Cleveland site location. Expressed in terms of the cost of this energy, the ERDA study (Reference 1) has reported that this no energy storage system results in a cost which is about 50 percent less than the second best system. However, this potentially attractive system configuration is not without drawbacks which mainly concern the use of the utility as an infinite sink for excess power. In the absence of feedback of power to the utility, the power system must use on-site energy storage to accommodate the diurnal nature of the solar array output. The analysis of systems with on-site lead-acid batteries has shown that the basic direct charge system, called UNREG, with the battery connected directly to the solar array bus is superior to the other maximum power tracking systems with storage.

The RPST program must answer fundamental questions regarding power system implementation which can only be addressed in a full scale system level experiment. Accordingly, the following set of design objectives was formulated to enable the evolution of the experiment design. These objectives, as listed below, are grouped into primary and secondary categories to indicate a relative importance.

Primary Design Objectives

1. Accommodate both the NOBATRY and the UNREG system implementations
2. Maximize photovoltaic system output
3. Instrument to collect system performance data to permit the refinement and ultimate verification of the analytical models

Secondary Design Objectives

1. Evaluate the quality of fed back power to the utility in the NOBATRY case
2. Allow for energy saving load programming

3. Permit the measurement of solar array performance on an individual circuit basis

4. Accommodate the use of dc power for the range/oven and hot water heater

The Task II performance evaluations have shown both the NOBATRY and the UNREG systems to be potentially the most promising in terms of overall system performance. Therefore, the evaluation of these two options should be the principal objective of this experimental program. Using an identical solar array configuration, the measured system performance with these two implementation approaches will provide conclusive evidence to substantiate the eventual choice of one approach for widespread application in a demonstration project. To accommodate this principal objective it is proposed to design the power system with the flexibility required to allow it to evolve in two stages. The first stage will consist of the basic NOBATRY system configuration. After a suitable evaluation period, on-site energy storage will be added and the basic system configuration will follow the UNREG model.

In either of these stages the power system should be designed to maximize photovoltaic system output. Since inverter efficiency is an important factor affecting net system output, special attention should be directed toward obtaining the best possible inverter performance within the budget and time constraints of the program. As discussed in Section 3.3.6, off-the-shelf self-commutated inverters with the required high efficiency over a wide range of output power levels are non-existent. Some development effort in this area is indicated in order to obtain the highest possible system output.

Each experimental RPST should be adequately instrumented to permit the acquisition of the data necessary to accurately measure system performance and to permit the refinement and ultimate experimentally verification of the analytical models. Once these models have been experimental verified at a few different sites with different climates, they can be used with high confidence to predict system performance and optimize component design over a wide range of climatic conditions. The experiment should be provided with adequate instrumentation to monitor the quality of the fed back power for the NOBATRY case. The reactive power required from the utility during all modes of operation should be measured. The power factor of the fed back power should also be determined. This information will aid the utility industry and governmental regulatory agencies in the assessment of the technical and economic aspects of distributed photovoltaic power generation.

The overall energy displacement factor for these experimental residences can be improved by energy saving load programming. To accommodate the experimental investigation of these options, the design should allow the load switching flexibility to enable operational control of specific loads. Prime candidates for operational control of this type are the heat pump and hot water heater. The hot water heater load can be programmed to heat the water during the hours of high insolation in order to reduce the demand for battery or utility energy during nighttime periods. The hot water heater could also be controlled to come on when shunt voltage limiter operation is detected in the

UNREG system implementation. In this way the dc bus voltage could be controlled by a dissipative load with storage of useable heat energy. The heat pump operation could be programmed to over-heat or over-cool the living space during periods of high insolation in order to reduce the demand during other times.

An important secondary objective of the experiment should be the measurement of solar array performance. The design should include the capability for the in-situ measurement of individual solar cell circuit I-V characteristics. This will enable the direct comparison of solar cell module performance among the various module suppliers which might be represented in the installation. Any time-dependent performance degradation can also be detected by the periodic measurement of individual circuit I-V characteristics.

The design should allow the flexibility to accommodate certain dc loads in the house. Large resistive loads, such as the range/oven and hot water heater, are prime candidates for the application of dc power. These appliances would have to be specially designed for the dc operation. The contactors on these appliances are normally suitable for ac operation only. The arc which is established as the contact pair opens is extinguished during the periodic current reversal. At the instant of zero current, the arc can be extinguished quite easily with inexpensive contact materials and small gap spacings. A dc switch must be designed to extinguish an established arc with voltage and current available to sustain it.

3.3.2 POWER SYSTEM IMPLEMENTATION

The power system has been configured to permit the systematic development and experimental investigation of the two system implementation approaches which were found to be most attractive based on the analytical model evaluation. A two-stage evolutionary development is proposed for the RPST power system. Stage I of this development is the basic NOBATRY system implementation as shown schematically in Figure 3-21. In addition to the solar array (discussed in Section 3.3.4.1), this power system approach requires a maximum power tracking controller (discussed in Section 3.3.4.4) and an inverter (discussed in Section 3.3.4.3). These two devices permit the conversion of power from the solar array at the maximum power operating point and the feedback of any excess ac power to the utility. During periods when the inverter output cannot meet the load demand, the utility supplies the difference. Thus, the utility grid functions as an "infinite" source and sink for power. Analysis has shown this system to have the best overall energy output and the lowest capital equipment costs.

Figure 3-22 shows the Stage II evolution of the power system. The solar array remains identical to the Stage I system, but the lead-acid battery (discussed in Section 3.3.4.2)

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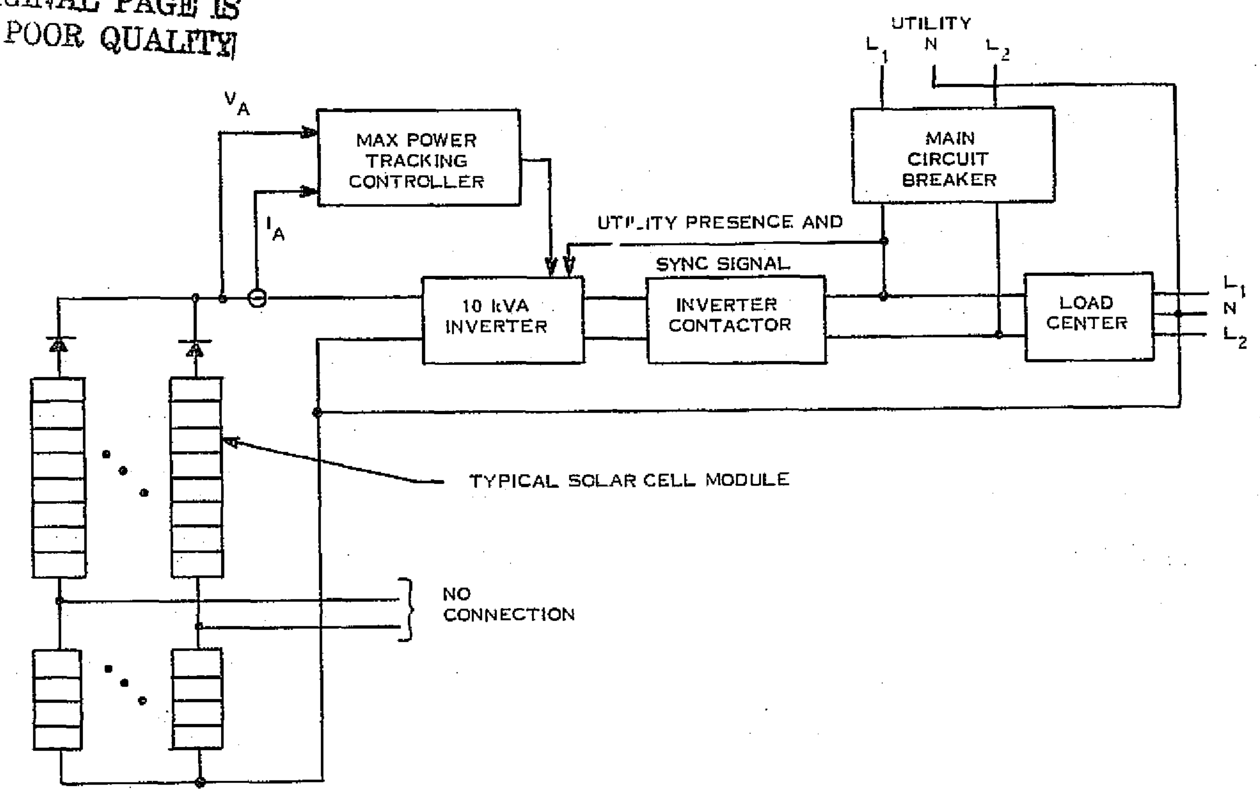


Figure 3-21. Functional Schematic of Stage I (NOBATRY) System Implementation

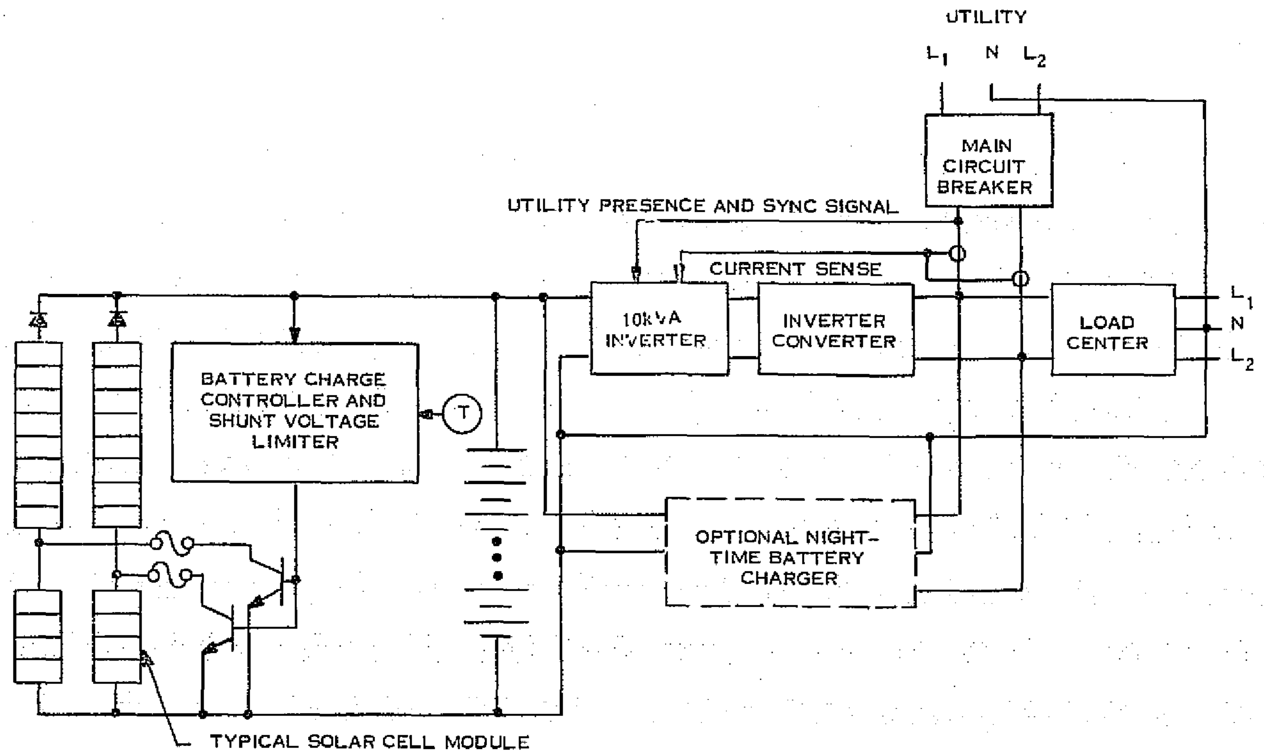


Figure 3-22. Functional Schematic of Stage II (UNREG) System Implementation

has been added along with the associated battery charge controller and shunt voltage limiter (discussed in Section 3.3.4.5). This system is the basic UNREG configuration which has the solar array bus connected directly to the battery terminals so that the solar array operating point is established by the battery voltage. The number of solar cell modules in series in relation to the number of battery cells in series is a function of the solar cell module voltage and site location as discussed in Section 3.2.4.2. For purposes of discussion in this report a baseline system has been defined with 12 series connected solar cell modules per circuit for both system configurations and with 96 series connected battery cells for the Stage II system. This selection fixes the dc bus voltage level to within the nominal range of 188 to 240 Vdc for the Stage II system depending on the battery charge/discharge status and state-of-charge. The selection of this voltage level is somewhat arbitrary but should be as high as practical to reduce the I^2R losses in the solar array wiring from the roof to the battery/inverter. The inverter input voltage constraint is the most significant influence on the selection of this voltage level. As discussed in Section 3.3.4.3.2.1, the transformer coupled line-commutated inverter can accommodate this solar array voltage level with a 1.5 to 1 turns ratio on the output transformer. Certain existing self-commutated inverters (e.g., the Westinghouse PC-16) would require this voltage level to be lower. However, these existing designs are also characterized by a relatively low efficiency which results in less than achievable system output (see Section 3.2.4.5). The development of a new inverter for this specific application could enable the design to accommodate the voltage associated with 12 series connected solar cell modules.

Table 3-17 summarizes the key design parameters which describe the baseline designs for the two system configurations. The specified solar cell area of 78.19 m^2 repre-

Table 3-17. Summary of Baseline Photovoltaic Power System Design Parameters

Design Parameter	System Configuration	
	Stage I(NOBATRY)	Stage II(UNREG)
Solar Cell Area (m^2)	78.19	
Number of Series Connected Solar Cell Modules	12	
Number of Series Connected Battery Cells	No Battery Used	96
Battery Type	No Battery Used	Hybrid Lead-Acid
Battery Capacity	No Battery Used	48 kW$_e$-hr
Inverter Output Power Rating	10 kVA	

sents 84 subarrays in the baseline description. It is conceivable that the actual number of subarrays in the solar array for a RPST could vary from 84 to 106 depending on the area utilization efficiency of the selected modules and on the architectural design of the house. The solar array configuration should not change between the Stage I and Stage II implementations on the same RPST. Since the availability of modules from different suppliers will probably necessitate a difference in solar array configuration among the various regional RPST s, an effort should be made to keep the total solar cell area nearly equal for each RPST. The results of the ERDA study (Reference 1) show that a solar cell area between 80 and 90 m^2 per residence is near optimum in terms of the levelized cost of the energy for solar array costs that might be expected in the 1980-1985 time period.

The inverter output rating for the baseline description has been established as 10 kVA for both system implementations. This rating is adequate for the baseline NOBATRY system at a Cleveland site location and more than adequate for the baseline UNREG system. Since it is probable that a single inverter development will supply the hardware for all RPSTs, a standardized set of inverter design requirements should be established early in the program. Appendix A is a preliminary version of a design specification for such a 10 kVA inverter which could be used in all regional RPSTs.

3.3.3 INTEGRATION OF POWER SYSTEM WITH RESIDENTIAL STRUCTURE

The elements of the photovoltaic power system as well as the associated data acquisition and control equipment must be integrated within the structure of a single family residence to form the RPST. Figure 3-23 shows a pictorial view of such a typical RPST. The detailed floor plan and elevation views of this house are shown in Figure 3-24. These architectural drawings were developed for the purpose of establishing the physical interrationships of the photovoltaic system components and the normal architectural functions of a single family residence. No attempt was made to investigate other basic architectural concepts since this was considered beyond the scope of the contract. A review of Figure 3-24 reveals several areas of the house which are associated with the photovoltaic power system or the data acquisition and display required for the operation of the experiment.

The RPST related functional additions to the normal residence are:

1. A photovoltaic solar array mounted above the south facing roof
2. A photovoltaic system (PVS) components room located adjacent to the garage
3. A data/control room located within the living area of the house
4. A display panel mounted on a recreation room wall
5. A two mast air terminal lightning protection system

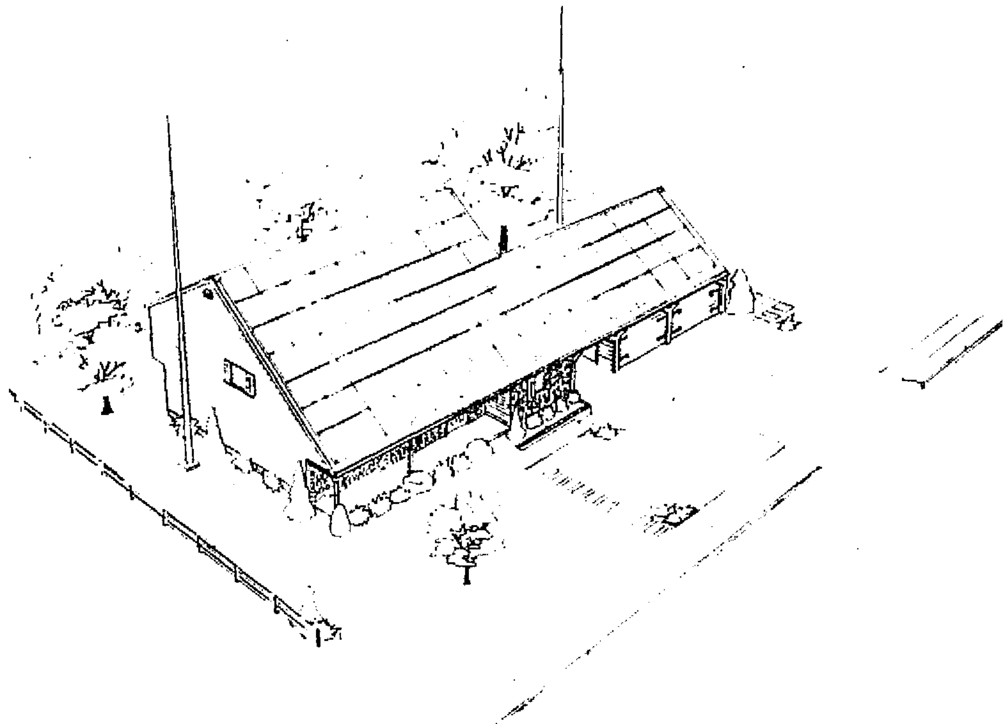
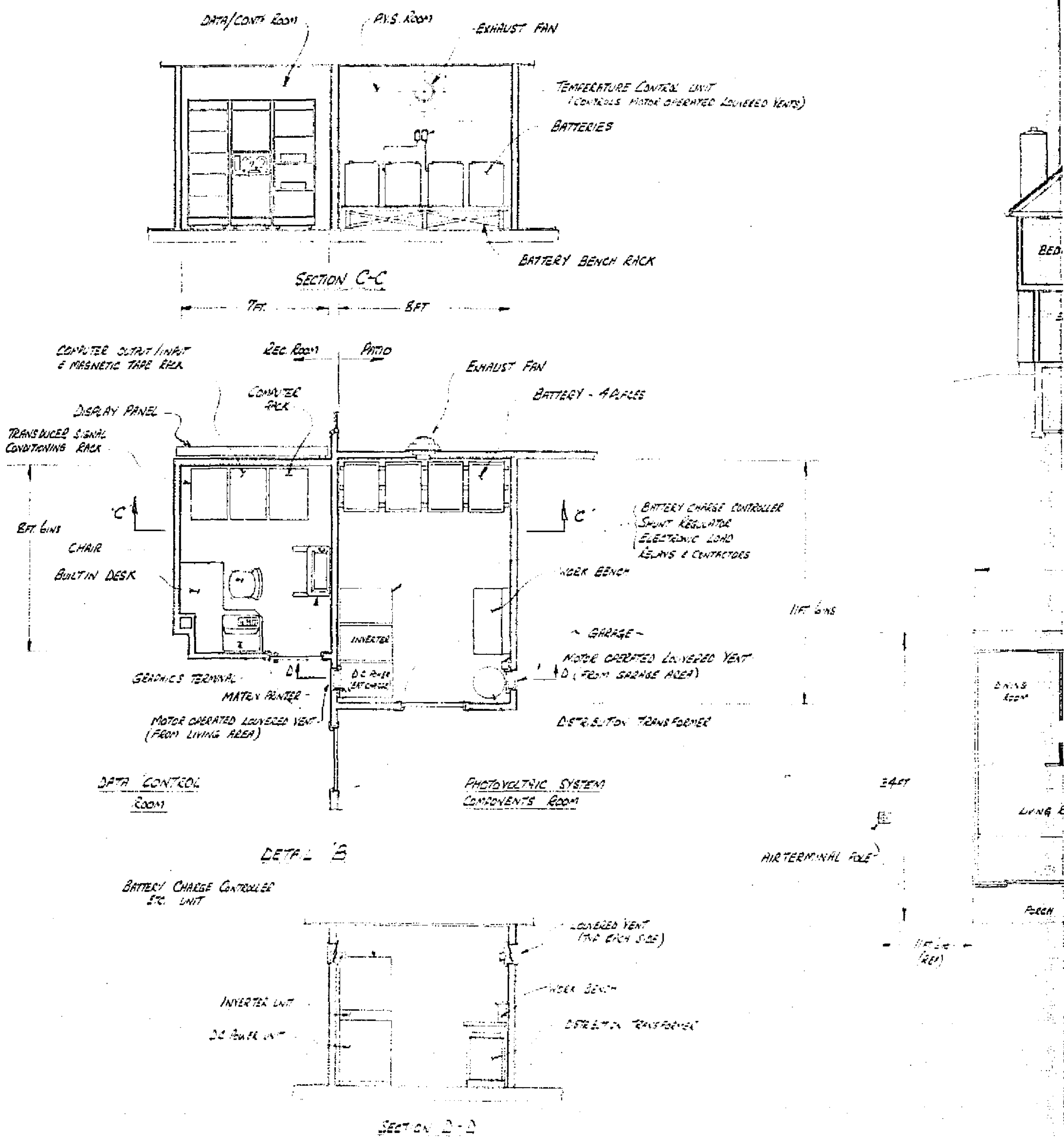


Figure 3-23. Pictorial View of Typical RPST

The architectural design shown meets the energy conservation guideline of ASHRAE Standard 90-75 and provides for the installation of 87 subarrays above the south facing roof. The solar array configuration and possible design concepts for mounting installation are discussed in Section 3.3.4.1.

The PVS Components Room is an insulated room adjacent to the garage area but with an entrance directly from the outside. This room houses all batteries and power conditioning components for either the Stage I or Stage II power systems. An exhaust fan on the rear wall of the room runs continuously to achieve a complete change of air for the room every 15 minutes. This exhaust system will assure that the concentration of hydrogen gas from the batteries (when used) is below the one percent level at all times. This room is not actively heated or cooled except when the battery temperature is sensed to be outside the limits of 10 to 35°C. Within these limits the air from the garage area is circulated through the room by the exhaust fan. If the battery temperature exceeds the 35°C level, as sensed by a fluid filled bulb attached to the battery, the temperature controller drives open the louvered vent to allow conditioned house air to cool the room while at the same time closing the vent into the garage to prevent the entrance of hot outside air. Similarly if the battery temperature falls below the lower 10°C limit, the temperature controller drives open the louvered vent to allow conditioned house air to heat the room while at the same time closing the vent into the garage to prevent the



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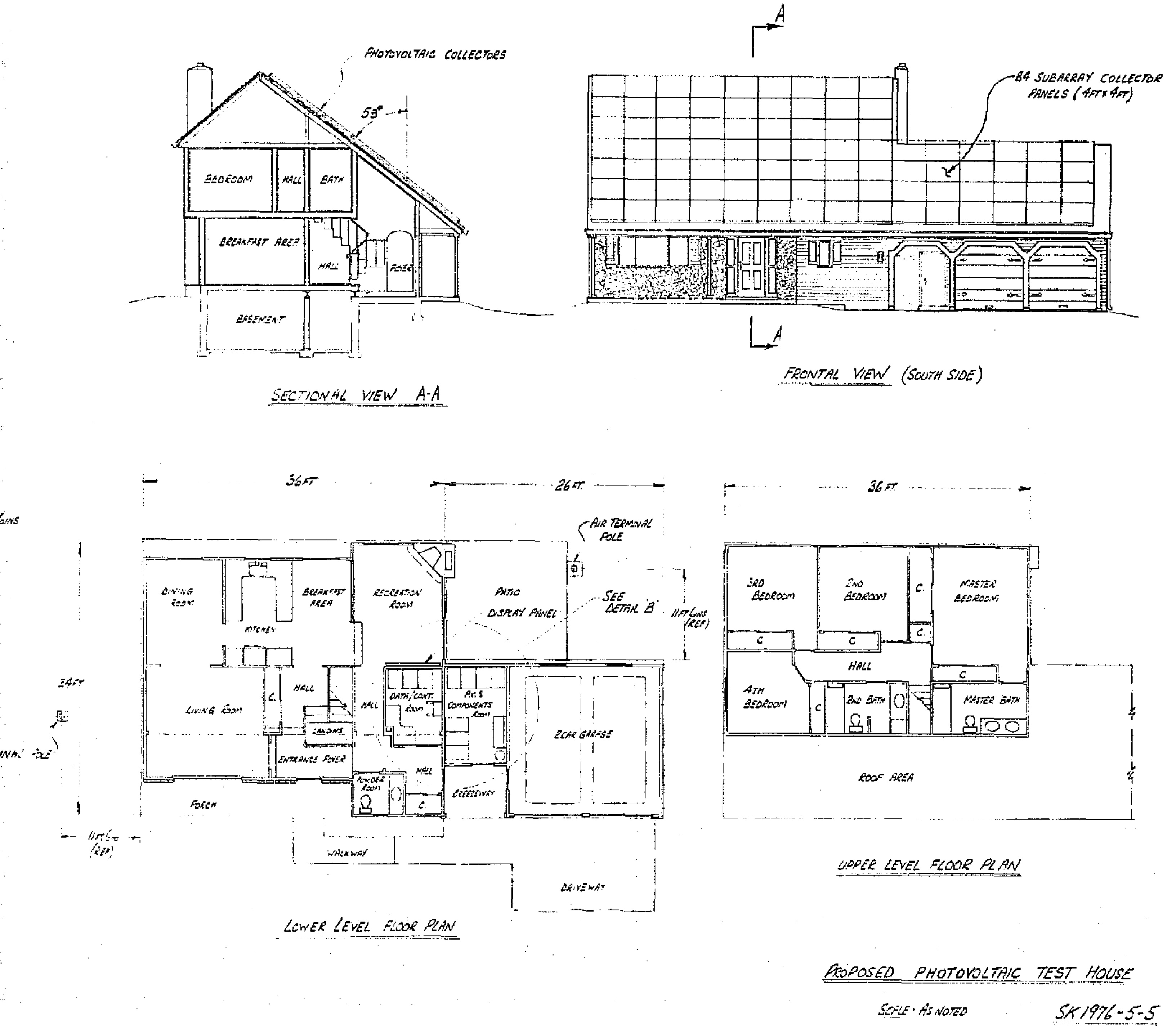


Figure 3-24. Floor Plan and Elevation Views of Typical RPST

entrance of cold outside air. The four modules which constitute the 96 cell, 250 Ampere-hour lead-acid battery are situated along the south wall of the room directly under the exhaust fan. The west wall of the room is occupied by the inverter and by a rack of equipment which includes: (1) the relays and contactors required to switch individual solar cell circuits and interrupt the entire solar array, (2) the electronic load used to measure individual solar cell circuit I-V characteristics, (3) the battery charge controller logic (for the Stage II system), (4) the maximum power tracking controller (for the Stage I system) and (5) the shunt regulator components (for the Stage II system). Additional space on the west wall is provided for a dc power supply to perform nighttime battery charging from the utility. A work bench and inverter isolation transformer are housed along the east wall of the room.

The Data/Control Room is located within the living area of the house adjacent to the PVS Components Room. All data acquisition and control equipment is housed within this area. The graphical display panel is mounted on the south wall of the recreation room. Ample space is available within the recreation room to allow seating for about 20 people with a clear view of the display panel.

A two mast air terminal lightning protection system is provided to place the entire house within a 1:1 "cone of protection". These "flag pole" air terminals are recommended as a precautionary measure to protect these valuable experimental installations. A complete discussion of the lightning protection problem is contained in Appendix B.

3.3.4 DESCRIPTION OF MAJOR SUBSYSTEMS

3.3.4.1 Solar Array

The solar arrays for the RPST program are to be assembled using modules procured by JPL under the Large Scale Production Task of the Low Cost Silicon Solar Array Project. JPL Request for Proposal (RFP) No. BQ-6-6829-16 (Reference 14) establishes the requirements for the initial RPST installation. Table 3-18 summarizes the most significant solar cell module design requirements from this RFP. A wide range of choices for module geometry are possible as shown in Figure 3-25. Since the process of proposal evaluation and contract negotiation was underway during the performance period of this contract and is not complete as of this report preparation date (May 21, 1976), no information was available on the actual module configurations which are available for use on the RPST program. Therefore, to enable the conceptual design of the solar array to proceed, the specific configuration shown in Figure 3-26 and described in Table 3-19 was arbitrarily established. This hypothetical arrangement provides for up to seven different module suppliers (A through G) with module geometries which cover the range of 3 to 9 modules per subarray and results in 37 circuits in the total solar array. This complement of subarrays leaves room for three additional subarrays which may or may not be installed as part of the power system. If three subarrays of four modules each were used in these locations an additional 12 module circuit could be added to the solar array output.

Table 3-18. Summary of Solar Cell Module Design Requirements from JPL RFP No. BQ-6-6829-16

• Modules must mount within 4 x 4 ft subarrays
• Allow a 1-inch border around the subarray perimeter (46 x 46 inch mounting area)
• Module maximum power voltage between 15.8 and 17 Volts at AM1, 100 mW/cm^2, and 60°C cell temperature
• Greater than 60 Watts of power output per subarray at AM1, 100 mW/cm^2 and 60°C cell temperature
• Minimize cell temperature consistent with minimizing module cost per unit power output
• Provide mounting holes at each end of module substrate structure
• Output terminals designed for 5 Amperes at 20 Volts
• $\pm$ 50 lb/ft^2 loading normal to module front surface
• No projections higher than 0.125 inch above illuminated surface

Figure 3-27, which shows a detailed view of the upper left hand corner of Figure 3-26, illustrates the connections required to wire 12 modules in series to form one of Supplier A's circuits. Figure 3-28 shows the electrical schematic for the six circuits which represent the 12 subarrays for Supplier A. All circuits for a given supplier are wired to a common return (-) bus for that particular supplier. The positive connection for each string of 12 series connected modules is independently wired from the roof to the PVS Components Room. A shunt tap connection is made on each circuit at a point four modules up from the common return. This tap point location was selected based on the criterion that the open circuit voltage of the unshunted (or upper) portion of the circuit should not exceed the lowest value of the battery charge voltage limit under the coldest outside ambient temperature condition. Figure 3-29 gives the open-circuit voltage per module as a function of solar cell temperature for several values of module maximum power voltage at 60°C. This figure was developed using 1.288 as the ratio of open-circuit voltage-to-maximum power voltage at 60°C. For the 96-cell battery selected for the baseline system, 220 Volts (2.29 V/cell) represents the lowest value of battery charge voltage limit (from Figure 3-35 for a battery temperature of 35°C). Table 3-20 lists the winter design temperature for a number of locations throughout the U.S. For a Cleveland, Ohio site location, with a -16.7°C winter design temperature, Figure 3-29 yields an open-circuit voltage of 26.9 Volts per module based on the reference solar cell characteristic given in Figure 3-8. Thus, four modules would require shunting to stay under the minimum charge voltage limit value of 220 Volts.

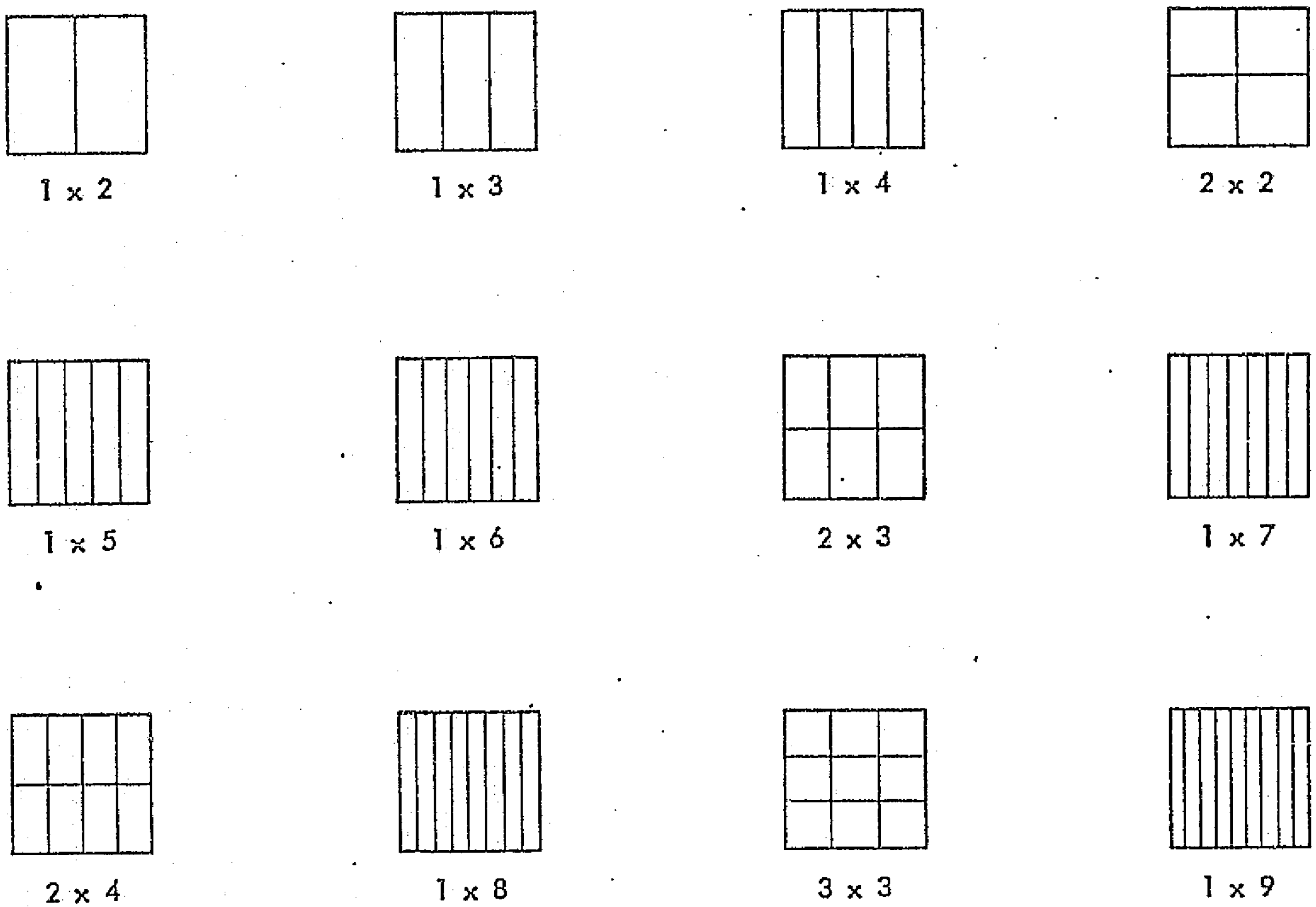


Figure 3-25. Typical Subarray Module Arrangement in Response to JPL RFP No. BQ-6-6829-16

Table 3-19. Circuit Arrangement for Representative Solar Array Configuration

Supplier	Module Configuration	Number of Circuits
A	1 x 6	6
B	1 x 3	3
C	2 x 2	4
D	1 x 9	9
E	1 x 5	5
F	2 x 3	6
G	2 x 2	4

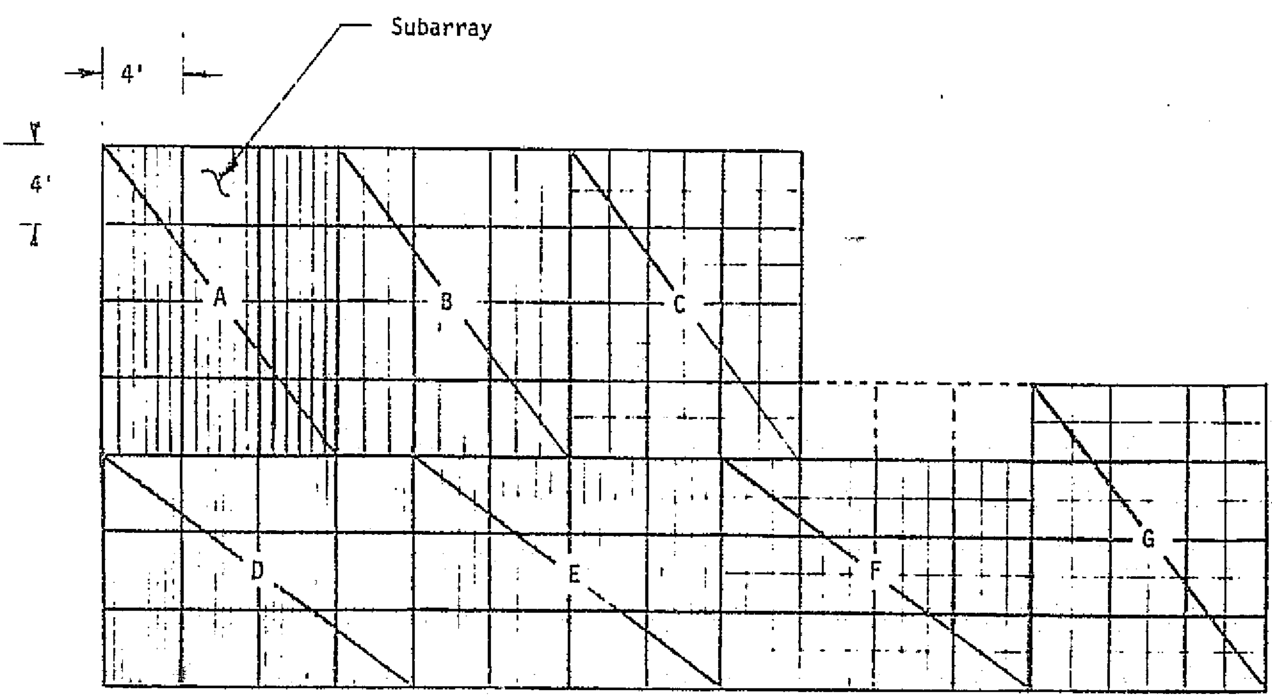


Figure 3-26. Typical Installation of Subarrays on the Roof

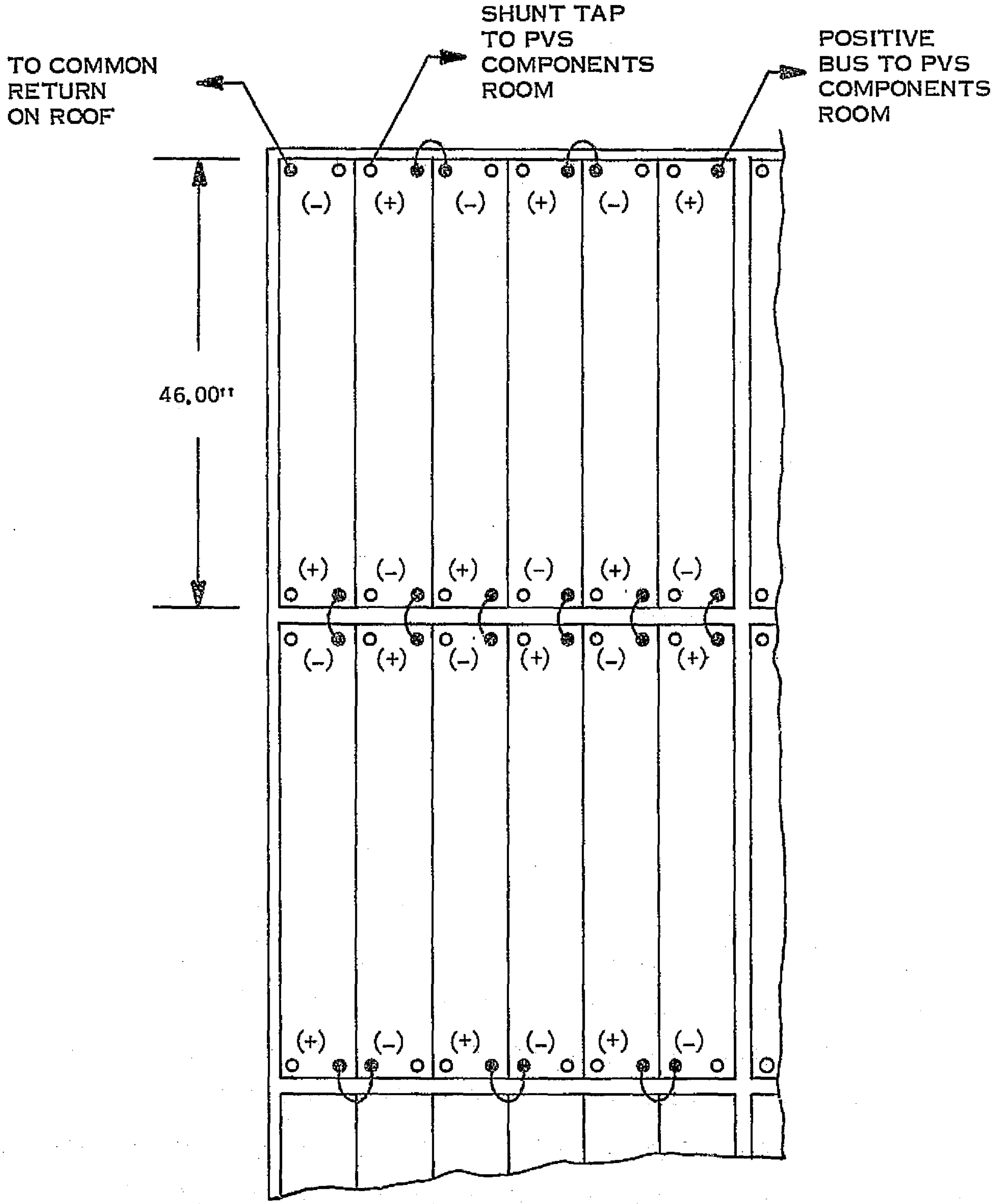


Figure 3-27. Detail of Typical Solar Cell Module Interconnection of Supplier A

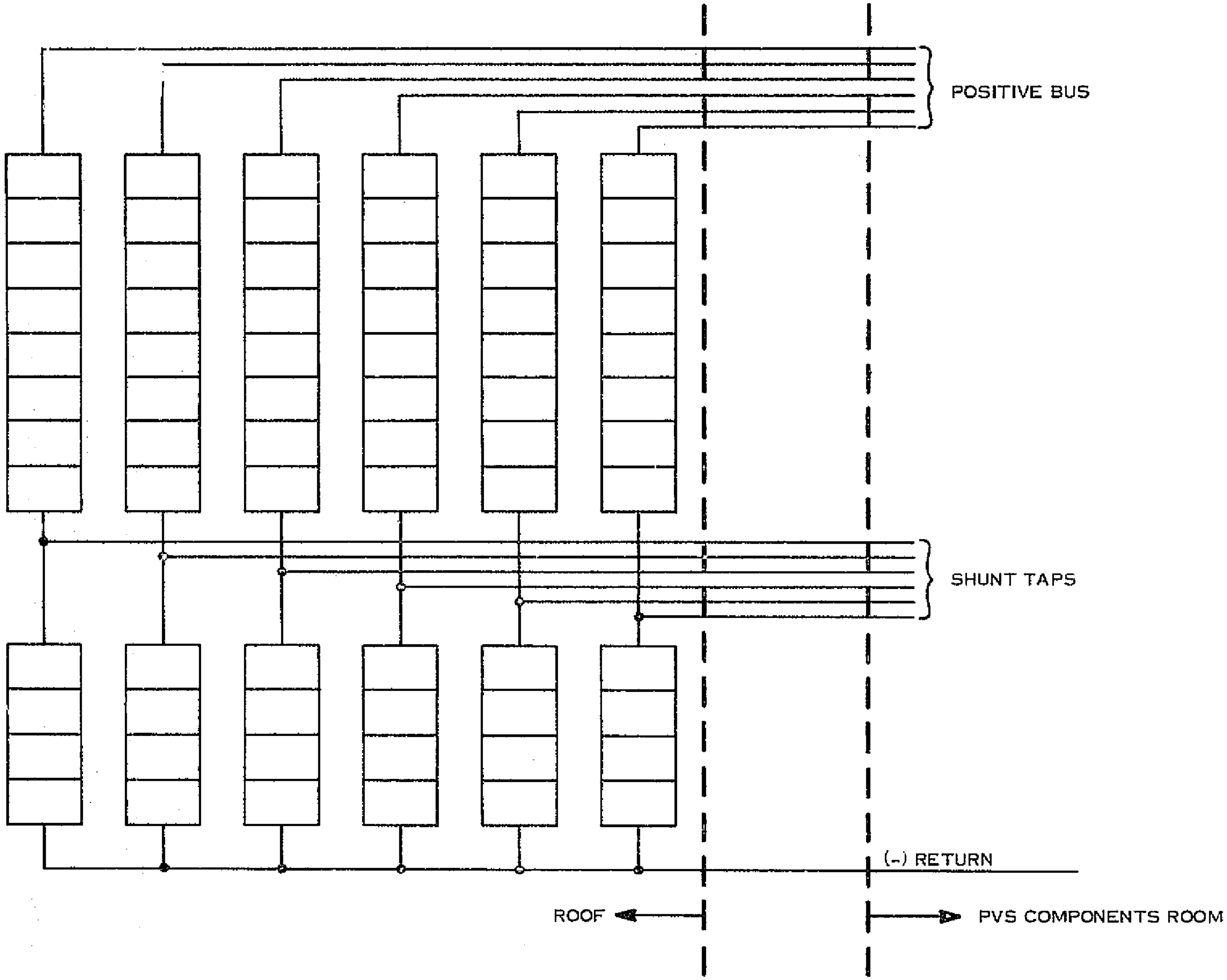


Figure 3-28. Solar Cell Circuit Schematic for Supplier A

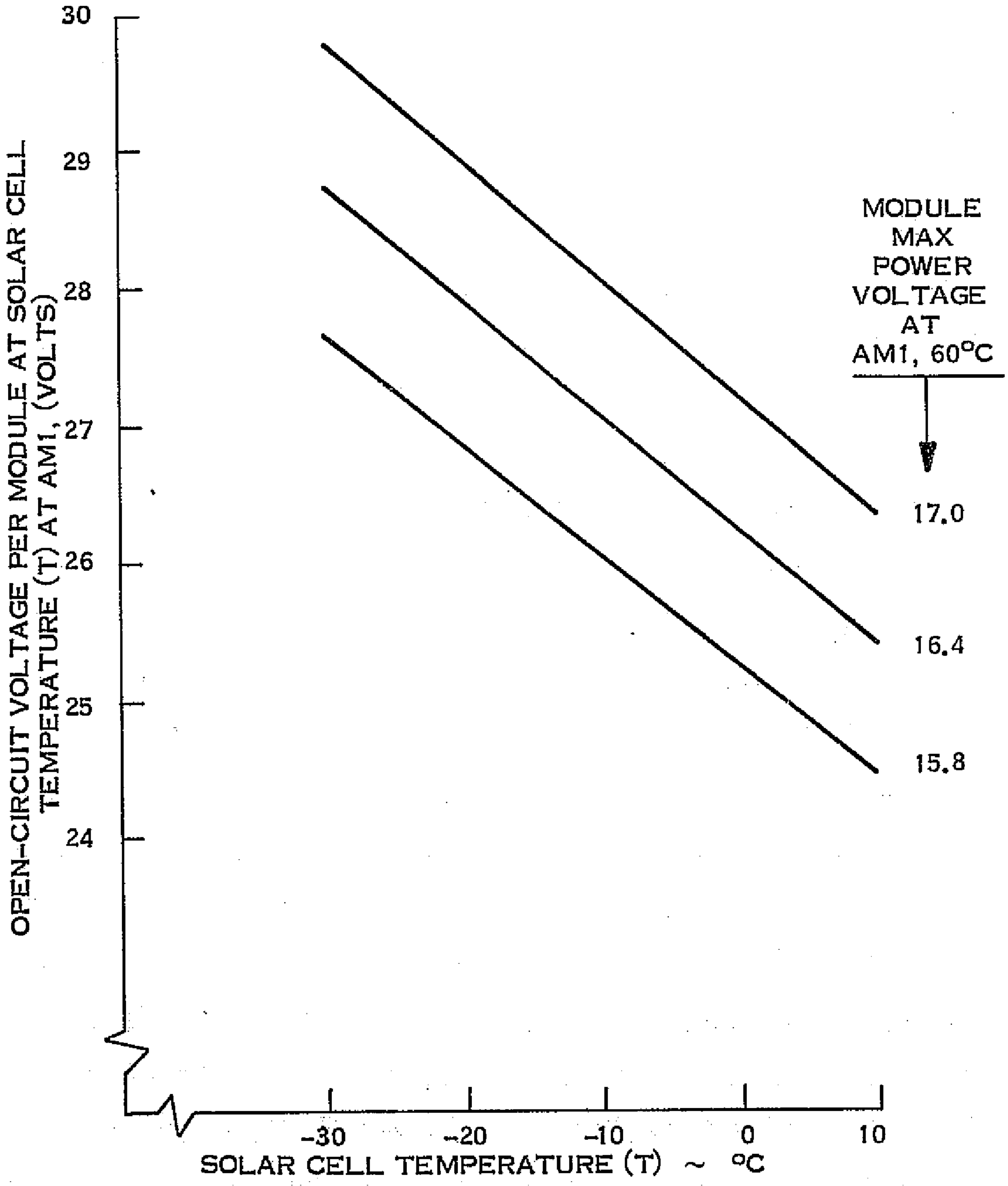


Figure 3-29. Solar Cell Module Open-Circuit Voltage vs Temperature

Table 3-20. Winter Design Temperature for Selected U.S. Locations

Station Location	Winter Design Temperature (^oC)*
Phoenix Airport (AP)	-0.6
Los Angeles AP	5.0
Chicago, Midway AP	-20.0
Cleveland AP	-16.7
Albuquerque AP	-10.0
New York, Kennedy AP	-8.3
Boston AP	-14.4
San Francisco AP	1.7
Houston AP	-2.2

*From Reference 16. Represents that temperature which is equaled or exceeded 99 percent of the total hours (2160) in December, January, and February. In a normal winter there would be 22 hours with a temperature at or below the value listed

Figure 3-30 shows a simplified schematic of the interface of the Supplier A solar cell circuits with the remainder of the system in the PVS Components Room. Solar array current from the six independent positive lines from the individual circuits first passes through an isolation diode (1N1615 or equivalent). These isolation diodes serve three functions: (1) prevent a short circuit on the main dc bus due to a short-to-substrate failure within a solar cell module, (2) prevent a circuit with a saturated shunt pass element from appearing as a low resistance load on the main dc bus, and (3) prevent battery discharge through the dark solar cell circuits during nighttime operation. These solar array positive lines will also be protected against the possibility of lightning induced high voltage presents by the installation of suitably sized Metal Oxide Varistors. Double-pole, single-throw relays are used in each positive bus line and in each corresponding shunt tap line. These relays permit the switching of individual solar cell circuits from the main dc bus and onto the electronic load for the measurement of individual circuit I-V characteristic. After passing through these individual relay contacts the solar array circuit lines for Supplier A are paralleled to form a common Supplier A positive bus. The current monitor for Supplier A circuits is placed downstream of this common point but before the connection point for the other suppliers' circuits that feed the main dc bus. Each individual shunt tap line is provided with a fuse as indicated on the figure. This fuse functions to remove the shunt pass element in the event that a short-circuit failure of the circuit isolation diode causes a high current to flow through the saturated pass element. Note that the shunt tap lines are only connected for the Stage II system implementation. These lines will be wired from the solar array to the PVS Components Room, but will remain unconnected for the Stage I experiment evaluation period.

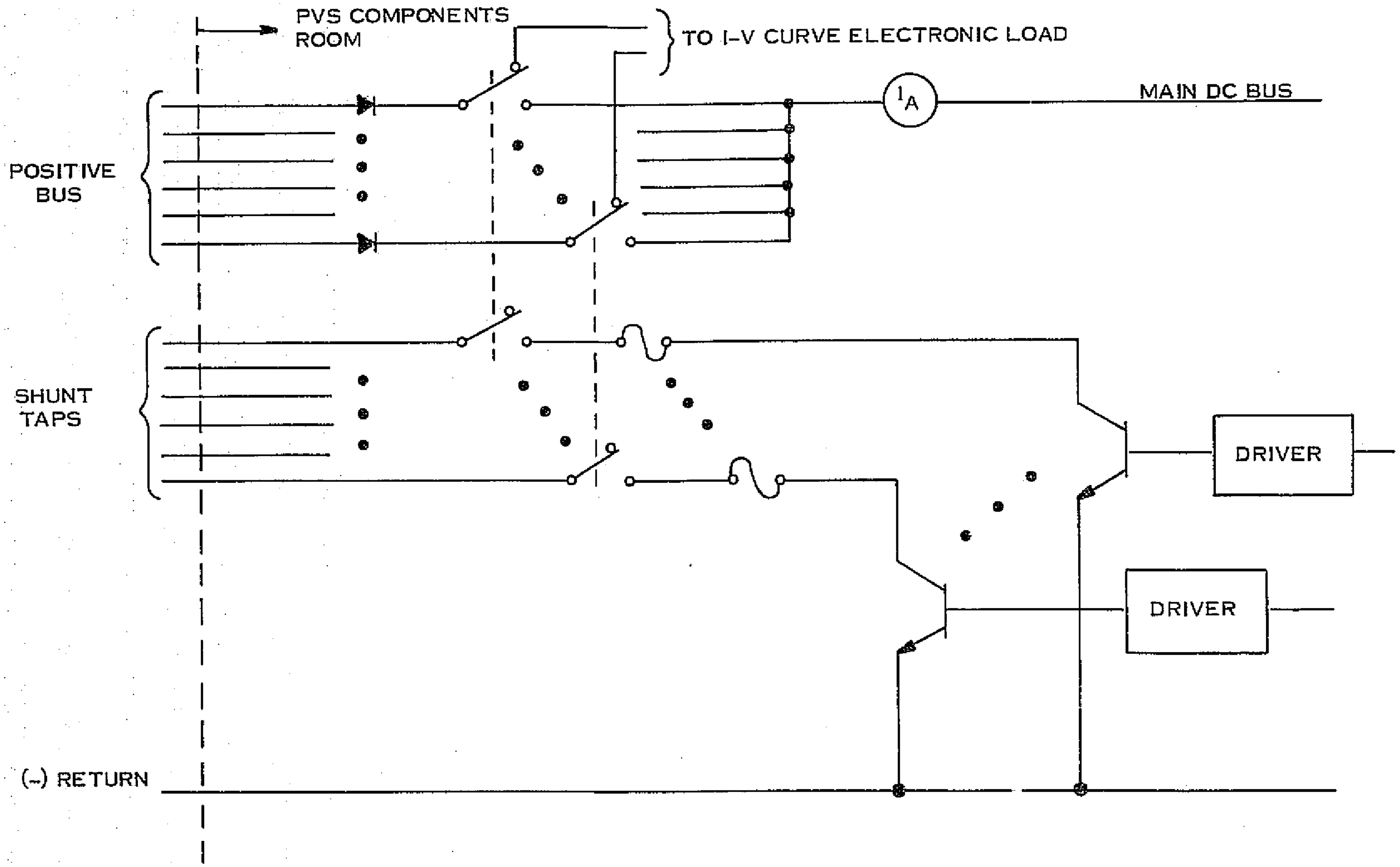


Figure 3-30. Interface of Supplier A's Solar Cell Circuits with PVS Components Room Equipment

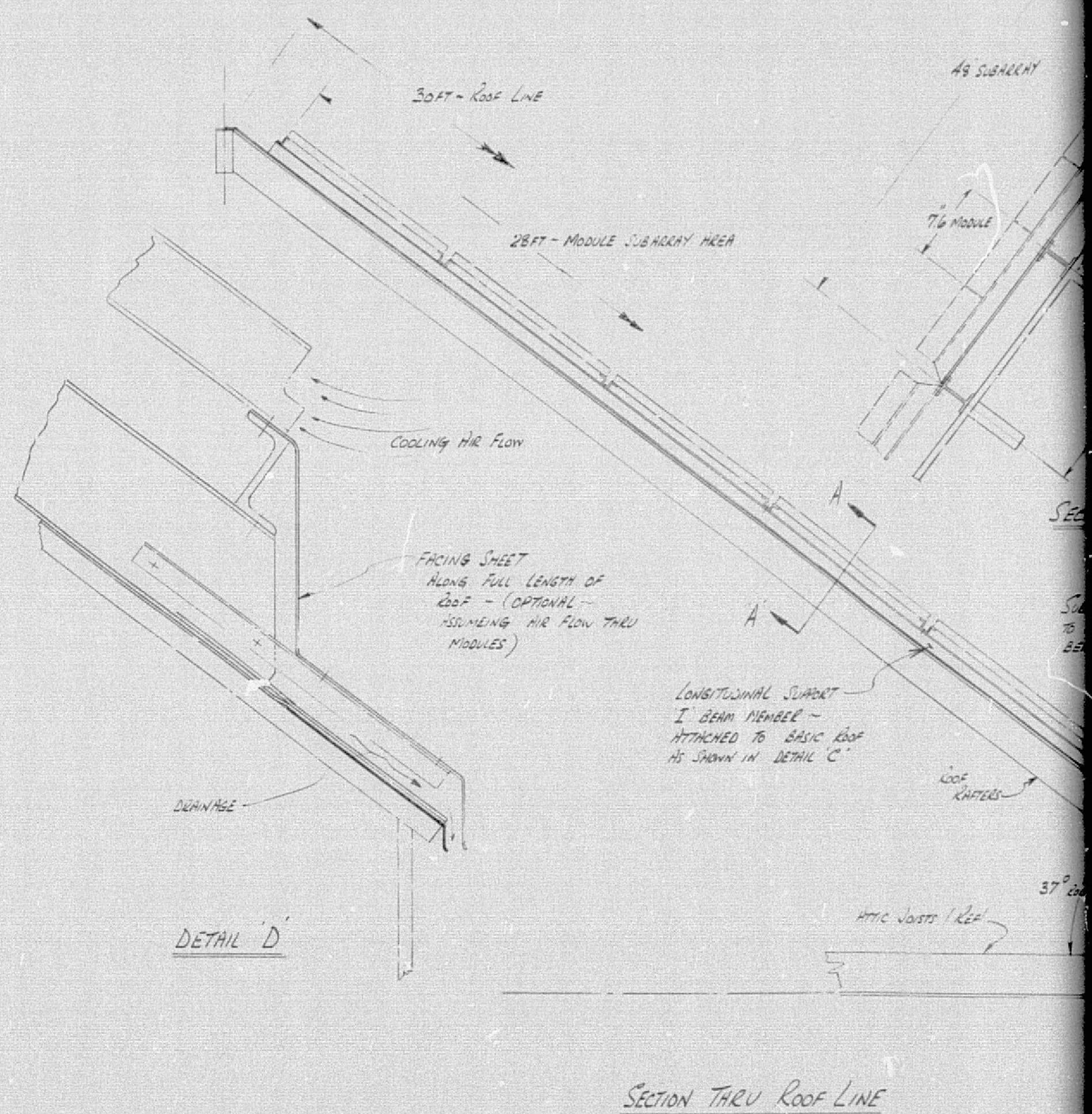
Several concepts were developed for the mounting of the solar cell modules and associated subarray structure. The first of these, shown in Figure 3-31, employs aluminum I-beams which are positioned above each roof rafter and attached with wood screws as shown in Detail "C". The solar cell module mounting structure consists of Z members which run in the east-west direction and are clamped to the I-beams. For a typical module thickness of 51 mm (2 inches), this design provides 178 mm (7 inches) of separation between the illuminated surface of the modules and the roof surface. The second concept, shown in Figure 3-32, is similar to the first except that the members which transfer the module loading to the roof rafters are attached only at the ends. These Z members are attached to the ridge beam at the top with individual anchor brackets. At the bottom a support bracket provides the lateral bracing required. The third concept, shown in Figure 3-33, uses prefabricated 203 mm (8 inch) deep space truss members as the principal support for the modules. This truss member structure can be supported by the roof rafter system or by independent column supports as shown in the figure. The use of this open truss member provides a greater separation distance between the illuminated module surface and the roof surface.

The ultimate selection of a module mounting structure design approach will depend on the details of the module design as well as the actual architectural design of the house. The use of the open truss member for the standoff support from the roof has the advantage of improved rear side cooling compared to the first two concepts discussed.

3.3.4.2 Energy Storage

The energy storage function in the Stage II power system implementation is provided by a lead-acid battery with a so called "hybrid" construction. The positive plates contain 4 to 6 percent antimony grid, while the negative plates contain a 0.07 percent calcium grid. The lead antimony positives provide the deep cycle characteristics required for this application and the lead calcium negatives assure a longer useful life with reduced maintenance and simplified charge control. The cells are housed in high density, cross-linked polyethylene containers which is non-burning and virtually unbreakable. The high impact molded rubber cover has lead brushing inserts to eliminate post corrosion and leakage. The vent caps are explosion proof ceramic flash arrestors. Figure 3-34 gives the overall dimensions of a 24 cell battery module with an actual 10 hour capacity of 332 Ampere-hours. This value has been derated by 25 percent to assure the required cycle life. This cell capacity is based on an electrolyte temperature of 25°C and will vary in proportion to this temperature at the approximate rate of 0.9 percent per °C.

As long as the battery temperature is maintained within the range of 10 to 35°C, no operational difficulties (charge unacceptance or insufficient capacity) will be experienced. The ventilation system required to maintain the battery within these temperature limits is described in Section 3.3.3. Care should be exercised not to place the modules near sources of heat and that no obstructions impede the proper cooling of the modules. For this cell size, every Ampere-hour of overcharge releases 456 cm^3 of hydrogen gas per cell. Ventilation must be provided to keep the hydrogen gas concentration within the PVS Components Room below four percent.



30 FT - ROOF LINE
28 FT - MODULE SUBARRAY AREA
4S SUBARRAY
7'6 MODULE
COOLING AIR FLOW
FACING SHEET ALONG FULL LENGTH OF ROOF - (OPTIONAL - ASSUMEING AIR FLOW THRU MODULES)
A
A'
LONGITUDINAL SUPPORT 'I' BEAM MEMBER - ATTACHED TO BASIC ROOF AS SHOWN IN DETAIL 'C'
ROOF RAFTERS
DRAINAGE
37°
ATTIC JOISTS (REF)
DETAIL 'D'
SECTION THRU ROOF LINE

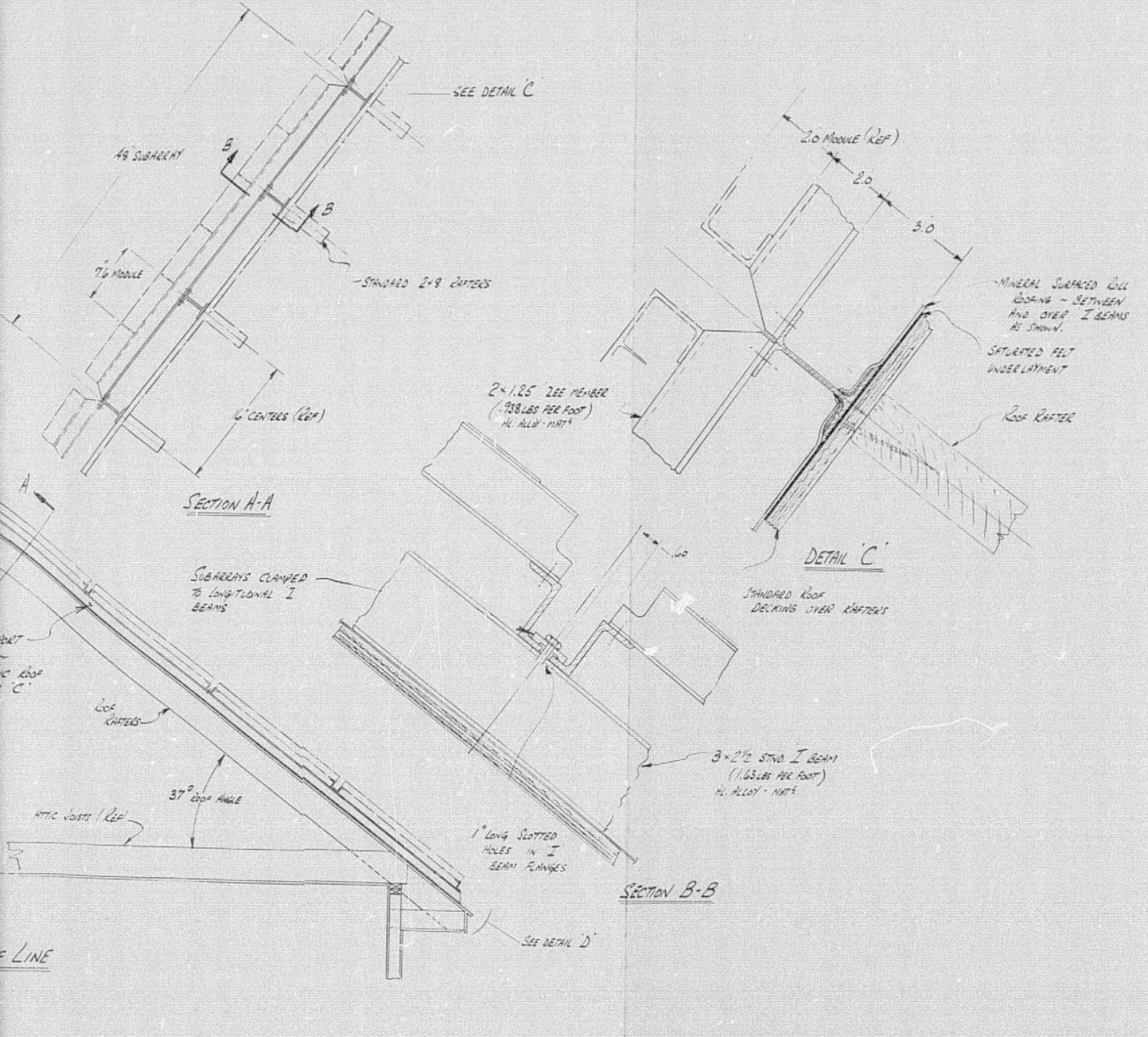
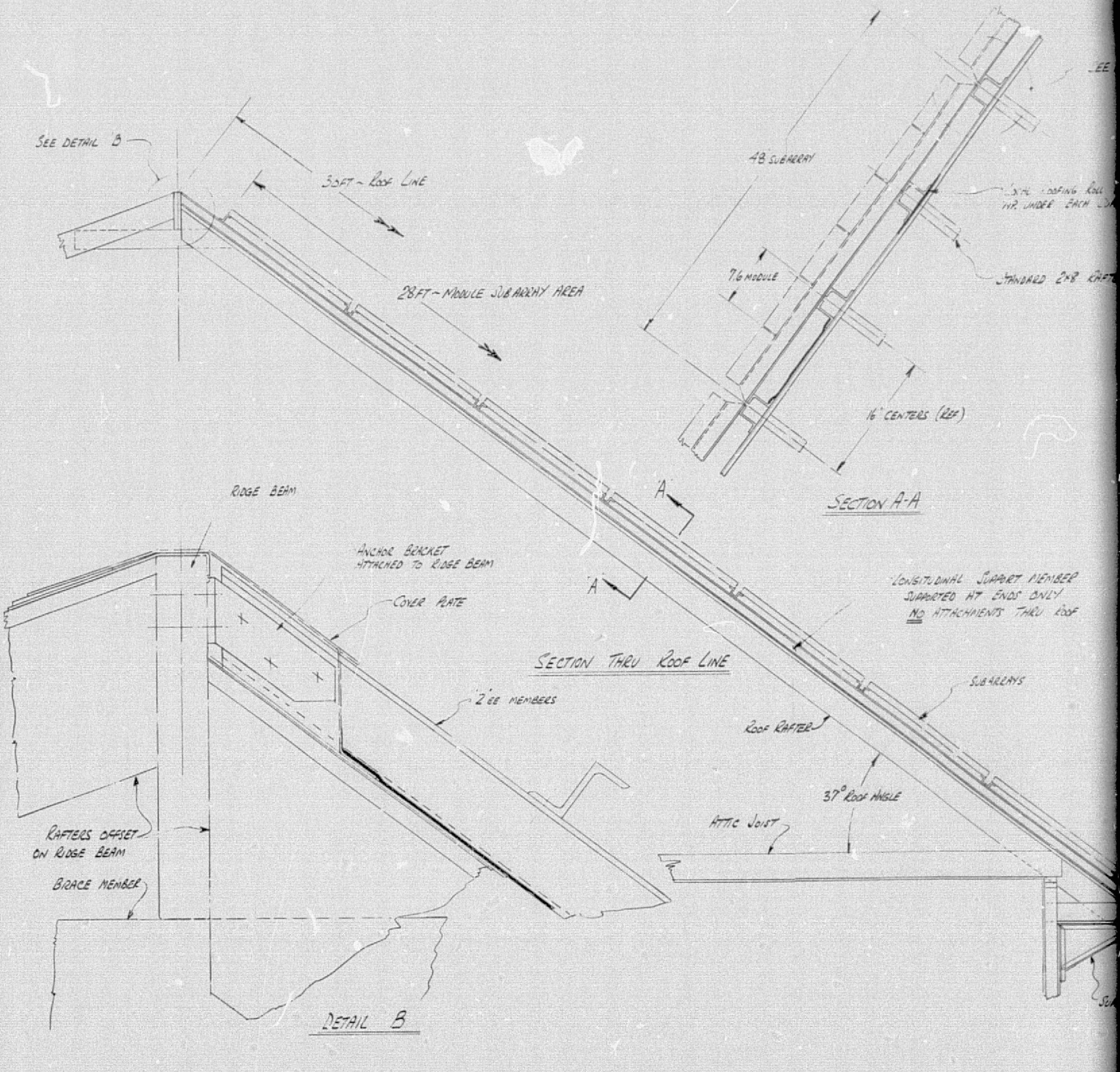


Figure 3-31. Concept 1 for Mounting of Solar Cell Modules



SEE DETAIL B
30FT ~ ROOF LINE
28FT ~ MODULE SUBARRAY AREA
48" SUBARRAY
7.6 MODULE
16" CENTERS (REF)
SECTION A-A
A
A
RIDGE BEAM
ANCHOR BRACKET ATTACHED TO RIDGE BEAM
COVER PLATE
LONGITUDINAL SUPPORT MEMBER SUPPORTED AT ENDS ONLY NO ATTACHMENTS THRU ROOF
SECTION THRU ROOF LINE
ZEE MEMBERS
SUBARRAYS
ROOF RAFTER
37° ROOF ANGLE
ATTIC JOIST
RAFTERS OFFSET ON RIDGE BEAM
BRACE MEMBER
DETAIL B

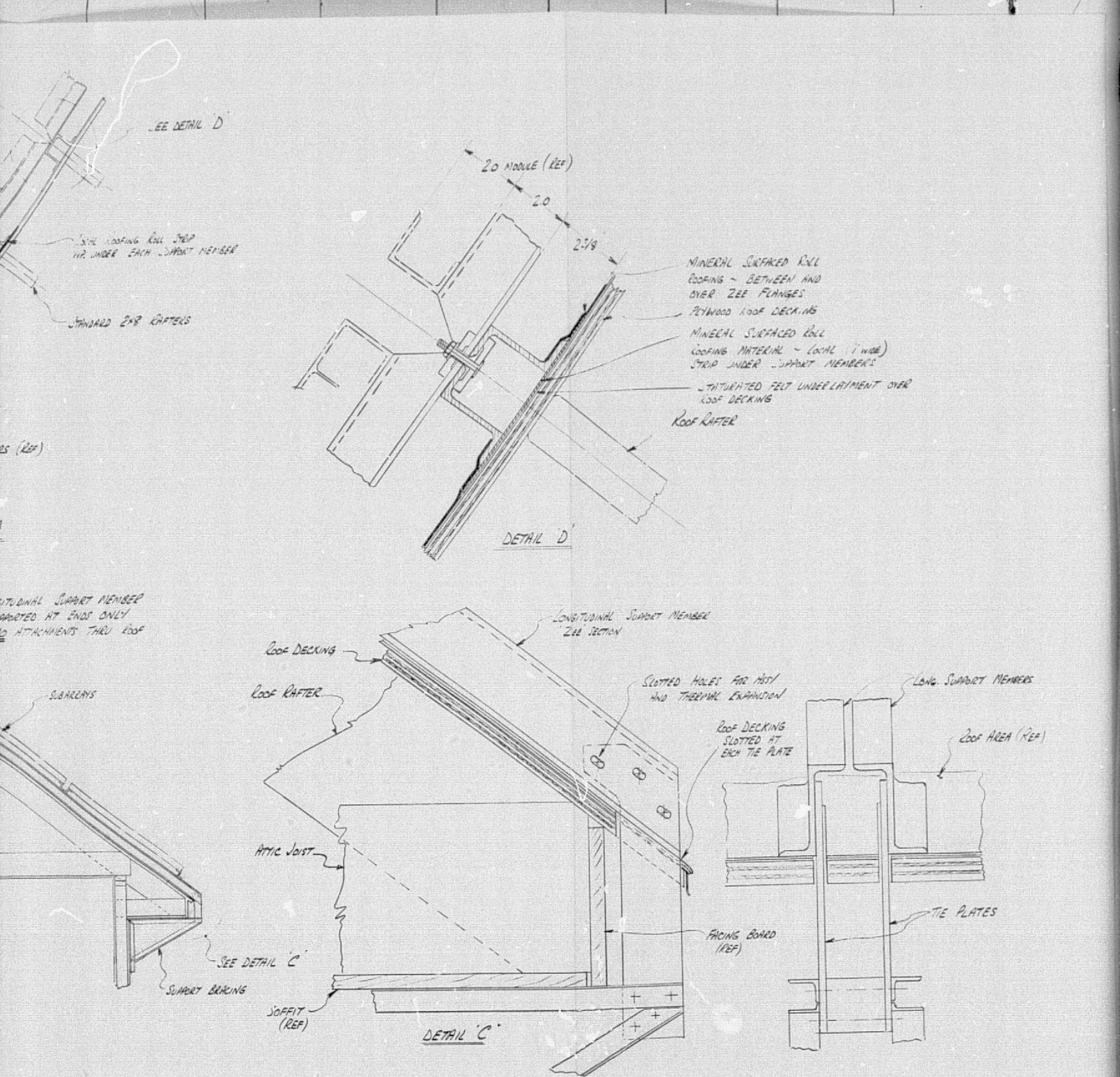
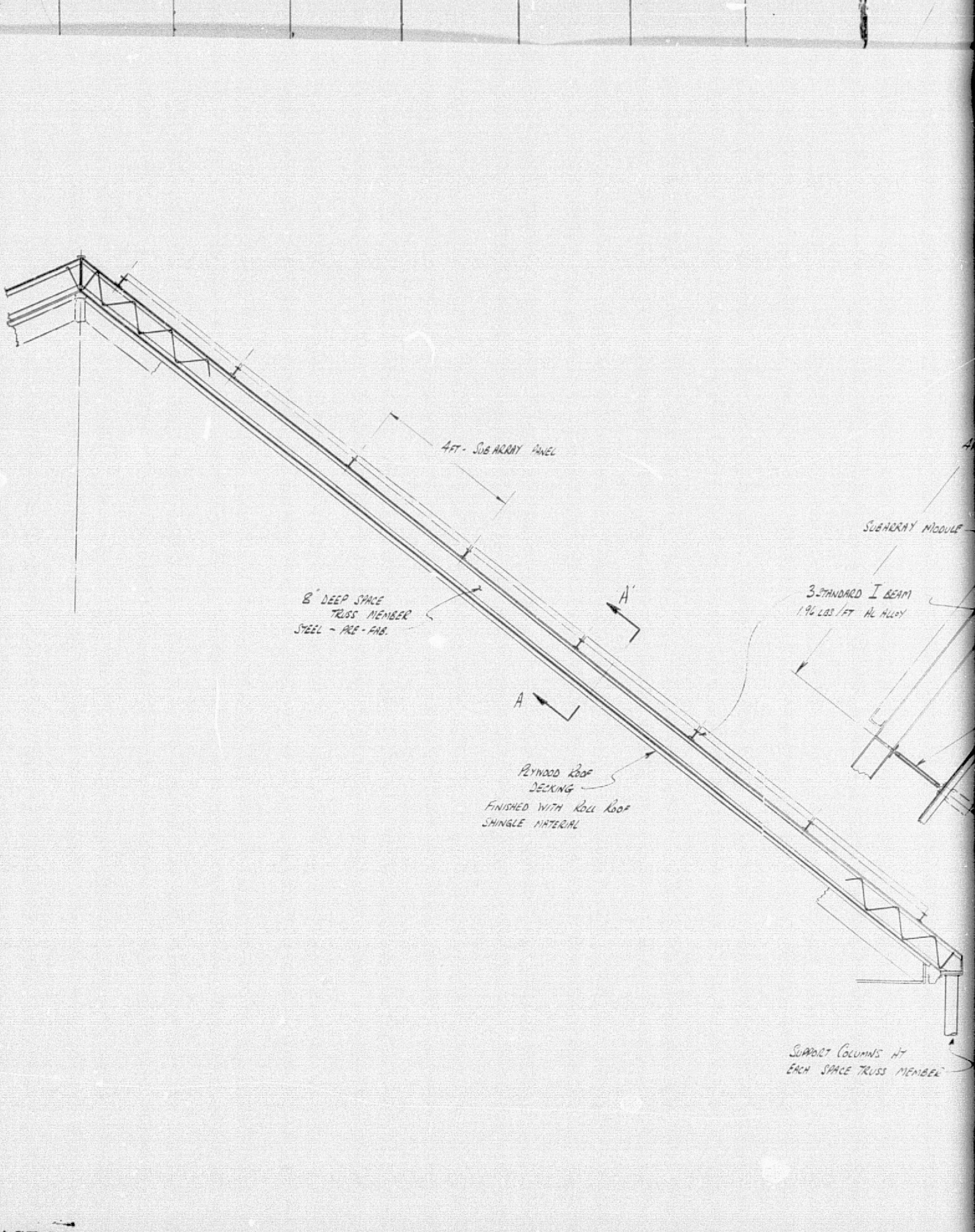


Figure 3-32. Concept 2 for Mounting of Solar Cell Modules

FOLDOUT FRAME 2


4FT - SUBARRAY PANEL
SUBARRAY MODULE
3" STANDARD I BEAM
1.96 LBS/FT AL ALLOY
A'
8" DEEP SPACE
TRUSS MEMBER
STEEL ~ PRE-FAB.
A
PLYWOOD ROOF
DECKING
FINISHED WITH ROLL ROOF
SHINGLE MATERIAL
SUPPORT COLUMNS AT
EACH SPACE TRUSS MEMBER

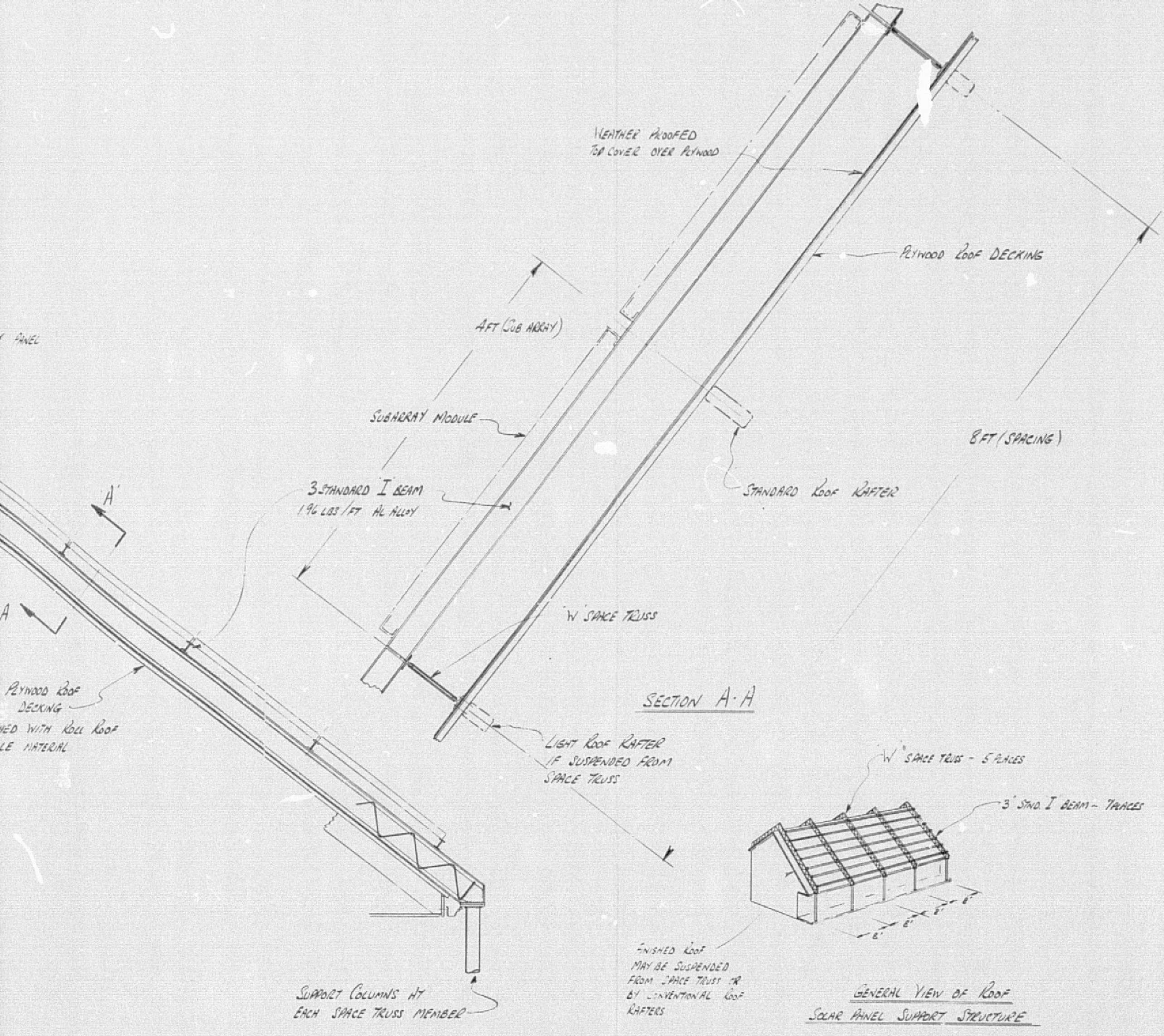
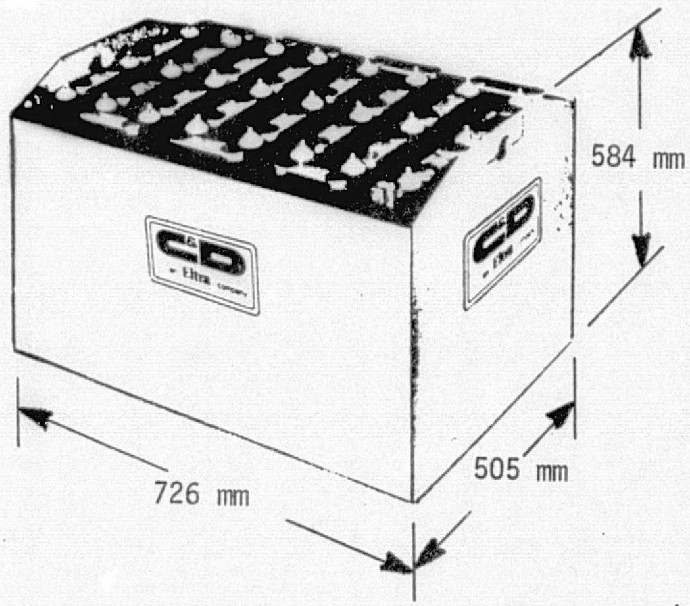


Figure 3-33. Concept 3 for Mounting of Solar Cell Modules

C.2

FOLDOUT FRAME 2



- LIGHT-WEIGHT, HIGH-STRENGTH ALUMINUM OR EQUIVALENT TRAY FOR MAXIMUM POWER-PER-POUND
- COMPLETELY SEALED TOP TO PREVENT ACCUMULATION OF FOREIGN MATERIAL AND ELECTROLYTE SPILLAGE BETWEEN CELLS
- ELECTROSTATICALLY APPLIED EPOXY COATING PROTECTS AGAINST CHIPPING, CRACKING AND ABRASION.
- Module Weight = 558 kg

Figure 3-34. Hybrid Lead-Acid Battery Module (24 Cells)

Using the reference solar cell characteristic (see Figure 3-38) as the basis for the calculation of solar array performance, the analysis in Section 3.2.4.2 has shown that the complete battery for a Cleveland site location should consist of four series-connected 24 cell modules. This 96 cell battery will be charged at a safe rate, which is limited by the solar array output, until the terminal voltage reaches the value given on the upper curve on Figure 3-35. This value of charge limit voltage is compensated for battery temperature as shown in the figure. With a 23°C battery temperature, the upper limit voltage is 235.2 Volts (2.45 Volts/cell). After one hour of operation at this upper voltage limit, the battery charge controller will automatically reduce the voltage limit to the corresponding value on the lower limit curve (226 Volts at 23°C). Continuous overcharge at this lower voltage level will result in a minimal heat dissipation in the battery and a minimal requirement for water addition.

The potentially hazardous nature of this relatively large, high voltage battery requires that the following safety precautions be strictly observed.

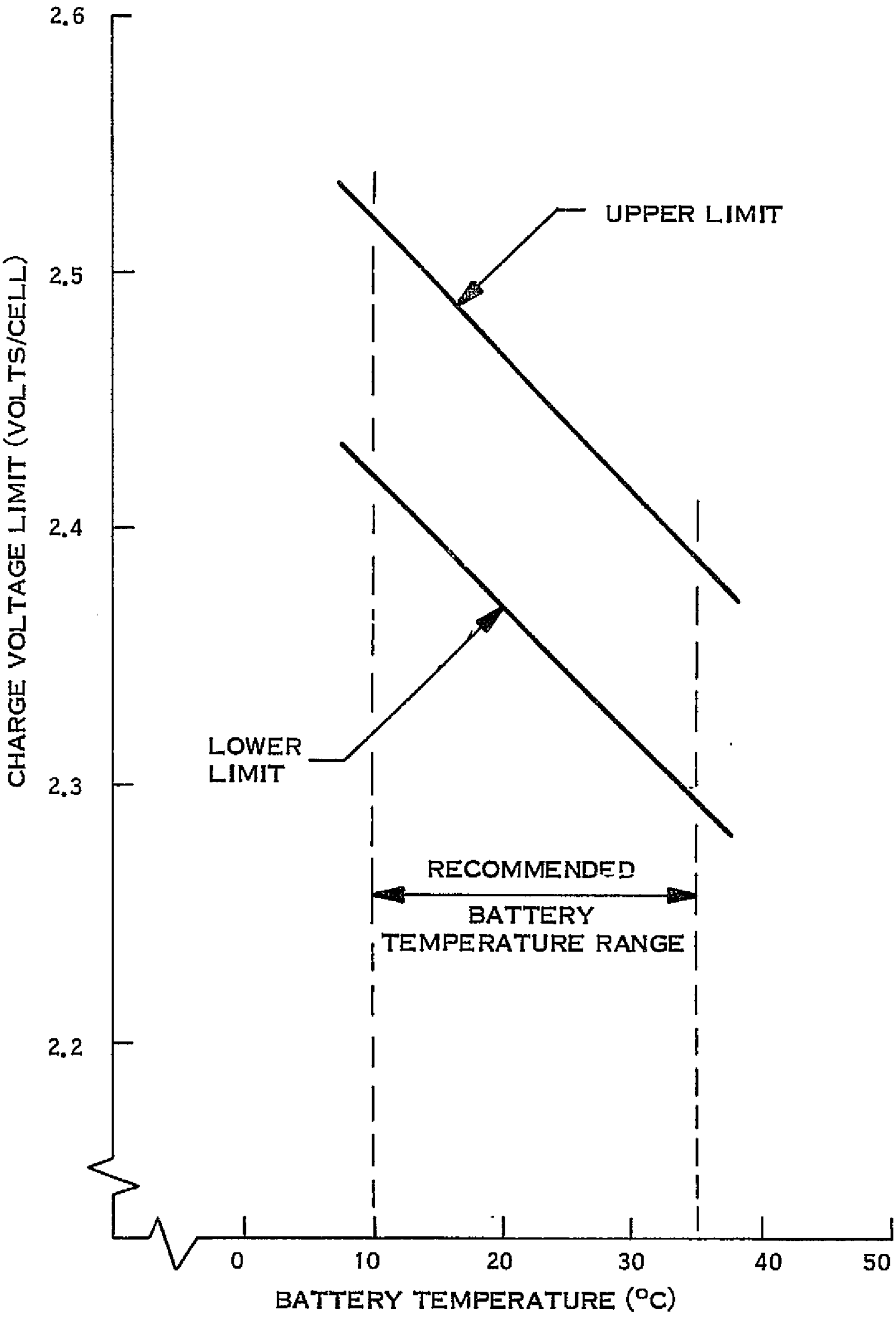


Figure 3-35. Temperature Compensated Charge Voltage Limit Operating Curves

1. The battery room must be accessible to authorized personnel only.
2. The room must be ventilated to remove hydrogen gas. A forced ventilation system which is designed to maintain the hydrogen concentration at less than 4 percent is required. Battery charging must be automatically interrupted in the event of a failure of the ventilation system.
3. No smoking is permitted in the battery room.
4. Rubber shoes and gloves must be worn when servicing the battery.
5. The battery must not be grounded.
6. No tools or equipment must be placed on batteries.
7. No open flames or spark producing equipment can be permitted in battery room.
8. Keep flash arrestors in cells at all times.
9. Always have fresh water available in case of electrolyte splash or spillage.

3.3.4.3 Inverter Power Conditioner

In both of the system implementations proposed for this experimental program an inverter power conditioner is required to invert the generated or stored dc power to 120/240 Volt single phase ac power for use by the residential loads and feedback to the utility system. The functional relationship between this inverter power conditioner and the other photovoltaic system components is shown in Figure 3-36. Two basic inverter types were considered for this application: (1) the line commutated inverter, and (2) the self-commutated inverter.

3.3.4.3.1 Design Requirements

3.3.4.3.1.1 Solar Array Constraints. The solar array output characteristics for the baseline system located in Cleveland, Ohio were analyzed to determine the statistical distribution of maximum power point voltage and power output. Fifteen representative days (150 hourly data points) were selected from the annual hourly output tabulation. Figure 3-37 shows the distribution of these 150 data points with respect to maximum power point voltage and power. Included in this data sample was the highest output power level day (April 20th) and the highest output voltage level day (January 10th). Figure 3-38 gives the complete solar array I-V characteristic for these particular extremes of output as well as for a hot sunny day (August 1st) at sunrise and at midday. This data set was analyzed to yield the distribution curves shown in Figures 3-39 and 3-40, for maximum power output and maximum power point voltage, respectively. From Figure 3-39, it is clear that 85 percent of the solar array energy output will occur at or above the 3 kW maximum power level and that 9.2 kW is the maximum solar array output power level for this year in Cleveland, Ohio. Figure 3-40 shows that the maximum power point voltage ranges from about 180 to 255 Volts. If the lower limit were raised to 195 Volts, only 3 percent of the solar array output would not be tracked at the maximum power point.

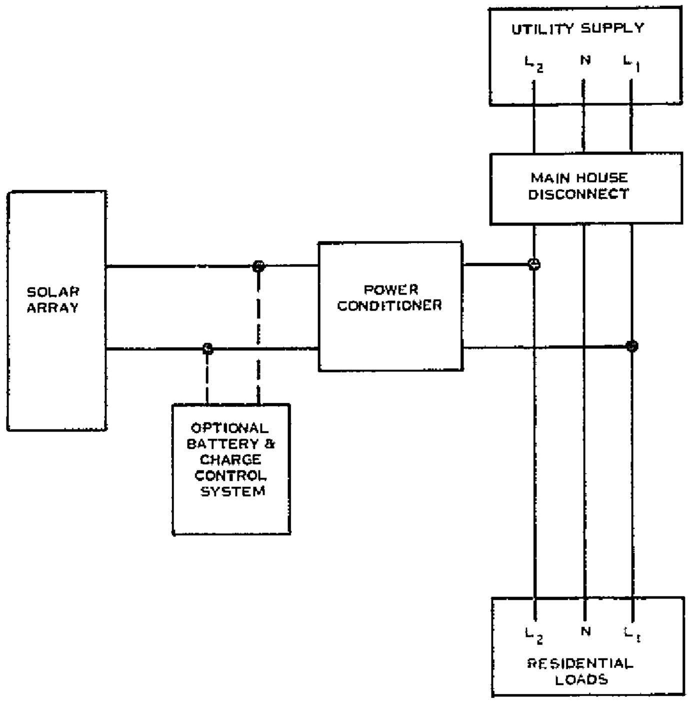


Figure 3-36. Basic Component Arrangement in Photovoltaic Power System

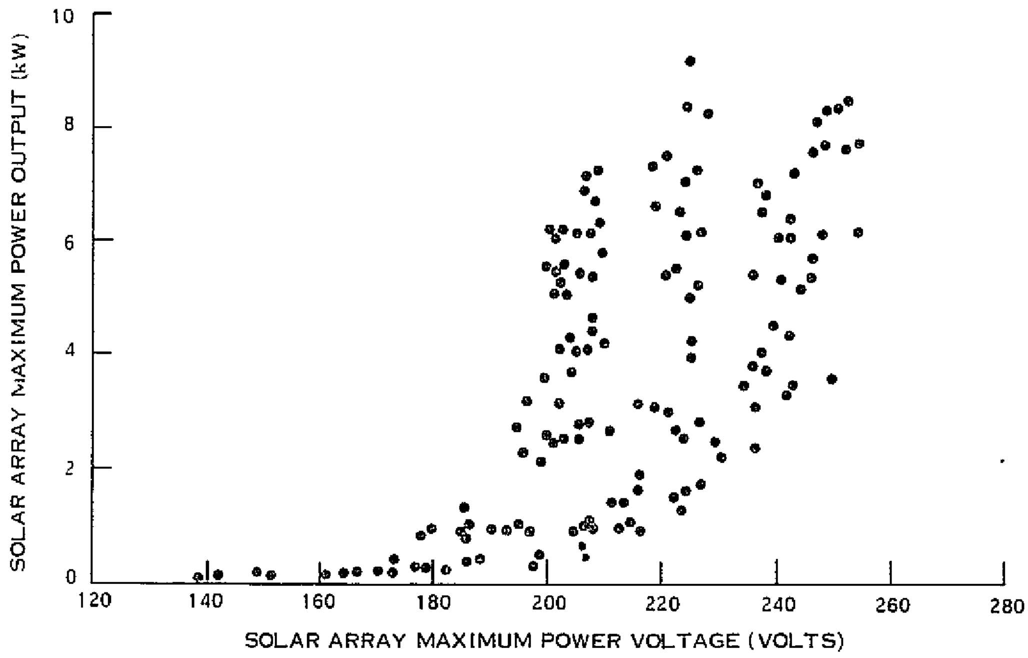


Figure 3-37. Sampling of Solar Array Maximum Power Point Operating Conditions of Power and Voltage for Cleveland Site Location

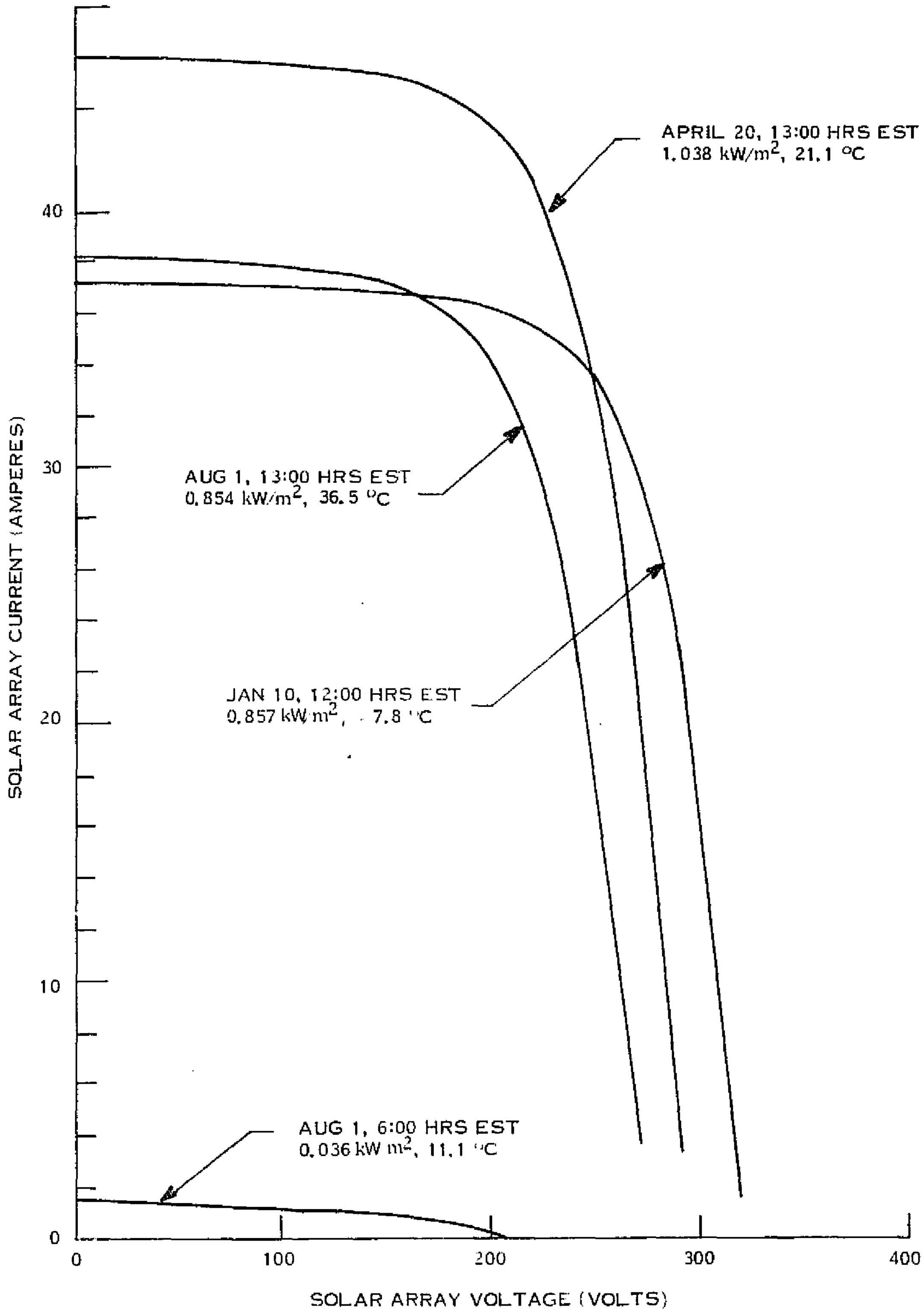


Figure 3-38. Typical Solar Array I-V Characteristics for Cleveland Site (78.19 m^2 of Total Cell Area)

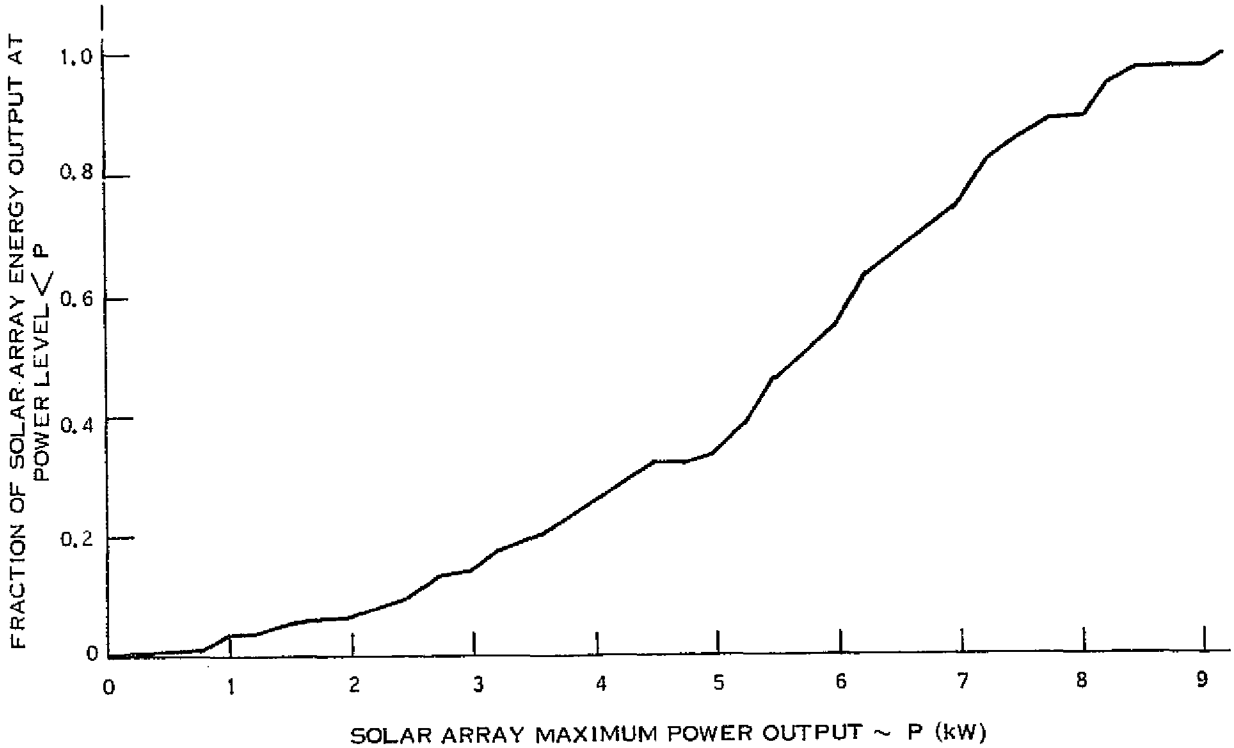


Figure 3-39. Distribution of Solar Array Maximum Power Point Power Output Level for a Cleveland Site Location

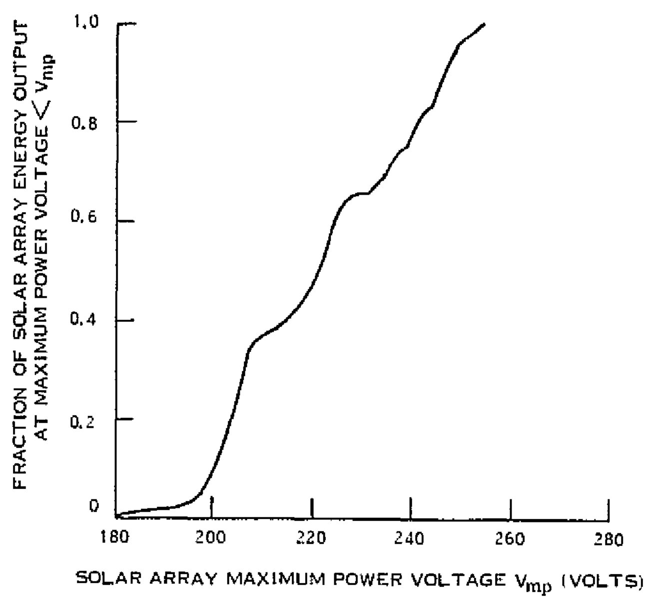


Figure 3-40. Distribution of Solar Array Maximum Power Point Voltage Level for a Cleveland Site Location

It should be emphasized that these data pertain only to the baseline solar array configuration at the Cleveland, Ohio site location. Other solar array configurations and other site locations will require further analysis of this type to define the statistical distribution of solar array maximum power point performance parameters.

3.3.4.3.1.2 Harmonic Content. The utility and residential system can withstand limited amounts of harmonic distortion. Two types of home appliances will be subject to harmonic voltages on the utility line. First the induction coupled appliances such as induction motors (refrigerators, room air conditioners, furnance blowers, clock motors) and transformer coupled (fluorescent light ballasts, and TV power supplies) will be susceptible to significant levels of the lower harmonics, such as 3rd and 5th. Induction motors rely on a minimum amount of the fundamental voltage for their load characteristics. It is considered safe for these loads to be supplied with up to 15 percent total voltage distortion as long as the fundamental component remains above 100 Volts (rms).

In systems where the utility system is operated in parallel with the power conditioner it is usually assumed that the impedance of the utility system is sufficiently low to allow high levels of current distortion since this distortion will not be translated into a voltage distortion by the utility. As the quality of the utility system decreases (rural areas with long feeds), or the number of power conditioners in an area increases, this assumption must be studied closely. For single power conditioners in a stiff system induced harmonic utility currents of 15 to 25 percent should be satisfactory.

The second class of appliances affected by harmonic content on the line is communications equipment such as radios and televisions. Figure 3-41 is a plot of the conducted interference which is considered adequate to protect the AM radio band. A level of 200 μV in the 550 kHz to 2.5 MHz band will allow most commercial radios to operate in a rural area. In urban areas with higher signal strengths, the 400 μV level would be adequate for satisfactory reception. It is anticipated that these levels of conducted interference would not interfere with the television RF signal since RF bypass capacitors are more effective at higher frequencies. However, a degradation of the 60 Hz waveshape, such as to modify the zero crossing information can sometimes create problems with vertical hold in some television sets. These effects have not been fully documented but are not expected to cause severe problems.

3.3.4.3.1.3 Unbalanced Lines. The neutral to line voltages of the utility can be as much as 2 to 5 percent different. This can depend on the utility distribution system as well as unbalanced loads on the system. If an inverter with a centertapped output transformer is placed across an unbalanced utility line heavy currents will flow in the transformer. However, the system must be able to supply power to 120 Volt loads (those only connected from line to neutral such as B in Figure 3-42). In this case, the utility can supply the neutral current if the output transformer is attached across the L_1-L_2 lines as shown in Figure 3-42. This will increase the current in the utility transformers, but will only be present with large unbalanced loads.

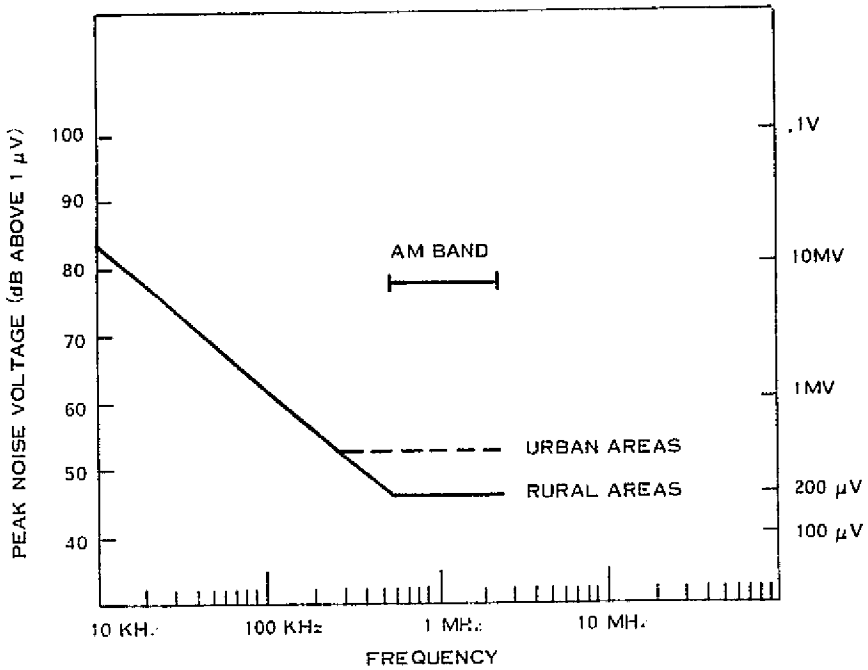


Figure 3-41. Limits of Acceptable Conducted Interference to Protect the AM Radio Band

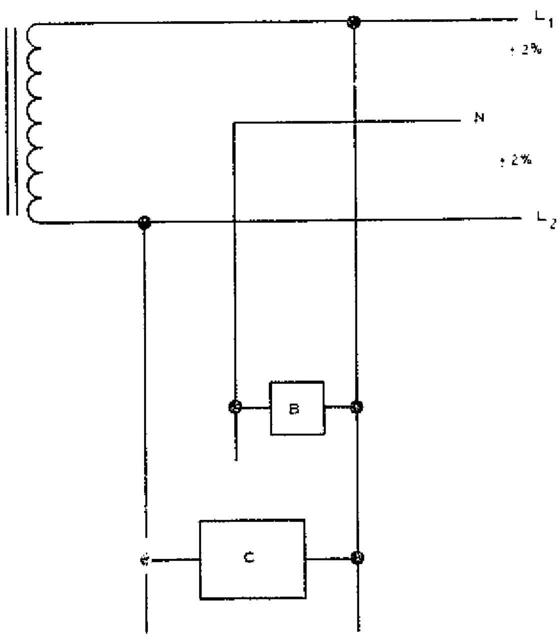


Figure 3-42. Unbalanced Loads and Phase Voltage

3.3.4.3.2 Implementation Considerations

3.3.4.3.2.1 Line-Commutated Inverter

(a) Transformer Coupled

In systems where the power conditioner is required to operate in parallel with a utility line, it is possible to utilize the line voltage commutated inverter system. A typical full bridge, transformer-coupled system is shown in Figure 3-43. Inductor ℓ_1 is used to provide continuous current for the controlled rectifiers. This circuit can be used to supply energy to the ac line over a wide range of source voltages V_a.

The circuit operation can be visualized using the waveforms at the bottom of Figure 3-43. Assuming that the inverter is operating and there is current in inductor ℓ_1 then SCR_1 and SCR_2 are turned on at some retard angle α between 90^o and 180^o. The voltage applied to the inductor ℓ_1 will be the difference between the array voltage (V_a) and the instantaneous line voltage as shown in the cross-hatched area of Figure 3-43. This will first increase the current in inductor ℓ_1 and then as the sum becomes negative will decrease the current. At steady-state the total forward volt-seconds on ℓ_1 will equal the negative volt-seconds to result in no net flux change in ℓ_1. At that time, SCR_3 and SCR_4 will be triggered. This causes SCR_1 and SCR_2 to be reverse biased to allow proper commutation by the time forward voltage is again applied. The action during the on time of SCR_3 and SCR_4 is the same as SCR_1 and SCR_2 with SCR_1 and SCR_2 firing at α to reverse bias SCR_3 and SCR_4 and thereby enabling commutation. Power flow is controlled by modifying the retard angle α. A decrease in α will increase current in the inductor ℓ_1 and therefore increase output power. An increase in α will decrease the output power. As the array voltage varies the phase angle must also be varied to keep the volt-second relationship on ℓ_1 balanced. This is usually accomplished in the ℓ_1 current feedback loop.

Based on the solar array contraints presented in Section 3.3.4.1.1, the preliminary component sizing calculations have been made for a transformer coupled line commutated inverter. Figure 3-44 shows the proposed inverter design envelope superimposed on the baseline system maximum power point loci. A 10 kW input power rating has been assumed to allow for a 10 percent safety margin. From Figure 3-44 it can be seen that the peak expected array current of 45 Amperes will occur at an output voltage of 220 Volts.

The design of an inverter for this application will revolve around the current and voltage impressed on the smoothing reactor ℓ_1 in Figure 3-43. The transformer turns ratio can be determined by remembering that the average voltage across ℓ_1 must be zero for stable operation. This neglects the IR drop across ℓ_1 which is assumed to be small. From rectifier theory, the maximum back EMF (V_{max}) of the rectified line is given by:

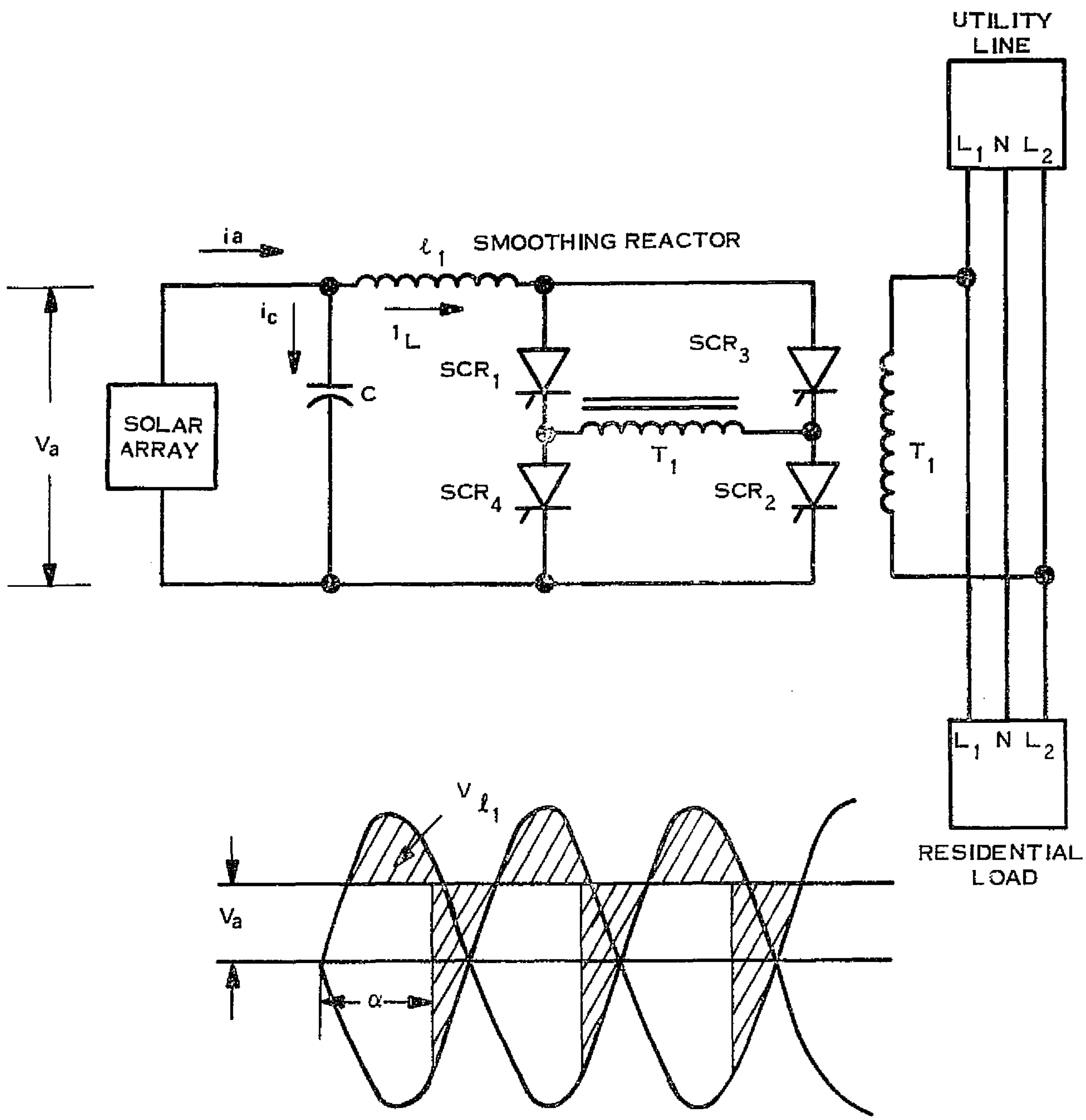


Figure 3-43. Transformer Coupled Line Commutated Inverter

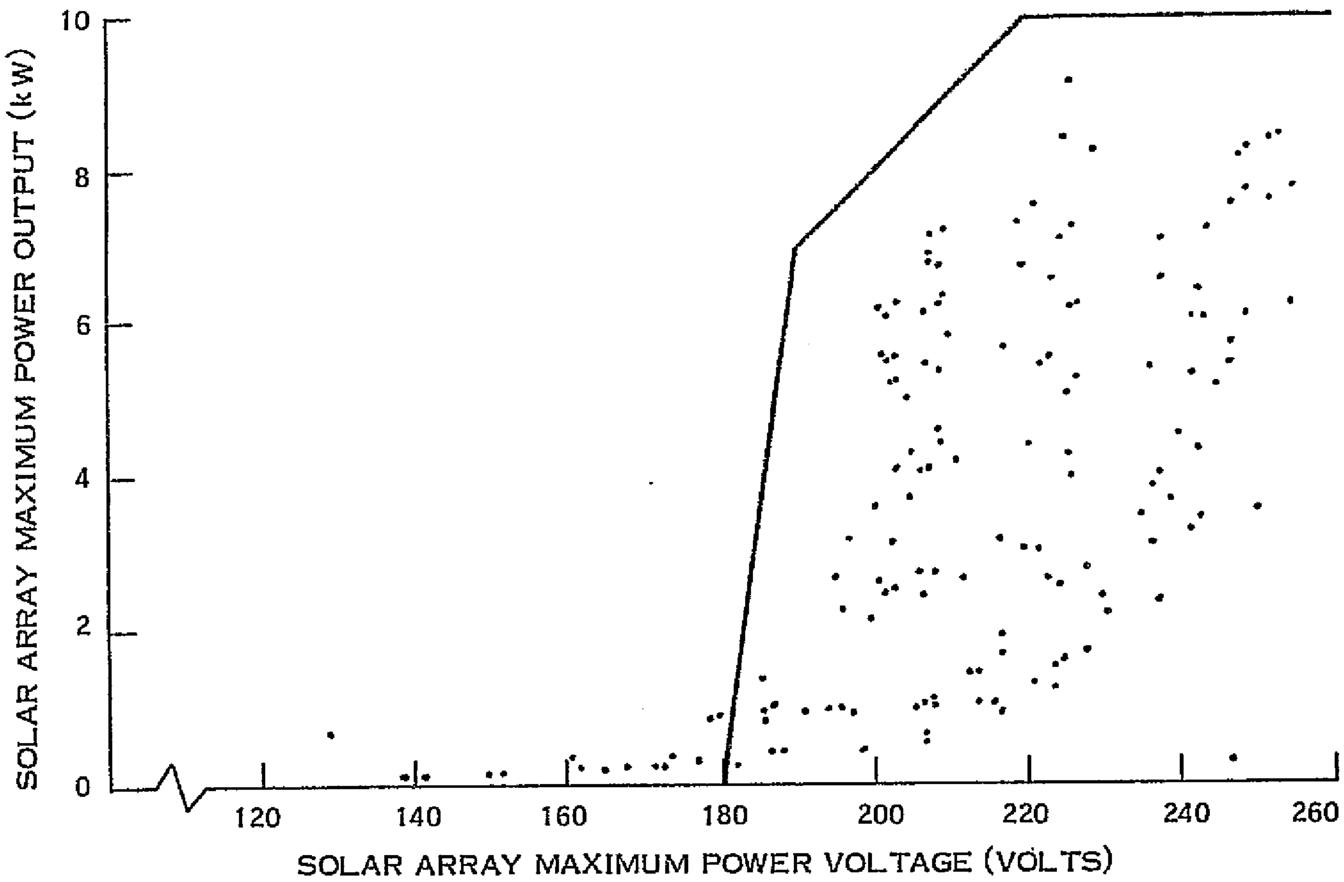


Figure 3-44. Inverter Load Range Relative to Solar Array Operating Point Location

$$V_{max} = \frac{2}{\pi} \sqrt{2}\, V_{rms},$$

where:

$$V_{rms} = \text{rms ac line-to-line voltage (Volts).}$$

The value of V_{rms} can be expected to vary between 210 and 250 Vac for a nominal 240 Vac system. Under these extremes of ac line voltage the values of V_{max} are 225 and 189 Vdc for the maximum and minimum expected ac line voltage conditions, respectively. Allowing for a 1 msec interval for commutation at maximum phase retard, a maximum retard angle (α) of 160 degrees was selected. With this maximum retard angle, the back EMF of the rectified line under low ac line voltage conditions is given by:

$$189 \cos 160^{\circ} = 178 \text{ Vdc.}$$

The transformer turns ratio must allow operation at the maximum value of solar array voltage at the peak power point (260 Vdc) under low ac line voltage conditions. Thus, the required transformer turns ratio (N_2) is given by:

$$N_2 = \frac{260}{178} = 1.46 \text{ (or 1.5 for a small safety margin).}$$

The transformer current rating can be calculated from the expected array maximum output current of 45 Amperes. Assuming that the smoothing reactor current is continuous with less than 50 percent ripple, then the transformer input current will be a square wave of 45 Ampere average value at the solar array maximum output current operating point. Therefore, the reflected output current will be 1.5 (45) = 67.5 Amperes rms. The transformer rating should then be the simple product of voltage (240 Volts ac) and current rating (67.5 Amperes) or 16.2 kVA. Realizing that distribution transformers are rugged designs with high overload capability and that the maximum solar array operating current will never occur for long intervals, a 15 kVA unit should be adequate for this application. Table 3-21 summarizes the transformer design specifications.

Table 3-21. Distribution Transformer Specifications

Parameter	Value
Primary Voltage (Volts)	240
Secondary Voltage (Volts)	360
Primary Current (Amperes)	67.5
Secondary Current (Amperes)	45

It should be noted that the transformer will be a significant factor in the overall efficiency of the system. A 15 kVA transformer will have a mass of 98 kg with the laminations accounting for 60 percent of this value. Since present transformer designs stress the iron to a loss level of approximately 2.2 Watts/kg, a constant loss of 130 Watts should be expected at 240 Volts on the utility. This magnetic loss is independent of any I^2R losses in the windings. To avoid this loading on the utility during nighttime periods, it is recommended that the transformer be disconnected from the line during this time.

The smoothing reactor (ℓ_1) voltage waveform is shown as the crosshatched area on the curve at the bottom of Figure 3-43. The Fourier series analysis of this voltage waveform can be obtained by classical methods. The ripple current in the reactor will be caused by the higher order harmonic voltages. The first ac term in the series is the 120 Hz term which dominates the series and will dominate the ripple current since higher order currents will be attenuated more effectively by the inductor. This 120 Hz component, expressed as a fraction of the line voltage magnitude, has been plotted in Figure 3-45 as a function of the retard angle α. For the inverter case only angles from 90 to 180 degrees are considered. The inductance required to limit the ripple current to any given value can be calculated by using the F_2 factor plotted in Figure 3-45. The 120 Hz current in the inductor ($I_{120\ Hz}$) is given by:

$$I_{120\ Hz} = \frac{V_{120\ Hz}}{2\pi f \ell_1} = \frac{F_2 V_{in}}{2\pi (120) \ell_1}$$

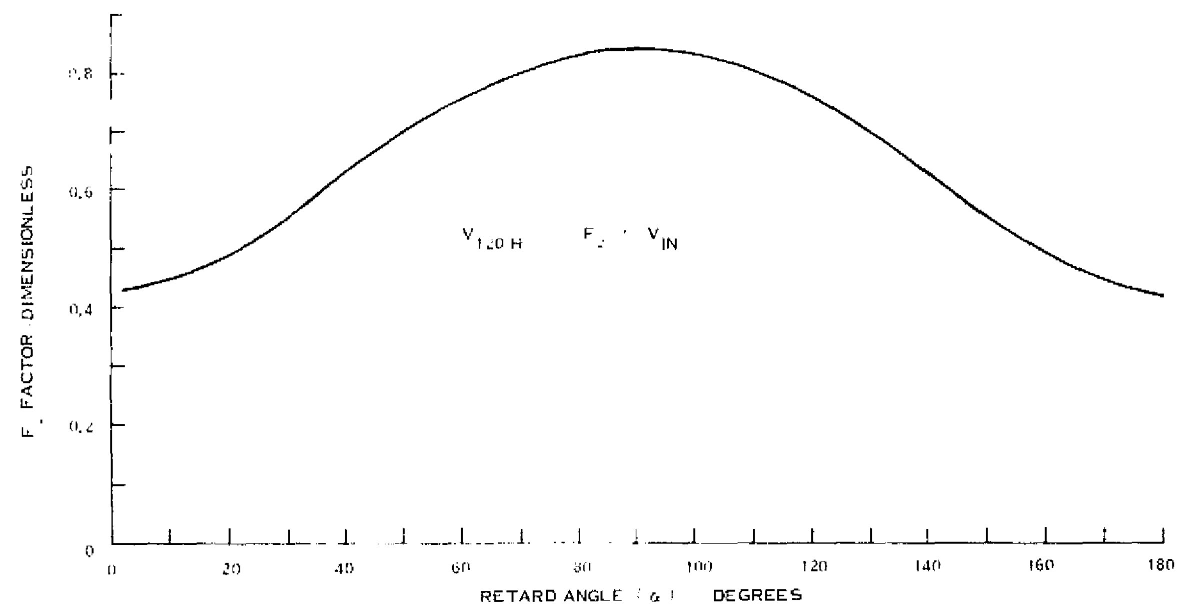


Figure 3-45. Magnitude of the 120 Hz Component of the DC Line Voltage

For a value of V_{in} = 240 Vac (rms) and for a typical operating retard angle of 140 degrees (F_2 = 0.64), the above equation can be evaluated to yield the value of inductance required for any maximum allowable ripple current specification. Table 3-22 summarizes the smoothing reactor design parameters associated with two values for maximum allowable 120 Hz ripple current. The maximum allowable ripple current will be a matter of system design. The 14 Amperes rms ripple will cause a significant reduction in solar array output. This ripple current will also be seen as an increased rms-to-average ratio in the transformer and ℓ_1 windings. This, in turn, will increase the I^2R losses in these units. Therefore, the largest ℓ_1 consistent with the economic constraints of the system should be used. A 15 mH value should be regarded as a minimum value.

Table 3-22. Smoothing Reactor Design Parameters

	Maximum Allowable 120 Hz Ripple Current (Amperes rms)	
	7	14
Inductance (mH)	29.1	14.6
Average dc current (Amperes)	45	45
Peak Current (Amperes)	55	65
Smoothing Reactor Mass (kg)	27	20

A smoothing capacitor, C, must be used to minimize the voltage effect of the ℓ_1 ripple current. The current in C is seen to be the difference between the solar array current (i_a) and the ℓ_1 current (i_L) as given by:

$$i_c = i_a - i_L$$

However, the capacitor voltage and current are related by:

$$i_c = C\frac{dV_a}{dt}$$

For small perturbations about the steady-state value, the array voltage and current are related by:

$$i_a = -K\,V_a + b$$

where:

K = the slope of the solar array I-V curve

b = is the intercept with the current axis

If the inductor current is assumed to be:

$$i_L = I_{DC} + I_{AC} = I_{DC} + I_L \sin \omega t,$$ the current equation becomes,

$$C \frac{dV_a}{dt} = -KV_a + b - I_{DC} - I_L \sin \omega t.$$

The steady-state solution to this equation is:

$$V_a = \frac{I_L \sin(\omega t + \theta)}{C\sqrt{\omega^2 + \left(\frac{K}{C}\right)^2}}$$

Therefore, V_a will be sinusoidal with a magnitude of

$$V_a = \frac{I_L}{\sqrt{(\omega C)^2 + K^2}}$$

or

$$V_a = \frac{I_L}{\sqrt{[2\pi(120)\,C]^2 + K^2}}$$

Figure 3-46 is a plot of the system transfer function

$$\frac{V_a}{I_L} = \frac{1}{\sqrt{[2\pi(120)\,C]^2 + K^2}}$$

It can be seen from Figure 3-46 that as K becomes large, the amount of filter capacitor becomes less. Therefore, the capacitor should be chosen with the lowest value of K to be expected under normal solar array operating conditions. From Figure 3-46, the lowest value of K at the maximum power point is approximately 0.01. Using the previously established values for maximum allowable 120 Hz ripple current of 7 and 14 Amperes (rms), or $\pm$ 10 and $\pm$ 20 Amperes peak, values of V_a/I_L of 1. and 0.5 will limit the solar array voltage swing to $\pm$ 10 Volts for each of the ℓ_1 choices in Table 3-21. These values of transfer function are achieved with C values of 1500 μF and 3000 μF, which correspond to previously calculated ℓ_1 values of 29.1 mH and 14.6 mH, respectively.

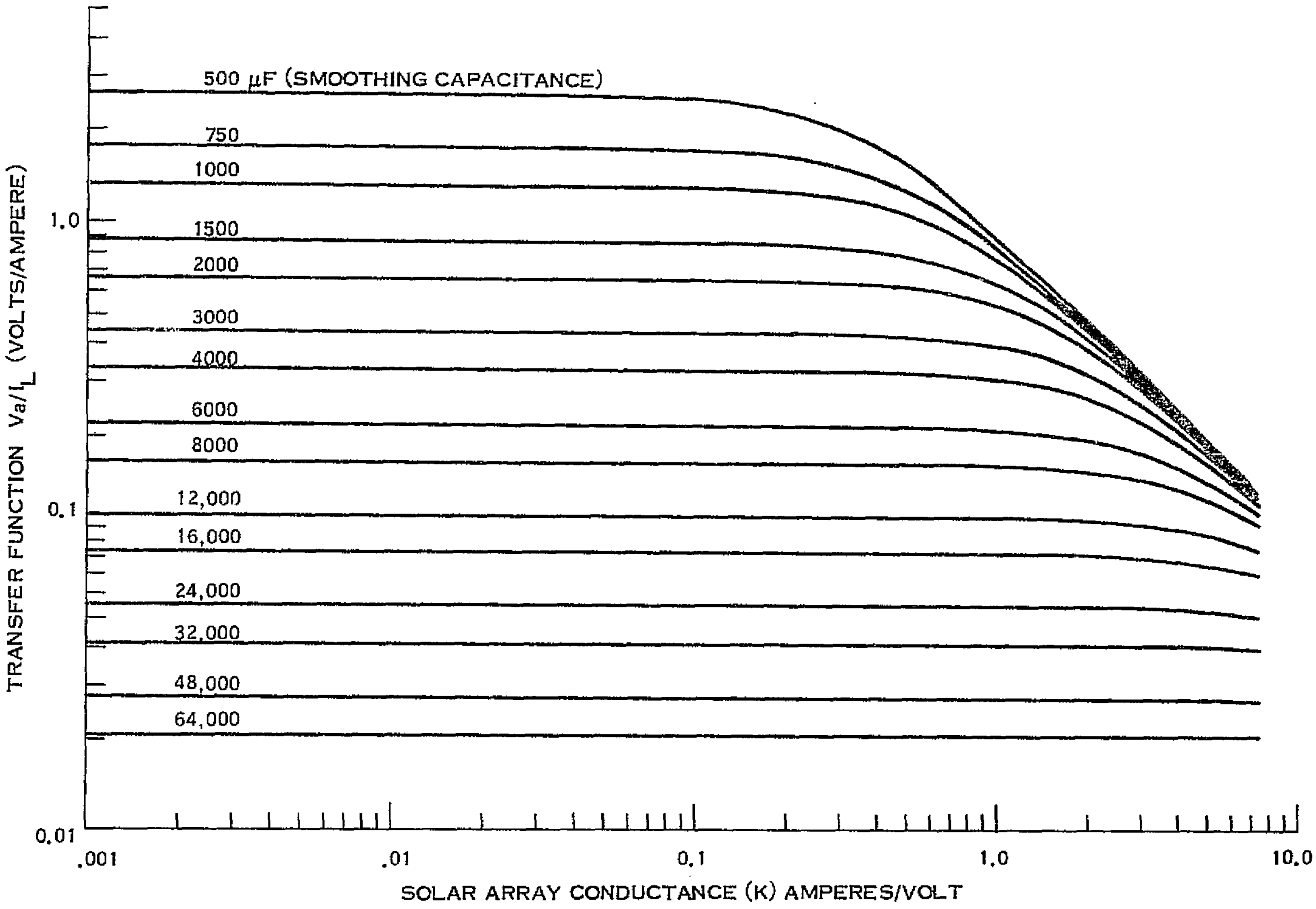


Figure 3-46. Smoothing Capacitor Transfer Function

The SCRs for use in an inverter of this type can be specified by both their current and voltage ratings. Full bridge devices will experience the reflected peak line voltage which is $1.5\sqrt{2}\ 250 = 530$ Volts. Thus, 600 or 700 Volt units should be specified for this application. Since the maximum solar array operating current is 45 Amperes and each SCR is ON 50 percent of the time, the thermal or average current rating would be 22.5 Amperes. The commutation time has been assumed to be less than 1 msec in the selection of 160 degrees as the maximum retard angle. If this 20 degrees of phase margin is to be practical, then the current in the leakage reactance of the coupling transformer T_1 must be reversed in less than 20 degrees. This requirement dictates a transformer leakage reactance of less than 0.5 mH.

(b) Direct Coupled

If the array voltage will never exceed 63 percent of the minimum peak line voltage, then a transformerless version of the circuit may be used as shown in Figure 3-47. The clear advantage of this circuit is the elimination of the large, heavy, noisy, and costly 60 Hz transformer. However, ℓ_1 is retained to provide the continuous current operation and to control the rates of current change. This circuit operates identically to the transformer coupled version shown in Figure 3-43.

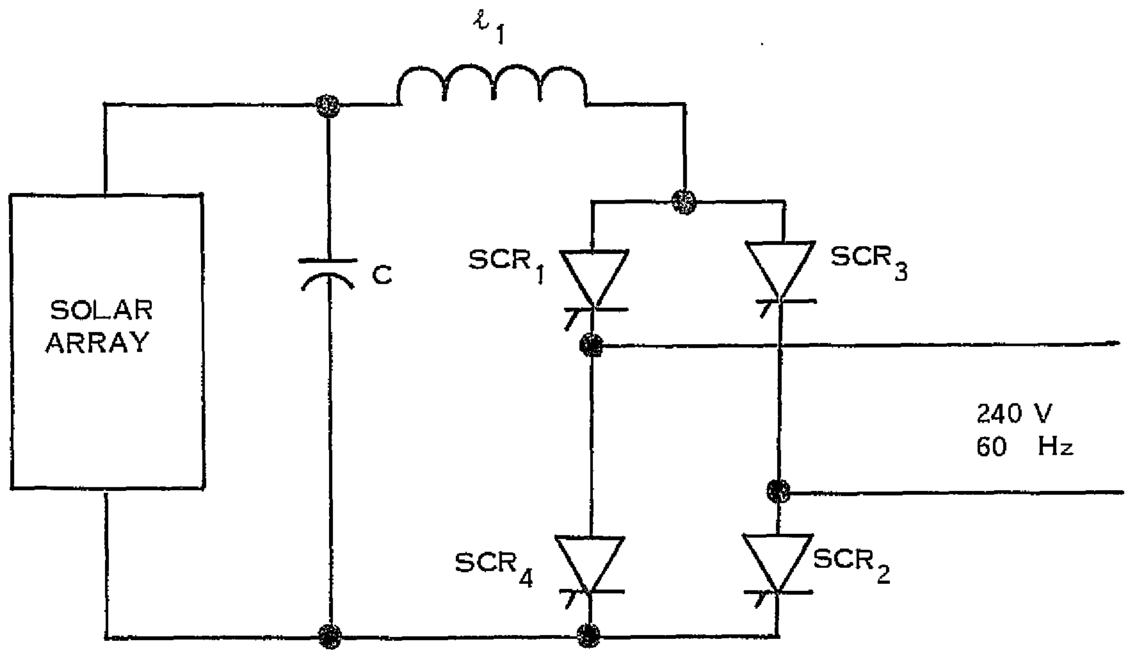


Figure 3-47. Direct Coupled Line Commutated Inverter

(c) Advantages

The main advantage of this class of circuit is its power circuit simplicity. In the ultimate case of transformerless operation the unit only passes the array energy through two components, the smoothing inductor ℓ_1 and the switching bridge. This enables a suitably designed system to achieve high efficiency (>90%) with low cost. The currents in the SCRs are almost square in the ideal case with maximum ℓ_1 and almost triangular in the limit case. Since the SCRs are on 180^o this maximizes the device utilization. In the transformerless case, the SCR voltage rating is limited by the maximum peak line voltage, again maximizing the device utilization.

In summary, the advantages of this circuit type revolve around its efficient utilization of a limited number of components.

(d) Disadvantages

The circuit simplicity which is the line commutated inverters major advantage over other systems is also its major disadvantage. This system relies on the utility to commutate off the current carrying SCRs. If after turning on SCR_1 and SCR_2 at a retard angle α, as shown in Figure 3-43 the utility line is reduced in magnitude for as little as 4 msec during the commutation interval, the current in ℓ_1 will double and the SCR will have less time and reverse voltage to commutate successfully. This can lead to a commutation failure. In the case of the transformerless system this will place a short circuit across the solar array and ℓ_1 until the utility reestablishes commutating voltage. This is not a catastrophic failure mode for either the array or inverter, as the array cannot produce infinite current in a short circuit. However, it may be possible for the utility to supply infinite power to the inverter so that fast acting fuses should be included in the output to prevent catastrophic failure. Secondly, if there is a control circuit failure which allows α to reduce below the 90^o point, the bridge will become a voltage source in series with the solar array and ℓ_1. This voltage source will be polarized to aid the array voltage and current. Therefore, the array output current will build up beyond its design limit. A series array diode will not protect the array in this case as the current is in the proper direction. In this case it would be possible to develop the full line voltage across the array while still forward biasing the protection diode. The reverse avalanche rating of the solar array may be sufficient to withstand this voltage. However, during a bright day the reverse leakage current could be sufficient to cause cell damage.

The second major disadvantage is the poor power factor exhibited by this class of inverter when operating into a utility. This circuit produces both out of phase fundamental current as well as harmonic currents. Since only the in-phase component of the fundamental component can produce useful output power the power factor is always poor with this system. This will lead to increased utility distribution costs which may or may not be passed on to the customer. In a single installation there should be no problem. However, if a transformer is used in the circuit, both the reactive and real power must be transformed increasing the rating of the transformer significantly. The poor power factor could double the current rating of the transformer.

The transformerless system does not allow the array to be grounded. The inverter alternately connects the array negative terminal to L_1 and L_2 at a 60 Hz rate. Capacitive displacement currents to ground could become quite severe in this case with an array of 100 m^2. It is possible that these displacement currents could reverse bias some cells in some physical designs of the system.

Utility generated line transients would be fed back through a transformerless converter directly to the array as no grounding is possible. Therefore, induced voltages on the line would present serious problems for the direct coupled system. Induced voltage on the utility line would not be a severe problem with a grounded, transformer coupled system. Because of its isolation the array could be adequately protected with voltage limiting devices such as the Metal Oxide Varistors. These devices, in conjunction with ℓ_1, should be sufficient to limit any utility line induced transient.

3.3.4.3.2.2 <u>Self-Commutated Inverters.</u> Self-commutated inverters can be either SCR or transistor switched units. As opposed to the line commutated inverters, these power conditioners can be designed to operate independently of the connected load. The simplest of this class of inverter would be the square wave unit shown in Figure 3-48. The simple push-pull circuit of Figure 3-48 (a) could use SCR switches as well as transistors if suitable commutating circuitry were included. Both of these circuit types produce pseudo square waves of voltage which require the filter inductors in their outputs if they are to be connected directly to a utility line. It has been shown that if 120^o conduction periods are chosen for the switches the third harmonic component of the square wave can be eliminated. However, this practice increases the peak currents through the switches by a factor of $180^o/120^o$ or a 50 percent increase. In many systems where the power supply varies over wide ranges it is possible to use two of the simple push-pull or bridge circuits on series primary windings of the output transformer. By controlling the relative phase angle of the two 120^o square waves the value of the fundamental 60 Hz component can be controlled while the third harmonic is eliminated. At the same time the required peak currents are halved due to the increased number of switches. This technique can be extended to any number of series connected primaries on the output transformer. With each addition the waveshape becomes more sinusoidal and the peak current on the devices are lowered. One commercial inverter uses 24 switches to produce a wave with only 5 percent total harmonic distortion. With suitable commutation circuits or base drive circuits in the case of transistors these systems can operate with high efficiencies (> 90%).

A second class of self-commutated inverter is the pulse width modulated inverter. In this case the same circuits of Figure 3-48 are switched many times during the 60 Hz cycle. By varying the duration of the on times of the switches, it is possible to synthesize a waveform which is rich in the fundamental 60 Hz component whose harmonic content is primarily in the higher order harmonics which can easily be filtered with mod-

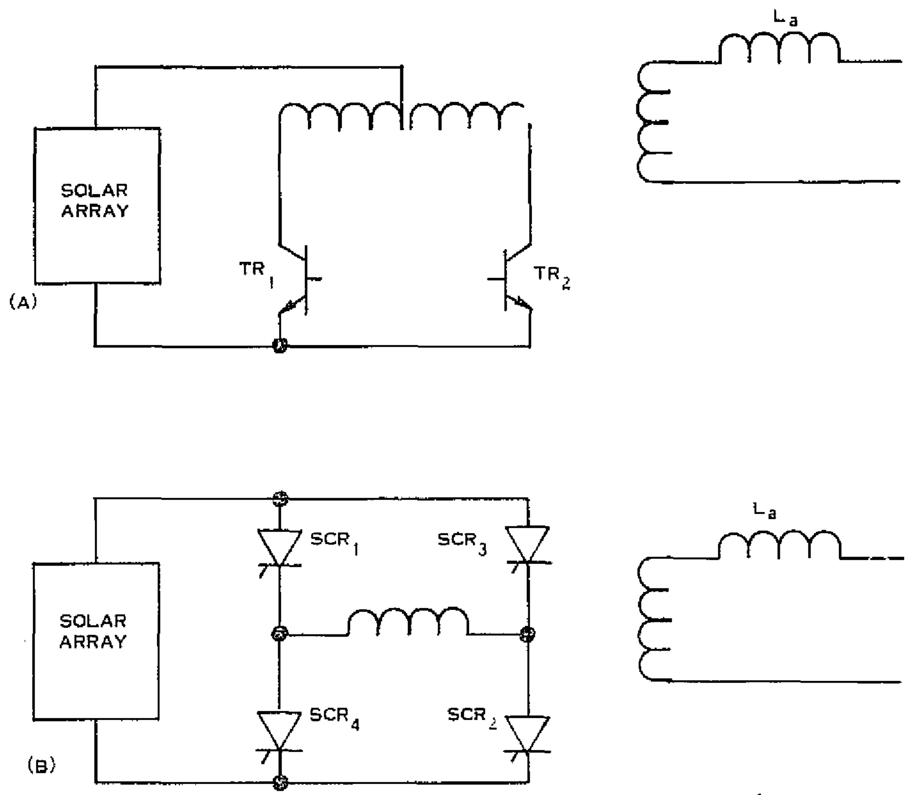


Figure 3-48. Self-Commutated Inverters

erately sized reactors. This class of inverter cannot be as efficient as simple systems because of the increased switching losses associated with the high frequency pulse width modulation. Typically 75 to 85 percent can be expected from this system. However, very large swings in both line voltage and source voltage can be tolerated with this type of circuit.

A preliminary specification for a 10 kVA self-commutated inverter is included as Appendix A to this report. The inverter for a residential photovoltaic power system must have a high efficiency that remains high at light loads. Figure 3-49 (from Reference 1) shows the circuit diagram of an inverter which is designed to meet this objective. The basic double-bridge arrangement of eight main power thyristors and diodes permits both voltage control (magnitude and phase) and third harmonic elimination by stepped-wave techniques. An explanation of the operating characteristics of this circuit is contained in Reference 1.

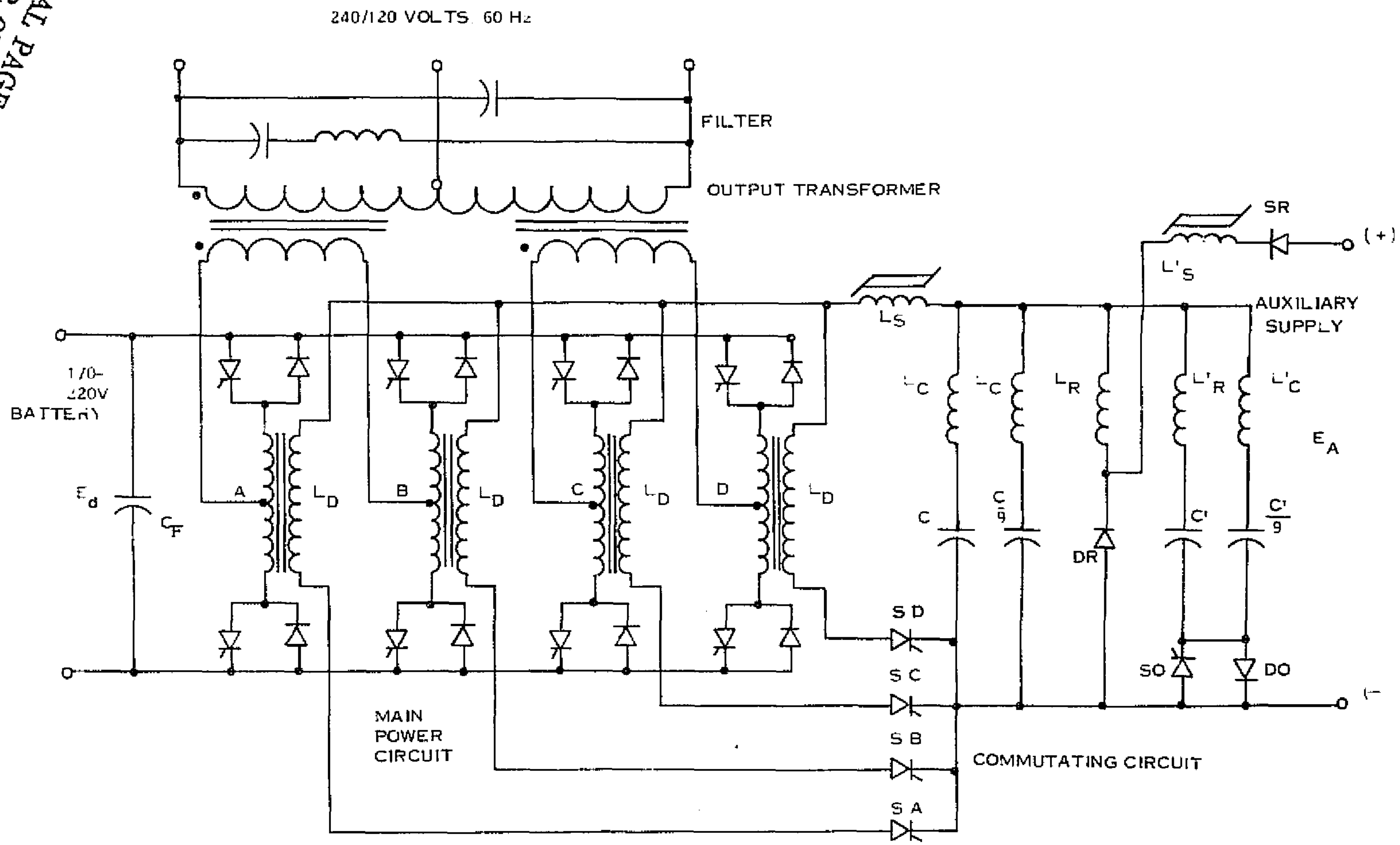


Figure 3-49. Double Bridge Inverter with Shared Transformer-Coupled Commutating Circuit, Including a Two-Level, Square-Pulse-Forming Network

(a) Advantages

The main advantage of these circuits is their ability to continue operation with no utility present. For stand alone systems this is necessary.

The second advantage is the ability to control the phase angle of the output waveform as well as its magnitude. This enables the residential system to present a nearly unity power factor to the utility line. Only the harmonic currents will reduce the power factor. A waveshape with 30 percent harmonic content will present a .7 power factor to the line.

Most of these systems require an isolating transformer as outlined before. Therefore, the system will have the advantage of lower susceptibility to line induced transients.

(b) Disadvantages

The main disadvantage of this system is the complexity of the circuit. The power component count for the 24 switch converter may be as high as 10 times higher than the simple line commutated system. This results in a potentially more expensive system. This is especially true for small production quantities. However, at high production rates the lower peak currents of the 24 switch inverter may allow simpler interconnection techniques not available at the higher currents.

Also, a relatively complex control circuit is necessary for the operation of these inverters. It is assumed, however, that LSI (Large Scale Integration) technology will make this complexity as reliable as that for the line commutated system.

The rapid switching of self-commutated systems quite often produces pronounced switching transients leading to high levels of conducted and radiated radio frequency interference. Some of this can be filtered but this is an added problem with self-commutated systems.

3.3.4.4 Maximum Power Tracking Controller

The maximum power tracking controller required for the Stage I system can be implemented by detecting the variations in array voltage and current due to the ripple current in C and ℓ_1 (see Figure 3-43). If a four quadrant multiplier is used to calculate the instantaneous power of the solar array, then the phase relationships between power and voltage can be used to detect whether the operating point is above or below the maximum power point (MPP). This method is described in Reference 17. Figure 3-50 is a diagram of the expected array voltages and power for the case of sinusoidal current perturbations of $\pm$ 2.5 Amperes about an operating point. The operating point is above the MPP in Figure 3-50 (a), at the MPP in Figure 3-50 (b), and below the MPP in Figure 3-50 (c). It can be seen that the power and voltage are in-phase above the MPP, out-of-phase below the MPP, and the power is a double frequency at the MPP. If the

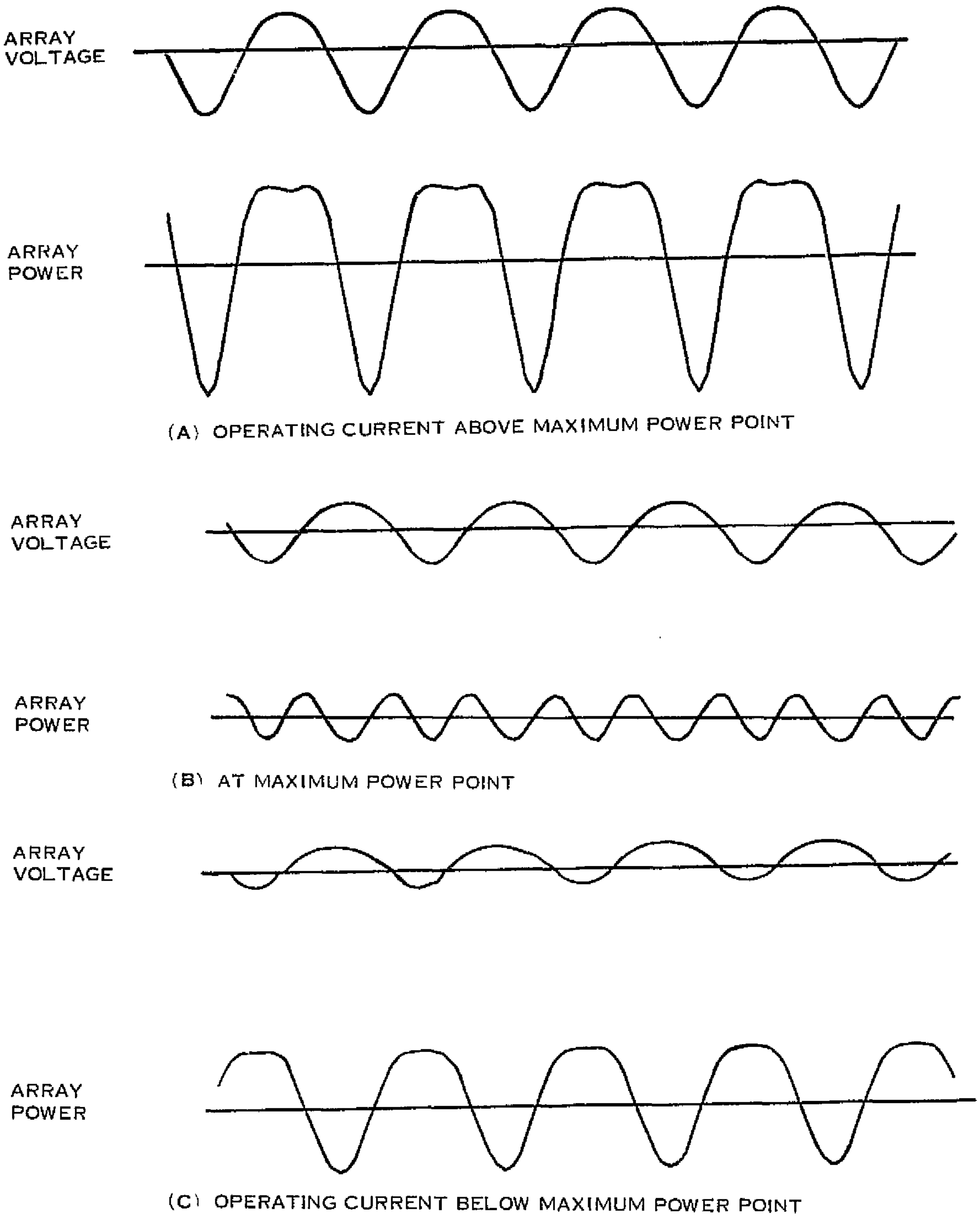


Figure 3-50. Solar Array Voltage and Power Waveforms

signals of Figure 3-50 are ac coupled and clipped to detect zero crossings, then the waveforms of Figure 3-51 result. The waveforms labeled OUTPUT in Figure 3-51 are the resultant waveforms if a coincidence circuit is used. This circuit will give a high output whenever the voltage and power are of the same sign. It can be seen that the dc value of the detected output is high above the MPP, low below the MPP, and 0.5 at the MPP.

A circuit capable of detecting these relationships is shown schematically in Figure 3-52. The ac components of voltage and current are detected and amplified in Section 1 of this circuit. A standard ac coupled operational amplifier can be used for the voltage signal. The current transformer can operate into a virtual short with the circuit shown. A powdered metal (molypermalloy) core can be used in the current transformer to minimize the effects of the dc steady state current.

In Section 2 of the circuit these voltage and current signals are input directly into a four quadrant multiplier to derive a power signal. This signal as well as the voltage signal are amplified and clipped to determine their phase relationships. The simple network shown in Section 3 of the diagram can detect the coincidence conditions. This output signal can then be compared to a reference with the difference integrated to change the current set point of the inverter. The specific circuits used for the comparison and integration are not shown here since this design will depend on the details of the inverter current control loop design.

Since ac coupling can be used on the input to this system, the gain of the input amplifier can be kept high without the drift problems associated with detecting small perturbations on large offset voltages and currents. Care should be taken however, in eliminating phase errors as the system is dependent on faithful reproduction of the phase relationships. Since the fundamental perturbation frequency is 120 Hz, this should not present a significant problem.

3.3.4.5 Battery Charge Controller and Shunt Voltage Limiter

The schematic of the Battery Charge Controller and Shunt Voltage Limiter is given in Figure 3-53. The battery terminal voltage is sensed through a voltage divider consisting of R_1, RT_1, R_2 and R_3, where RT_1 is a thermistor mounted on the battery. The signal from this voltage divider along with a voltage reference are fed to the input of an op amp. With R_3 shorted by the contacts of relay K1, the operating temperature-compensated voltage limit characteristic is that of the upper curve of Figure 3-35. When the battery terminal voltage reaches this upper curve value, the op amp output begins to rise. At this point the linear shunt element also begins to divert current through the shunt instead of to the load. When the linear shunt reaches 10 percent of its capacity as sensed at the op amp output, the inverter is enabled and the 1-hour timer is started. If there is a need for more current to be shunted, then the op amp voltage will continue to rise. When the linear shunt element reaches 90 percent of its capacity as sensed at the op amp output, the up-down counter will be allowed to count up by one. This turns

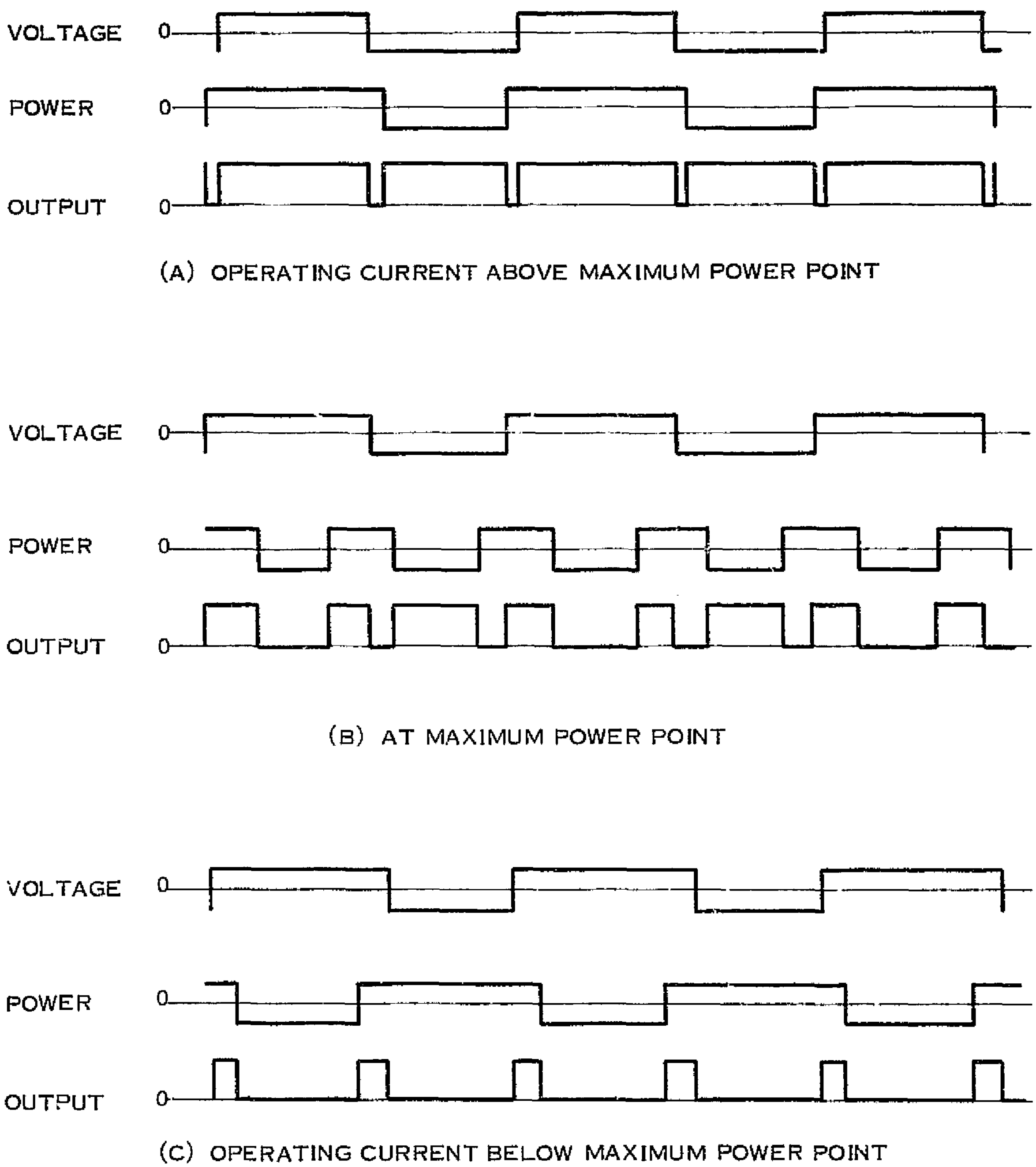


Figure 3-51. Conditioned Solar Array Waveforms

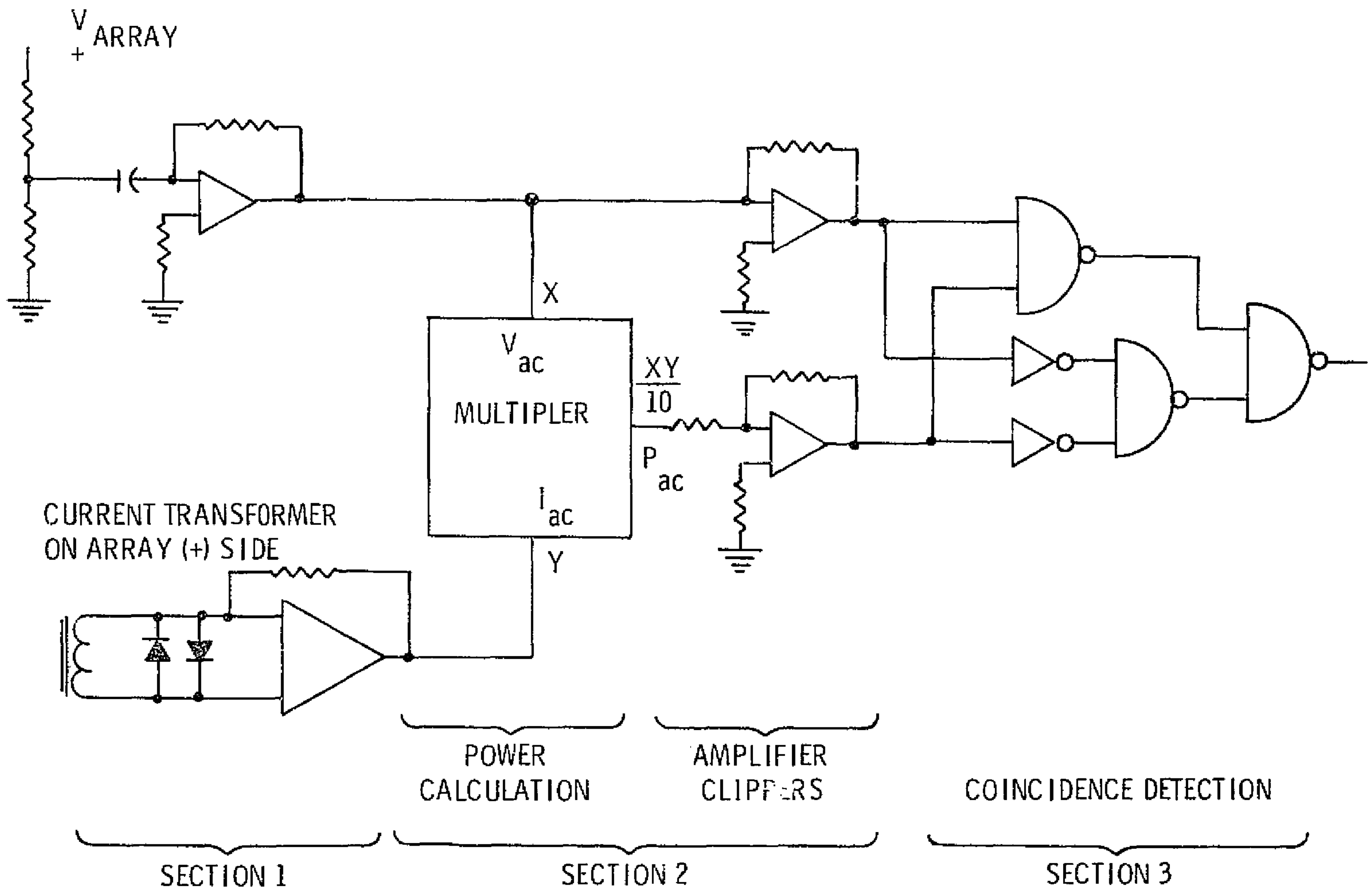
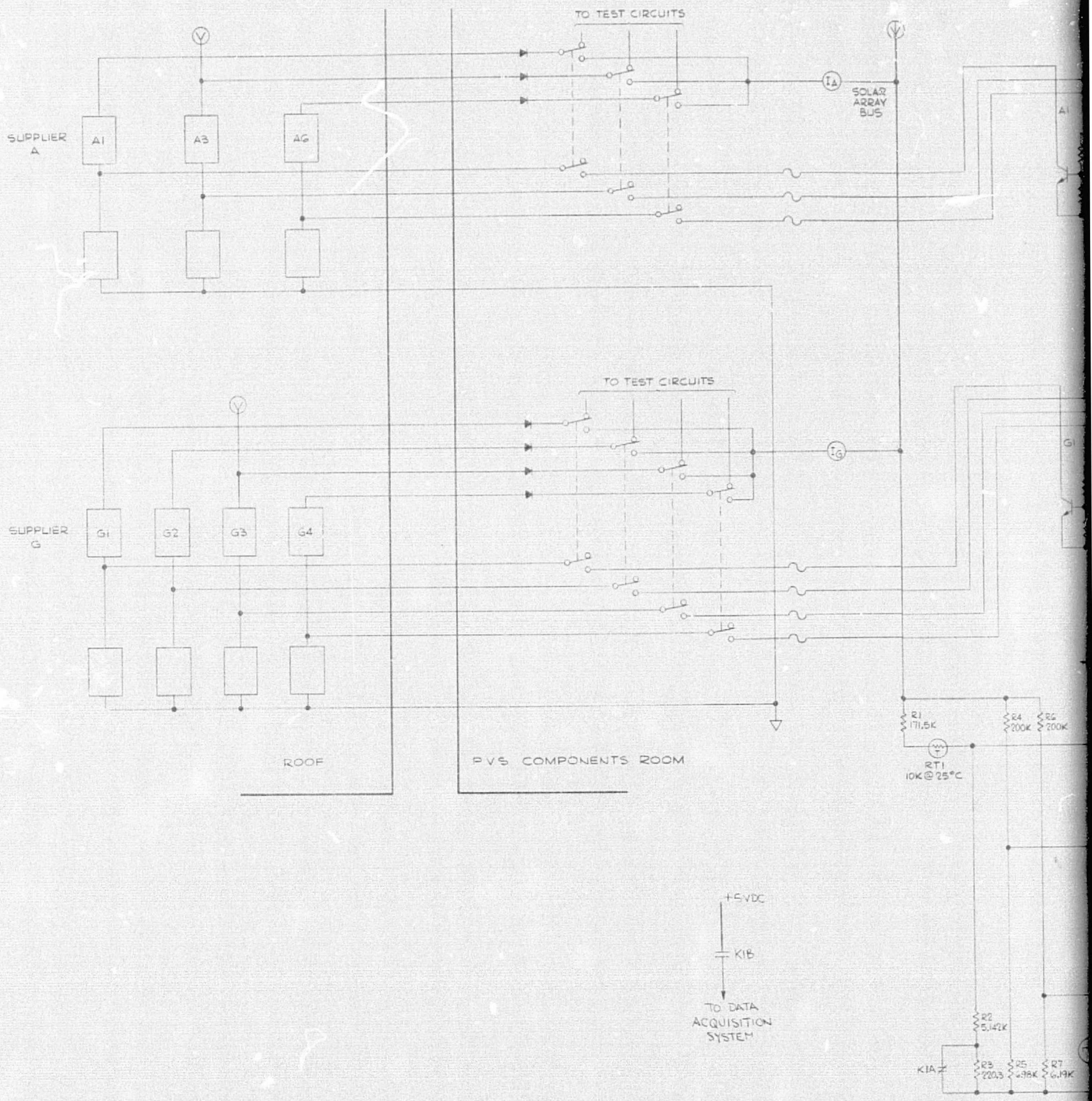


Figure 3-52. Maximum Power Tracking Controller Simplified Schematic



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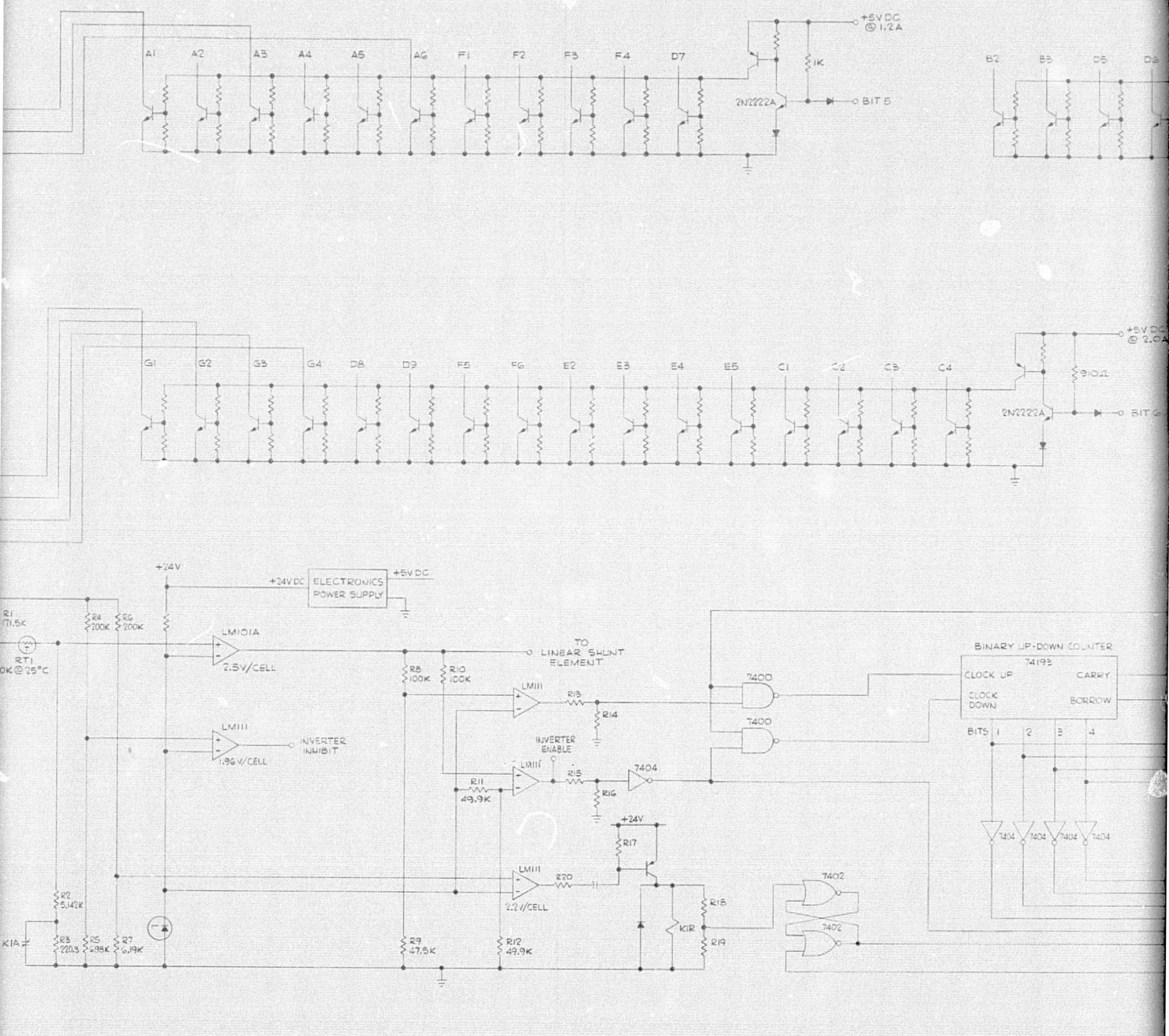

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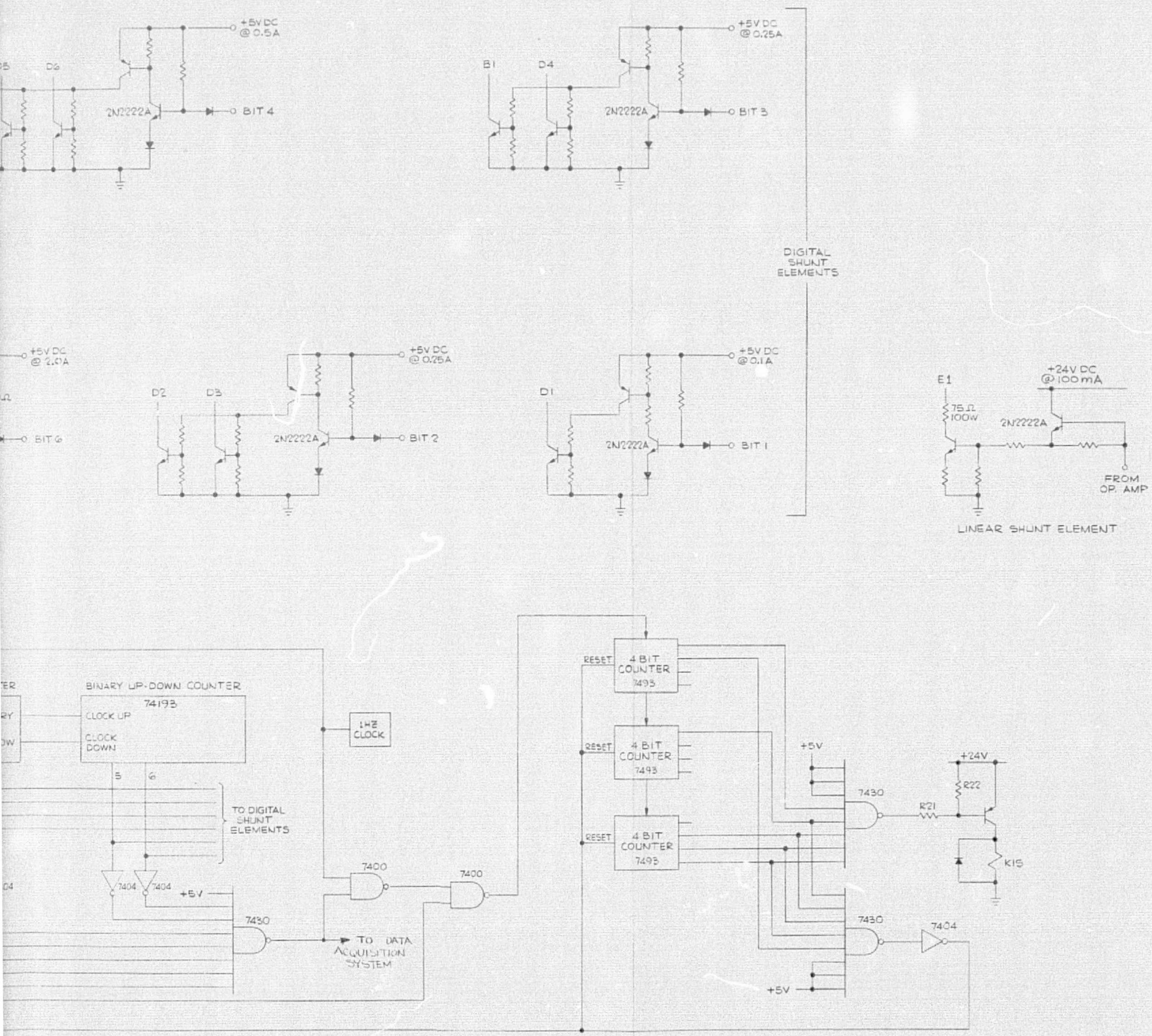

Figure 3-53. Battery Charge Controller and Shunt Voltage Limiter Schematic Diagram

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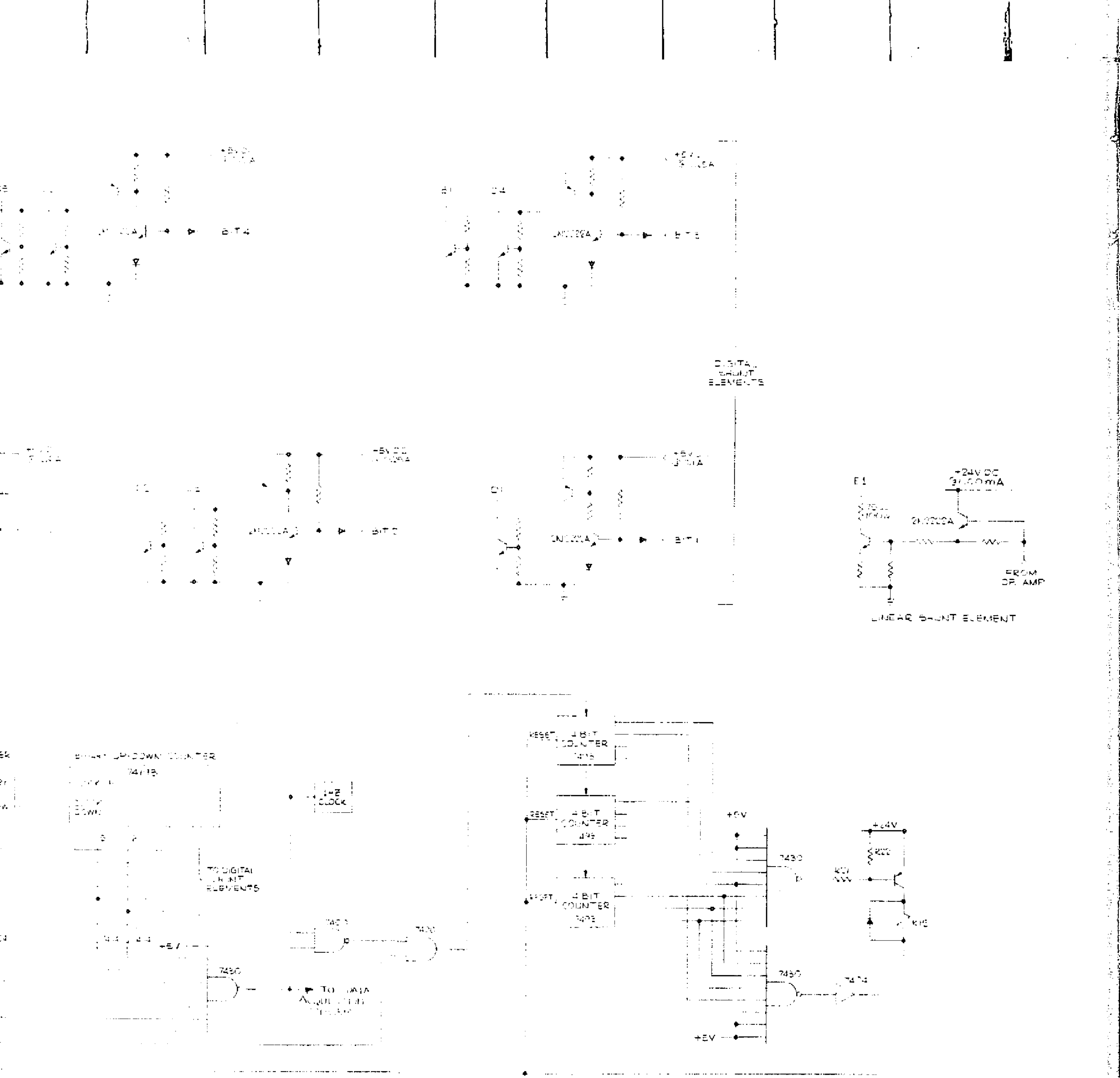

Figure 3-53. Battery Charge Controller and Shunt Voltage Limiter Schematic Diagram

on a digital shunt and drops the linear shunt current below the 90 percent level. The binary weighted digital shunt will count up as more shunted current is required. If the shunted current requirement drops to a point where the linear element is below the 10 percent level, the digital counter will count down one step an thus remove a binary step from the shunted current. If 80 percent of the linear shunt capacity is greater than the largest step of the digital shunt, smooth control of the bus voltage will be provided throughout the range of the digital shunts.

If the linear shunt is above the 10 percent level or any of the digital shunts are activated and K1 is reset, the 1 Hz clock will be enabled to drive the 4 bit counters. When these counters have totaled 3600 seconds (1 hour), an output NAND gate will change state and activate K1S. On the next count, the counters will be reset to zero, through the eight input NAND gate and inverter, and the clock will be disabled through the latch and two input NAND gate which passes the clock signal through to the counters.

When K1 opens, the voltage divider is changed such that the circuit regulates to the lower curve of Figure 3-35. When the battery voltage drops below 2.2 Volts/cell, K1 is reset and the latch is reset to enable the clock signal through the 4-bit counters. The clock signal will not be present at the other input of the two input NAND gate since no shunt elements are on when the battery voltage is at the 2.2 Volts/cell level.

The inverter is disabled when the sensed battery voltage drops to the 1.96 Volts/cell level.

3.3.5 ELECTRICAL INTEGRATION

The electrical integration of the photovoltaic power system considered the following areas: (1) lightning protection, and (2) grounding.

3.3.5.1 Lightning Protection

The lightning protection of a RPST was investigated by Mr. F.D. Martzloff of the General Electric Company, Corporate Research and Development Laboratory. Mr. Martzloff's report on this subject, as it particularly relates to a Cleveland site location, is contained in Appendix B. The following discussion is a summary of this work as it directly relates the protection of a residential structure with a solar cell module roof.

The lightning interception by an unprotected single family residence on flat land, in the Cleveland area, is estimated at one strike per 200 years on the average. The nature of this experimental residence and the cost associated with the power system strongly indicate the need for an air terminal system which places the complete structure within a 1:1 cone of protection. The side flash phenomenon between the down conductors carrying the lightning current to ground and adjacent but unconnected metallic parts, such as the solar cell modules and supporting structure, dictates a large physical separation between these elements. A lightning mast system, as shown in Figure 3-23, which is designed with overlapping cones to place the complete structure within either of the cones, is recommended for each RPST. These air terminal masts, which could double as flag poles, should be placed at least 3 meters from the solar cell module structure to avoid the side flash problem.

The major indirect effect of lightning strokes is the voltage induced on the power system by the rapidly changing magnetic flux associated with the high di/dt of the lightning current. A less important, but still significant, effect would be the voltage produced by electrostatic coupling between the roof array and the charges associated with atmospheric electricity. Typical lightning strokes involve currents of 50kA reaching a crest in 1 μsec. Thus, the di/dt near the lightning conductors will be quite high and capable of inducing destructive voltages in any loop which would link a substantial flux from the lightning current. Therefore, the solar cell circuits and interconnection wiring must be designed to minimize intrinsic coupling.

The magnitude of transient over-voltage entering the house wiring system from the utility has been measured at 6kV (References 18 and 19). This level occurs infrequently but still often enough to cause concern for sensitive electronics. A wide variety of commercial devices (e.g., Metal Oxide Varistors) are available to suppress these surges. Suitably selected devices of this type should be installed on both the ac line and the power system main dc bus.

3.3.5.2 Grounding

The incoming 240 Vac, 3-wire service should have the neutral grounded on the line side of the main contactor by suitably clamping to the water piping. The impedance between the point of connection and the surrounding soil should be less than 25 Ohms. Similarly the negative side of the 2-wire dc system should be grounded to this same contiguous metallic system. In addition to this system grounding it will also be necessary to ground the noncurrent-carrying conductive parts of equipment within the residence. This equipment grounding performs the following functions: (1) prevents electric shocks to personnel, (2) provides adequate current-carrying capability due to faults without creating fire or explosion hazards, and (3) enhances effectiveness of electromagnetic control. The following equipment types should be grounded:

1. Inverter enclosures
2. Transformer cases and cores
3. Conduits, cable armor, etc.
4. Relay cases and switchgear enclosures
5. Control electronics racks
6. Motor frames

7. Heat pump enclosures

8. Data acquisition equipment racks

3.3.6 SUBSYSTEM COST DATA AND LEAD TIMES

The estimated costs for the photovoltaic system components are given in Table 3-23. These costs have been categorized as non-recurring design and development and recurring equipment costs. The non-recurring costs include the engineering, drafting and testing required for a new development or for a modification of an existing design. These non-recurring costs are all engineering estimates based on knowledge of the complexity of the equipment involved. In the case of the line commutated inverter, these costs reflect the modification of an existing Gemini Unit (Trade name of Windworks, Mukwonago, Wisconsin) to add the necessary isolation transformer as discussed in Section 3.3.4.3.2.1. The costs associated with the self-commutated inverter are based on the development of a unit similar to the concept shown in Figure 3-49. The battery costs reflects an ROM estimate from C&D Batteries Division, Eltra Company for a hybrid lead-acid design consisting of four 24-cell, 332 Ampere-hour modules as described in Section 3.3.4.2.

Table 3-23. Estimated Photovoltaic System Costs

	Non-recurring Design and Development Cost ($ 1976)		Recurring Cost ($ 1976)	
System Implementation / Component	I	II	I	II
Battery (four 24-cell, 250 A-H modules)	-	-	-	8400
Line-Commutated Inverter(1)	15000	-	2500	-
Self-Commutated Inverter	-	70000	-	10000
Maximum Power Tracking Controller	10000	-	1500	-
Battery Charge Controller and Shunt Voltage Limiter	-	10000	-	1500
Utility Battery Charger	-	-	-	2500
Wiring and Miscellaneous Hardware	-	-	500	700
Total	25000	80000	4500	23100

(1) Includes isolation transformer

The procurement lead times associated with this equipment are expected to be within 4 months after receipt of the order with the exception of the self-commutated inverter development which may require between 9 and 12 months. Thus, it is important that this development effort be initiated promptly in order to meet the proposed test plan schedule as described in Section 3.4.2.

A survey of potential self-commutated inverter suppliers has resulted in the following list of companies which are thought to be best able to meet the requirements as outlined in the preliminary specification (see Appendix A):

- Lorain Products
- Sola Electric
- Topaz Electronics
- Unitron
- Deltec
- ALS Electronics

The advanced techniques of waveform synthesis used by ALS Electronics seems ideally suited to this application.

In addition to these equipment costs, it is estimated that solar cell module installation and overall system integration will require 800 hours of engineering labor and 2000 hours of technician labor.

3.4 TEST PLANNING (TASK IV)

3.4.1 TEST OBJECTIVES

The objectives of the test phase of the RPST project follow the theme set by the design objectives as outlined in Section 3.3.1. The primary test objective is to provide the planning, instrumentation, and data acquisition system which are necessary for the measurement of those parameters which define instantaneous as well as long term system performance and allow the quantitative comparison of the two basic system approaches which are proposed for implementation as part of this experimental project.

The test phase of the project must be of sufficient duration to permit the acquisition of representative data covering the seasonal changes in site climatological conditions.

Since an important objective of this experimental project is the verification of the analytical models used to predict terrestrial photovoltaic system performance, it is necessary that the parameters measured correspond to that data required for the execution of the analytical models. The presentation of the experimental data should also allow for the quick comparison of experimental results with the analytical model predictions. The adequacy of the one hour calculation interval, which is used in the analytical models, is a question which can be resolved by the experimental results. To permit this evaluation by comparison with predictions using smaller calculation intervals, it is important that the experimental data acquisition and recording onto the permanent record be performed on a time interval which is small compared to one hour.

Each RPST should include the man-machine interfaces required for direct on-site control of the experiment and for the graphical and tabular display of instantaneous or accumulative results. It is also important that each RPST be equipped with a display panel to allow the continuous visual display of significant system performance parameters as well as the accumulative energy status of the experiment. Such a display panel would serve as a valuable educational tool for visitors and newly assigned project personnel.

3.4.2 RECOMMENDED TEST PLAN AND SCHEDULE

The recommended test plan for the experiment operational period is given in Table 3-24. Based on the implementation of the two basic power system approaches as described in Section 3.3.2, the overall test plan has been established to identify six stages, three for each power system approach, which can be distinguished by various combinations of inverter type, battery charging mode, or load management options. As specified in Table 3-24, experiment operational stages Ia, Ib, and Ic all relate to the NOBATRY system implementation which is the first basic power system approach to be investigated during the operational period. As shown on Table 3-24, the first implementation of this system will be with a transformer coupled line commutated inverter. As discussed in Section 3.3.4.3.2.1, this is the simplest inverter which could be used in this application. Its availability and relatively low cost both indicate an early application in this experimental project. The distinction between Stages Ia and Ib is in the load management option. The so-called "Normal Operating Mode" refers to the load sequencing which closely follows the expected normal residential patterns. Under this operating mode both the heat pump and hot water heater are operated under normal thermostatic control. For the NOBATRY implementation, the so-called "Energy Saving Load Management" option refers to the operational programming of the hot water heater to turn on during the hours of peak insolation on sunny days. The heat energy stored during this period will reduce the hot water heating load demand during unilluminated periods. The programming of the heat pump to over-heat or over-cool the living space during peak insolation hours is also a load shaving method which could be considered under this Stage Ib testing.

Experiment Stage Ic reflects the replacement of the line commutated inverter with a more sophisticated self-commutated inverter. The use of this inverter will greatly improve the power factor of the power fed back to the utility grid.

Table 3-24. Overall Test Plan and Evaluation Criteria

Experiment Stage	Basic System Implementation	Inverter Option	Battery Charging Option	Load Management Option	Primary Experiment Evaluation Criteria
Ia	NOBATRY (Figure 3-21)	Transformer Coupled Line Commutated Inverter		Normal Operating Mode	• Net system output (kW_e-hr) • Total load demand (kW_e-hr) • Total solar array output (kW_e-hr) • Total insolation on solar array surface (kW-hr) • True power from utility (kW_e-hr) • Reactive power from utility (kVA-hr) • True power to utility (kW_e-hr) • Reactive power to utility (kVA-hr) • Energy from utility or to utility accumulated in hourly time slots • Energy to load accumulated in hourly time slots • Net system energy output accumulated in hourly time slots
Ib				Energy Saving Load Management	
Ic		Self-Commutated Inverter		Normal Operating Mode	
IIa	UNREG (Figure 3-22)	Self-Commutated Inverter	Normal Charging Mode	Normal Operating Mode	• Net system output (kW_e-hr) • Total load demand (kW_e-hr) • Total solar array output (kW_e-hr) • Total insolation on solar array surface (kW-hr) • True power from utility (kW_e-hr) • Reactive power from utility (kVA-hr) • Battery charge energy (kW_e-hr) • Battery discharge energy (kW_e-hr) • Energy from utility accumulated in hourly time slots • Energy to load accumulated in hourly time slots • Net system energy output accumulated in hourly time slots
IIb				Energy Saving Load Management	
IIc			Nighttime charging from utility	Normal Operating Mode	

The criteria listed in the right-hand column of Table 3-23 reflect those measures of system performance which are the most significant in the overall evaluation of the various experiment options as proposed.

The UNREG system approach, which is designated as Stages IIa, IIb, and IIc in Table 3-24, uses the same self-commutated inverter as previously used in the NOBATRY system under Stage Ic. However, under this mode of operation there is no feedback of power to the utility since a lead-acid battery has been added to the system to absorb the excess power during the peak insolation periods. The "Normal Charging Mode", under the "Battery Charging Option" column of Table 3-24, refers to the normal battery charge control method which consists of direct charging from the solar array until the temperature compensated charge voltage limit is reached. The battery terminal voltage is controlled at this level by the operation of the partial shunt voltage limiter as described in Section 3.3.4.5. Excess power during this voltage limiting charging period is dissipated on the solar array and in the shunt pass elements. The distinction between Stages IIa and IIb is in the method of load management. The "Normal Operating Mode" is the same as previously described for Stage Ia. For the Stage IIb experiment phase, the "Energy Saving Load Management" option refers to the programming of the hot water heater load to be turned-on when the battery voltage limit is reached and current shunting is required to maintain regulation at this voltage. If the hot water heater load is turned-on at this time, this additional load will reduce the battery charging current to a low enough value to force the charging voltage to drop below the voltage limit setting. In this way the energy dissipation in the shunt voltage limiter can be eliminated as a system loss by transferring this dissipation to a useful load which has the inherent ability to store this energy for later use.

Stage IIc envolves the use of an ancillary battery charger which will allow charging from the utility source during nighttime hours when the next days weather is predicted to be cloudy. This approach to energy management has the possibility of reducing or eliminating the dependence on utility power during the normal peak afternoon hours.

Figure 3-54 gives a proposed schedule for the experiment operational period which includes both the Stage I or NOBATRY phase and the Stage II or UNREG phase. This operational period is preceded by a four month period of experiment set-up and checkout. All elapsed time on this schedule is measured from the completion of the residential structure as determined by the issuance of an occupancy permit by the local government. The scheduled duration of the Stage I operational phase is 12 months with phases Ia, Ib, and Ic occupying 5, 2, and 4 months, respectively. An additional one month period between Ib and Ic has been allowed for the replacement and checkout of the system with the self-commutated inverter. The change-over from the Stage I to Stage II system implementation is scheduled at two months including the necessary system debug and checkout. The Stage II operational period of the experiment is also scheduled for 12 months duration with phases IIa, IIb and IIc occupying 6, 2, and 4 months, respectively. Thus, a total of 24 month of experiment operation is provided in a total of 30

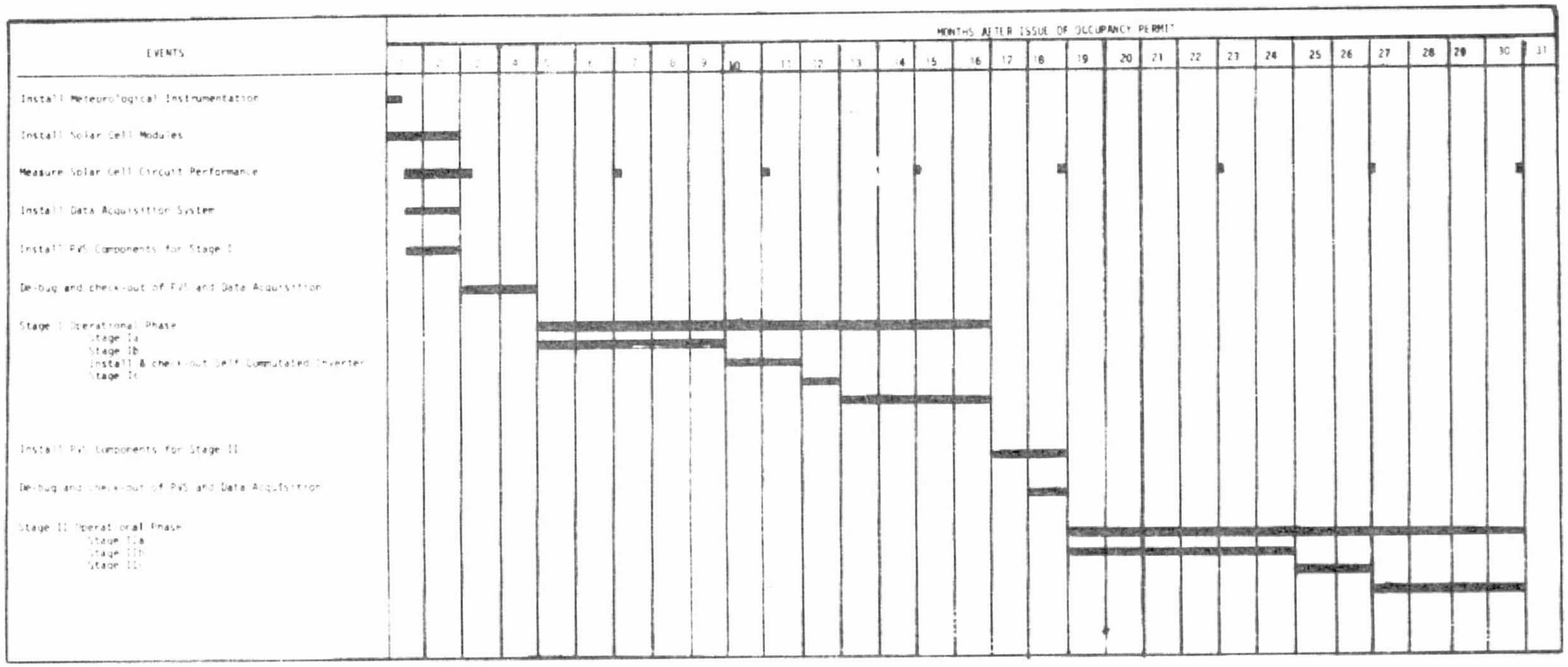

Figure 3-54. Proposed RPST Operational Schedule

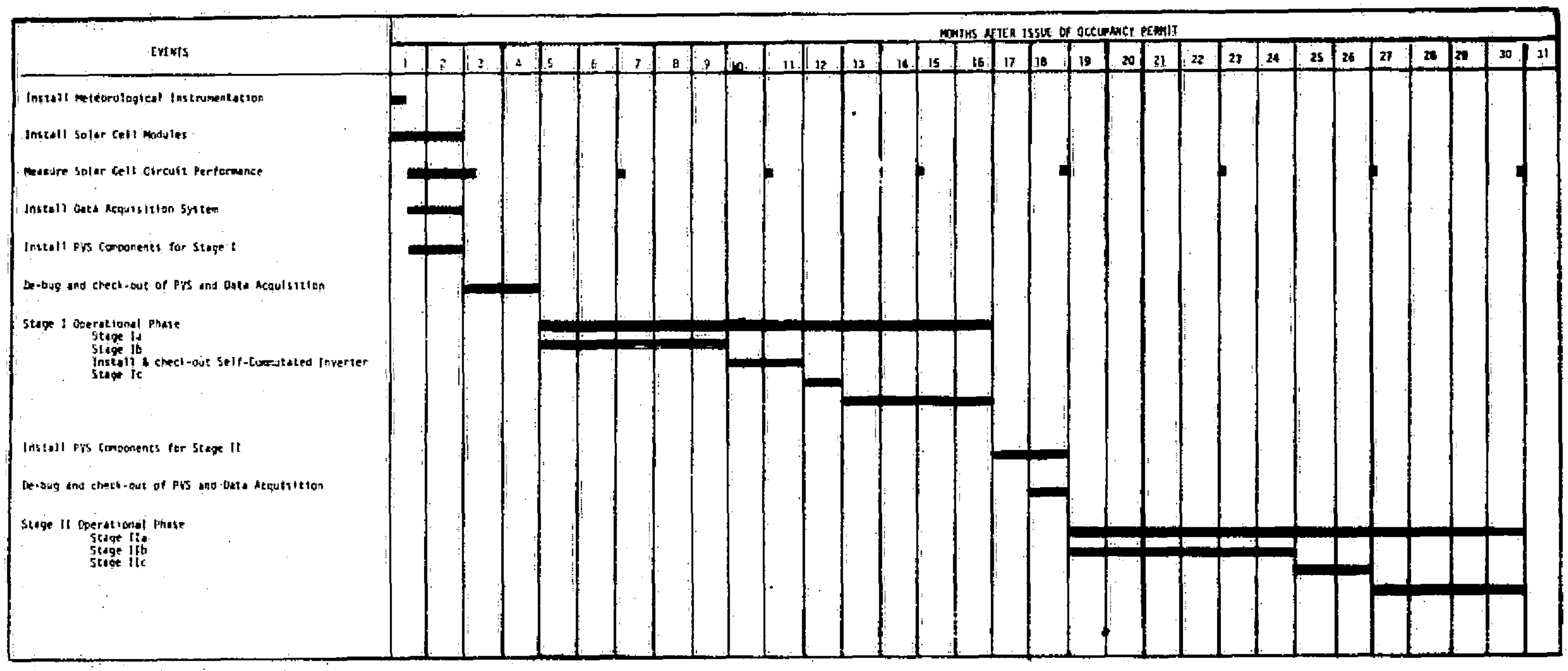

Figure 3-54. Proposed RPST Operational Schedule

months of elapsed time. Periodic measurements of solar cell circuit I-V characteristics are scheduled as indicated on the Figure 3-44. These measurements can be made without interruption of the power system operation.

3.4.3 DATA REQUIREMENTS

The data required to adequately evaluate the system performance and to verify the analytical model predictions are defined in Tables 3-25 and 3-26. Table 3-25 lists those parameters which are related to a particular regional RPST installation. The first three items on this list can be obtained from a land survey of the site location. Item No. 4 can be readily measured with an inclinometer. Item Nos. 5 and 6 are required for the calculation of battery state-of-charge. The measurement of these parameters will require testing of the battery at the component level prior to installation in the RPST. The last two parameters will enable the calculation of overall system end-to-end conversion efficiency. If the solar array is made up of modules from more than one supplier, it is important to know the number of solar cell modules from each supplier and the solar cell area and panel area associated with each supplier. This data will permit the assessment of the relative overall conversion efficiency among the various suppliers.

Table 3-25. Physical Parameters of Site Installation

Parameter	Units	Recommended Accuracy
1. Site Latitude	Degrees N	± 0.1 degree
2. Site Longitude	Degrees W	± 0.1 degree
3. Solar Roof Azimuth Orientation	Degrees from due South (+ West of South)	± 0.1 degree
4. Solar Roof Slope (or Tilt Angle)	Degrees from horizontal	± 0.1 degree
5. Average Ampere-hour Charging Efficiency	Percent	± 5 percent
6. Actual Battery Capacity at the 10 Hour Discharge Rate	Ampere-hour	± 5 percent
7. Total Solar Cell Area	m^2	± 0.2%
8. Total Solar Array Panel Area	m^2	± 0.2%

Table 3-26. Experiment Data Acquisition Requirements

Parameter	Symbol	Units	Utilization		Acquisition Method		Frequency of Acquisition	Accuracy of Measurement or Calculation
			Stage I	Stage II	Measurement	Calculation		
1. Date	DAY	Days from Jan 1st	x	x	x		1/min	±1 min
2. Time	TIME	LST	x	x	x		1/min	±15 sec
3. Solar Hour Angle	SHR	Degrees	x	x		x	1/min	±0.1 deg
4. Angle of Incidence on Horizontal Surface	THETAH	Degrees	x	x		x	1/min	±0.1 deg
5. Angle of Incidence on Inclined Surface of Solar Array	THETAI	Degrees	x	x		x	1/min	±0.1 deg
6. Extraterrestrial Radiation on Horizontal Surface	HEXT	kw/m^2	x	x		x	1/min	±1.5%
7. Total Radiation on Horizontal Surface	HBAR	kw/m^2	x	x	x		1/sec	±1.5%
8. Total Radiation on Inclined Surface of Solar Array.	HTOTAL	kw/m^2	x	x	x		1/sec	±1.5%
9. Wind Speed	WSP	m/s	x	x	x		1/min	±1%
10. Wind Direction	WDIR	Degrees from North	x	x	x		1/min	±3%
11. Outside Air Dry Bulb Temperature	TAMB	°C	x	x	x		1/min	±0.5°C
12. Outside Air Relative Humidity	RH	Percent	x	x	x		1/min	±5%
13. Inside Air Dry Bulb Temperature	TIN	°C	x	x	x		1/min	±0.5%
14. Inside Air Relative Humidity	RHI	Percent	x	x	x		1/min	±5%
15. thru 28. Solar Cell Module Temperature	T1 through T14	°C	x	x	x		1/min	±0.5°C
29. Standard Solar Cell Short Circuit Current	ISC	mA	x	x	x		1/sec	±0.5%
30. Standard Solar Cell Temperature	TSC	°C	x	x	x		1/sec	±0.5%
31. Supplier A Circuit Voltage	SVA	vdc	x	x	x		1/min	±0.5%
32. Supplier B Circuit Voltage	SVB	vdc	x	x	x		1/min	±0.5%
33. Supplier C Circuit Voltage	SVC	vdc	x	x	x		1/min	±0.5%
34. Supplier D Circuit Voltage	SVD	vdc	x	x	x		1/min	±0.5%
35. Supplier E Circuit Voltage	SVE	vdc	x	x	x		1/min	±0.5%

Table 3-26. Experiment Data Acquisition Requirements (Continued)

Parameter	Symbol	Units	Utilization		Acquisition Method		Frequency of Acquisition	Accuracy of Measurement or Calculation
			Stage I	Stage II	Measurement	Calculation		
36. Supplier F Circuit Voltage	SVF	vdc	x	x	x		1/min	±0.5%
37. Supplier G Circuit Voltage	SVG	vdc	x	x	x		1/min	±0.5%
38. Supplier A Circuit Current	SIA	Adc	x	x	x		1/min	±0.5%
39. Supplier B Circuit Current	SIB	Adc	x	x	x		1/min	±0.5%
40. Supplier C Circuit Current	SIC	Adc	x	x	x		1/min	±0.5%
41. Supplier D Circuit Current	SID	Adc	x	x	x		1/min	±0.5%
42. Supplier E Circuit Current	SIE	Adc	x	x	x		1/min	±0.5%
43. Supplier F Circuit Current	SIF	Adc	x	x	x		1/min	±0.5%
44. Supplier G Circuit Current	SIG	Adc	x	x	x		1/min	±0.5%
45. Total Solar Array Current	IA	Adc	x	x	x		1/min	±0.5%
46. Main dc Bus Voltage	V	vdc	x	x	x		1/sec	±0.5%
47. Inverter Input DC Power	PIN	watts	x	x	x		1/sec	±0.5%
48. AC Line-to-Line Voltage	VAC	vac	x	x	x		1/min	±0.5%
49. Inverter Output AC True Power	POUT	watts	x	x	x		1/sec	±0.5%
50. Inverter Output AC Reactive Power	VAROUT	volt-amperes	x	x	x		1/sec	±0.5%
51. Utility AC True Power	PUTIL	watts (- for feed back)	x	x	x		1/sec	±0.5%
52. Utility AC Reactive Power	VARUTIL	volt-amperes (- for feedback)	x	x	x		1/sec	±0.5%
53. Total Load Demand AC True Power	PLOAD	watts	x	x	x		1/sec	±0.5%
54. Total Load Demand AC Reactive Power	VARLOAD	volt-amperes	x	x	x		1/sec	±0.5%
55. Heat Pump AC True Power	PHP	watts	x	x	x		1/sec	±0.5%
56. Hot Water Heater AC True Power	PHW	watts	x	x	x		1/sec	±0.5%
57. Other Loads AC True Power	POTHER	watts	x	x	x		1/sec	±0.5%
58. Battery Charge/Discharge Current	IB	Adc (+ charging)		x	x		1/sec	±0.5%
59. Battery Temperature	TB	°C		x	x		1/min	±0.5%

Table 3-26. Experiment Data Acquisition Requirements (Continued)

Parameter	Symbol	Units	Utilization		Acquisition Method		Frequency of Acquisition	Accuracy of Measurement or Calculation
			Stage I	Stage II	Measurement	Calculation		
60. Nighttime Charger Input Power	PNIGHT	watts	x	x			1/sec	±0.5%
61. Inverter Energy Output	KWHROUT	kw-hr	x	x		x	1/sec	±0.75%
62. Inverter Energy Input	KWHRIN	kw-hr	x	x		x	1/sec	±0.75%
63. Utility Energy Demand	KWHRUTIL	kw-hr	x	x		x	1/sec	±0.75%
64. Utility Energy Feedback	KWHRBACK	kw-hr	x			x	1/sec	±0.75%
65. Load Energy Demand	KWHRLOAD	kw-hr	x	x		x	1/sec	±0.75%
66. Heat Pump Energy Demand	KWHRHP	kw-hr	x	x		x	1/sec	±0.75%
67. Hot Water Heater Energy Demand	KWHRHW	kw-hr	x	x		x	1/sec	±0.75%
68. Other Loads Energy Demand	KWHROTHR	kw-hr	x	x		x	1/sec	±0.75%
69. Battery Charge/Discharge Power	PB	watts (+ for charging)		x		x	1/sec	±0.75%
70. Integrated Total Radiation on Inclined Surface of Solar Array	SHTOTAL	kw-hr/m^2	x	x		x	1/sec	±1.75%
71. Integrated Total Radiation on Horizontal Surface	SHBAR	kw-hr/m^2	x	x		x	1/sec	±1.75%
72. Battery Charge Energy	KWHRCHG	kw-hr		x		x	1/sec	±1.2%
73. Battery Discharge Energy	KWHRDHG	kw-hr		x		x	1/sec	+ ±1.2%
74. High Charge Voltage Limit Reached	HIGHVL	Status		x	x		1/min	
75. Low Charge Voltage Limit Reached	LOWVL	Status		x	x		1/min	
76. Integrated Battery Charge Current	AMPHRCHG	amp-hr		x		x	1/sec	±0.75%
77. Integrated Battery Discharge Current	AMPHRDHG	amp-hr		x		x	1/sec	±0.75%
78. Battery State-of-Charge	SOC	percent		x		x	1/min	±5%
79. Solar Array Power Output	PSA	watts		x		x	1/sec	±1.0%
80. Solar Array Energy Output	KWHRSA	kw-hr		x		x	1/sec	±1.2%
81. Nighttime Charger Energy Input	KWHRNITE	kw-hr		x		x	1/sec	±0.75%
82. Temperature-corrected Std. Cell I_{SC}	CISC	mA	x	x		x	1/sec	±0.75%
83. Integrated Temperature-corrected Std Cell I_{SC}	SCISC	mA-hr	x	x		x	1/sec	±1.0%

Table 3-26. Experiment Data Acquisition Requirements (Continued)

Parameter	Symbol	Units	Utilization		Acquisition Method		Frequency of Acquisition	Accuracy of Measurement of Calculation
			Stage I	Stage II	Measurement	Calculation		
84. Integrated Inverter Reactive Power Output	KVHROUT	kVA-hr	x	x		x	1/sec	±0.75%
85. Integrated Utility Reactive Power Demand	KVHRUTIL	kVA-hr	x	x		x	1/sec	±0.75%
86. Integrated Utility Reactive Power Feedback	KVHRBACK	kVA-hr	x			x	1/sec	±0.75%

Table 3-26 lists the experimental data which is felt to be required to meet the stated test objectives with the conceptual design as defined in Section 3.3. This table lists each parameter by a descriptive phrase which should be adequate to completely define the measurement. A suggested symbol, of eight characters or less, and the units of measure are also listed for each parameter. SI units are suggested for all data relative to the RPST program. The units for electrical energy have been specified as kilowatt-hours as opposed to Joules because the former approach is more commonly used.

The column labeled "Utilization" in Table 3-26 refers to whether the particular measurement is required in the Stage I (NOBATRY) and/or Stage II (UNREG) system implementations as outlined in Section 3.3. The "Acquisition Method" column indicates whether a particular parameter is obtained by direct measurement on the RPST or by calculation from other measured data. The "Frequency of Acquisition" column indicates the data sampling frequency which is felt to be required to accurately utilize these measurements to assess system performance. Two basic rates have been specific in this column: "1/min" or once/minute and "1/sec" or once/second. The faster sampling rate is used for those measurements which will be summed by the computer to yield an accumulative total. The slower rate is considered adequate for data which is to be recorded and displayed as instantaneous values only.

The column entitled "Accuracy of Measurement or Calculation" indicates that accuracy which is thought to be reasonable based on knowledge of the instrumentation which is available for each measurement. The first two measurements (viz., date and time) are the basic time tag of the data. Along with the site latitude and longitude and solar array panel slope angle these data permit the calculation of the equation of time, solar declination and subsequently the solar hour angle and angle of incidence on the inclined surface and on the horizontal surface.

The other data on the list is reasonably self-explanatory with the possible exception of the items discussed below with a brief explanation of the purpose and method of measurement or calculation. The extraterrestrial radiation on the horizontal surface (Item no. 6 in Table 3-26) is calculated as the product of the cosine of the angle of incidence on this surface and the value of the air-mass-zero intensity which has been corrected for the earth-sun distance. The ratio of the measured total radiation on the horizontal surface to the calculated extraterrestrial radiation on the horizontal surface is an important parameter used in the analytical model to calculate the total radiation on the inclined surface of the solar array. By calculating this total radiation and comparing the results with the measured total radiation on the inclined surface it should be possible to experimentally determine a correction factor for the Liu and Jordan relationship as given in Reference 10. The standard cell short-circuit current and temperature (Item nos. 29 and 30) are used as a check against the pyranometer reading of the total radiation on the inclined surface. Previous results have shown a close correlation between the temperature-corrected solar cell short-circuit current and total radiation as measured by a pyranometer. Thus, these two independent measurements of total radiation in the plane of the inclined solar array will serve as a check on this most important measure of system input energy. The temperature-corrected standard solar cell short-circuit current reading is potentially the most accurate instrument for this measurement since it responds to the same spectral distribution of the energy as the solar array.

The measurement of the total current contribution for each of the module suppliers will allow a direct measurement of the fraction of the total solar array current which is supplied by each module type. The measurement of circuit voltage on the roof and main dc bus voltage will permit the calculation of the voltage drop in the wiring between the roof and the PVS Components Room and in the circuit isolation diodes.

For the Stage I (NOBATRY) system, the inverter input dc power measurement (Item no. 47 in Table 3-26) is also the solar array output power, but for the Stage II (UNREG) implementation the solar array output power (Item no. 79) must be determined by the product of total solar array current (Item no. 45) and main dc bus voltage (Item no. 46).

All energy related parameters are calculated using a one second sampling and integration time. The battery state-of-charge (SOC) is calculated according to the following relationships:

$$SOC_t = SOC_{t-1} + \eta \frac{(AMPHRCHG_t - AMPHRCHG_{t-1}) - (AMPHRDGH_t - AMPHRDGH_{t-1})}{C}$$

where

SOC_t = State-of-charge at current time t

SOC_{t-1} = State-of-charge at previous time (t-1)

$AMPHRCHG_t$ = Accumulative Ampere-hours charged at current time t

$AMPHRCHG_{t-1}$ = Accumulative Ampere-hours charged at previous time t-1

$AMPHRDHG_t$ = Accumulative Ampere-hours discharged at current time t

$AMPHRDHG_{t-1}$ = Accumulative Ampere-hours discharged at previous time t-1

η = Average Ampere-hour charging efficiency

C = Battery capacity (Ampere-hours)

The battery SOC calculation is reinitialized to a value of one by the receipt of the "low charge voltage limit reached" signal. The AMPHRCHG and AMPHRDHG values are also set equal to zero at this time and the accumulation and calculation of SOC proceeds with a clean slate.

3.5 TEST EQUIPMENT REQUIREMENTS AND PROCEDURES (TASK V)

The following presents the results of the task activity to establish requirements and define the selected data acquisition/control system and test procedures required to conduct the Residential Photovoltaic System Test (RPST) program.

3.5.1 SYSTEM TEST REQUIREMENTS

To conduct the RPST program, the following data acquisition and control system functions were defined to establish test equipment requirements:

1. House electrical load control and simulation
2. Photovoltaic System (PVS) override control to permit exercising the system in non-routine operational modes
3. Data acquisition in the normal as well as special test modes

A control program is necessary to operate house electrical loads (heating/cooling, hot water, appliances, lighting, etc.) so that conditions that are somewhat typical of a "lived-in" residence are simulated. Control of house electrical loads also permits evaluation of various energy saving techniques and their impact on the residential photovoltaic system.

A PVS control system is required to supplement, but not replace, the stand alone controls to be built into the selected PVS components. This control system should merely provide the flexibility to exercise all possible system operating modes by overriding the built-in controls. Exercising the PVS in non-routine operational modes and conducting special subsystem tests are essential for thorough evaluation of a prototype system where components are to be periodically replaced, added or removed in order to evaluate their performance as part of a complete operational system. In addition, PVS override control capability in conjunction with house electrical load control permits obtaining performance data essential for optimizing a residential photovoltaic system design.

Data acquisition in the normal system operating mode as well as in special test modes is needed to validate and update the theoretical programs utilized in developing the prototype designs, as well as to provide operational and performance data over an extended evaluation period. The raw transducer data acquired must be manipulated, converted (e.g., integrated, averaged, compared, etc.), displayed, recorded, and stored. An appropriate on-site visual display of system operation will serve as an educational tool for visiting officials, the public and newly assigned project personnel. The display panel should also provide alarm status as well as facilitate troubleshooting.

Detailed operational data should be available at the site on a timely basis since the residential photovoltaic prototype system is primarily a test bed for evolving an optimum design. On-going evaluation of data and trends is essential to assure a technically and cost effective test program. Special tests will have to be conducted based on conditions at a particular site. In this regard, the data and control programming (whether manual or automatic) can generally be applicable to all site locations, but with sufficient capability to permit local variations to account for the different climatological conditions, time zones, utility rates and photovoltaic subsystems. All this points up the need for the on-site personnel interface with the system during the conduct of the test program, particularly with regard to programming, conduct of special tests, and timely evaluation of data and trends.

3.5.2 ALTERNATE TEST EQUIPMENT SYSTEMS

A number of control and data acquisition test equipment systems ranging from the manual to completely automatic were analyzed from the standpoint of meeting the defined test system requirements.

In view of the previously discussed need for a personnel on-site interface during the conduct of the test program, a photovoltaic system fully and solely controlled by a distant central station computer was ruled out as a potential option. Evaluation of the combination of a central station tied in by phone line, for real time communication, with each remote photovoltaic system installation containing its own local microprocessor and man/machine interface peripherals (e.g., graphic CRT terminal and printer) did not prove cost effective. Central station operating costs and telephone line charges for a two-year test program, prorated against the several remote installations presently planned, outweighs the additional cost of computing equipment at each remote site. In addition, sharing of responsibility with a central station reduces on-site operational flexibility and any central station outage affects all remotes. Consequently, this combined approach was also eliminated. However, there is a unique situation where the combined central station/remote processor should be considered. If appropriate central station computing equipment is available at a site selected for a prototype residential photovoltaic system installation which can be hardwired to a remote microprocessor/peripheral system developed as slaved units to the computer, then the central station option becomes a viable approach. Telephone charges are eliminated and the computer in all probability services other base remote operations to which charges can be prorated. Since this represents a unique situation at some potential sites, it is mentioned here but obviously not included as a possible option in the foregoing comparative systems analysis.

Table 3-27 lists a variety of equipment options that could meet the requirements as set forth for the data acquisition and control functions previously outlined. These test equipment options were combined into a number of test systems and their operational features compared. Table 3-28 presents this comparative analysis.

The data acquisition and control system that most adequately meets the requirements when considering both the operational and cost aspects is the minicomputer system option. This system includes, in addition to the processor with 32k main memory, two 2.4 megabyte disc drives, a real time operating program, background/foreground capability, high level programming, a computer compatible 9-track magnetic tape unit, line printer, a graphic CRT/terminal/hard copier unit, 72 analog input channels and 80 relay closure output channels. All subsystems of this modular minicomputer system are readily expandable to meet possible future growth requirements.

Table 3-27. On-Site Test Equipment Options

	System Test Function		
Equipment Option	Load Control	PVS Override Control	Data Acquisition
Meters and Registers			X
Manual PVS Disconnect Devices		X	
Manual Turn On/Off of Appliances/Lighting	X		
Automatic Timers Turn On/Off Appliances/ Lighting	X		
General Purpose Data Acquisition Unit (With data storage and print peripherals)			X
Microprocessor Controlled Data Acquisition and Control System (with data storage, print and graphic CRT peripherals)	X	X	X
Minicomputer Controlled Data Acquisition and Control System (with data storage, print and graphic CRT peripherals)	X	X	X

3.5.3 INSTRUMENTATION

As presently planned, the prototype PVS to be initially installed in the residential home will contain the solar arrays and a maximum power tracker controlled inverter and be tied in parallel with the electrical utility. Depending on the house electrical load demand, the PVS can provide the entire load, be supplemented by utility power or feedback to the utility any excess power available.

The instrumentation for this PVS configuration, designated Stage I, will include the transducers depicted in Figure 3-55. A summary of the number and type of analog channels is presented on page 3-133.

Table 3-28. On-Site Test System Options

Test System	Operational Features
• Meters and Registers • Manual PVS Disconnect Devices • Manual Turn On/Off of Appliances/Lighting	• Manual data taking on log sheets • No real time correlation of data • Personnel on at least two shifts to record data and operate appliances/lighting • Special testing would require manual set-up, data-taking and reduction (or additional equipment; e.g., IV curve generation would require an X-Y plotter) • Extensive follow-on effort for data conversion and reduction • Considerable delay in obtaining reduced data • Extensive auxiliary equipment for automatic alarming • Considerable number of integrating type readout meters
• Meters and Registers • Manual PVS Disconnect Devices • Automatic Timers Turn On/Off Appliances/Lighting	• Same as manual system above with exception of reduction of manual effort for turn on/off of appliances/lighting
• General Purpose Data Acquisition unit (with data storage and print peripherals) • Manual PVS Disconnect Devices • Automatic Timers Turn On/Off Appliances/Lighting	• Eliminates manual effort associated with data logging • Real time correlation of data • Automatic alarming capability • Printout of sensor data on site converted to engineering units • General purpose data acquisition unit cannot provide extensive processing of data. Therefore, stored data requires reduction at a central computer site • Peripheral data storage device (e.g., cassette, cartridge, floppy disc, or magnetic tape reel) • Considerable delay in obtaining data requiring processing, due to manual transmittal of stored data medium (Note: automatic transmission of data by phone line to central station either real time or a number of times daily is not cost effective in view of the limited number of PVS sites presently planned) • Expensive adjunct electromechanical integrators required for on-site integrated values (e.g., insolation, kW-hrs, etc.) • PVS override controls require manual operation • Special testing would require manual set-up, some data taking, and reduction of data
• Microprocessor Controlled Data Acquisition and Control System (with data storage, print and graphic CRT peripherals)	• Provides all the advantages of using a general purpose data acquisition unit with added capability of processing all the data on-site • Handle load control and PVS override control programs automatically, in addition to data acquisition and processing requirements • Addition of graphic CRT peripheral particularly useful for displaying trend data • Permits automating special testing • Considerable hardware/software development project using microprocessor system • Cannot program on-site while operational programs in progress • Programming changes could become involved
• Minicomputer controlled data acquisition and control system (with data storage, print and graphic CRT peripherals)	• Same as microprocessor system above but without need for considerable hardware/software development • Real time operating programs available from minicomputer manufacturers, permitting multi tasking capability as well as foreground/background operation (programming while operational programs in progress) • Programming changes can be readily executed • Considerable expansion capability for addition of system test functions over and above the three presently defined as basic requirements (load control), PVS override control, and data acquisition)

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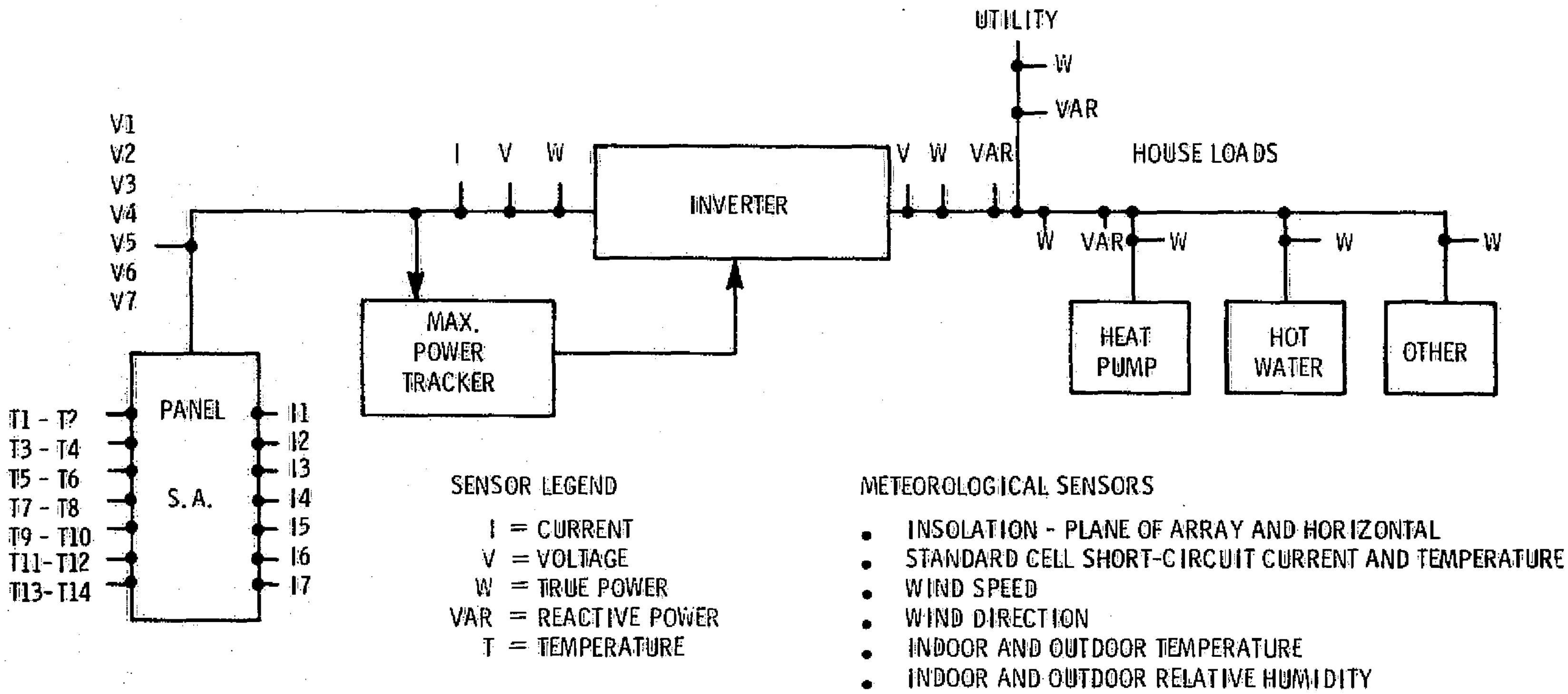


Figure 3-55. Stage I Instrumentation

Transducer Category	Number of Channels
Meteorological	10
Temperature (T)	14
DC Voltage (V)	8
AC Voltage (V)	1
DC Current (I)	8
DC True Power (W)	1
AC Reactive Power (VAR)	3
AC True Power (W)	6
Total	51

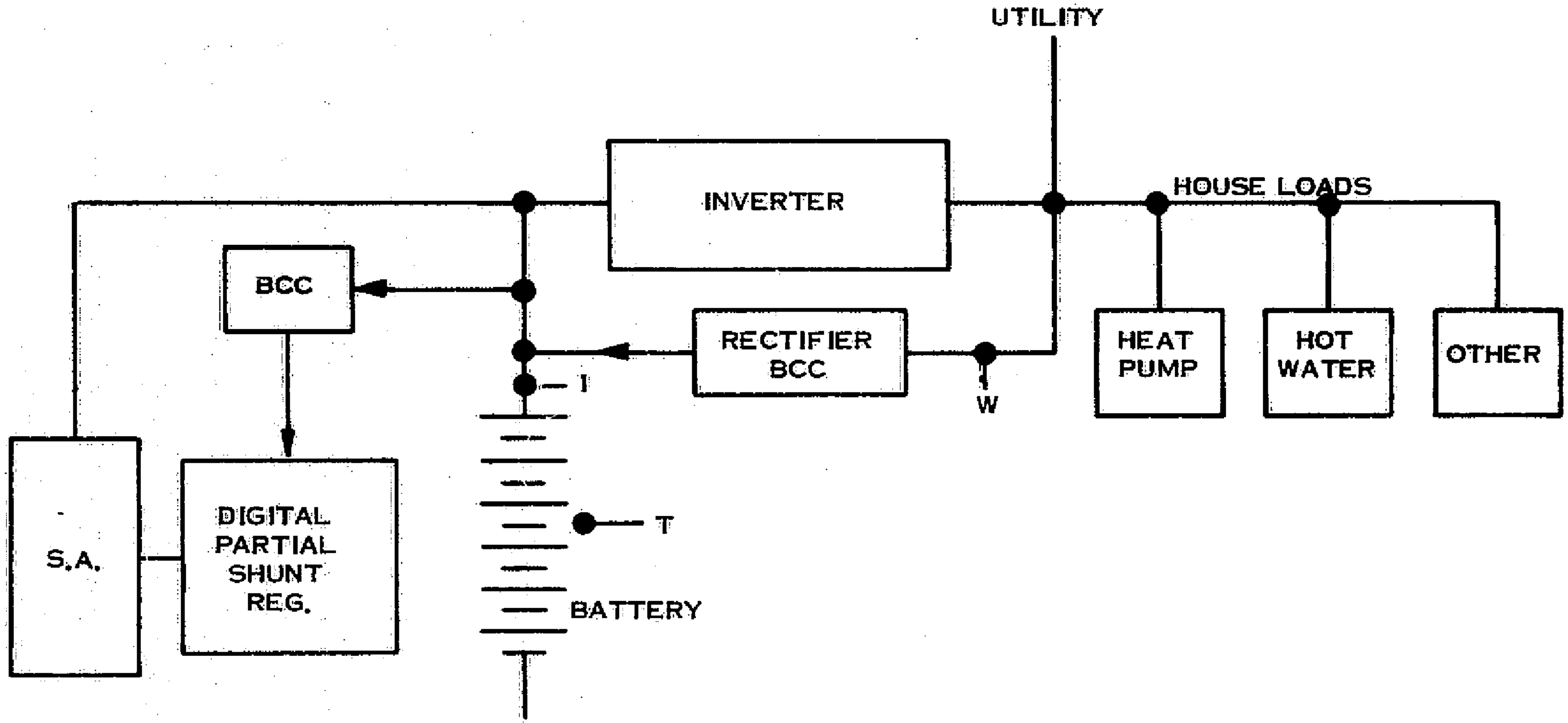
Power factors are calculated from the measured true power and reactive power, and where voltage is also measured, the total current can be readily determined.

The Stage II PVS installation will include a battery storage system as well as utility nighttime battery charging capability. Three additional transducers (as indicated in Figure 3-56) will be added to those provided in Stage I, increasing the total analog channels to 54. The three additional transducers include battery temperature (T), battery charge/discharge current (I), and utility true power (W) fed to the battery.

A listing of required transducers by specific type, their point of application in the system, and the output range requirements to insure compatibility with display/data acquisition equipment is presented in Table 3-29. In addition, a typical potential supplier for each transducer, the designated model number, its accuracy and catalog price are provided.

3.5.4 DATA ACQUISITION, DISPLAY AND CONTROL EQUIPMENT

Figure 3-57 presents a pictorial layout of the RPST Data Acquisition, Display and Control Equipment. A Data/Control Room contains a transducer/signal conditioning rack, two bays of computer equipment and computer associated peripherals. The PVS Components Room, to be located adjoining the Data Control Room, houses the major components of the photovoltaic system as well as the computer controlled PVS control relay rack. As previously indicated, these relays will permit computer override of the photovoltaic system self-contained control system. A display panel located in the recreation room will provide PVS operating status and selected performance data. By providing a visual presentation of system operation and conditions and the energy distribution of the PVS, the display panel will serve as a very effective educational device. In addition, this panel will complement the computer in the troubleshooting mode. A separate electrical utility line is required for powering all the instrumentation, data



SENSOR LEGEND

I = CURRENT
T = TEMPERATURE
W = TRUE POWER

NOTE: SENSORS INDICATED TO BE ADDED TO THOSE INSTALLED IN STAGE I

Figure 3-56. Stage II Instrumentation

Table 3-29. Instrumentation List

MEASUREMENT	SENSOR TYPE	LOCATION(S)	POTENTIAL SUPPLIER	MODEL NO.	OUTPUT RANGE	ACCURACY	UNIT COST	QUANTITY REQD.	TOTAL COST
INSOLATION	STANDARD CELL 2CM X 2CM	PLANE OF SOLAR ARRAY	LeRC	--	0-120MV	--	--	1	--
	PYRANOMETER	PLANE OF SOLAR ARRAY	EPPLY LABORATORY	8-48	0-14.5MV		$590	2	$1080
		HORIZONTAL PLANE				± 1.5% WITH TEMPERATURE COLL.			
	SIGNAL CONDIT.	(FOR PYRANOMETER IN PLANE OF ARRAY)	TEXAS ELECTRONICS	PA-03-1	0 TO ~1V (TO BE BASED ON PYRANOMETER CAL. CURVE)	--	41	1	41
WIND SPEED	3 CUP ANEMOMETER WITH A.C. GENERATOR	ROOF MAST	"	SYSTEM 3011 TV-114 (A.C.GEN.)	0-450 MV (0-45M/SEC)	± 1%	204	1	204
	SIGNAL CONDIT.	"	"	SC-11-2	--		23		23
WIND DIRECTION	WIND VANE WITH POTENTIOMETER	ROOF MAST	"	SYSTEM 3010 TD-104P(0-360°)	0-360 MV (0-360°)	± 1% 0-357° ± 3% 357-360°	214	1	214
	SIGNAL CONDIT.	--	"	SC-10-2			35		35
OUTDOOR TEMP.	LINEAR THERMISTOR RESISTOR NETWORK	ROOF MAST	"	SYSTEM 3015 TD-101 ENCLOSURE TT102	0-500MV (-40+50°C)	SENSOR ± 1°F -20 TO 110°F ENCL. ± 1°F 95° TO 110°F	95	1	95
	SIGNAL CONDIT.	--	"	SC-15-1			67		67
INDOOR TEMP.	SAME AS OUTDOOR TEMP. SENSOR WITHOUT ENCLOSURE						45 67	1	45 67
OUTDOOR RELATIVE HUMIDITY	HYDROSCOPIC INORGANIC SENSING ELEMENT AND LVDT	ROOF MAST	"	SYSTEM 3013 2013	0-1V (0-100% RH)	± 5% 5-15% RH ± 2% 16-95%RH ± 4% 96-100% RH	223	1	223
	SIGNAL CONDIT.	--	"	SC-13-1			177		177
INDOOR RELATIVE HUMIDITY	SAME AS OUTDOOR RELATIVE HUMIDITY WITH FLANGE MOUNTING						223 177	1	223 177
DC VOLTAGE	VOLTAGE DIVIDER METAL FILM PRECISION RESISTORS 1/2 WATT; 300V 1KΩ RESISTOR 294KΩ RESISTOR	ARRAY OUTPUT BUS INVERTER INPUT BUS	TRW/IRC	CCB	0-1V	± 0.5%	--	8 SETS	--

Table 3-29. Instrumentation List (Continued)

MEASUREMENT	SENSOR TYPE	LOCATION(S)	POTENTIAL SUPPLIER	MODEL NO.	OUTPUT RANGE	ACCURACY	UNIT COST	QUANTITY REQD	TOTAL COST
DC CURRENT	SHUNT TO AMP; 100 MV	OUTPUT LINES FROM EACH ARRAY SUPPLIER	EMPRO	TYPE HA	0-100 MV	<+0.02% CHANGE IN RESISTANCE FROM 10-70°C	$10	7	$70
	SHUNT 75 AMP; 100MV	IN SERIES WITH BATTERY	"	"	"	"	10	1	10
	SHUNT 50 AMP; 100 MV	INPUT LINE TO INVERTER	"	"	"	"	10	1	10
	SHUNT/ISOLATION/ AMPLIFIER	(ACROSS ALL DC SHUNTS)	SCIENTIFIC COLUMBUS	6271A	0-1 ma	± 0.5%	238	9	2142
DC POWER	ELECTRONIC MULTIPLIER	INPUT TO INVERTER	"	6268	0-1 ma	± 0.5%	500	1	500
	SHUNT 75 AMP; 100 MV	(USED WITH ELECTRONIC MULTIPLIER)	EMPRO	TYPE HA	0-100 MV	<+0.02% CHANGE IN RESISTANCE FROM 10-70°C	10	1	10
AC VOLTAGE	VOLTAGE TRANSDUCER HALL EFFECT	INVERTER OUTPUT	SCIENTIFIC COLUMBUS	VT-11042-1	0-1 ma	± 0.25%	70	1	70
AC TRUE POWER	WATT TRANSDUCER HALL EFFECT	INVERTER OUTPUT UTILITY LINE INPUT TO HOUSE INPUT TO HEAT PUMP INPUT TO HOT WATER INPUT TO DIVERSIFIED LOAD LINE FROM UTILITY TO BATTERY	"	XL31K5A2	0-± 1 ma	± 0.25%	272	7	1904
	CURRENT TRANSFORMER 50/5 A RATIO BURDEN 0.5	(TWO FOR EACH WATT TRANSDUCER)	GENERAL ELECTRIC	TYPE JKMO	0-5a	0.3% ACCURACY CLASS	78	14	1092
AC REACTIVE POWER	VAR TRANSDUCER HALL EFFECT	OUTPUT OF INVERTER UTILITY LINE INPUT TO HOUSE	SCIENTIFIC COLUMBUS	XLV31K5A2	0-± 1 ma	± 0.25%	$285	3	855
	CURRENT TRANSFORMER 50/5 A RATIO BURDEN 0.5	(TWO FOR EACH VAR TRANSDUCER)	GENERAL ELECTRIC	TYPE JKMO	0-5a	0.3% ACCURACY CLASS	78	6	468

Table 3-29. Instrumentation List (Continued)

MEASUREMENT	SENSOR TYPE	LOCATION(S)	POTENTIAL SUPPLIER	MODEL NO.	OUTPUT RANGE	ACCURACY	UNIT COST	QUANTITY REQD	TOTAL COST
TEMPERATURE	THERMOCOUPLE COPPER CONSTANTAN (TYPE T) EXTENSION WIRE - 24 GAUGE	TWO ON EACH OF SEVEN ARRAY PANELS ONE ON STD. CELL ONE ON BATTERY	OMEGA	TT-T-24	0-5 MV	± 1 1/2%	25¢/ FT.	1000 FT.	250
	MALE CONNECTOR	(USED WITH THERMOCOUPLE WIRE)	"	ST	--	--	3	15	45
	JACK PANEL 24 FEMALE TYPE ST CONNECTORS	"	"	SJP-2-24-24T	--	--	108	1	108
	UNIFORM TEMP. REFERENCE 32 CHANNEL	"	KAYE INSTRUMENTS	UTR-AS RTD-20 PROBE	--	PROBE REPEATABILITY ±0.03°C ACCURACY ±0.14°C.	490	1	490

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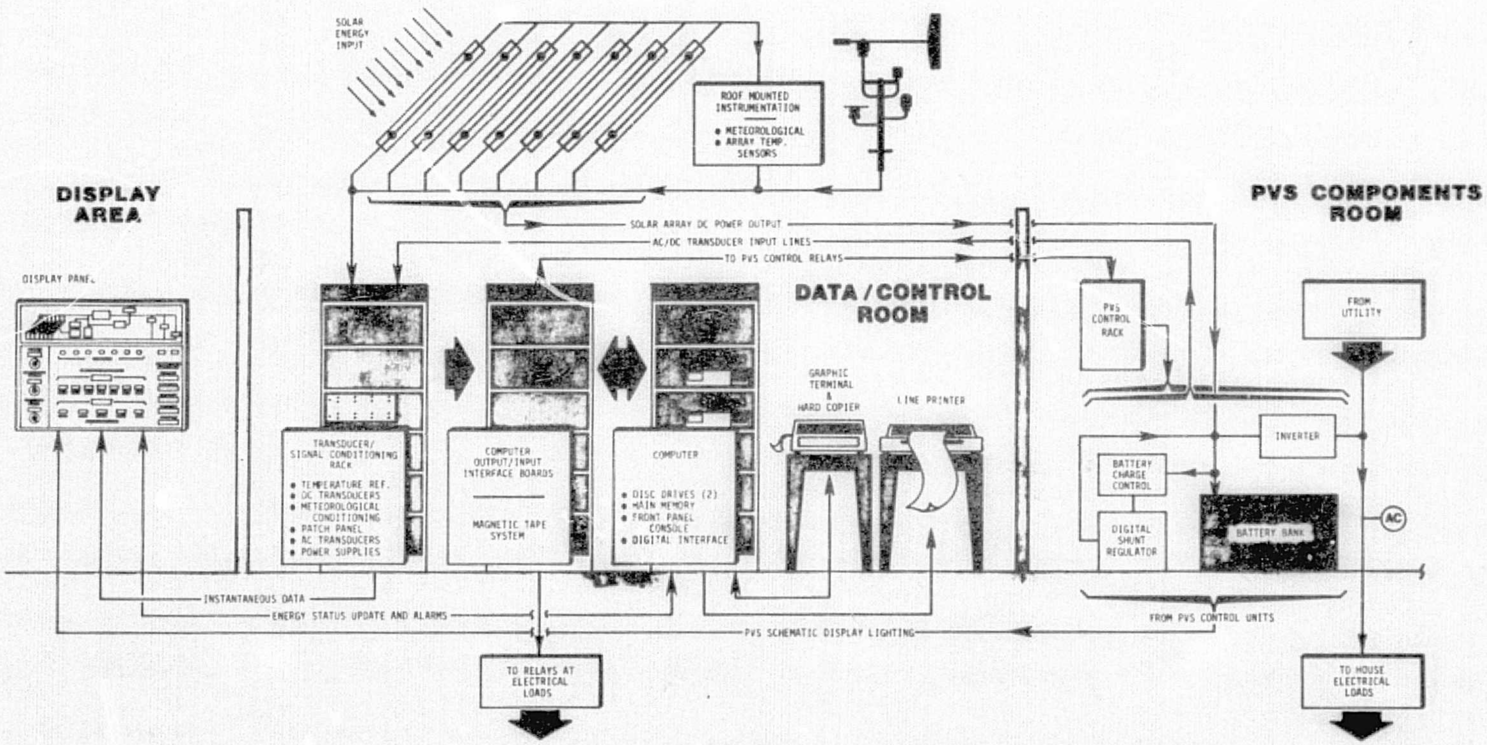

Figure 3-57. Pictorial Layout of Photovoltaic House Equipment

acquisition and control system, and the display panel. This line will be separate (its own utility meter) from the utility line feeding the house load in conjunction with the PVS.

Signals from roof mounted and inside-the-house meteorological transducers as well as temperature sensors mounted on the solar cell modules will be fed into the transducer/signal conditioning rack in the Data Acquisition/Control Room. Wires from the individual solar cell circuits will also be run into current, voltage and power transducers located in this same rack. Conditioned signals will then be fed to the multiplexing/analog to digital conversion modules of the computer Industrial Control Subsystem (ICS) as well as to the display panel. Computer outputs processed through the ICS will branch out to the display panel with cumulative electrical energy status and alarm data, to the PVS control relay rack, and to relays located throughout the house for activating appliance and lighting circuits. Signals from PVS components will activate lights on the display panel schematic to depict system operational status.

The computer system (Figure 3-58) is all Digital Equipment Corporation (DEC) hardware and software (see Section 3.5.4 for minicomputer vendor selection). The heart of the system is a PDP 1134 minicomputer with 32k main memory and two 2.4 megabyte disc drives. An RSX-11M software package is provided and high level programming in both Fortran and Basic will be possible. A DR 11C digital interface tied into the DEC bus and located in the same cabinet as the computer will provide the interface with the Display Panel. DECs Industrial Control Subsystem (ICS) located in an adjoining rack operates under program control as an input/output device, interrogating analog inputs and driving both analog and digital outputs. The ICS is a rack mounted file capable of holding up to 16 functional I/O modules with a self-contained power supply, printed circuit backplane and interface and control module for operation with a PDP-11 minicomputer. I/O modules initially installed will provide 72 analog input channels (5 modules) and 80 relay closure output channels (5 modules) which are more than adequate for the required 54 sensor input channels and the 73 relay closure (see Table 3-30) outputs. Since only 10 modules will initially be installed in the ICS, expansion capability exists for six additional I/O analog or digital modules. Located in the same rack with the ICS is a 9-track magnetic tape system that uses industry standard 800-bpi NRZ1 recording format. The tape unit consists of a master tape drive, controller and power supply. The 600-foot, 7-inch diameter tape reel has a capability of 5 million 8-bit characters which will permit storing approximately ten days of data based on the recording interval specified below. An on-line interactive CRT terminal that has graphics capability and hard copy printout, and a 180 character/second matrix line printer complete the complement of DEC peripherals provided in this system.

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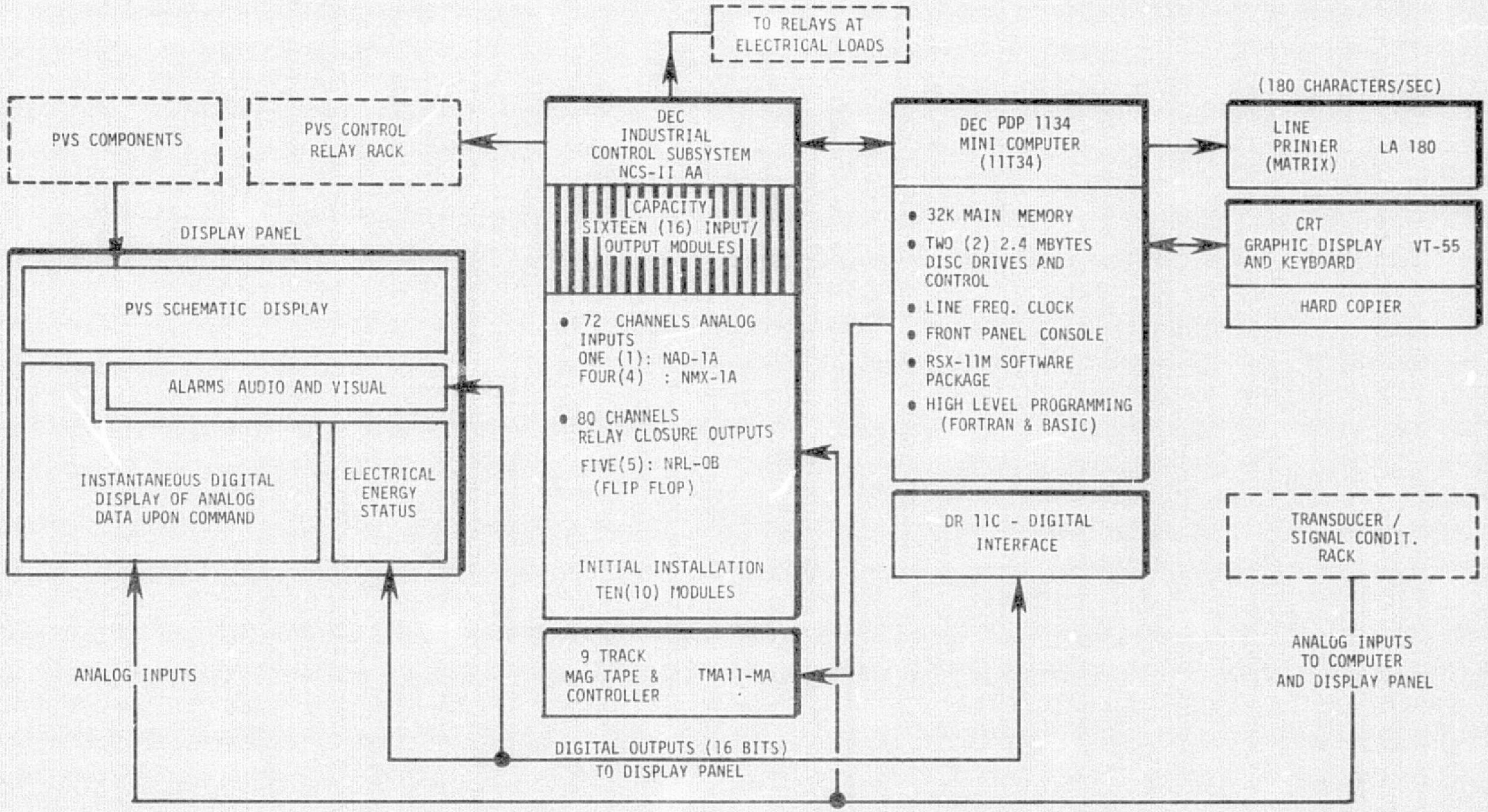

Figure 3-58. Data/Control Processing Equipment Definition

Table 3-30. Computer Output Channel Requirements

	No. of Channels
I) For Automatic Operation of House Electrical Loads:	
Lighting	23
Clothes Dryer	1
Clothes Washer	1
Range	1
Dishwasher	1
Television	1
Hot Water Heater	1
Hot Water Dump	1
Heat Pump	2
Total for Electrical Load Control	32
II) PVS Controls (Override of Self Regulated Control System):	
Solar Array Circuits	37
Inverter Input Bus	1
Inverter Output Bus	1
Total House Load Bus	1
Utility Battery Charge Bus	1
Total for PVS Override Controls	41
Total Computer Output Channels	73

Every second the computer will automatically scan those analog input channels (13 for a Stage II installation) containing data that will be integrated (e.g., insolation, power and battery current). Every minute all other channels (41) will be scanned for instantaneous data. After a 5-minute interval, the integrated values and the average of 5 samples of instantaneous data will be stored on disc and permanently recorded on magnetic tape. The computer will also combine six sets of 5-minute data for disc storage, magnetic tape recording and printout on the line printer as a 30 minute report. Two hours of 5-minute data and 24 hours of 30-minute data will be stored on disc file for demand callout by the CRT terminal in the form of alphanumeric or graphic data. Out-of-limit conditions determined from the one minute scans will be automatically printed on the line printer and recorded on magnetic tape. The CRT terminal will provide the prime operator computer interface for demand data, limit setting and operational mode selection.

The Display Panel consists of the following four subsystems:

1. A schematic presentation of the photovoltaic system and house loads
2. Digital displays of instantaneous analog data upon command
3. Digital displays of electrical energy status continuously updated
4. Audio and visual alarms activated on component out-of-limit or failure conditions

A detailed layout of the Display Panel is depicted in Figure 3-59. The schematic presentation at the top of the panel contains electrical lights for indicating the on/off operating status of major components of the system. These lights will be activated directly from the PVS components. Two lights are provided for the battery simulator which indicate the charge or discharge state. The series of lights that are activated on the schematic at any particular time provides an indication of the system operating mode.

The computer will feed integrated energy data for display to the section of the Display Panel designated ELECTRICAL ENERGY STATUS. The data will consist of intgrated energy provided by the PVS and the utility for both house electrical loads and battery charging. Battery state-of-charge in percent of rated capacity will also be displayed. All this data will be updated on a continuous basis by the computer over an entire month. At the start of a new month, the computer will reset all the digital readouts in this section of the Display Panel to zero (with the exception of the battery state-of-charge), indicate the new month, and commence the updating process. The computer will also signal an out-of-limit condition and PVS component failure by activating audio and visual devices in the section of the panel labeled ALARMS.

The instantaneous data section of the Display Panel consists of a series of pushbuttons and selector switches that present meteorological, electrical, temperature and power data on demand. Selector switch positions correlate with alphanumeric markings on the schematic for each of the array panel temperature and current measurements as well as the power measurement points throughout the system. Engraved lettering associated with each pushbutton switch indicates the particular meterological, current or voltage measurement available.

3.5.5 MINICOMPUTER SYSTEM COMPARATIVE COST ANALYSIS

A general specification for the minicomputer system (including peripherals) that meets test equipment requirements was prepared in order to obtain a cost comparison of various manufacturer's offerings. The prime elements of this specification include the following:

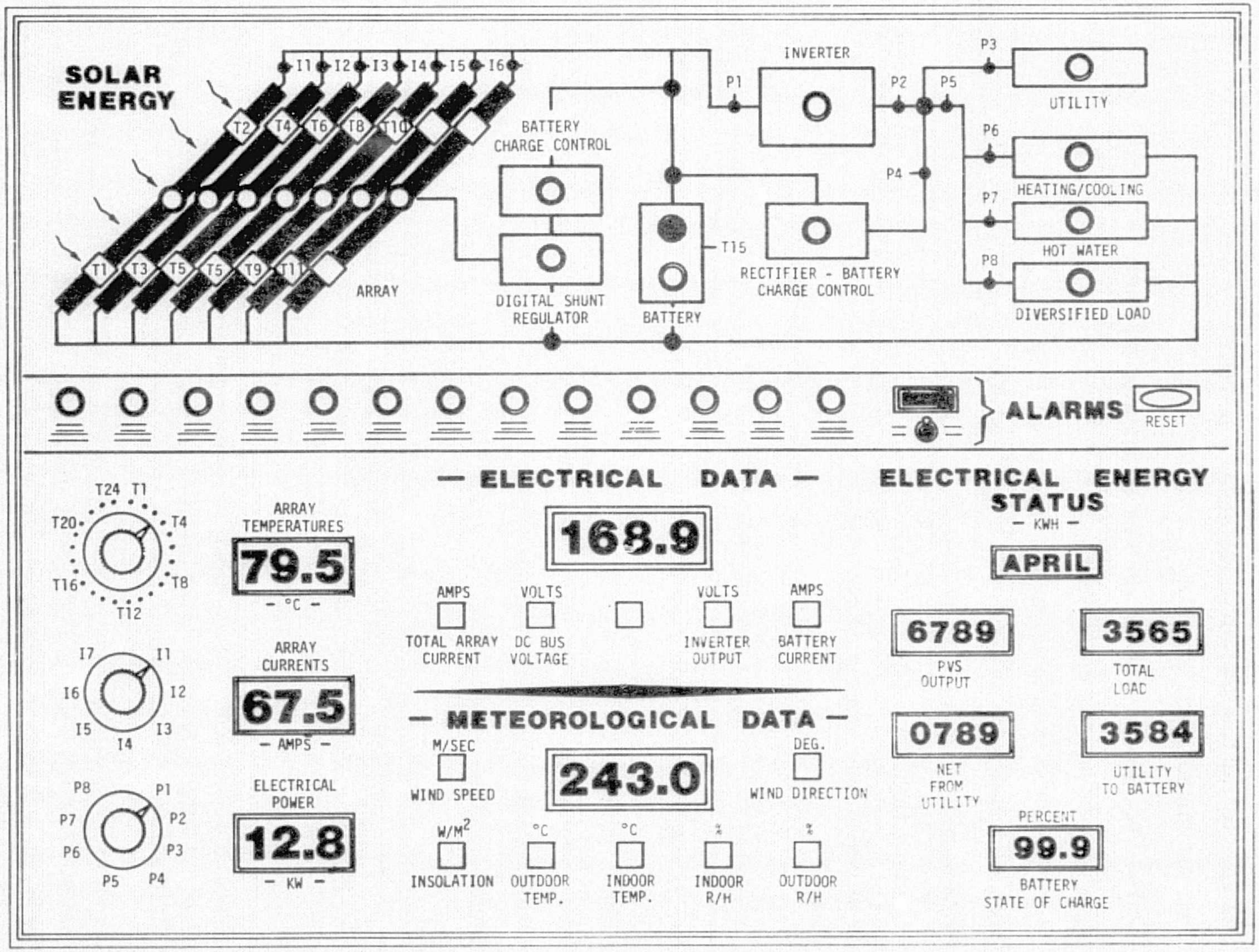

Figure 3-59. Layout of Display Panel

Minicomputer System General Specification

1. Minicomputer
2. 32k (16 bit word) solid state memory
3. Two 2.4 megabyte disc drives
4. Matrix line printer (165 or 180 characters per second)
5. Graphic CRT terminal and hard copier
6. 9-Track magnetic tape drive (800 bpi; 45 or 75 ips)
7. Real time operating system; multi-tasking and background/foreground capability
8. Fortran and Basic high level programming
9. 64 analog input channels
10. 80 digital (relay contact closure) output channels
11. 16-bit general purpose interface (output to display panel)

The total list price (no OEM or END USER discount included) for the above listed equipment at the time of investigation (May 1976) showed very close correlation for four of the seven potential suppliers as listed below:

1. Digital Equipment (PDP 11/34)
2. Data General (Nova 830)
3. Hewlett Packard (HP 21MX/2108A)
4. Modular Computer (Modcomp 11/221)

Digital Equipment (DEC) provides 72 analog input channels as opposed to the specified 64 because of their particular modular arrangement. All of the above suppliers, with the exception of DEC, do not make a graphic CRT terminal and hard copier, but do provide the appropriate interfaces for the Textronix CRT terminal 4006-1 and hard copier 4631. The list price of this Textronix's equipment was added to each of the minicomputer supplier's prices, with the exception of DEC. DEC manufactures a combined graphics terminal and hard copier unit, VT55, which they include as part of a central processor package price. Another variation from the spec involves the use of core main memory instead of solid state by Data General and Modular Computer.

The price of the DEC equipment could be still further reduced by the use of a slower speed magnetic tape drive (Model TS03; 12.5 IPS, 600-foot reel). This unit, which is adequate for the test program, was not called out in the general specification since the other suppliers do not provide a slow speed magnetic tape unit. In order to provide a common base for comparison, the higher speed unit was specified.

The three other potential suppliers investigated include IBM (System 7), Honeywell Information System Division (725S), and Honeywell Process Control Division (HS 4400). Their offerings were much higher priced since their basic equipment configuration was considerably higher powered than necessary for this particular application.

3.5.6 TEST PROCEDURES

3.5.6.1 Electrical Load Control and Simulation

In order to establish a simulation plan for electrical utilization in the RPST, a hypothetical family was selected and a typical daily activities schedule developed.

Since there are no published representative schedules of activities for occupants of residences and the characteristics of family activities vary widely based on geographic and other considerations, the developed activities schedule affecting electrical utilization, as presented in Table 3-31, is based on assumptions by the authors. The occupants are assumed to be a family of six, composed of a father, mother, two girls (ages 13 and 17) and two boys (ages 7 and 9). The family size and activities schedule selected are commensurate with the floor plan of the four bedroom single family residence described in Section 3.3.3.

Within the family activities schedule defined, typical appliances and lighting fixtures were selected for automatic operation under minicomputer control. The appliances selected for installation in the RPST include those that represent the major energy users, such as range, clothes washer and dryer, dishwasher, television, refrigerator and freezer. The minor appliances and electrical devices that are commonly found in most homes today (e.g., vacuum cleaner, toaster, clock radio, disposal, iron, etc.) were not included since they represent a very small percentage of the total yearly electrical energy load and would add considerable cost for automating their functions. An electric resistance type hot water heater and heat pump with supplemental electric resistance heating completes the all-electric house equipment.

Table 3-32 presents a listing of the selected appliances/lighting, their automatic control configuration and the necessary typical control components. Daily operating time intervals and estimated electrical energy consumed by each device, as well as their contribution to the total yearly electrical load is also defined. The appliance/lighting on-off control is effected by computer flip-flop relay outputs which impress or remove a low level voltage signal (24 Vdc) to a secondary relay whose contacts control the power to the specific electrical device. The low level voltage was selected to safely permit installation of control wiring from the Data/Control Room to the secondary relay located at the appliance without the need for conduit enclosures. Each of the appliances/lighting, with the exception of the refrigerator, freezer, heat pump and hot water heater, will operate under computer control for the time periods specified in Table 3-31. Those appliances under computer control require initial set-up and proper wiring of their

Table 3-31. Typical Daily Activities Schedule for a Family of Six

		Time of Day
Lighting and Hot Water Use Related		
Master Bedroom	Mother dresses	0645-0700
	Father dresses	0715-0730
	Mother/Father prepares for bed	2230-2300
Master Bathroom	Father	0630-0645
	Mother	0700-0715
	Father	2230-2245
	Mother	2245-2300
Kitchen	Breakfast preparation	0700-0830
	Breakfast clean-up	0830-0900
	Lunch preparation eating and clean-up (Mother)	1200-1230
	Dinner preparation	1700-1830
	Dinner Clean-up	1900-1930
Breakfast Area	Breakfast (in shifts)	0730-0900
Dining Room	Dinner meal (entire family)	1830-1900
Living Room	Miscellaneous activities	1900-2230
Recreation Room	Miscellaneous activities (children)	1700-1830
		1900-1930
		2030-2130
2nd Bedroom	17-year old Daughter dresses	0715-0730
	Prepares for school	0800-0830
	Studies	1930-2030
	Prepares for bed	2230-2300
2nd Bathroom	17-year old Daughter	0700-0715
	13-year old Daughter	0715-0730
	7-year old Boy	2030-2045
	9-year old Boy	2045-2100
3rd Bedroom	13-year old Daughter dresses	0800-0830
	Studies	1930-2030
	Prepares for bed	2130-2200
Powder Room (downstairs)	7-year old Boy	0745-0800
	9-year old Boy	0800-0815
	Mother	1030-1045
	Children (after school)	1545-1600
	Family (pre-dinner wash up)	1845-1900
4th Bedroom	9 and 7-year olds dress	0800-0830
	Study	1930-2030
	Prepare for bed	2030-2100
Laundry Room	Clothes washing/drying [illegible]	[illegible]

	Dinner preparation	1700-1830
	Dinner Clean-up	1900-1930
Breakfast Area	Breakfast (in shifts)	0730-0900
Dining Room	Dinner meal (entire family)	1830-1900
Living Room	Miscellaneous activities	1900-2230
Recreation Room	Miscellaneous activities (children)	1700-1830
		1900-1930
		2030-2130
2nd Bedroom	17-year old Daughter dresses	0715-0730
	Prepares for school	0800-0830
	Studies	1930-2030
	Prepares for bed	2230-2300
2nd Bathroom	17-year old Daughter	0700-0715
	13-year old Daughter	0715-0730
	7-year old Boy	2030-2045
	9-year old Boy	2045-2100
3rd Bedroom	13-year old Daughter dresses	0800-0830
	Studies	1930-2030
	Prepares for bed	2130-2200
Powder Room (downstairs)	7-year old Boy	0745-0800
	9-year old Boy	0800-0815
	Mother	1030-1045
	Children (after school)	1545-1600
	Family (pre-dinner wash up)	1845-1900
4th Bedroom	9 and 7-year olds dress	0800-0830
	Study	1930-2030
	Prepare for bed	2030-2100
Laundry Room	Clothes washing/drying, ironing, etc.	0900-1030
Front Entrance/Porch		1800-0730
Rear Entrance/Patio		1800-2300
Driveway (Spot Light)-Individuals Leaving with Cars		1945-2000
		2045-2100
Upper Level Hallway (and stairs)		1700-2300
Appliance Use Related		
Breakfast Preparation	for Mother and Father for Children	0700-0730
		0730-0830
Dinner Preparation		1700-1830
Clothes Washing		0900-0930
Clothes Drying		0935-1045
Dishwashing		1930-2030
Television	Mother	1100-1200
	Children	1600-1700
	Family	1900-2230

Table 3-32. Appliance/Lighting Automatic Operation Definition

APPLIANCE/ DEVICE	RECOMMENDED TYPE	SETTINGS	AUTOMATIC CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL NOS.	CONTROL COMPONENTS LOCATION	DAILY OPERATING PERIOD(S)	APPROX DAILY KWHRS.	APPROX YEARLY KWHRS
RANGE	30" FREESTANDING (ADD RAISED SCREEN MESH ENCLOSURE OVER SURFACE UNITS FOR PERSONNEL SAFETY)	ONE LARGE SURFACE UNIT SET TO MEDIUM. ONE SMALL SURFACE UNIT SET TO MEDIUM OVEN SET TO BAKE AT 400°F. (NO ACTUAL COOKING NECESSARY)	RELAY N.O. CONTACTS ACROSS 240 V POWER INPUT LINES TO RANGE. RELAY COIL ENERGIZED BY COMPUTER OUTPUT CLOSURE. COMPUTER OUTPUT CLOSURE TO REMAIN CLOSED FOR OPERATING PERIOD SPECIFIED.	RELAY: GENERAL PURPOSE POWER RELAY. 240 V.AC, 30A CONTACTS DPST-N.O. 24 V. DC COIL (NOTE: RANGE SETTINGS TO REMAIN FIXED AS SPECIFIED TO PREVENT RELAY OVERLOAD	POTTER & BRUMFIELD PRD7DGØ-24 (WITH DUST COVER)	AT APPLIANCE	0710-0725 1700-1830	3.23	1178
CLOTHES WASHER	TWO CYCLE UNIT WITH AGITATOR THAT SIMULATES LOAD (EXTENDED FINS BOLTED ON TO AGITATOR TO SIMULATE STANDARD 7 LB LOAD)	TIMER KNOB PULLED OUT. SET WASH WATER TEMP. TO WARM AND RINSE TEMP. TO COLD. WATER LEVEL SETTING TO MED. (NO LOAD NECESSARY)	RELAY N.O. CONTACT IN TIMER MOTOR CIRCUIT COMPUTER OUTPUT CLOSURE (TO REMAIN CLOSED FOR APPROX. 2 1/2 MINUTES) ENERGIZES RELAY WHICH ADVANCES WASHER TIMER MOTOR FROM OFF TO WASH POSITION. WASHER WILL AUTOMATICALLY RUN THROUGH CYCLE (APPROX. 30 MIN. RUN TIME).	RELAY: GENERAL PURPOSE. 120 V.AC, 5A CONTACTS 24 V.DC COIL SPDT	POTTER & BRUMFIELD KA5DY- 24 (WITH DUST COVER)	AT APPLIANCE	0900-0930	0.23	84
CLOTHES DRYER	SINGLE CYCLE UNIT WITH PUSH TO START FEATURE	BY-PASS PUSH-TO-START SWITCH WITH JUMPER. DISCONNECT TIMER MOTOR & PLACE TIMER DIAL IN TIMED-DRY POSITION.	RELAY N.O. CONTACT IN NEUTRAL LINE OF ELECTRICAL POWER INPUT TO DRYER. COMPUTER OUTPUT CLOSURE WILL POWER DRYER DRIVE MOTOR. COMPUTER OUTPUT CLOSURE TO REMAIN CLOSED FOR OPERATING PERIOD SPECIFIED.	RELAY: GENERAL PURPOSE. 120 V.AC, 10A CONTACTS 24 V.DC COIL SPDT	POTTER & BRUMFIELD KA5DG- 24 (WITH DUST COVER)	AT APPLIANCE	0935-1015	3.3	1204

Table 3-32. Appliance/Lighting Automatic Operation Definiton (Continued)

APPLIANCE/ DEVICE	RECOMMENDED TYPE	SETTINGS	AUTOMATIC CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL NOS.	CONTROL COMPONENTS LOCATION	DAILY OPERATING PERIOD(S)	APPROX. DAILY KWHRS.	APPROX. YEARLY KWHRS.
DISHWASHER	SIX CYCLE WASHER WITH PUSH-TO-START FEATURE	BYPASS PUSH-TO START SWITCH WITH JUMPER CLOSE DOOR SWITCH. SET FOR NORMAL SOIL (NO LOAD NECESSARY).	RELAY N.O. CONTACT IN TIMER MOTOR CIRCUIT. COMPUTER OUTPUT CLOSURE TO REMAIN CLOSED APPROX. 1 MIN.) WILL ENERGIZE RELAY TO START DISHWASHER TIMER MOTOR. DISHWASHER WILL AUTOMATICALLY RUN THROUGH WASH/DRY CYCLE (APPROX. 1 HOUR).	RELAY: GENERAL PURPOSE. 120 V.AC, 5A CONTACTS 24 V. DC COIL SPDT	POTTER & BRUMFIELD KA5DY-24 (WITH DUST COVER)	AT APPLIANCE	1930-2030	0.75	274
TELEVISION	COLOR-SOLID STATE	--	RELAY N.O. CONTACT IN POWER INPUT LINE TO TELEVISION. COMPUTER OUTPUT CLOSURE WILL TURN ON THE TELEVISION. COMPUTER CLOSURE TO REMAIN CLOSED FOR OPERATING PERIODS SPECIFIED.	RELAY: SAME AS ABOVE.	SAME AS ABOVE	AT APPLIANCE	1100-1200 1600-1700 1900-2230	1.1	402
HOT WATER DUMP	--	--	ELECTRICALLY ACTIVATED VALVE (OPERATED BY RELAY N.O. CONTACT) IN HOT WATER FEED LINE TO SINK. COMPUTER OUTPUT CLOSURE TO OPEN VALVE FOR OPERATING PERIODS SPECIFIED.	VALVE: 1/2" ACTUATOR. PRESSURE REGULATOR: 1/2", 3 1/2 GPM. TRANSFORMER: 110/24V. RELAY: SAME AS ABOVE.	TACO 555 569 719 SAME AS ABOVE	USE LAUNDRY ROOM OR POWDER ROOM SINK. "T"-OFF 1/2" HOT WATER LINE TO SINK AND INSTALL VALVE AND PRESSURE REGULATOR. OUTLET SIDE OF VALVE TO SINK DRAIN PIPE (ABOVE TRAP LEVEL & OPEN TO ATMOSPHERE).	0700-0701 0800-0801 0900-0901 1230-1232 1600-1601 1900-1901 2030-2031 2045-2046 2200-2201 2215-2216 2230-2232 2245-2247	-	-

Table 3-32. Appliance/Lighting Automatic Operation Definition (Continued)

APPLIANCE/ DEVICE	RECOMMENDED TYPE	SETTINGS	AUTOMATIC CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL NOS.	CONTROL COMPONENTS LOCATION	DAILY OPERATING PERIOD(S)	APPROX. DAILY KWHRS.	APPROX. YEARLY KWHRS.
REFRI-GERATOR	21 CU.FT., TOP MOUNT. FROST FREE	FRESH FOOD SETTING OF "7" FREEZER SECTION SETTING OF "C" (NO FOOD, NO DOOR OPENINGS)	PLUG INTO 110 V. RECEPTACLE. OPERATES UNDER ITS OWN INTERNAL THERMOSTATIC CONTROLS.	--	--	--	--	5.0	1825
FREEZER	15 CU. FT., UPRIGHT FROST FREE	SET AT "5" (NO FOOD, NO DOOR OPENINGS)	PLUG INTO 110 V. RECEPTACLE. OPERATES UNDER ITS OWN INTERNAL THERMOSTATIC CONTROLS.	--	--	--	--	5.4	1970
HOT WATER HEATER	80 GALLON CAPACITY, UPPER & LOWER 4500 WATT ELECTRICAL HEATERS.	UPPER & LOWER THERMOSTATS SET AT 140°F NORMALLY OPERATE UNDER ITS OWN INTERNAL THERMOSTATIC CONTROLS	RELAY N.C. CONTACTS IN SERIES WITH UPPER AND LOWER HEATER THERMOSTATS. COMPUTER CONTACT CLOSURE TO ACTIVATE RELAY FOR DESIRED LOAD SHAVING PROGRAM.	RELAY: GENERAL PURPOSE. POWER RELAY 240 V.AC, 30A CONTACTS DPST-NC 24 V. DC COIL	POTTER & BRUMFIELD PR08DG0-24 (WITH DUST COVER)	AT APPLIANCE	--	16.8	6132
HEAT PUMP	2 1/2 TON (30,000 BTU/HR) SPLIT TYPE WITH 4.8 KW RESIS-TANCE HEATER	70°F INDOOR TEMP.SETTING. NORMALLY OPERATE UNDER ITS OWN INTERNAL THERMOSTATIC CONTROLS	RELAYS (2OF) WITH N.C. CONTACTS, ONE IN SERIES WITH STARTER COIL RELAYS FOR COM-PRESSOR & INDOOR FAN (FOR COOLING CUT-OFF); THE OTHER IN SERIES WITH STARTER COIL RELAYS FOR RESIS-TANCE HEATER & INDOOR FAN (FOR HTG. CUT-OFF). COMPUTER CONTACT CLOSURE TO ACTIVATE THESE RELAYS FOR DESIRED LOAD SHAVING PROGRAM	RELAY: (2OF): GENERAL PURP. 120 V.AC, 5A CONTACTS, 24 V. COIL DPDT	POTTER & BRUMFIELD KA11DY-24 (WITH DUST COVER)	AT APPLIANCE	-	-	10,500 (EST. FOR 1750 SQ. FT. 2 STORY HOUSE IN LOUISVILLE, KY. WITH 6" ATTIC & 3 1/2" WALL INSULATION. ENERGY UTILIZED WILL VARY WITH TYPE OF CON-STRUCTION, ORIENTATION, INDOOR TEMP. SETTINGS, ETC.)

Table 3-32. Appliance/Lighting Automatic Operation Definition (Continued)

APPLIANCE/ DEVICE	RECOMMENDED TYPE	SETTINGS	AUTOMATIC CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL	CONTROL COMPONENTS LOCATION	DAILY OPERATING PERIOD(S)	APPROX. DAILY KWHRS.	APPROX. YEARLY KWHRS.
LIGHTING	FIXED & PORTABLE (LAMP) LIGHTING-INCANDESCENT & FLUORESCENT (SEE BELOW) LOW VOLTAGE REMOTE CONTROL SWITCHING SYSTEM. INDIVIDUAL LIGHTING CIRCUIT TO CEILING FIXTURE OR WALL OUTLET. (NOTE: A NUMBER OF INDIVIDUAL LIGHTING CIRCUITS CAN BE TIED INTO ONE CIRCUIT BREAKER)	ALL MOMENTARY CONTACT TYPE SWITCHES IN EACH ROOM INITIALLY SET TO "OFF"	TWENTY-THREE (23) MECHANICAL LATCHING TYPE RELAYS ACTIVATED BY COMPUTER CONTACT CLOSURE/ OPENING FOR ON/ OFF OPERATION OF INDIVIDUAL LIGHTING CIRCUITS. WALL MOUNTED (FOR EACH CIRCUIT) PUSH BUTTON TYPE MOMENTARY SWITCH WIRED IN PARALLEL WITH COMPUTER ACTIVATED CIRCUIT TO CONTROL RELAY (TO PERMIT MANUAL OVER-RIDE OF COMPUTER SIGNAL).	RELAY (23 OF): MECHANICAL LATCHING-SPLIT COIL. SPST 24 V.AC COIL (1/2 WAVE RECTIFIED) 125 V.AC, 20A CONTACTS TRANSFORMER (2 OF): 110/24V. 40 V.A CONTINUOUS REMOTE CONTROL INTERFACE (60 OF) CONVERT CONTROL INPUT SIGNAL (ON/OFF) TO MOMENTARY PULSE TO OPERATE RELAY RECTIFIER (2 OF) 1/2 WAVE RECT. 24 V. COMPONENTS CABINET (1 OF): WALL SWITCH (17 OF) PUSH BUTTON, MOMENTARY TYPE 25 V. AC, 3A.	GENERAL ELECT. RR7 RT1 RC1-1 RA16 RB3 RCS2	LIGHTING REMOTE CONTROL COMPONENTS CABINET LOCATED ADJACENT TO HOUSE CIRCUIT BREAKER PANEL		4.625	1685
LIVING ROOM	1 FIXED-INCAND. 2 PORT.- "	100 WATT 100 WATT EA.	-- --	-- --	-- --	-- --	2030-2230 1900-2230	(0.1) (0.7)	
KITCHEN	1 FIXED-FLUORESC.	40 WATT	--	--	--	--	0700-0900 1200-1230 1700-1930	(0.2)	
BKFT. AREA.	2 FIXED- "	40 WATT EA.	--	--	--	--	0730-0900	(0.12)	

Table 3-32. Appliance/Lighting Automatic Operation Definition (Continued)

APPLIANCE/ DEVICE	RECOMMENDED TYPE	SETTINGS	AUTOMATIC CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL NOS.	CONTROL COMPONENTS LOCATION	DAILY OPERATING PERIOD(S)	APPROX. DAILY KWHRS.	APPROX. YEARLY KWHRS.
LIGHTING(CONT) DINING ROOM	6 FIXED - DECORATIVE	40 WATT EA.	--	--	--	--	1830-1930	(0.24)	
RECREATION ROOM	2 FIXED - INCANDES. 2 PORT. - "	75 WATT EA. 100 WATT EA.	-- --	-- --	-- --	-- --	1700-1830 1900-1930 2030-2130	(0.30) (0.2)	
ENTRANCE FOYER	1 FIXED - "	40 WATT	NOT UNDER AUTO. CONTROL	--	--	--	--	--	
LOWER LEVEL HALL	1 FIXED - "	40 WATT	" " " "	--	--	--	--	--	
LAUNDRY ROOM	1 FIXED - "	100 WATT	--	--	--	--	0900-0915 1000-1030	(0.075)	
POWDER ROOM	2 FIXED - FLUORESC.	20 WATT EA.	--	--	--	--	0745-0915 1030-1045 1530-1545 1845-1900	(0.04)	
PVS COMP. ROOM	1 FIXED - INCANDES.	100 WATT	--	--	--	--	--	--	
FRONT ENTRANCE/ PORCH	1 FIXED - "	40 WATT	--	--	--	--	1800-0730	(0.53)	
REAR ENTR./ PATIO	1 FIXED - "	40 WATT	--	--	--	--	1800-2300	(0.20)	
GARAGE	2 FIXED - "	40 WATT EA.	NOT UNDER AUTO CONTROL	--	--	--	--	--	
DRIVEWAY	1 FIXED-SPOTLIGHT	150 WATT	--	--	--	--	1945-2000 2045-2100	(0.075)	
MASTER BEDROOM	2 FIXED - INCANDES. 2 PORT. - "	75 WATT EA. 100 WATT EA.	-- --	-- --	-- --	-- --	0645-0700 0715-0730 2230-2300 2230-2300	(0.15) (0.1)	
2ND BR	2 FIXED - " 1 PORT. - "	60 WATT EA. 100 WATT	-- --	-- --	-- --	-- --	0715-0730 0800-0830 1930-2030 2230-2300 1930-2030	(0.27) (0.1)	
3RD BR	2 FIXED - " 1 PORT. - "	60 WATT EA. 100 WATT	-- --	-- --	-- --	-- --	0800-0830 1930-2030 2130-2200 1930-2030	(0.24) (0.1)	

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Table 3-32. Appliance/Lighting Automatic Operation Definition (Continued)

APPLIANCE/DEVICE DEVICE	RECOMMENDED TYPE	SETTINGS	AUTOMATIC CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL NOS.	CONTROL COMPONENTS LOCATION	DAILY OPERATING PERIOD(S)	APPROX. DAILY KWHRS.	APPROX YEARLY KWHRS.
LIGHTING(CONT).									
4TH BR	2 FIXED-INCAND.	60 WATT EA.	--	--	--	--	0800-0830 1930-2030	(0.18)	
	1 PORT.- "	100 WATT	--	--	--	--	1930-2100	(0.05)	
BEDROOM CLOSETS (4 OF)	4 FIXED- "	25 WATT EA.	NOT UNDER AUTO CONTROL	--	--	--	--	--	
UPPER LEVEL HALL	1 FIXED- "	60 WATT	--	--	--	--	1700-2300	(0.36)	
MASTER BATHROOM	2 FIXED(WALL)-FLUORESCENT 1 FIXED(CEILING) FLUORESCENT	20 WATT EA. 75 WATT	--	--	--	--	0630-0645 0700-0715 2230-2245 2245-2300	(0.115)	
2ND BATH	2 FIXED(WALL)-FLRS. 1 FIXED(CEILING)"	20 WATT EA. 75 WATT	-- --	-- --	-- --	-- --	0700-0730 2030-2100 2200-2230	(0.18)	
ATTIC	1 FIXED- INCANDES.	75 WATT	NOT UNDER AUTO CONTROL	--	--	--	--	--	
BASEMENT	2 FIXED- "	60 WATT EA.	" " " "	--	--	--	--	--	

associated secondary relay contacts as specified under the column headings "SETTINGS" and "AUTOMATIC CONTROL ARRANGEMENT". The refrigerator, freezer, heat pump and hot water heater merely need to be plugged into their power outlets for operation under normal thermostatic control. The heat pump and hot water heater, however, will be capable of computer initiated shutdown (override of their self-contained thermostatic controls) for specific time intervals based on a load shaving program that can be developed as part of the overall test program. Hot water use is simulated by computer on-off control of an electrically operated valve located in the hot water feed line of a sink (e.g., laundry room) with direct dump into the adjoining sink drain line. Approximately 326 liters (86 gallons) of hot water will be used daily by the family of six. Of this total, one dish wash per day requires 68 liters (18 gallons), the clothes wash 30 liters (8 gallons), and the remainder for cooking, cleaning and personal use.

No food or clothing loads are necessary since appropriate compensating techniques have been applied. The refrigerator and freezer temperature control settings are specified somewhat lower than the normal average to compensate for no food load and no door openings. The clothes washer is outfitted with a special agitator (used by the manufacturers in conducting factory tests) containing fins which simulate the effects of a standard 3.2 kg (7 lb) laundry load. The clothes dryer is operated for a longer period to compensate for the no-load condition.

The house lighting arrangement includes both fixed and portable (lamps) units of the incandescent and fluorescent bulb types. Though primarily standard incandescent bulbs are specified, decorative incandescents are called for in the dining room and fluorscents in the kitchen, breakfast area, powder room, master bathroom and second bathroom, and a spotlight to cover the driveway area. A packaged commercially available remote control low voltage relay system was selected for automatic lighting control. This system is compatible for direct tie-in to a computer, with the computer flip-flop relay outputs providing the lighting on-off signals. The system consists of a control components cabinet that can accommodate up to 24 split coil latching relays (one required for each controlled lighting circuit), two 110V/24V transformer and rectifier assemblies (to provide the split coil relays with holding power) and six remote control interfaces (for tie-in to computer output closure circuits) as well as the necessary bus bars and terminal strips. This system permits installation of individual momentary type wall switches in each room for local override of the existing computer signal state. The lighting control components cabinet is located adjacent to the house circuit breaker panel for direct tie-in between the lighting circuit breakers and the 110V lighting distribution wiring.

3.5.6.2 PVS Override Control Functions

Each of the planned PVS designs (i.e., Stage I and Stage II concepts as previously described) include their own self contained and independent control systems and will operate automatically in a near real life environment. However, provision must be made to obtain: (1) special test data at the subsystem level and (2) system performance data under imposed conditions that vary the PVS from its normal operating mode. This type of capability along with the ability to vary the house electrical load will permit programming a broad range of operating conditions for providing a complete evaluation of PVS performance.

The computer initiated PVS override control options available and the necessary control components are listed in Table 3-33.

The roof mounted solar array baseline design presented in this report provides for up to 37 individual electrical circuits. Accordingly, provision has been made to disconnect from the PVS each of these circuits or any combination of circuits and connect them to the electronic load for generating IV curves. This data will permit obtaining a comparison of the various suppliers' solar cell modules, information regarding interactions associated with electrically tying together a number of different module designs, and any change in performance as a function of time in operational use. Provision has also been made to permit disconnecting the inverter at either its input or output bus. Disconnect at the input side of the inverter will cut off all solar array power to the house in both the Stage I and Stage II designs, but permits battery power supply through the inverter in the Stage II installation. Disconnecting the inverter on its output side cuts off all PVS power to the house regardless of the type of PVS installation. In this situation, only the utility can feed power to the house. Ability to disconnect utility power used for charging the batteries in a Stage II installation is also provided. In addition, a complete cut off of all electrical power from both the PVS and utility will be possible by virtue of a contactor to be located in the power lines leading to the house main circuit breaker.

Relays and contactors associated with disconnecting dc power lines contain magnetic blow out devices to minimize potential arcing problems. All the override control relays and contactors, with the exception of the inverter output and total house load contactors, will be located in a control rack in the PVS Components Room. The inverter and total house load ac contactors, because of their size - 60-Ampere and 100-Ampere capacity respectively - will be enclosed and mounted on the PVS Components Room wall facing the garage.

3.5.7 TEST SYSTEM EQUIPMENT COSTS

A budgetary cost estimate for the test equipment system outlined in this section is $189,000.

This estimate assumes that a single contractor is assigned responsibility for design, procurement, fabrication, factory checkout at the subsystem level, and delivery of all the components of the test equipment system. It does not include installation, field interconnection wiring, start-up, or field checkout and debugging of the test system interfaced with the PVS. No formal set of drawings or system operational/maintenance manuals other than electrical schematics, interconnection wiring lists, installation sketches and vendor data are provided for in this estimate as deliverable items.

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Table 3-33. PVS Override Control Components Definition

CONTROL MODE	AUTOMATIC OVER-RIDE CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL NO.	CONTROL COMPONENTS LOCATION
DISCONNECT EACH SOLAR CELL CIRCUIT FROM PHOTOVOLTAIC SYSTEM AND CONNECT TO ELECTRONIC LOAD FOR GENERATING IV CURVES. NOTE: CONCEPTUAL DESIGN DEFINES A TOTAL OF 37 SOLAR CELL CIRCUITS	RELAY WITH A N.C. CONTACT IN THE POSITIVE LINE AND DIGITAL SHUNT REGULATOR LINE OF EACH CIRCUIT. IN ADDITION A N.O. CONTACT WHICH PROVIDES A BY-PASS OF THE POSITIVE LINE TO THE ELECTRONIC LOAD WHEN THE N.O. CONTACT IS CLOSED. COMPUTER CLOSURE ENERGIZES RELAY WHICH DISCONNECTS CELL CIRCUIT FROM PVS AND CONNECTS IT TO ELECTRONIC LOAD.	RELAY (37 OF): GENERAL PURPOSE 275 V DC, 5 A CONTACTS DPDT MAGNETIC BLOWOUTS 24 V DC COIL	POTTER & BRUMFIELD PRD 11DHO-24	CONTROL RACK IN PVS COMPONENTS ROOM
DISCONNECT PHOTOVOLTAIC SYSTEM AT THE INPUT TO THE INVERTER	CONTACTOR WITH N.C. POLE IN POSITIVE 240 V.DC LINE TO INVERTER. COMPUTER CLOSURE DIRECTLY ENERGIZES THE CONTACTOR COIL WHICH OPENS THE POSITIVE LINE.	CONTACTOR: MAGNETIC NEMA SIZE 2 600 V DC, 50 A CONTACTS MAGNETIC BLOWOUTS, 1 N.C. POLE. 24 V. DC COIL	GENERAL ELECTRIC IC2800161BAF15 OPEN TYPE	"
DISCONNECT PHOTOVOLTAIC SYSTEM AT THE OUTPUT OF THE INVERTER	CONTACTOR WITH N.C. POLES IN BOTH 240 V. AC OUTPUT LINES OF THE INVERTER. COMPUTER CLOSURE ENERGIZES RELAY WHICH OPERATES CONTACTOR COIL, OPENING THE 240 V. AC INVERTER OUTPUT LINES.	CONTACTOR: MAGNETIC NEMA SIZE 2 600 V.AC, 60 A CONTACTS 2 N.C. POLES 120 V. AC COIL NEMA TYPE 1 ENCLOSURE RELAY: GENERAL PURPOSE 120 V.AC, 10A CONTACTS 24 V.DC COIL SPDT	AUTOMATIC SWITCH 4410C POTTER & BRUMFIELD KU5DT5-24 (WITH DUST COVER)	WALL MOUNTED IN PVS COMPONENTS ROOM

Table 3-33. PVS Override Control Components Definition (Continued)

CONTROL MODE	AUTOMATIC OVER-RIDE CONTROL ARRANGEMENT	CONTROL COMPONENTS	TYPICAL SUPPLIER & MODEL NO.	CONTROL COMPONENTS LOCATION
DISCONNECT UTILITY FEED LINES FROM BATTERY CHARGER (NIGHT TIME CHARGING)	RELAY N.C. CONTACT IN COIL CIRCUIT OF CONTACTOR WHICH IS AN INTEGRAL COMPONENT OF THE BATTERY CHARGING EQUIPMENT COMPUTER CLOSURE ENERGIZES RELAY WHICH OPERATES CONTACTOR COIL, OPENING UTILITY FEED LINES TO CHARGER	RELAY: GENERAL PURPOSE 120 V. AC, 10A CONTACTS 24 V. DC COIL SPDT	POTTER & BRUMFIELD KV5D15-24 (WITH DUST COVER)	CONTROL RACK IN PVS COMPONENT ROOM
DISCONNECT COMBINED PVS/ UTILITY POWER FEED LINES TO HOUSE MAIN CIRCUIT BREAKER.	CONTACTOR WITH N.C. POLES IN BOTH OF THE 240 V.AC POWER LINES TO MAIN DISCONNECT SWITCH. COMPUTER CLOSURE ENERGIZES RELAY WHICH OPERATES CONTACTOR COIL, OPENING THE 240 V.AC LINES FEEDING THE HOUSE.	CONTACTOR: MAGNETIC NEMA SIZE 3 600 V.AC, 100 A CONTACTS 2 N.C. POLES 120 V. AC COIL NEMA 1 TYPE ENCLOSURE RELAY: GENERAL PURPOSE 120 V.AC, 10A CONTACTS 24 V.DC COIL SPDT	AUTOMATIC SWITCH 4416C POTTER & BRUMFIELD KV5D15-24 (WITH DUST COVER)	WALL MOUNTED IN PVS COMPONENTS ROOM

The cost breakdown listed below, by item, reflects the fully burdened cost including material as well as engineering design and manufacturing/assembly labor costs.

	Cost Item	Total Cost (1976 $)
1.	Computer System and Peripherals[1]	$ 86,000
2.	Transducer/Signal Conditioning Rack (Power Supplies, Patch Panel, etc.)	14,500
3.	Transducers and Signal Conditioning Equipment	15,000
4.	PVS Control Rack and Wall Mounted ac Contactors[2]	20,500
5.	Appliance/Lighting Control Components	3,500
6.	Display Panel	26,500
7.	Interconnection Wiring Lists and Installation Sketches	6,000
8.	Management, Contracts, Finance, Production Control and Secretarial	14,000
9.	Travel and Living	1,500
10.	Pack and Ship	1,500
		189,000

Notes:

1 List prices as of May 1976 (no OEM or END USER discount)

2 Does not include cost of Battery Charge Controller and Shunt Voltage Limiter, both components of the PVS, to be housed in this rack containing the PVS override control relays and contactors

Six man months of programming effort (not included in the above hardware costing) will be required for:

1. Coordination with test engineering
2. Systems analysis and flow diagramming
3. System generation and configuration using RSX-11M
4. Applications programming in Fortran (primarily the three basic operational functions - data acquisition/conversion/output load control, and PVS override control/special testing)

These tasks should be undertaken at an existing computer center containing the appropriate DEC equipment. Personnel assigned to the programming effort should have experience with real time operating systems (preferably RSX-11M) and the PDP11 series of computers. It should be pointed out that the six man month estimate is predicted on the assignment of programming personnel with the specified experience.

This central programming effort applicable to all the PVS installations must be scheduled for completion just prior to completing the installation of the first test system hardware in a PVS residence. A programmer should then be assigned for a two-month period (as a member of a team) during on-line checkout and debugging of the test system hardware and software.

3.5.8 TEST PROGRAM MANAGEMENT AND CONTROL REQUIREMENTS

The necessary operational, support and maintenance groups to fulfill the objectives of the RPST program are presented in block diagram form in Figure 3-60. In addition to a central program office responsible for overall program management and control of the design, construction and test phases of the program; site offices, access to a central computer facility, and computer and electronic instrumentation maintenance service groups support will be required.

The general requirements and responsibilities of each of the functional groups participating in this program are tabulated below.

<u>Program Office</u>

1. Overall RPST program management
2. RPST site selection
3. Selection of contractors for design/construction
4. Selection of national computer and electronic instrumentation service groups for on-call site maintenance (Note: These service groups could be divisions of or under contract to the RPST design/construction contractor)
5. Staffing of office sites
6. Financial control of RPST program funding; allocation of budgets for each site
7. Interface with central computer/data file service group (central programming, summary reports, etc.)

<u>RPST Site Office</u>

1. Monitor construction, checkout, and start-up of regional RPST
2. Technical and administrative responsibility for site operations

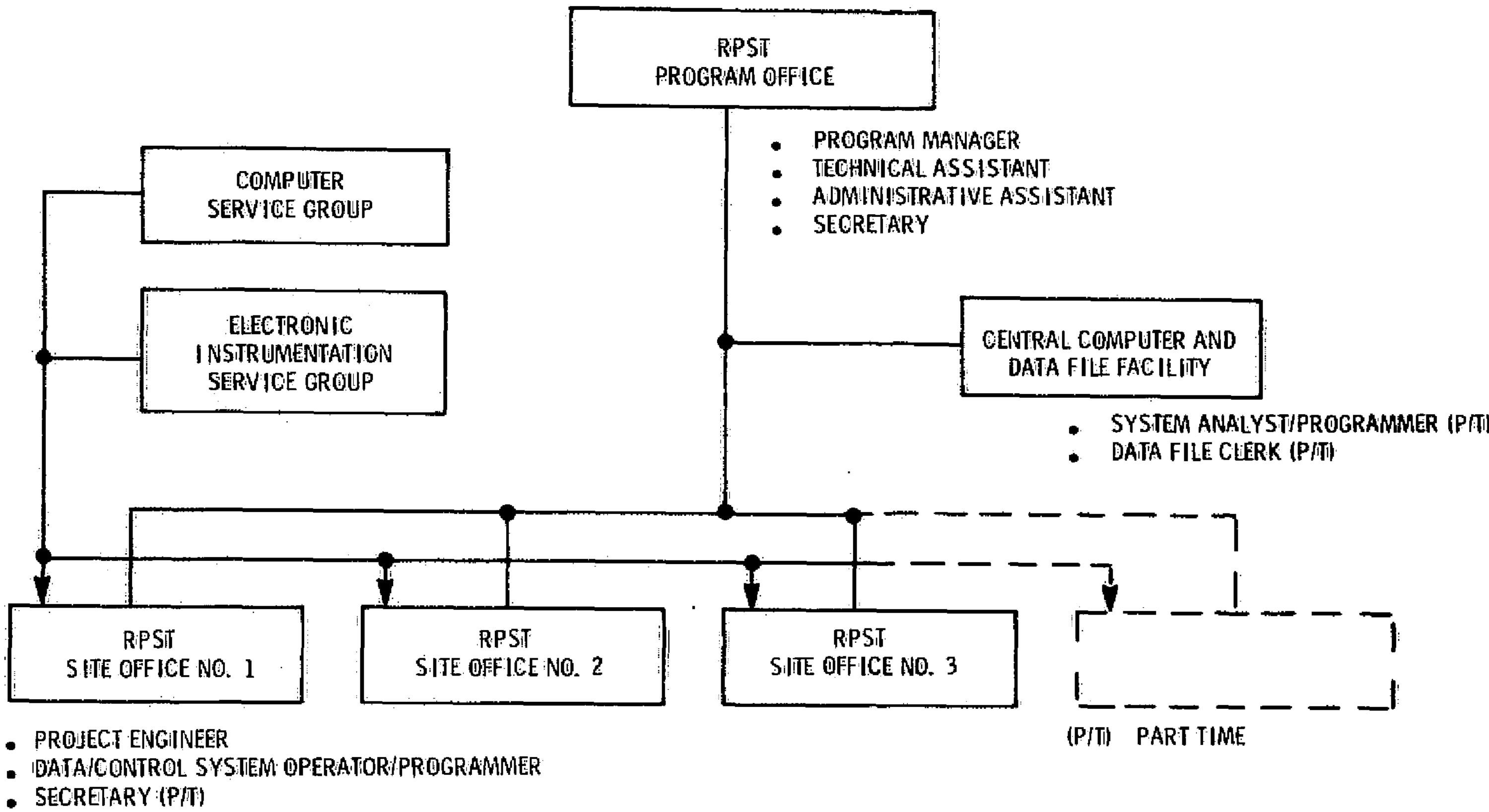

Figure 3-60. RPST Program Operation/Maintenance Functional Block Diagram

3. Implement detail test program
4. Interface with local offices of national computer and electronic instrumentation service groups
5. Undertake any site unique programming; interface with central computer/data file personnel assigned system programming responsibility
6. Responsible for budgetary cost limits assigned to specific site
7. Submit regular reports (from maintained logs) to central program office during construction/operation/test phases of program
8. Forward computer compatible magnetic tapes containing test, alarm, and maintenance data to central computer/data file facility

Maintenance Service Groups

The computer and electronic instrumentation maintenance service groups selected should have nationwide field offices to insure that qualified service personnel are located within reasonably close proximity to the regional RPST sites. Availability of computer software specialists as consultants at the field level is another important factor in the selection criteria.

These service groups should participate in the installation/calibration/checkout/start-up phase of the Test Data/Control System to insure an early thorough working knowledge of the equipment to be maintained. During the checkout and start-up phase of the Test Data/Control System, the instrumentation service personnel should become faimilar with the PVS components which they will also service.

Maintenance service should include both the routine as well as emergency. Computer service personnel follow a definite detailed routine maintenance program (as specified by the manufacturer) for the minicomputer and associated peripherals. As for the PVS, the battery is the only presently identifiable component requiring routine maintenance - the addition of water. Though none of the transducers and signal conditioning equipment require regularly scheduled routine maintenance or calibration, it is recommended that they be inspected on a six month interval and recalibrated/cleaned, if necessary. The analog input conversion modules (front end) of the minicomputer will automatically be electrically self-checked, and data values adjusted internally for any deviation. Should the internal adjustment reach a specified limit (as indicated by computer printout) service personnel will be required to recalibrate the input modules.

All service calls should be limited to the normal work week (i.e., Monday through Friday, 8:00 A.M. to 5:00 P.M.) with emergency call response required within 24 hours. More stringent service response criteria is not warranted in view of the excessive cost and the fact that the PVS will have its own self-regulating and cutoff controls to prevent operation when out-of-limit conditions occur.

At the completion of the detail design phase, a complement of spare parts for the PVS and Test Data/Control System (excluding the minicomputer and peripherals) should be selected for stocking at each site to minimize down time due to component failure. Adequate computer and peripheral spare parts are stocked at the local field office and regional centers by the computer service groups. Consequently, stocking of computer/peripheral components at each site is not recommended.

Central Computer Facility

Access to a central computing facility (e.g., an existing government group) for periodic summary report processing and maintenance of the residential prototype PVS test program data file will be required. Use of this facility will be on a very limited basis in view of the small number of test sites planned. The system analyst/programmer involved in preparing the basic data/control programs for site use (see Section 3.5.7) could be a member of this central computer group. His services, on a part time basis as a consultant and programming coordinator, will be required by the field site offices during the entire test program.

The following computer oriented tasks will be performed by the central computer facility.

1. Monthly processing of site tapes (approximately three tapes per month from each site) to provide summary data such as energy savings, number of hours PVS in operation, etc., for each of the sites

2. Issue a monthly report detailing the maintenance effort at each site. This report will tabulate, by site, the failures by subsystem and component, the parts replaced, the amount of PVS down time, and the hours expended in actual troubleshooting and repair. These cumulative type reports will serve as the basis for initial predictions of component/subsystem/system reliability as well as anticipated maintenance costs for a RPST. (Note: It is recommended that in addition to obtaining maintenance data for the PVS, that this type of information also be maintained for the data/control system in order to properly allocate costs during the life of the test program)

3. Processing of actual climatological data from each site with the theoretical model used to predict system performance for comparison with actual results. On the basis of these ongoing evaluations, the theoretical models will be revised to provide improved design tools for predicting operating results

4. Compilation in a computer based data file of pertinent information (e.g., installation and operational problems) obtained from regular site project engineering monthly reports submitted to the program office for review and coding prior to processing by the central computer facility.

3.5.9 STAFFING AND OPERATIONAL COSTS

To adequately conduct all facets of the RPST program, as outlined in Section 3.4.2, will require the following level of staffing and yearly man-hour expenditures:

Program Office	Yearly Man-Hours
1. Program Manager	2000
2. Technical Assistant	2000
3. Administrative Assistant	2000
4. Secretary	2000
Regional RPST Site Office (each site)	
1. Project Engineer	2000
2. Data/Control System Operator/ Programmer	2000
3. Secretary (part time)	1000

Since the PVS and Data/Control System operate in an automatic mode, site personnel need only be in attendance during the normal work week to conduct their assigned tasks.

Central Computer/Data File Facility (in support of three sites).

	Yearly Man-Hours
1. System Analyst/Programmer (Part Time)	500
2. Data File Clerk (Part Time)	500

Yearly support services and operating material costs include the following:

Regional RPST Site Office (each site)

	Yearly Dollars
1. Electronic instrumentation maintenance service	\$ 9,000
2. Computer/peripherals maintenance service	6,500

3. PVS and Data/Control system spare parts(1) — 3,500

4. Mag tape, hard copier paper, print paper, etc. — 1,200

5. Purchased electricity (to operate Data/Control System, and to supplement PVS supply to house loads) — 1,500(2)

Central Computer/Data File Facility (in support of three sites)

1. Computer processing, tape storage, keypunch, report printouts, etc. — $1,500

3.6 INSTITUTIONAL PROBLEMS (TASK VI)

Potential institutional problems associated with the implementation of the RPSTs were addressed by this task activity. As defined by the contract statement of work this task is to consider two major issues related to the RPSTs.

1. Legal liability during and after installation
2. Labor practices, buildir - restrictions and architectural design guides

3.6.1 LEGAL LIABILITY

The legal liability questions arising from the RPST program were investigated and reported by Mr. Roy C. Cobb, Jr. of the law firm of Jones, Day, Reavis, and Pogue of Cleveland, Ohio. In this report, which is included in its entirety as Appendix C., Mr. Cobb presents in general terms the potential non-contractural liabilities of the United States Government arising from the construction, operation and maintenance of these prototype homes and the steps which the Government can take to limit such liabilities. The principal conclusions of this investigation are summarized below. The reader is referred to the Appendix for a more detailed discussion of these issues.

Any non-contractual liability of the United States to persons other than Federal employees would be by, virtue of the Federal Tort Claims Act. Two important limitations to the Governments liability under this act are now well established:

(1) Does not include cost for any silicon cell array module spares
(2) Will vary with site location and solar array size

1. Any liability must be premised on some showing of negligence or fault by an employee of the United States, and

2. The United States cannot be held liable for negligence of its independent contractors

In view of these limitations, the potential liabilities arising from design and construction of the prototype homes can be largely eliminated through the use of independent contractors, provided that the Government exercises due care in selecting competent contractors to perform the work and does not exercise such a degree of supervision and control as to destroy the contractors' "independent" status.

Since the construction workers will be making use of some property under Government ownership and control, injuries arising from such use could lead to liability. To minimize such potential liability, the areas accessible to the construction contractor and subcontractors and their employees should be strictly limited.

Special care should be taken that the design includes safety features for at least any readily perceivable hazards resulting from the installation and operation of the solar array and of the battery. During and subsequent to installation, access to the roof of the prototype home and to the battery should be strictly limited and readily visible warning signs posted. Any access by "visitors", e.g., the general public, visiting Congressmen, etc., should be under close supervision. If such visitors are to be allowed it is especially important that any dangerous equipment be secured and made as tamper-proof as possible. What may be adequate precautions where a technician thoroughly familiar with the prototype is concerned, obviously may not be in other situations.

As long as the actual possession and control of the RPSTs is vested in NASA-LeRC, a conveyance of the owernship of a RPST to the department or agency owning the real estate on which it is built will probably in no way decrease the responsibilities of NASA-LeRC.

It is generally recognized that Federal agencies and Federal installations are not subject to state or local regulations relative to zoning restrictions or building permits unless there is a Federal statute or executive order authorizing such regulation.

3.6.2 LABOR PRACTICES

Local labor practices will have to be studied in detail for each of the selected site locations. In general, the problems arising will center around construction and installation of hardware not currently covered under local labor practices, such as solar cell modules. Revision in the local labor practices may be necessary to define which contractors will do the design, construction, and installation of new types of equipment. The decision on how to distribute the work will depend upon the interfaces set up between the participants in the design and construction of the prototype system test residences.

Because solar photovoltaics is a new type of energy system, setting up the interfaces between the procuring agency, an architect, a construction engineer, a consultant, and the construction trades may be difficult. The limits of responsibility for each participating group will have to be defined.

Recently the General Electric Company participated in the New Jersey Environmental Center Solar Heating and Cooling Project. Table 3-24 gives the assigned responsibilities for the New Jersey Park Commission, an architect, a construction engineer, and the contractors for the definition and installation of the solar collector system components of the project.

Figure 3-61 shows a possible classical interface structure for the photovoltaic system. This interface structure may vary depending on such things as local labor practices and the local architect, construction engineer, and general contractor chosen. Also, the local government facilities engineering group may give the procuring agency a good portion of or total responsibility for choosing and supervising the subcontractors rather than doing it themselves.

If a new labor practice needs to be defined, a ruling will have to be made based on criteria submitted by all interested parties. Two examples of possible new labor practices are that the electrical workers installing the solar cell modules may need to be educated on the fragile nature of these modules and the potentially dangerous voltage level that can be generated. Installation of these modules should be limited to the nighttime with a low level of surrounding illumination.

3.6.3 BUILDING RESTRICTIONS

Building restrictions are found in national and local building codes and standards. The following building restrictions, which may apply to a single family residential photovoltaic system test, have been postulated by studying the BOCA Basic Building Code (Reference 20) and the HUD Minimum Property Standards for one and two family dwellings (Reference 21). Possible problems have been found that are not currently directly covered by these guides. The building restrictions at the selected site location may be more severe depending upon the local building codes and standards.

The lead-acid batteries that would be used for electrical energy storage emit small quantities of hydrogen into the surrounding air. Inferring from Sections 202.0 and 203.0 of the BOCA Code, the threat of hydrogen exploding and the presence of acid constitutes a high hazard and the batteries may have to be located in a high hazard building. Section 400.9 of the BOCA Code infers that the Battery Room or building can not be attached to a single family residence that has an unprotected frame construction. Section 203-1 of the HUD standards does not allow hazards on a HUD residential property. Therefore, it appears that the batteries may have to be placed in a high hazard building that is a safe distance, not as yet determined, from the residence or residential area.

Table 3-34. Assigned Responsibilities for New Jersey Environmental Education Center Solar Heating and Cooling Project

	PARK COMMISSION	GE (SUBCONTRACTOR)	HALSEY & RYDER (ARCHITECT)	BECHT ENGINEERING	GENERAL CONTRACTOR (PROGRESS)	HVAC SUBCONTRACTOR (RODNER)	ELECTRICAL SUBCONTRACTOR (DYNAMIC)
<u>DEFINITION</u>							
Collector Installation			X				
Collector Interconnection		X					
Flow Rates		X					
TES Size & Insulation		X		input			
Collector Quantity & Orientation		X					
System Schematic		X		input			
Piping & Component Layout				X			
Heat Exchangers		input		X			
Pumps		input		X			
Control Valves		X		input			
Weather Station	X	input					
Control Panel		X					
Wiring Schematic (electrical)		X					
Electrical Layout				X			
Instrumentation		X					
Instrumentation Consoles	input	X					
Display Panel	input	X					
Insulation	input			X			
Filters				X			
Roof Glazing			X				
<u>HARDWARE</u>							
Solar Collectors		X				0	
Hoses, Clamps, Tools & Plugs		X				0	
Control Valves						XO	
Flow Meters		X				0	
Heat Exchangers						XO	
Pumps						XO	
Expansion Tanks, Valves						XO	
TES Tanks						XO	
Filters						XO	
Control Panel		X					0*
Control Components		X				0	
Instrumentation		X					0*
Instrumentation Console		X					0*
Instrumentation Wiring		X					0*
Weather Instruments	XO						
Wiring for Weather Instr.	X						0*
Insulation (thermal)						XO	
Power Wiring							XO
Electrical Components						input	XO
Display Panel & Wiring	X						0*
Arkla Chiller						XO	
Control Wiring						XO	

*Electrical contractor will run wire from sensor to panel or junction box - GE will terminate at console and sensors.

X - Supply

0 - Installation

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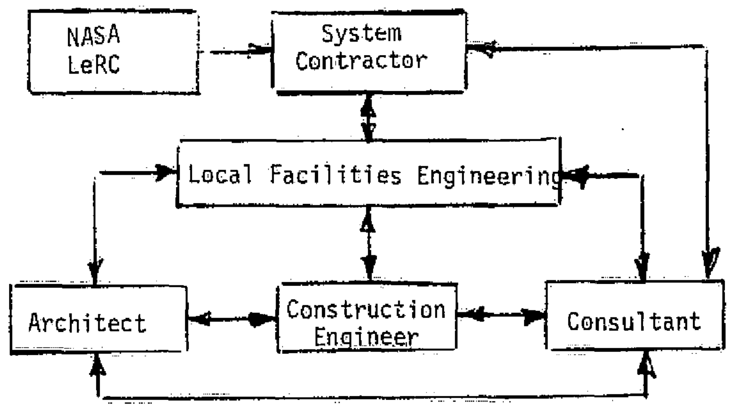
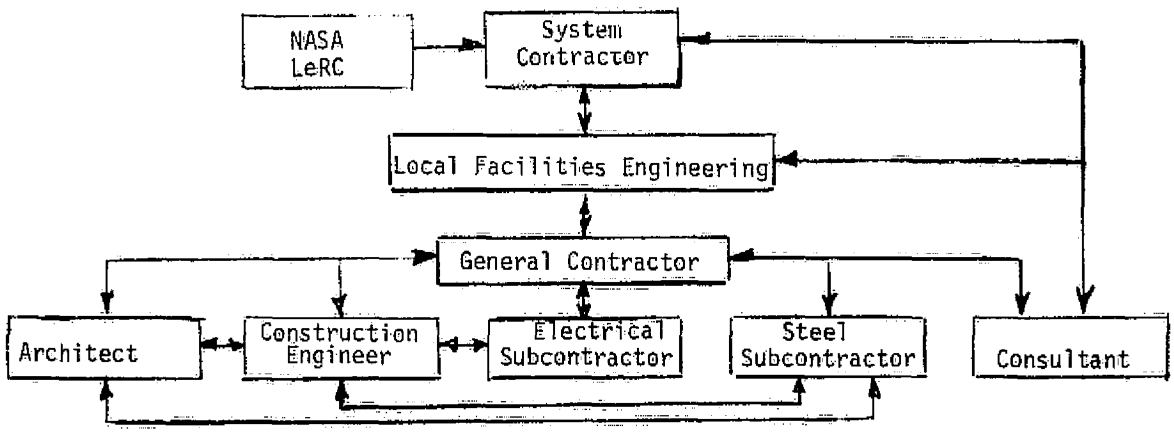
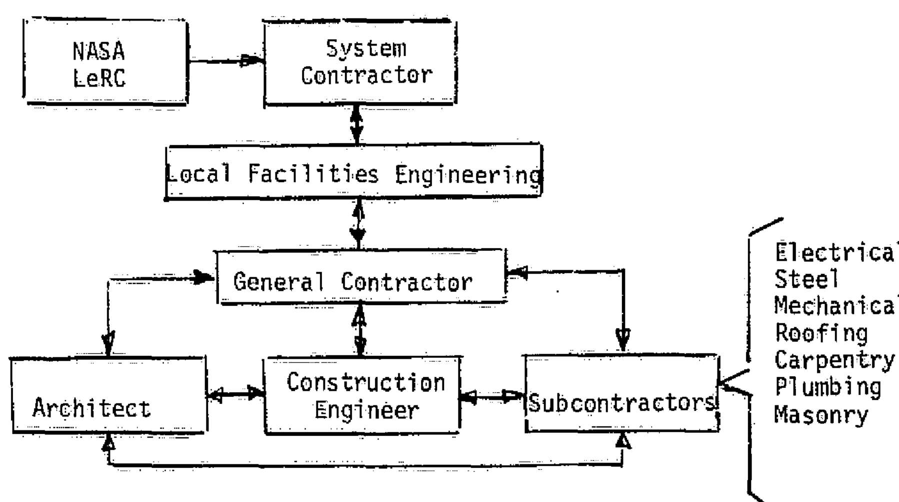


(a) Design of Residence and Photovoltaic System



(b) Construction of Photovoltaic System



(c) Construction of Residence

Figure 3-61. Possible Working Interface Structure

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Other sections relative to high hazard buildings are found in the BOCA Code. Section 400.7 of this code states that fire fighting and extinguishing equipment will be needed in a high hazard building. Sections 400.5 and 413.6 define the type of light and electric wiring and type of electrical equipment required. Section 402.0 states that, for structures occupied with explosion hazards, venting devices will have to be provided. Section 505.0 gives the ventilation requirements, for various types of structures and rooms, but a ruling will be needed for a battery storage building.

Height limitations, as a function of type of construction, for one and two family residences and for a high hazard building are given in Table 6 of the BOCA Code. Section 310.1 of this code states that ventilating, air conditioning, and similar building service equipment shall not be included in the height of the building. A ruling is necessary to determine if solar cell modules and their support structure can be included in the latter category.

Section 711.1 of the BOCA Code defines the minimum roof loads. A ruling is necessary to define the minimum roof load or loads for structural frames which support the solar cell modules.

All electrical wiring and equipment should be installed in accordance with provisions of Article 15 of the BOCA Code and the National Electrical Code. The electrical standard defined in Sections 516 and 616 of the HUD Minimum Property Standards may also be applicable to the photovoltaic residences.

Those residences with the attached solar cell modules and support structures and the battery storage building, if used, will have to be designed to minimize earthquake damage, if the buildings are located in an earthquake prone area, as defined in Section 719.0 of the BOCA Code. Appendix K-11 of this code is applicable for those buildings that need to be designed to handle predicted earthquake loads.

In Section (301-2.3) of the HUD minimum Property Standards, it is stated that vegetation which can be saved within the site design shall be preserved. The photovoltaic residence should be so located that it minimizes the cutting down of trees while also minimizing the shading on the solar cell modules. Fire protection standards for HUD residences are given in Section 405 of this standard. It is recommended that photovoltaic residences meet these standards.

Standards applicable to roof coverings that may be applicable to these residences are defined in Section 509-3 of the HUD Standards.

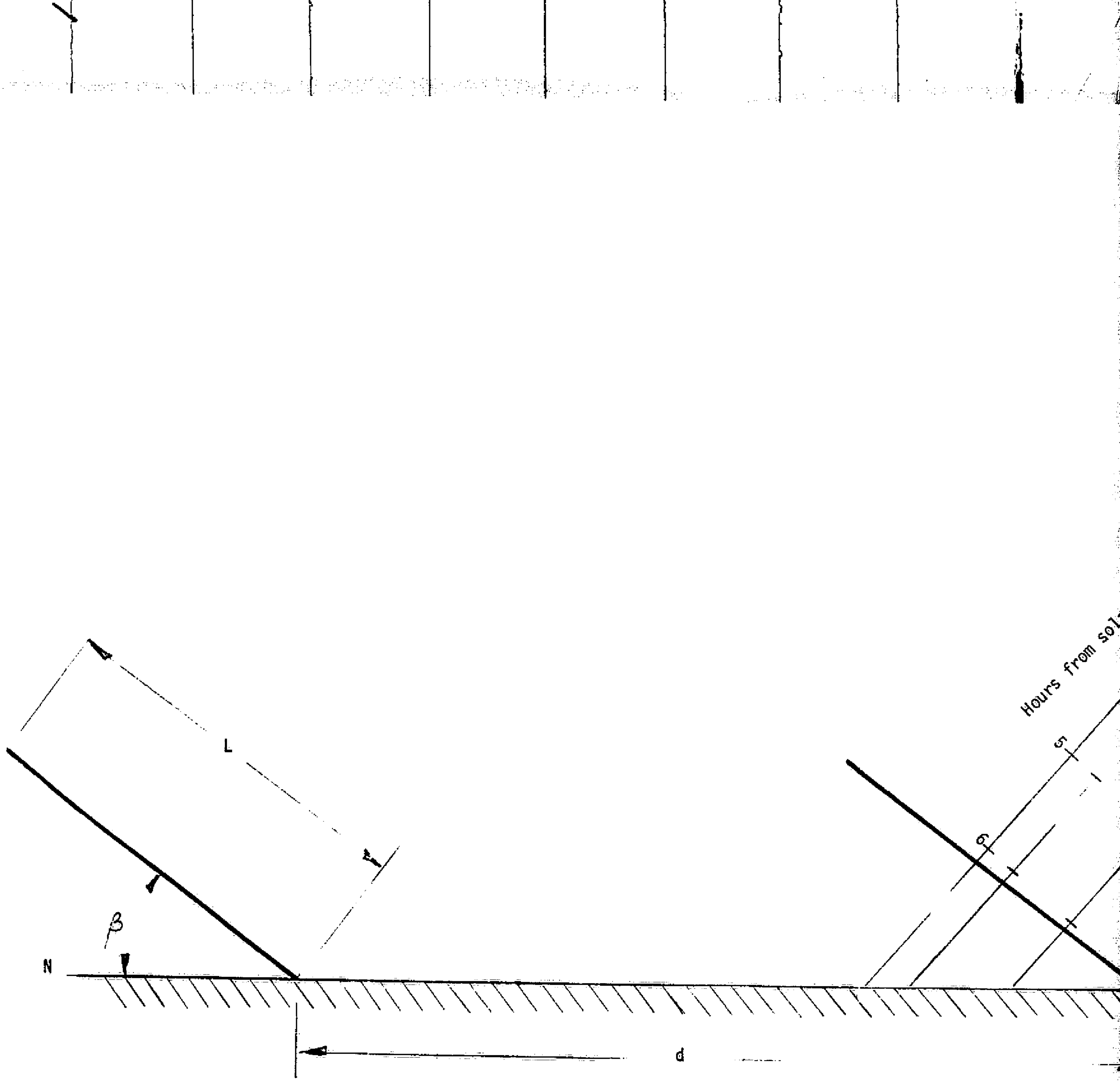
Energy conservation should be an important design consideration in the RPST program. Conservation should result in a lower total electrical energy requirement with a correspondingly higher fraction of this demand being satisfied by the solar photovoltaic system output. It is recommended that the energy conservation standards specified by ASHRAE

Standard 90-75 (Reference 22) be imposed on the RPST design. As reported in Reference 23, a recent study by Arthur D. Little, Inc. has indicated that ASHRAE Standard 90-75 can be an effective tool in reducing building energy usage with initial investment and annual operating costs which are favorable to building owners. A comparative analysis of the annual energy consumption for a conventional vs an ASHRAE 90-75 modified prototypical single-family residence has yielded calculated reductions of 14.7, 15.1, 7.7, and 7.5 percent for New York, Omaha, Atlanta and Albuquerque, respectively.

3.6.4 ARCHITECTURAL DESIGN GUIDES

The architect will prepare detailed drawings that have taken into account local building restrictions, the design restrictions of his client, and his personal preferences. The number of renderings the architect has to complete will depend greatly upon the depth of detail of the design restrictions of his client. More renderings will be needed if the client requires a learning curve to define his design restrictions.

The following examples of possible client design restrictions for a single family photovoltaic residence should be considered. Shadowing of solar cell modules can have a significant affect on overall system energy output. Any sharply defined shadow which shades any single cell within a solar cell circuit has the affect of reducing the output from the entire circuit to near zero at the system operating voltage. The design and placement of the house should avoid shadowing on the solar cell modules from trees and adjacent structures including other portions of the house. If the solar cell modules are mounted in more than one plane, the effects of mutual shadowing from one plane of modules onto the active area of another plane should be considered in the design. Figure 3-62 shows two typical east-west rows of solar cell modules arranged in a sawtooth configuration on a flat roof building. Superimposed on this figure is a nomograph which can be used to define the angle between the horizontal plane and the projection of the earth-sun line onto a vertical north-south plane. Using this nomograph, the projection of the earth-sun vector is simply determined by drawing a line from the hour point for a particular date to the origin of the plot. An example of the projected vector is shown for 0900 hrs (or 1500 hrs) local solar time on December 21st (Winter Solstice). With the particular installation geometry shown ($d/L = 2.25$, $\beta = 37^{\circ}$), this figure indicates that the second and subsequent rows of the array will experience some shadowing during the early morning and late afternoon hours during the winter months. Table 3-35 shows the actual calculated loss in solar array energy due to this type of shadowing for a four row installation in Cleveland, Ohio. For this calculation the assumption was made that any shadowing will result in the entire loss of power output except from the first row of subarrays. This represents a worst case assessment since diffuse skylight illumination should produce some output from shadowed subarrays. Significant reductions in solar array energy output are indicated for the months of November, December and January. The total annual loss in solar array energy output is 2.6 percent due to this mutual shadowing.



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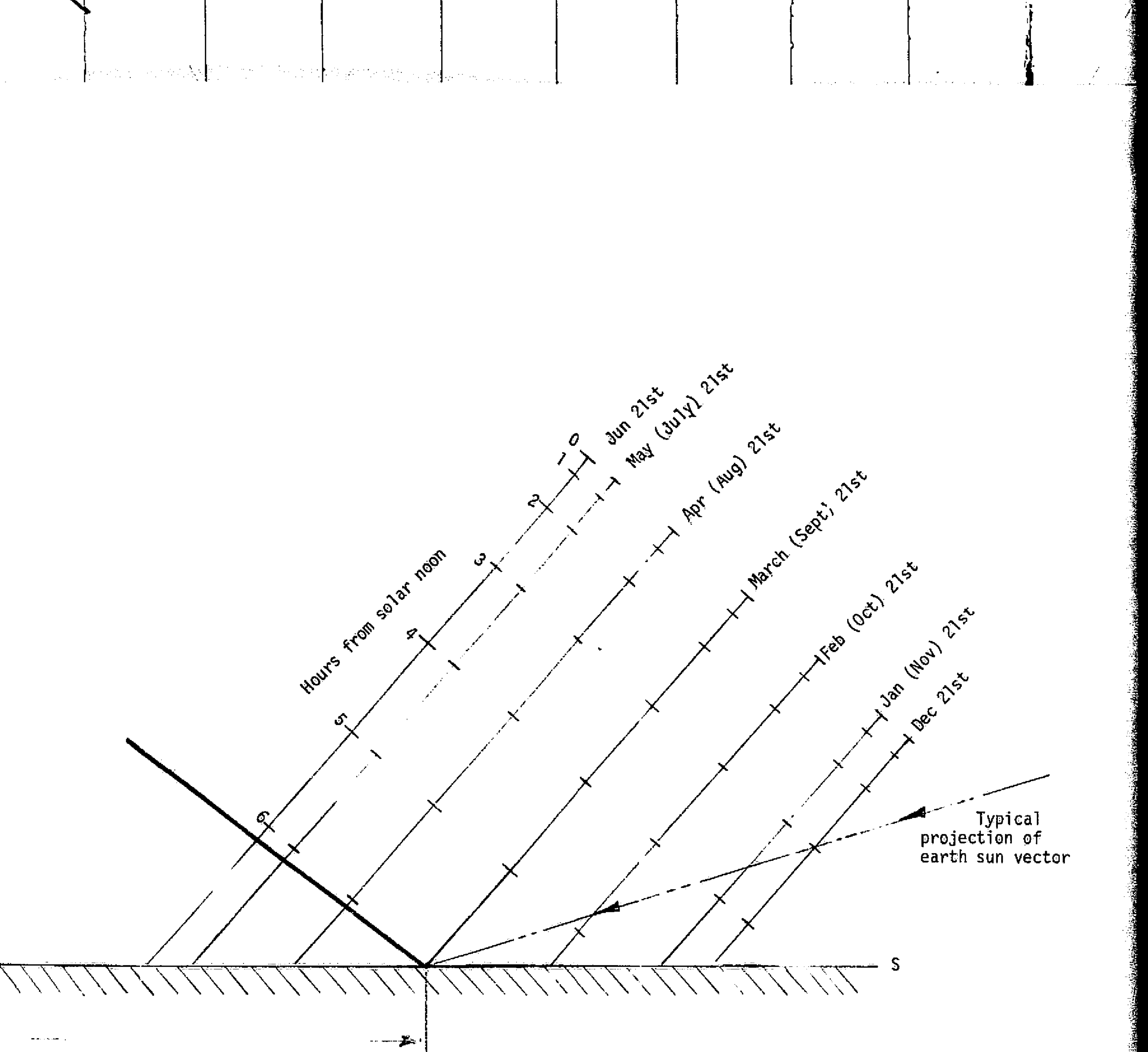

Figure 3-62. Geometrical Shadowing Considerations for an East-West Multiple Row Panel Installation (Latitude = 41.4°N)

Table 3-35. Loss of Solar Array Energy Output Due to Mutual Shadowing in a Four Row East-West Installation (Latitude = 41.1°, d/L = 2.25, $\beta = 37^{\circ}$)

Month	Fraction of Solar Array Energy Loss Due to Shadowing
Jan.	0.176
Feb.	0.026
Oct.	0.009
Nov.	0.121
Dec.	0.220
Total Annual	0.026

Another aspect of the shadowing consideration is associated with the self-removal of snow. For site locations within the snowfall areas of the country, it is important that the accumulated snowfall on the subarrays have room to slide off without piling up in such a way as to shadow the bottom portion of the active subarray surface. The self-removal of snow on a sunny day following a snowfall should be good since the subarray surface should heat to above the freezing point and allow the snow to slide off the relatively smooth module surface. Space should be provided for this snow to pile without shadowing the subarray active surface.

The relatively heavy weight of the solar cells modules ($\sim$ 21. kg/m^2) should be considered in the structural design of the building. In Reference 14, JPL specifies an environmental loading of 2394 Pa (50 lb/ft^2) to account for the combined loading due to wind, snow, ice, rain, etc.

Some of the sites may have to be designed to be protected against the threat of vandalism. Since solar modules can be damaged by flying missiles, such as rocks and B-B shot, it may be necessary to extend the distance between the residence and the nearest public land so that the residence is outside the range of such missiles.

SECTION 4

CONCLUSIONS

The primary conclusion which can be drawn from this overall study activity is that the RPST program is necessary to answer some basic questions concerning photovoltaic power system implementation. These fundamental questions are:

1. What is the best photovoltaic system configuration for residential applications?

2. Should on-site energy storage be provided?

3. What is the system energy output both with and without energy storage?

4. Do the analytical models accurately predict system performance?

To date the only answers to these basic questions have come from analytical models of the various system configuration options. These models are a necessary tool for the evaluation of terrestrial photovoltaic power systems, but no systems level experimental data is currently available to verify the prediction accuracy of these analytical models. The RPST program is necessary to supply this needed experimental verification. Drawing an analogy between terrestrial and aerospace photovoltaic power system applications, the RPST functions as the orbiting spacecraft in the verification of the analytical models and for the ultimate measure of system performance. Only a limited number of RPST installations are required to achieve what we feel is the primary objective of this experimental program. The climatological aspects of the analytical model could probably be adequately verified by a total of three RPSTs.

The following additional conclusions are based on the results of each of the six major tasks activities as indicated:

Task I - Site Selection

The ultimate RPST site selection is necessarily a subjective determination. The site selection task was performed using three criteria for evaluation: population, photovoltaic figure-of-merit (FOM), and the cost of electrical fuel. For each of these evaluation criteria it was possible to formulate a quantitative ranking for each potential site location. Equal weighting was assigned to each of these criteria (reference Section 3.1.5), yielding the following geographical order of selection, using the BEA divisions to represent the first eight regions in terms of the total score.

1. New York, NY
2. Los Angeles, CA
3. San Francisco, CA
4. Phoenix, AZ
5. Albuquerque, NM
6. Tucson, AZ
7. Fresno, CA
8. Boston, MA

If the importance of these three criteria were arbitrarily shifted by assigning unequal weighting factors as indicated in Table 4-1, the resulting geographical orders of selection are rearranged as indicated in the table. If the electrical fuel costs in Table 3-5 were replaced with the values from Reference 24 for the year 1985, then the resulting geographical order of selection would be as follows for the 1:1:1.5 weighting factor mix:

1. New York, NY
2. Miami, FL
3. Tampa, FL
4. Norfolk, VA
5. Orlando, FL
6. Washington, DC
7. Los Angeles, CA
8. Baltimore, MD

Table 4-1. Geographical Order of Selection with Different Weighting Factors

Geographical Order of Selection	Weighting Factors (Population: FOM: Cost)			
	1:1:1	1.5:1:1	1:1.5:1	1:1:1.5
1	New York, NY	New York, NY	Los Angeles, CA	New York, NY
2	Los Angeles, CA	Los Angeles, CA	New York, NY	Los Angeles, CA
3	San Francisco, CA	San Francisco, CA	San Francisco, CA	Phoenix, AZ
4	Phoenix, AZ	Phoenix, AZ	Phoenix, AZ	Albuquerque, NM
5	Albuquerque, NM	Albuquerque, NM	Albuquerque, NM	Tucson, AZ
6	Tucson, AZ	Tucson, AZ	Tucson, AZ	San Francisco, CA
7	Fresno, CA	Boston, MA	Fresno, CA	Boston, MA
8	Boston, MA	Chicago, IL	Tampa, FL	Fresno, CA

From these results it is clear that the geographical order of selection is not only a function of the relative importance assigned to each criterion, but is also a function of the source used to obtain the data for the evaluation of each criterion. The only two sites which appear on all lists presented above are New York, NY and Los Angeles, CA.

Task II - Parametric Sensitivity Analysis

In terms of overall system output, the NOBATRY approach offers significantly better performance when compared to all other systems investigated. The absence of on-site energy storage also makes this system the simplest to implement. Thus, this system approach, which utilizes a maximum power tracking inverter with feedback to the utility, is the obvious choice for the first phase of the RPST experiment. Many questions, which remain unanswered at this time, can only be satisfactorily addressed in a system level experiment. The feedback of power to the utility grid immediately raises questions concerning the power factor and harmonic distortion of the fed back power. The limits of acceptable performance must be determined experimentally. The stability and accuracy of the maximum power tracking controller operating in conjunction with the inverter must be verified over the wide range of solar array performance that can only be duplicated by actual system level operation.

The installation of on-site energy storage must also be investigated in the RPST program. Based on the results of this task activity, the UNREG system approach appears to offer the best system performance of all the energy storage approaches considered. It is therefore recommended that this system approach with energy storage be implemented as part of the RPST program. The size of the battery, the roof slope angle and the optimum number of series connected battery cells for a given solar array electrical arrangement should be determined based on the results of this sensitivity analysis. The subsequent verification of the analytical model by comparison with system level test results should establish the capability of this model to accurately calculate the optimum values for these parameters without the need for extensive experimental parameter variation at the system level.

With on-site energy storage it is important that the experiment include the capability to investigate the nighttime charging of batteries if the next day's weather is predicted to be cloudy. This operational flexibility will minimize the demand for utility power during the peak afternoon hours and thus perform a desirable load leveling function.

The implementation of a maximum power tracking system with energy storage (SMPT or PMPT) does not appear attractive based on the analysis performed under this task.

Task II - Conceptual Design

A photovoltaic power system can be readily integrated into a residential structure. The inclusion of on-site lead-acid battery energy storage adds a level of complication associated with assuring a fail-safe ventilation system for the battery room and providing adequate battery temperature control.

The design of the solar array for a specific site will require prior knowledge of the solar cell module I-V characteristics as measured under simulated AM1 illumination conditions. If more than one solar cell module type is to be used, the solar array designer must have some freedom to specify the type and number of modules of each type to be used in the installation. The specification of the optimum number of series connected solar cell modules will require an accurate prediction of solar cell temperature over a wide range of ambient conditions. Experimental measurements of solar cell temperature as a function of insolation, wind speed and direction, and panel slope angle are required for each module type to be considered for installation on a RPST.

A maximum power tracking power conditioner can be designed using either the simple line-commutated inverter or the more sophisticated self-commutated versions. Each of the inverter types have advantages and disadvantages as outlined in Section 3.3.4.3.2.

If the line-commutated inverter is to be used in conjunction with a large scale solar array, it is strongly recommended that transformer isolation be used in the system. Without the transformer isolation, an ungrounded direct line connected array would be susceptible to line induced transients. These line transients may come from utility tap switching, momentary shorts, motor contactor operation and nearby lightning strikes. The grounded solar array support structure would provide an ideal ground plane for any of the above transients to be capacitively coupled to the array.

The poor power factor associated with the line-commutated inverter may be a detriment to its use in applications of this type. This can only be evaluated by actual system level testing on the RPST program.

A self-commutated inverter which has the required high efficiency over a wide range of output power is unavailable as an existing design. A significant development effort will be required to produce the required inverter using one of several promising design approaches.

An air terminal lightning protection system is considered a necessity for each RPST installation, when the relatively small additional cost associated with this protection is weighed against the possible cost and embarrassment associated with a single direct strike.

Task IV - Test Planning

The evaluation of the two most promising system implementation options should be the principal objective of the experimental RPST program. To fulfill this objective a two stage experiment evolution is proposed. The first stage consists of the basic NOBATRY system configuration. After a 12-month evaluation period, on-site energy storage will be added and the basic system configuration will follow the UNREG model. This second stage will be similarly evaluated during a 12-month operational period.

Task V - Test Equipment Requirements and Procedures

A minicomputer controlled data acquisition and control system with on-site data storage, printer and graphic CRT peripherals was selected as the most cost effective approach for a two year duration test program with a limited number of remote site locations.

A graphical display panel was proposed for each RPST installation. This visual display of system operation and performance will serve as a valuable educational tool for visiting officials, the public and newly assigned project personnel.

The cost associated with the instrumentation and data acquisition and control portion of the RPST constitute a major fraction of the total system cost, exclusive of the solar cell modules.

Task VI - Institutional Problems

A detailed investigation of the legal liability aspects of the RPST program has yielded the following conclusions:

1. Any non-contractual liability of the United States to persons other than Federal employees would be by virtue of the Federal Tort Claims Act. Two important limitations to the Governments liability under this act are now well established:

   a. Any liability must be premised on some showing of negligence or fault by an employee of the United States, and

   b. The United States cannot be held liable for negligence of its independent contractors.

2. In view of these limitations, the potential liabilities arising from design and construction of the prototype homes can be largely eliminated through the use of independent contractors, provided that the Government exercises due care in selecting competent contractors to perform the work and does not exercise such a degree of supervision and control as to destroy the contractor's "independent" status.

3. Since the construction workers will be making use of some property under Government ownership and control, injuries arising from such use could lead to liability. To minimize such potential liability, the areas accessible to the construction contractor and subcontractors and their employees should be strictly limited.

4. Special care should be taken that the design includes safety features for at least any readily perceivable hazards resulting from the installation and operation of the solar array and of the battery. During and subsequent to installation, access to the roof of the prototype home and to the battery should be strictly limited and readily visible warning signs posted. Any access by "visitors", e.g., the general public, visiting Congressmen, etc., should be under

close supervision. If such visitors are to be allowed, it is especially important that any dangerous equipment be secured and made as tamper-proof as possible. What may be adequate precautions where a technician thoroughly familiar with the prototype is concerned, obviously may not be in other situations.

5. As long as the actual possession and control of the RPST's is vested in NASA-LeRC, a conveyance of the ownership of a RPST to the department or agency owning the real estate on which it is built will probably in no way decrease the responsibilities of NASA-LeRC.

6. It is generally recognized that Federal agencies and Federal installations are not subject to state or local regulations relative to zoning restrictions or building permits unless there is a Federal statute or executive order authorizing such regulation.

Based on previous experience with solar thermal panel installations, it can be concluded that local labor practices will need revision or further definition to cover the construction and installation of these new types of equipment. Since the government is generally not obligated to follow local building codes, no problems are expected in this area.

The importance of energy conservation in the architectural design of the house cannot be over emphasized. The energy conservation guidelines of ASHRAE Standard 90-75 should be considered as minimum design requirements for the RPST program.

SECTION 5

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MARCH 12, 1976

PRELIMINARY SPECIFICATION

FOR A

10 KVA POWER INVERTER

AND CONTROLLER

GENERAL ELECTRIC COMPANY
SPACE DIVISION
ADVANCED ENERGY PROGRAMS
P.O. BOX 8555
PHILADELPHIA., Pa. 19101

1.0 SCOPE

1.1 GENERAL

This specification establishes the performance, design, construction, and test requirements for a 10 KVA self-commutated power inverter and an associated controller which shall be used as part of a solar energy collection system. Figures A-1 and A-2 are generalized block diagrams of two modes of operation of the system. The basic function of the inverter is the same in either mode; consequently its design shall be such that it may be used in either application by simple manual reconnection of control interfaces. The controller function in the two modes is sufficiently different that the controller may be implemented as a single dual purpose unit or as two separate units.

1.2 MODE 1 - No On Site Energy Storage Mode

In this mode of operation (refer to Figure A-1) the DC power input to the inverter is obtained directly from a silicon solar cell array. The inverter shall convert the solar array output to 60 Hertz, 240/120 volt single phase ac power. The inverter output shall supply power to the variable load (typical domestic household type loads) with all excess power being fed into the utility power system. In the event the solar array output is insufficient to supply the load because of array capacity or reduced or no solar insolation the load power will be shared with or fed entirely by the utility power system. In the event of loss of commercial utility power, the inverter shall automatically shut down and disconnect from the utility power feed lines. The solar array output characteristics are described in detail in section 3. Briefly the

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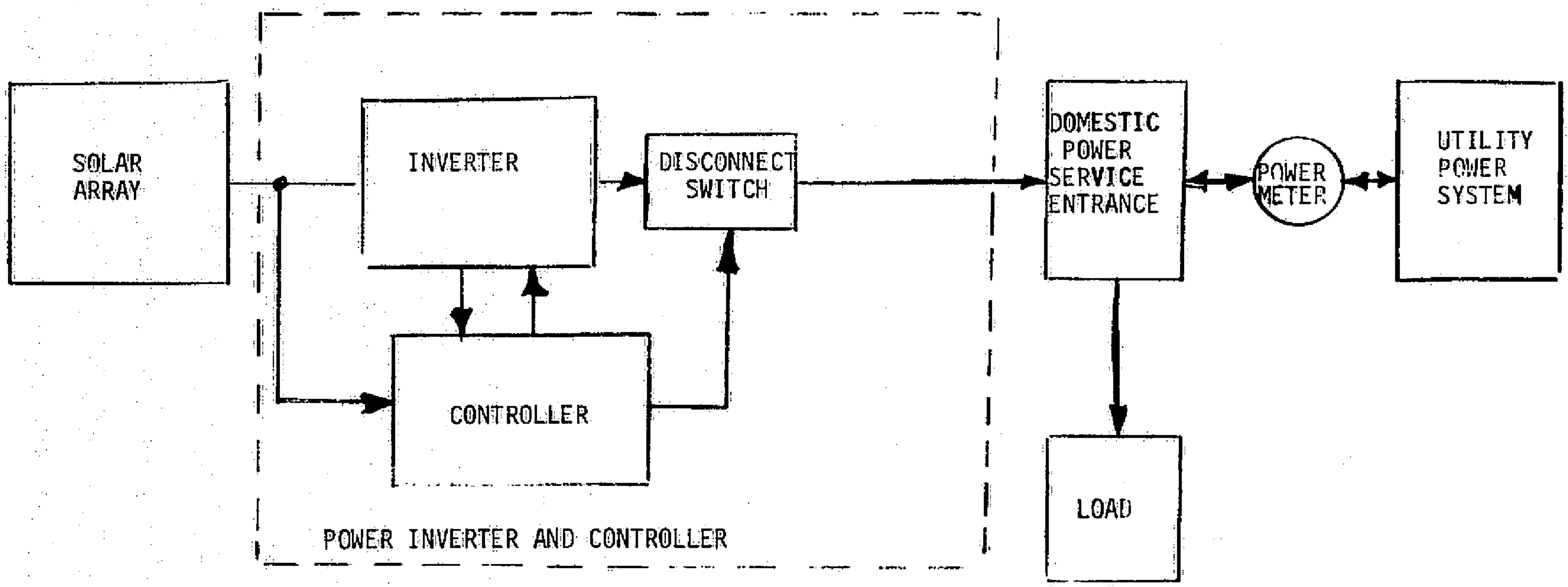


Figure A-1 Simplified Functional Block Diagram for Mode 1 (No On-Site Energy Storage)

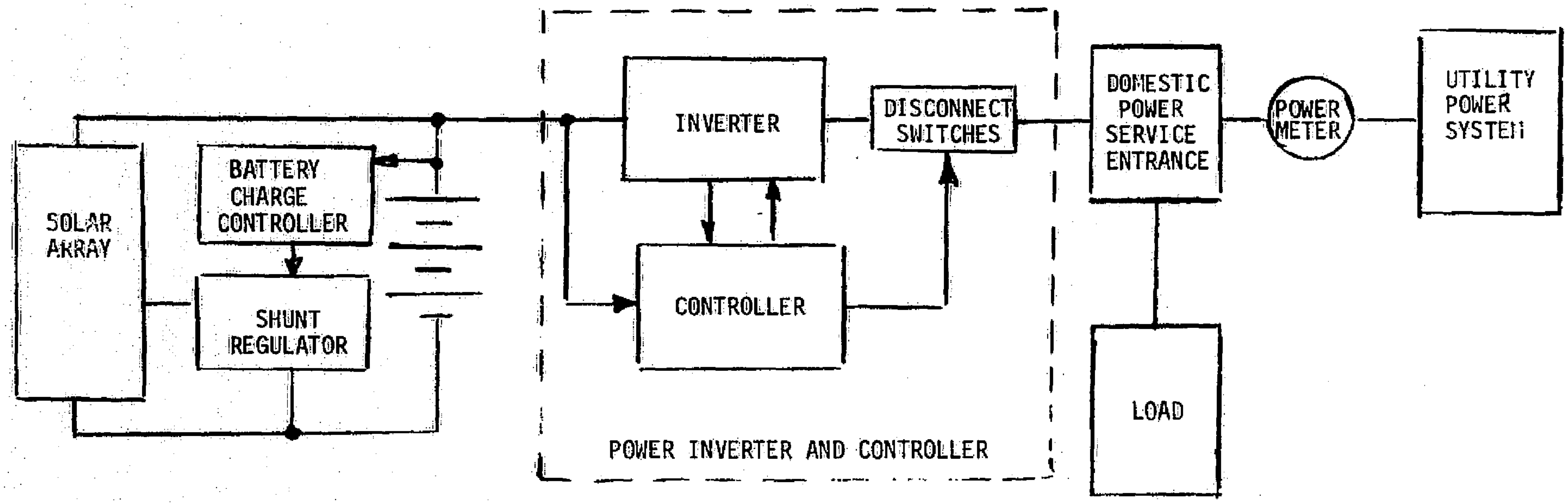


Figure A-2 Simplified Functional Block Diagram for Mode 2 (On-Site Energy Storage) power output of the array is a function of solar insolation, array temperature, and loading of the array. The array output is characterized by an "I-V" curve. The controller design shall incorporate a maximum power tracker to dynamically select the proper operating point on the "I-V" curve which will maximize conversion of available solar array power into real power delivered into the load or fed into the utility system. The inverter output frequency must be synchronous with the utility system frequency. The sharing of load and transfer of real and reactive power between the inverter and utility system is controlled by adjustment of inverter phase angle and generated voltage amplitude. Detailed performance requirements are specified in section 3.

1.3 MODE 2 - On Site Energy Storage Mode

In this mode of operation (refer to Figure A-2) solar array output is used to charge storage batteries in addition to supplying the inverter input power. The inverter output is paralleled with the utility system. The inverter output characteristics are controlled such that its output feeds the load only, with zero power transfer to the utility. The inverter is operative at all times when the battery bus voltage exceeds a predetermined level. When battery bus voltage drops below this level, the inverter shall shut down, disconnecting its output from the load and disconnecting from or presenting a high input impedance to the battery bus. When the battery is recharged to a preset level, the inverter shall restart and reconnect to the load. The utility system in this arrangement supplies all required power in excess of the inverter output capacity including required surge currents. The inverter output shall be synchronous with the utility system. In the event of failure of utility power, the inverter shall shut down and disconnect from the utility system. The inverter shall restart and reconnect to the load when utility power is restored assuming the battery bus voltage is above the appropriate limit.

2.0 APPLICABLE DOCUMENTS

2.1 The following documents form a part of this specification. The requirements as detailed herein shall govern in case of conflict between this document and the noted documents.

Specifications

General Electric Company

Solar Array Specification

Other Documents

National Electrical Code

3.0 REQUIREMENTS

3.1 FUNCTIONAL REQUIREMENTS

3.1.1 SOLAR ARRAY INTERFACE

The solar energy collector is a fixed solar cell array with a nominal 9 kw output. A simplified solar cell equivalent circuit is shown in Figure A-3. Figure A-4 defines the solar array characteristic I-V curves for several different conditions of insolation and cell temperature. The following specific solar array interface characteristics should be noted regarding these curves and the solar array properties in general: 1) a decrease in solar cell temperature translates the curve to the right, increasing open circuit voltage, 2) an increase in solar insolation translates the curve upward increasing short circuit current, 3) the maximum power point is located on the knee of the curve, 4) array output is a function of solar insolation (effected by angle of incidence, and cloud cover), and cell temperature, and 5) the solar array does not have significant energy storage capacity. Solar array capacitance is a linear function of junction current. A typical value of solar cell capacitance is 122 microfarads per ampere.

3.1.2 MAXIMUM POWER TRACKING (MODE 1)

The inverter and controller shall be capable of tracking the maximum power output point of the solar array when operated in the configuration shown in Figure A-1. Among suitable techniques for tracking maximum power are: 1) array excursions about the dc operating point with the resulting output

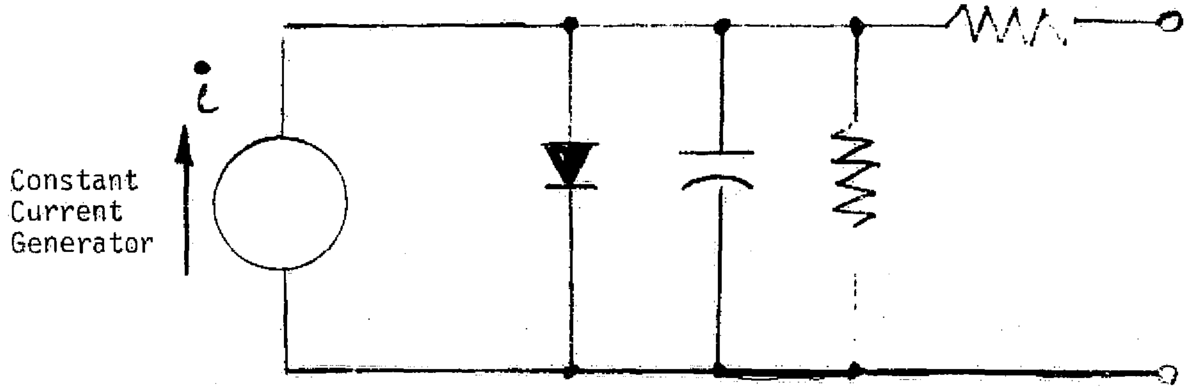


Figure A-3 Solar Cell Equivalent Circuit

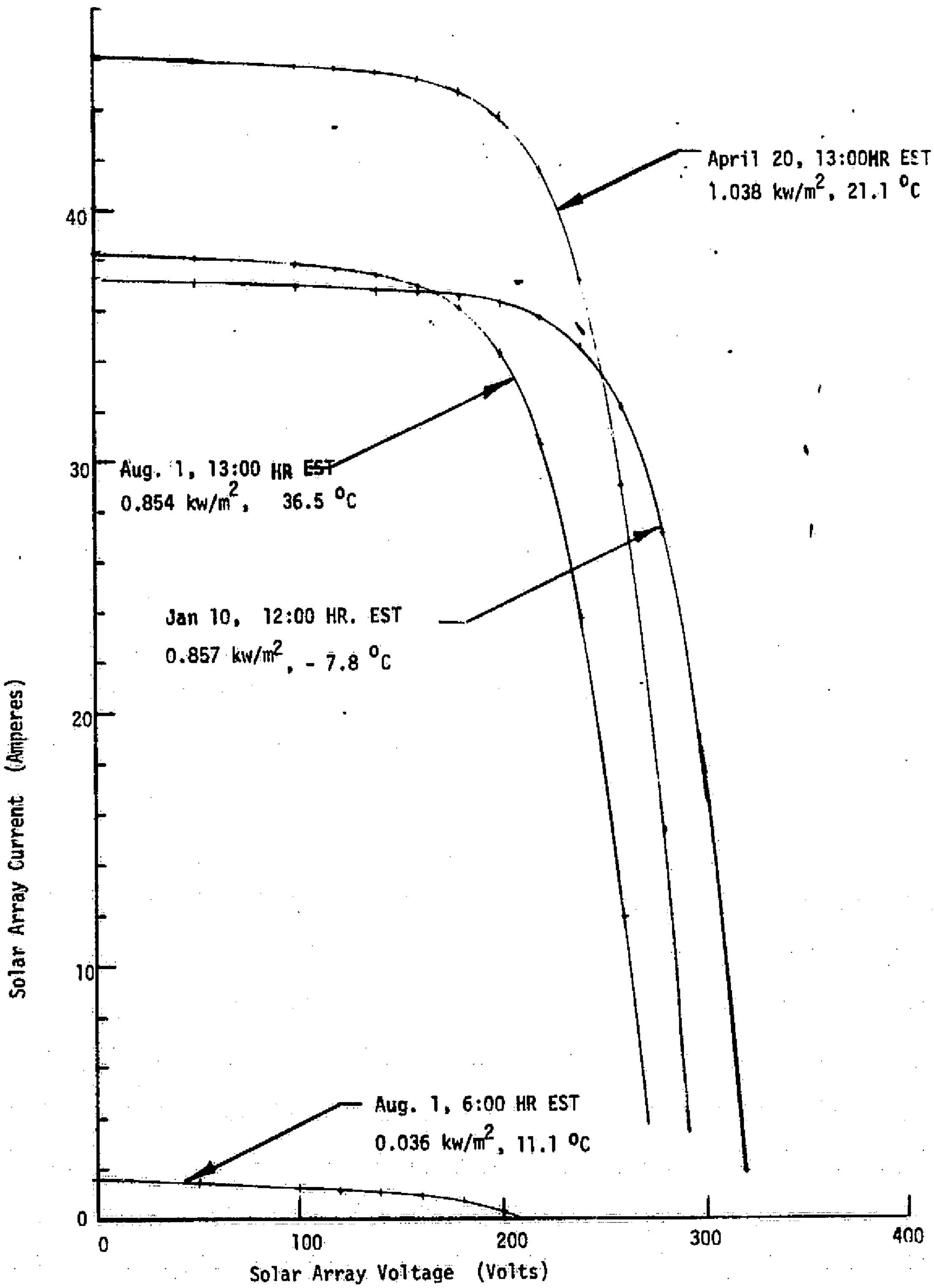


Figure A-4 Typical Solar Array I-V Characteristics voltage/current products being used to drive the dc operating point to the maximum power output point, and 2) an inverter output monitor of the product of VI cos θ which is used to drive the input circuit dc operating point to maximum for the combined array/inverter. This approach also requires a "dither" circuit. A somewhat less desirable approach is to use a small group of solar cells located on the array as a control group to determine the maximum power point of the array. In any case, the maximum power tracking circuit must take into account the dynamic characteristics of the solar array and inverter in order to minimize tracking errors resulting from array capacitance, and inverter input switching currents and input filter charactertistics.

3.1.3 FREQUENCY CONTROL AND SYNCHRONIZATION

The inverter shall be self-commutated. The internal oscillator shall free run at a frequency slightly different than the utility line frequency in order to permit it to be synchronized with the utility system frequency in both operating modes. In both operating modes inverter output frequency shall be synchronous and in-phase with the utility frequency prior to power paralleling or power transfer in order to eliminate transients. Return of the inverter oscillator frequency to its free run value may be used as a "loss of utility" indicator and be used to initiate disconnect from the utility line and inverter shutdown. Phase angle difference control shall be used in Mode 1 operation to control transfer of real power to the utility. In Mode 2 operation phase angle control is to control sharing of load power between the utility and inverter. This sharing shall be such that the inverter delivers full load power whenever possible but no power is to be fed into the utility system.

3.1.4 POWER DISCONNECT AND POWER TRANSFER

3.1.4.1 Mode 1 Operation

The controller shall incorporate a power disconnect switch and control circuitry which will automatically disconnect the inverter output from the utility line during periods of loss of utility system power. In addition the inverter input shall be disconnected or isolated from the solar array output during these periods.

3.1.4.2 Mode 2 Operation

The controller shall incorporate a power disconnect switch and control circuitry which will automatically disconnect the inverter output from the load and the utility line whenever the battery voltage drops to a preset level or when the utility synchronization signal is lost. During this time the inverter input shall also automatically disconnect from the battery bus. The inverter shall automatically restart and reconnect to the load and utility line whenever battery bus voltage is restored to the upper transfer voltage limit.

3.1.5 EXCESS POWER FEEDBACK TO UTILITY SYSTEM (MODE 1)

3.1.5.1 Mode 1 Operation

The inverter output amplitude and phase angle with respect to the utility system shall be continuously adjusted by the controller to provide transfer of excess real power to the utility system.

3.1.5.2 Mode 2 Operation

The inverter output amplitude and phase angle shall be continuously adjusted by the controller to deliver maximum required load power from the inverter. There shall be zero power fed back to the utility in this mode. Utility line current, voltage and phase angle may be sensed to establish that zero power is fed into the utility.

3.2 OPERATIONAL REQUIREMENTS

3.2.1 CONTROLS AND INDICATORS

The following controls and indicators shall be furnished as part of the controller and inverter.

1) Output Voltage Meter
2) Output Current Meter
3) Phase Lock Indicator
4) Input Power ON/OFF Switch
5) Output Power ON/OFF Switch
6) Output Power On Indicator
7) Transfer/Disconnect Switch Status
8) Overload Indicator
9) Overtemperature Indicator
10) Input Current Meter
11) Input Voltage Meter
12) Manual Controls for Voltage, Phase, and Frequency Adjust

3.3 PERFORMANCE REQUIREMENTS

3.3.1 INPUT VOLTAGE RANGE

3.3.1.1 Mode 1 Operation

In normal operation the inverter and controller shall maximum power track over a solar array output voltage range of 260 to 190 volts dc, with no degradation of performance, except of course that maximum power output is limited by the array I-V characteristics. The inverter input circuits shall be capable of withstanding input voltages of 0 to 350 volts dc without sustaining damage.

3.3.1.2 Mode 2 Operation

In normal operation, the inverter and controller shall be able to operate with an output no load to full load without degradation of performance over a battery bus voltage range of 240 volts to 186 volts dc.

3.3.2 Output Voltage and Regulation

The nominal inverter output voltage shall be 60 Hertz, single phase, 3 wire 240/120 volts ac with center tap grounded. In both modes of operation, the actual load voltage will be established by the utility system. The inverter shall be capable of operation with a commercial AC power line variation of +10% - 15%.

3.3.3 Output Power

3.3.3.1 Mode 1 Operation

In Mode 1 operation, the inverter output power is a direct function of available solar array power. A maximum steady state power output of 10 kilowatts is required.

3.3.3.2 Mode 2 Operation

In Mode 2 operation, the required output power is a function of system loads. A maximum steady state power output of 10 kilowatts is required.

3.3.4 Output Frequency

The inverter output frequency shall be synchronous with the commercial utility frequency. The inverter shall be self-commutated, and capable of tracking a 60 Hz line frequency. In the absence of utility power, the inverter shall have a free run frequency of 60.5 Hertz.

3.3.5 Total Harmonic Distortion

Total Harmonic Distortion (THD) shall be 15 percent or less. A THD of 5 percent maximum is desirable. For purposes of this specification, THD may be measured on the AC voltage waveform with the inverter operating into rated load without connection to the utility line or based on inverter output current waveform when operating into a resistive load with connection to the utility. Under all operating conditions the fundamental voltage shall be greater than 100 volts ac.

3.3.6 Power Factor

The inverter shall be capable of supplying no load to full load power factors of unity to 0.8. In addition, the inverter shall be capable of delivering all excess real power into the utility in Mode 1 operation, or supplying the full load with zero power transfer to the utility in Mode 2 operation.

3.3.7 Efficiency

Full load efficiency shall be 90 percent or greater for all input voltage conditions. At 15 percent of full load output, the efficiency shall be within 75 percent of its measured efficiency at full load.

3.3.8 Peak Demand and Overload

The inverter shall be capable of withstanding without damage peak loads of 150 percent of rated output for a period of one minute. Overload of 125 percent of rated output for a period of 15 minutes shall also be sustained without damage.

3,3,9 Short Circuit

The inverter and controller assembly shall be equipped with protective circuits and/or devices which will prevent damage to the inverter due to short circuit of the output.

3.3.10 Undervoltage/Overvoltage Protection

The inverter and controller assembly shall be equipped with protective circuits or devices which will prevent damage to the unit due to undervoltage or overvoltage at the inverter output. The inverter shall also not sustain damage due to an undervoltage condition appearing at the inverter input. The inverter must operate without failure during a one-half cycle drop-out of the utility line.

3.3.11 Load Unbalance

The inverter shall be capable of operation within specification with 100 percent load unbalance between each of the two 120 volt output legs (each half of the center tapped 240 volt output).

3.3.12 Output Grounding

Normal operation of the inverter shall be with the center tap of the 240 volt output grounded.

3.3.13 Transfer Time

Load transfer times shall not exceed 17 milliseconds.

3.3.14 Life

The inverter and controller shall be designed for a 20 year life. See paragraph 3.4.6 for maintenance definition.

3.4 Design and Construction Requirements

3.4.1 Physical Characteristics

There are no specific requirements placed on the size and weight of the inverter and controller other than the unit shall be capable of being installed in a typical single family residence. The unit shall be housed in a suitable cabinet (s) which meet the requirements of the National Electrical Code and which provide easy access for service and maintenance.

3.4.2 Service Conditions

A) Operating

Ambient Temperature	10° Celsius to 45° Celsius
Relative Humidity	Up to 95% non-condensing
Barometric Pressure	790 to 520 mm of mercury

B) Non-Operating

Ambient Temperature	-25°Celsius to 60° Celsius
Relative Humidity	Up to 95% non-condensing
Barometric Pressure	790 to 520 mm of mercury

C) Shock and Vibration

No specific levels of shock and vibration for operation or transportation are defined by this specification. The units shall be built to design practices to withstand normal handling and transportation environments.

3.4.3 Electrical Safety

The inverter and controller design and construction shall conform to the applicable requirements and practices of the National Electrical Code.

3.4.4 Electromagnetic Interference

Good design practices shall be followed to minimize electromagnetic interference and susceptibility. Conducted interference shall be less than 200µv between 5kHz and 3 MHz.

3.4.5 Thermal Dissipation and Cooling

The unit shall be designed to operate in the environment defined in paragraph 3.4.2 (A) without external cooling devices. Integral fans or blowers, if required, shall utilize ambient air.

3.4.6 Maintenance

3.4.6.1 Accessibility

The unit shall be designed to allow ready access for adjustment and maintenance. In so far as possible, plug in cards and modules will be utilized to facilitate troubleshooting and repair. Internal test points shall be provided to facilitate troubleshooting and repair.

3.4.6.2 Life

Specific mean time between failure levels are not specified by this document.

The unit shall be designed for a nominal 20 year life with a minimum of corrective maintenance. Preventive maintenance requirements shall be defined.

3.4.6.3 Spare Parts

A listing of spares required to support the unit will be provided in the Operation and Maintenance Manual. This list shall identify those items required for operational support and maintenance. Items not subject to wear-out or failure (e.g., hardware) will not be included on this list.

3.4.7 Documentation

3.4.7.1 Drawings

Six sets of schematics, wiring diagrams, and significant assembly drawings shall be provided with the unit.

3.4.7.2 Operations and Maintenance Manual

An Operations and Maintenance Manual shall be provided. It shall consist of the following:

1) General Description - (a brief overall description of function and performance).

2) Operating Instructions - (description of operating controls and sequences).

3) Adjustment Procedures - (set-up and calibration information).

4) Drawing List - (a list of applicable drawings and sketches).

5) Applicable Documents - (e.g.: Acceptance Test Procedures and Data Sheets).

6) Recommended spares list for operational support.

Six (6) copies of this material shall be provided.

4.0 ACCEPTANCE TEST

The unit shall be subjected to acceptance tests in accordance with a written detailed test procedure.

These tests shall demonstrate that the inverter meets the requirements of this specification in both modes of operation.

LIGHTNING PROTECTION

OF ROOF-MOUNTED SOLAR CELLS

F. D. Martzloff
Environmental Electromagnetics Unit
Corporate Research & Development
GENERAL ELECTRIC COMPANY
Schenectady, New York

SUMMARY

Lightning interception by an unprotected building 30 feet high x 45 feet long on flat land, in the Cleveland area, can be estimated at one strike per 200 years on the average. However, peculiar configurations can easily affect this estimate upward or downward. Means are available to install air terminals so that interception will be done by these, without harm to the roof-mounted photovoltaic array. Economic trade-off on the decision to invest in a lightning protection system during the life of the development project must also include intangible factors such as schedule delays and post-mortem apologies for insufficient protection.

LIGHTNING PROTECTION FOR ROOF-MOUNTED SOLAR CELLS

1.0 INTRODUCTION

This discussion is presented as an introductory guideline to alert system designers and provide a basic understanding of the phenomena governing the techniques of lightning protection. No definitive numerical prediction is given at this time, pending availability of architectural details; an example of estimated interception rate is given for an assumed building in the Cleveland area.

A brief description is given of the lightning phenomena, as well as of the basic concepts which need to be understood for effective application of protective techniques. Prevention of direct effects, that is, the effects associated with current flow in the system, to be avoided, is first discussed. Indirect effects are also mentioned, and the document is completed by a bibliography for further reading by interested designers.

2.0 LIGHTNING PHENOMENA

The phenomenon of lightning has been the subject of intensive study by many workers (see bibliography) and its behavior is fairly predictable in general terms, although the exact description of specific incidents is not predictable. Protection against lightning effects includes two categories: direct effects concerned with the energy, heating, flash, ignition of the lightning current, and indirect effects concerned with induced overvoltages in nearby electrical and electronic systems.

Claims to the contrary notwithstanding, there is no conclusive evidence that lightning can be prevented. Consequently, one has to design and implement a facility to recognize the possibility of a lightning strike, and take appropriate measures to make this strike harmless. Lightning protection is then an approach where one can make the proper moves if the characteristics of the enemy are anticipated.

Two concepts must be understood to apply effective lightning protection devices: the "cone of protection" and the "striking distance." These will be discussed with some detail in the following pages. Other fundamentals of electricity such as the impedance of a circuit to fast-changing currents impulses are assumed familiar to the reader.

We will first review current theories on the formation of lightning, then go on to the concept of the cone of protection and striking distance. The following descriptions are based on the work and papers of Fisher, Cianos & Pierce, and Golde.

2.1 Generation of the lightning flash

The energy that produces lightning is provided by warm air rising upward into a developing cloud. In detail, several theories vary, but all are based on the observed evidence that the cloud, except for the top, is negative, with

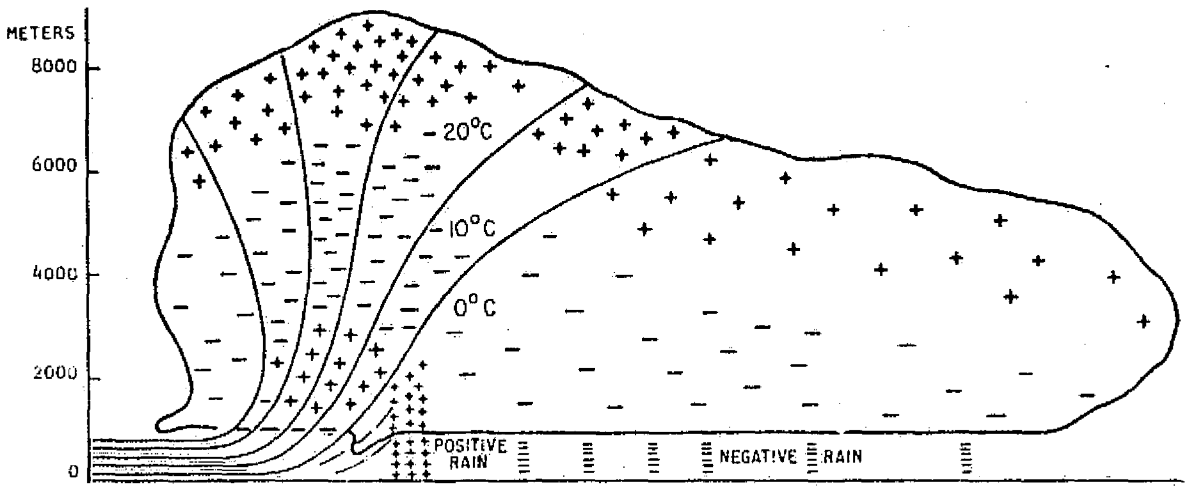


Figure B-1

Generalized diagram showing distribution of air currents and electrical charge distribution in a typical cumulonimbus

a small body of positive charge near the front base of the cloud. Figure B-1 shows a typical cloud distribution of charges; the solid lines represent the direction of the air movement in the cloud, with the cloud moving from right to left. As the cloud passes over a point on the ground, an electrical charge is attracted under the cloud on the ground. The average electric field at the surface of the ground will change from its fair-weather value of about 300 volts/meter to several thousand volts/meter. The gradient will be concentrated around sharp protruding points on the ground, and can exceed the breakdown strength of air, typically 30 kV/cm.

However, the first significant event toward formation of a lightning flash occurs at the cloud. A slow-moving column of ionized air forms at the cloud, called a pilot streamer, moving by steps of 30 to 50 meters, and followed by a more intense discharge, called a step-leader, because of the discontinuous process of ionization and filling of the column with charged particles.

The step-leader does not move in a straight line towards the ground, but seeks out the path with least electrical resistance, producing the familiar zig-zag pattern of the final stroke, with branches as several paths may be formed in the process of searching a weak path. The interval between the successive steps is about 50 microseconds, allowing progressive build-up of charges on the ground as the charged column advances toward the ground. Finally, a stage is reached with the step-leader being one step only away from the ground, when the last step is completed, either by continuation of the process, or by meeting a leader of positive charges originating from the ground. We will discuss the implications of this in some detail in the section dealing with the striking distance concept.

With the path now completed, a positive charge then flows upward from the ground into the negative channel left in the wake of the step-leader, neutralizing the charge in this channel and moving at roughly one third of the speed of light. This is what constitutes the lightning stroke, carrying the current at peaks of 1000 to 100,000 amperes, with a decrement to half-value in the order of 50 microseconds. The first one of these which occurs in a flash is called the return stroke.

The first return stroke neutralizes the ionized column as well as a small pocket of changes in the cloud; a second or more return strokes, sometimes called re-strikes or subsequent strokes, can take place, using the same ionized channel, but moving much faster. Thus, a series of strokes, such as shown in Figure B-2, can occur in an interval in the order of a second. Each of these strokes increases from a very low quiescent value to a very high amplitude in a very short time, resulting in rates of current change up to 1×10^{11} amperes/second.

When very tall objects are present, a step-leader can actually originate from this object, and travel upward to the cloud, rather than the more general case of downward-moving leader. Subsequent charges, however, will be similar, that is, move in the ionized channel left by the first discharge.

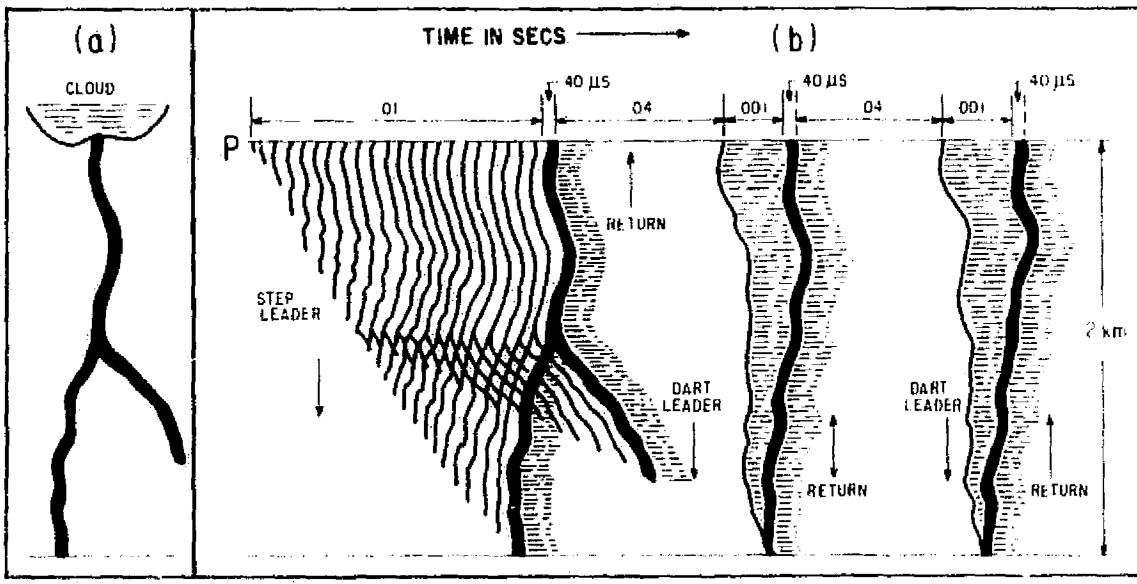


Figure B-2

Diagram of the development of a lightning flash

(a) Recording by conventional fixed camera
(b) Recording by camera with moving film resolving the progress of the leaders (After Schonland)

In addition to the short (tens of microseconds) discharges just described, a low amplitude current can exist between the individual strokes. Although low in amplitude (a few hundred amperes), the long duration of this continuing current (tens to hundreds of milliseconds) is significant because of its total charge, resulting in most of the burning and metal-melting effects of a lightning flash.

The wave form and amplitude of lightning stroke and continuing currents vary over such a wide range that information has to be presented in statistical form; Cianos & Pierce have published a comprehensive set of statistics, from which the data of Figures B-3 through B-8 are derived, giving the reader a feel for the orders of magnitude involved.

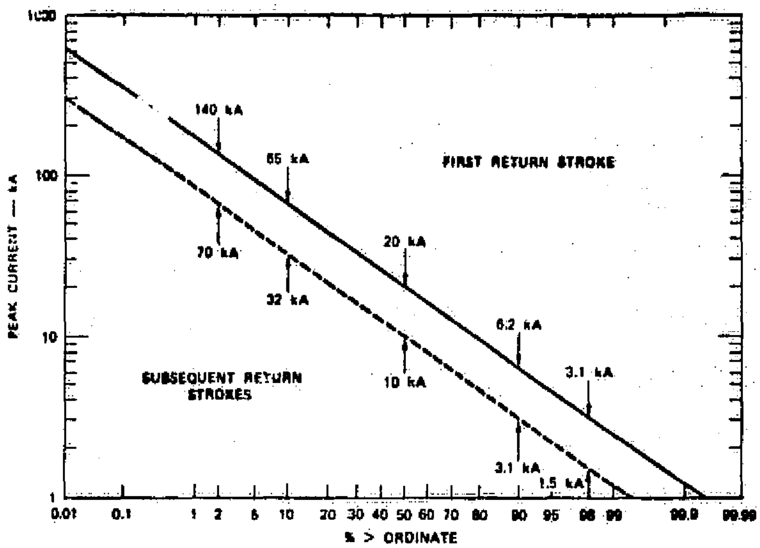


Figure B-3

Distribution of peak currents for first return stroke and subsequent strokes

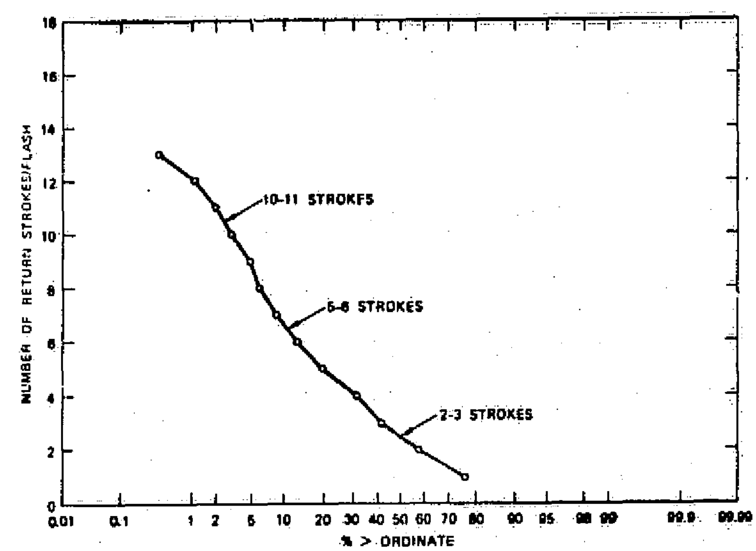


Figure B-4

Distribution of the number of return strokes per flash

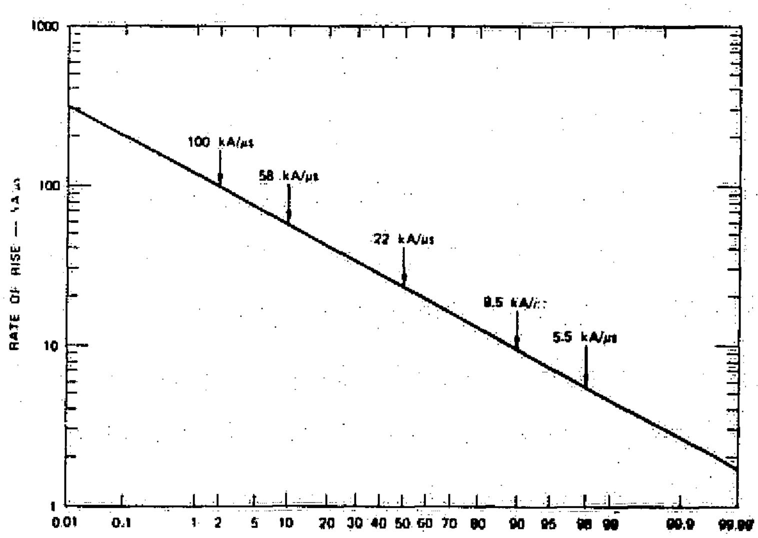


Figure B-5

Distribution of rates of rise

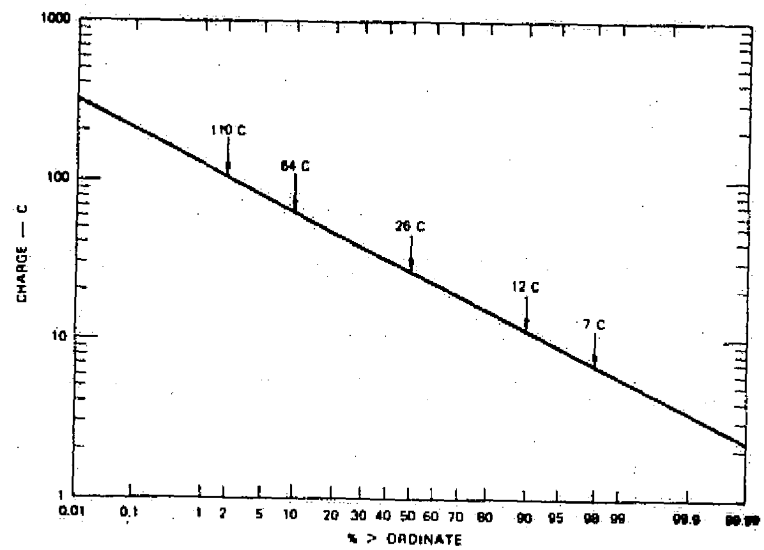


Figure B-6

Distribution of charges in continuing current

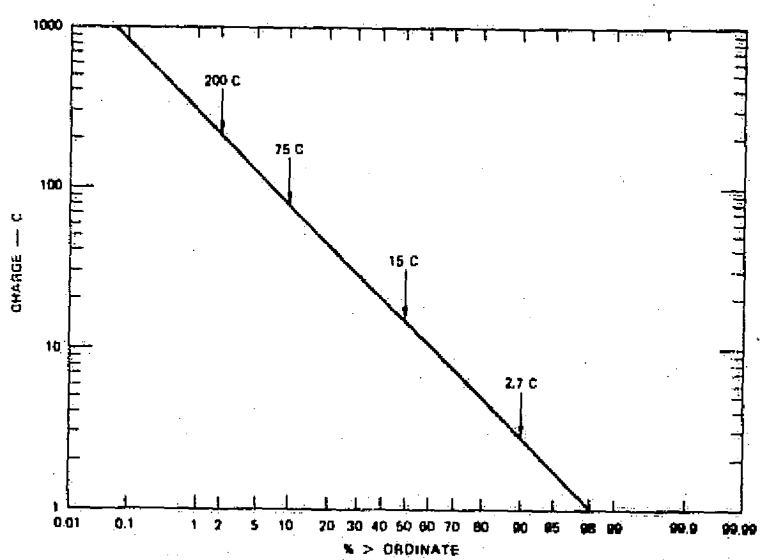


Figure B-7

Distribution of charge/flash

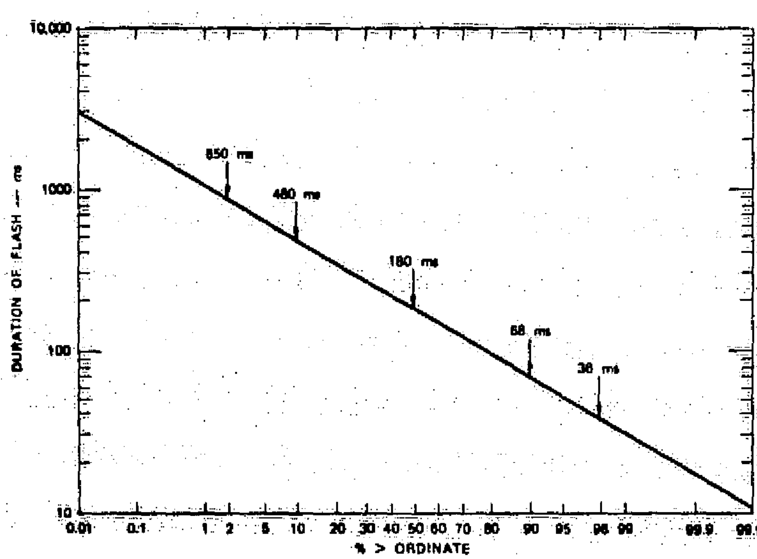


Figure B-8

Distribution of duration of flashes to earth

2.2 Frequency of occurrence

One of the major factors to consider in determining the probability of lightning damage, and thus the need for strong protection, is the number of lightning flashes to earth in a given area for a given time. This is not generally available, and instead the number of "thunderstorm days" is quoted. However, this does also include the cloud-to-cloud discharges, and does not represent an accurate parameter, since it does not include the duration and intensity of each storm. Progress is being made in improved statistics, but these are not yet available, and therefore the "isokeraunic level" maps, showing the number of storm-days per year, is still the most widely used description of the occurrence distribution. An empirical equation has been derived, relating the density of flashes to ground and the number of storms per year, as follows:

density in flashes per km^2 per year: D

thunderstorm-days per year: T

$$D = 0.02\ T^{1.6}$$

This corresponds to approximately 1 flash per year per km^2 at an isokeraunic level of 10, and 10 flashes per year per km^2 at a level of 40.

The significance of this situation is that, contrary to some popular beliefs, the density of lightning flashes, on the average, is independant of terrain. However, detail of the ground objects (trees, buildings, hills) will produce a bias in the local distribution of this average.

2.3 Striking distance

This distribution at the local scale is determined by the final stages of the step-leader coming from the cloud, so to speak, without knowing what it will find on the ground. Thus the actual pointof termination can be somewhat controlled, while the probability of a given area to receive a lightning stroke cannot. This is where the concept of the striking distance, as explained by Golde, becomes very useful.

As the step-leader has approached the ground in the haphazard path described above, the point is reached where one more strike in the discontinuous process will close the path. The distance between the top of the leader and the object about to be struck (or about to emit the meeting leader) is called striking distance. The length of this distance is affected by the field established by the leader, which in turn is determined by the amount of charges existing in the ionized channel coming from the cloud. With large charges in the channel, the field is more intense, so that breakdown can for longer distances, while a shorter distance is necessary to produce breakdown for the weaker fields established by smaller charges. Figure B-9 shows the relationship between the stroke current (which reflects the charge existing in the ionized channel) and the striking distance, as computed by Golde.

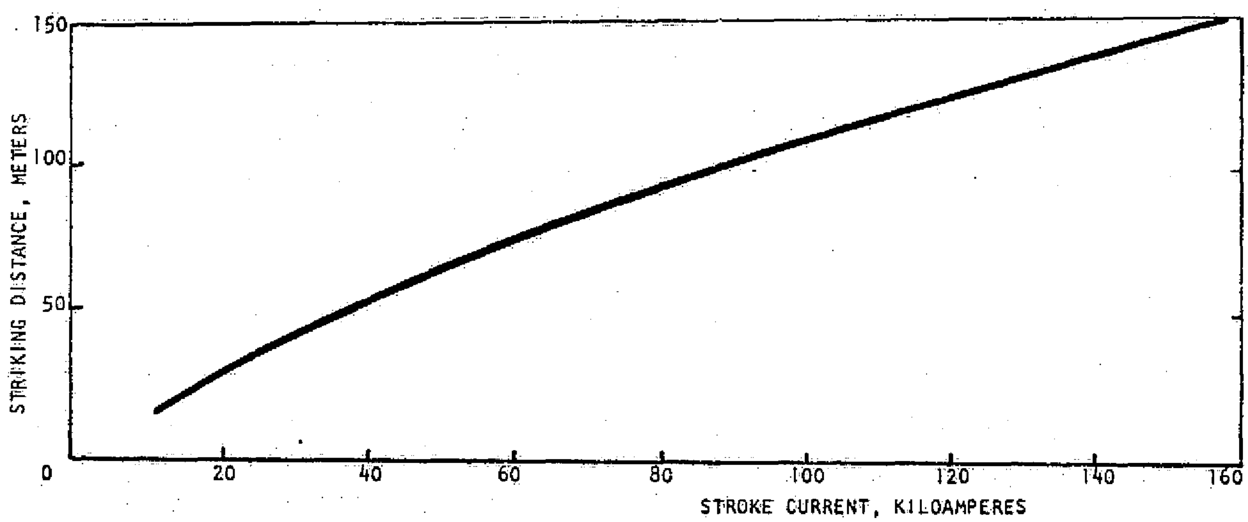


Figure B-9 Striking distance vs current amplitude

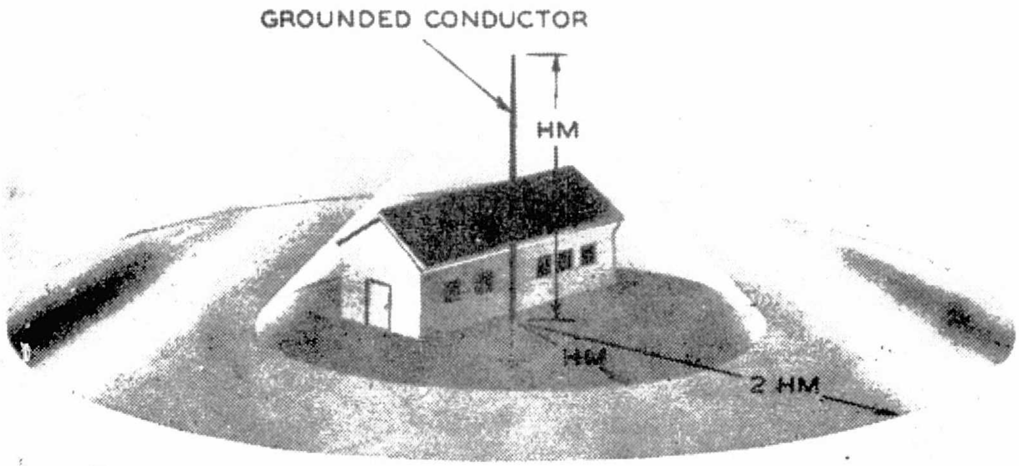
For instance, an average lightning current of 25 kA would correspond to a striking distance of 40 meters. Thus, for an average stroke, details of the terrain do not affect the point of termination of the stroke beyond this distance, but only within this distance will there be a race, or a competition, as to which point will receive the flash, or invite it by sending a meeting streamer. Conversely, very low amplitude flashes have an even shorter striking distance, meaning that they will ignore "attractive" points of termination, explaining some of the more puzzling exceptions to the generally assumed effect of tall structures, rods, etc. In other words, once a lightning step-leader has approached the ground within just short of the striking distance, no amount of devices beyond the striking distance will have any effect on the occurrence of the stroke, just the details of the area within the striking distance will determine the point of termination; the area is committed to receive the stroke, and it is now up to the humans controlling the shape of the objects on the ground to provide a least harmful point of termination, and make it most attractive to the approaching leader ("take me to your leader"...)

A number of photographs have been collected, and reported in the literature, showing a lightning flash approaching the ground in a somewhat wandering but generally downward direction, but with a sharp "turn" near the lower part of the path. This, according to the striking distance just described, can be readily explained as being the point where the downcoming step-leader met the upcoming leader from the ground. A photograph of a particularly clear occurrence of this will be found in the Appendix.

We are now ready to tackle the concept of the "cone of protection," having understood how the striking distance concept can explain some of the otherwise unexplained exceptions to the generally accepted and verified protection afforded by projecting objects, natural or artificial.

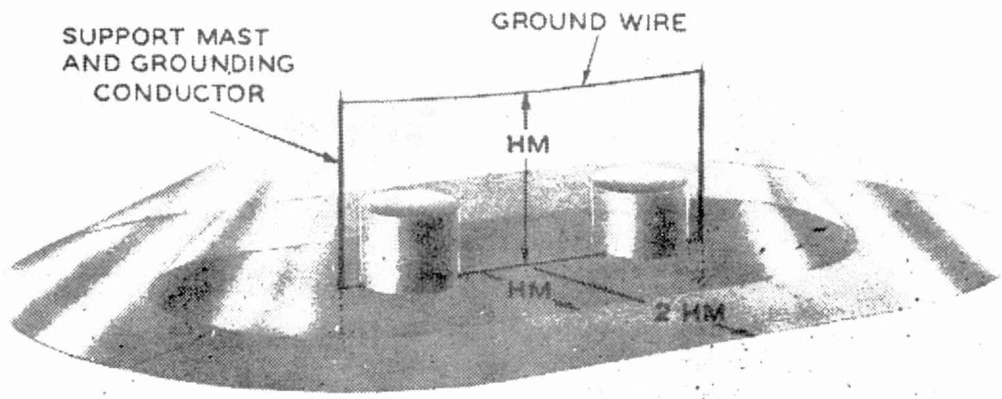
2.4 Cone of protection

From the days of Benjamin Franklin, the concept of a cone of protection has been used to provide effective protection of objects within the cone. Briefly, this concept states that objects contained within a cone of 1:1 or 1:2 ratio of height to radius (Figure B-10) will not receive the lightning stroke, but that the object at the apex of the cone will. In the elementary



A.

Cone of Protection Provided by a Vertical Grounded Conductor.



B. HM = Height of Mast.

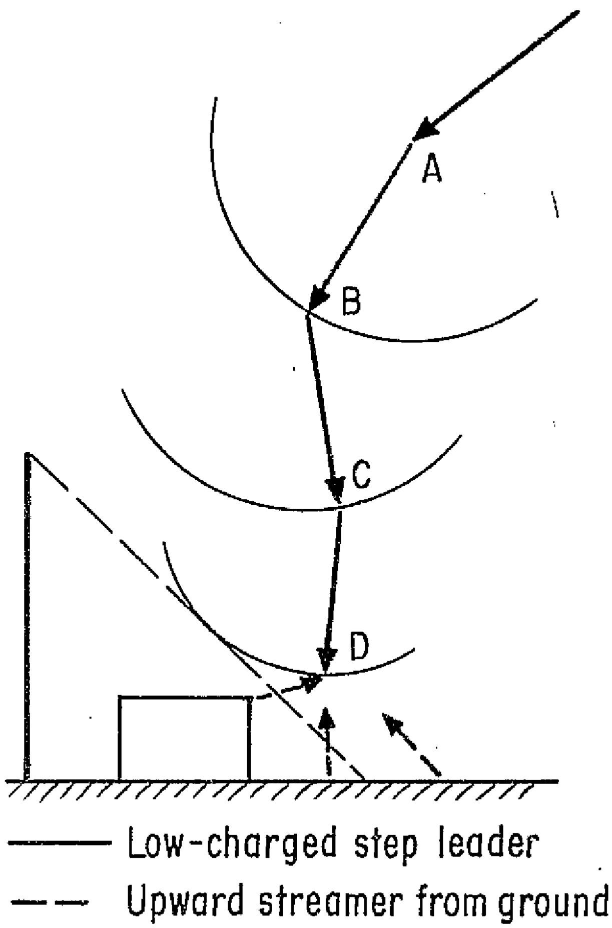
Zone of Protection Provided by a Horizontal Aerial Ground Wire.

Figure B-10

Cones of protection (from NFPA 78-1975)

concept, only one projecting object above a ground plane is being considered; in most practical situations involving buildings, multiple cones will be or should be considered.

Historically, a 1:2 cone was considered acceptable. However, some exceptions to the "rule" of protection (as if Zeus should abide by "rules") have recently led to a more conservative use of a 1:1 cone of protection; the exceptions can be explained by the striking distance concept, as we shall now see.



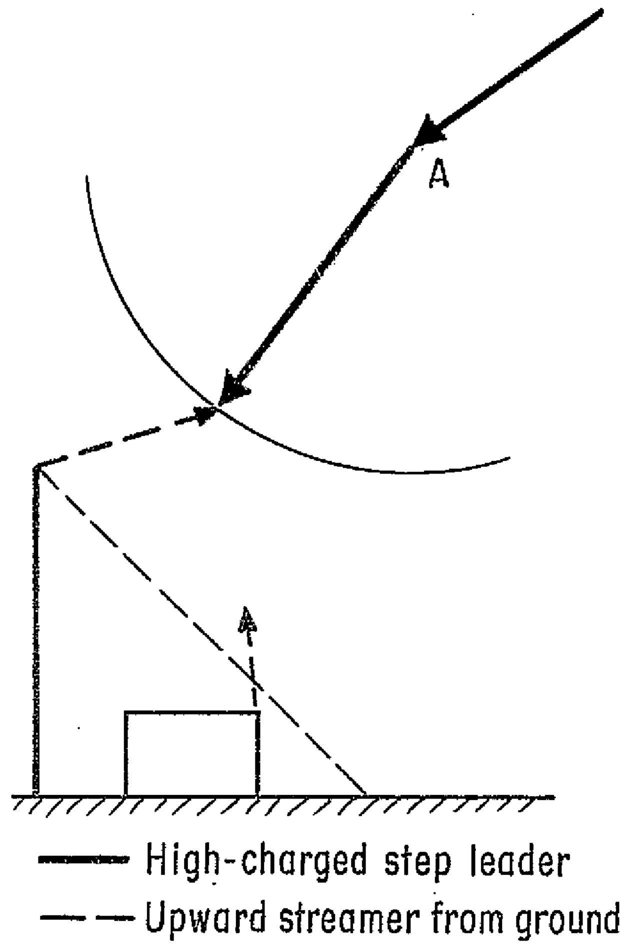


Figure B-11

Termination of stroke with short striking distance

Figure B-12

Termination of stroke with long striking distance

Classical "cone of protection" rule for the building shown in Figure B-11 would assure that the lightning mast shown provides dependable protection for the building against an approaching step-leader. However, if we consider the striking distance shown by the circles, at each step of the leader advance, we can see that the leader will have ignored the lightning mast, and that at the fateful last decision point D, the shortest distance is to the corner of the building within the "cone of protection," rather than to ground, even less to the lightning mast. The path drawn here also exhibits the tell-tale sharp inflexion of the last step mentioned above and often photographed.

By contrast, the step-leader drawn in Figure B-12 for the case of a stroke with higher prospective intensity, and thus longer striking distance, will terminate at the lightning mast, starting from the same point "A" of its path. This corresponds to the classical cone of protection situation; it implies that the step-leader can find within its striking distance a point of termination which is intentional, rather than an object which happens to be close enough and shaped in a manner promoting the initiation of a streamer which will "win" the race to meet the step-leader.

3.0 DIRECT EFFECTS

3.1 Conduction of current to ground

We have now reached the state where lightning has struck, and have seen that it may strike in some rather unexpected (and unprotected) locations, and are faced next with an evaluation of the effects of the stroke and continuing current flow. In the case of a roof-top array of voltage-sensitive cells, the real story begins with the flow of current below the first metallic termination point. Therefore, lightning protection in this context will mean making sure that the lightning does terminate where we want it to terminate, and that from there it is led to earth in an acceptable manner, along a safe, controlled path.

The most important consideration is then what happens to the potential drop along the current path to ground. We have seen that the current increases very rapidly on the front of the wave. Therefore the inductive drop L di/dt over the current path will be extremely large, in other words, during initial phase of the discharge, the "grounded" lightning rods and down-comers of a building network will be elevated to substantial potentials above earth ground, in the order of tens or hundreds of kilovolts. Any circuitous path in the downcomer will increase this voltage drop, with the attendant risk that a flashover may occur to bridge and shorten this path, defeating the intent of carrying the current directly to earth, away from the array.

Another consideration is the difference of potential established during the initial phase, when the current increases at extremely fast rates, between the lightning system and the cell array. The upper portions of the downcomers are elevated at very high potential because of the inductive drop, while the upper metallic parts of the array remain uninvolved in the current path, and therefore remain at "gound" potential. We are writing "ground" in quotes as this is an arbitrary definition in the context of potential distribution during a lightning stroke.

With reference to Figure B-13, the "ground" point can be represented as the common point "G" at which the electric power system of the house is tied to the downcomer conductors; any further impedance below point "G" and "true" earth is not relevant to the difference of potential V established across the wall of the building at point A. If the length (inductance) between points B and G is large, and the distance between A and B small, the voltage V will exceed the dielectric strength of the AB gap, and a "side flash" will occur between A and B, with possible disastrous effect.

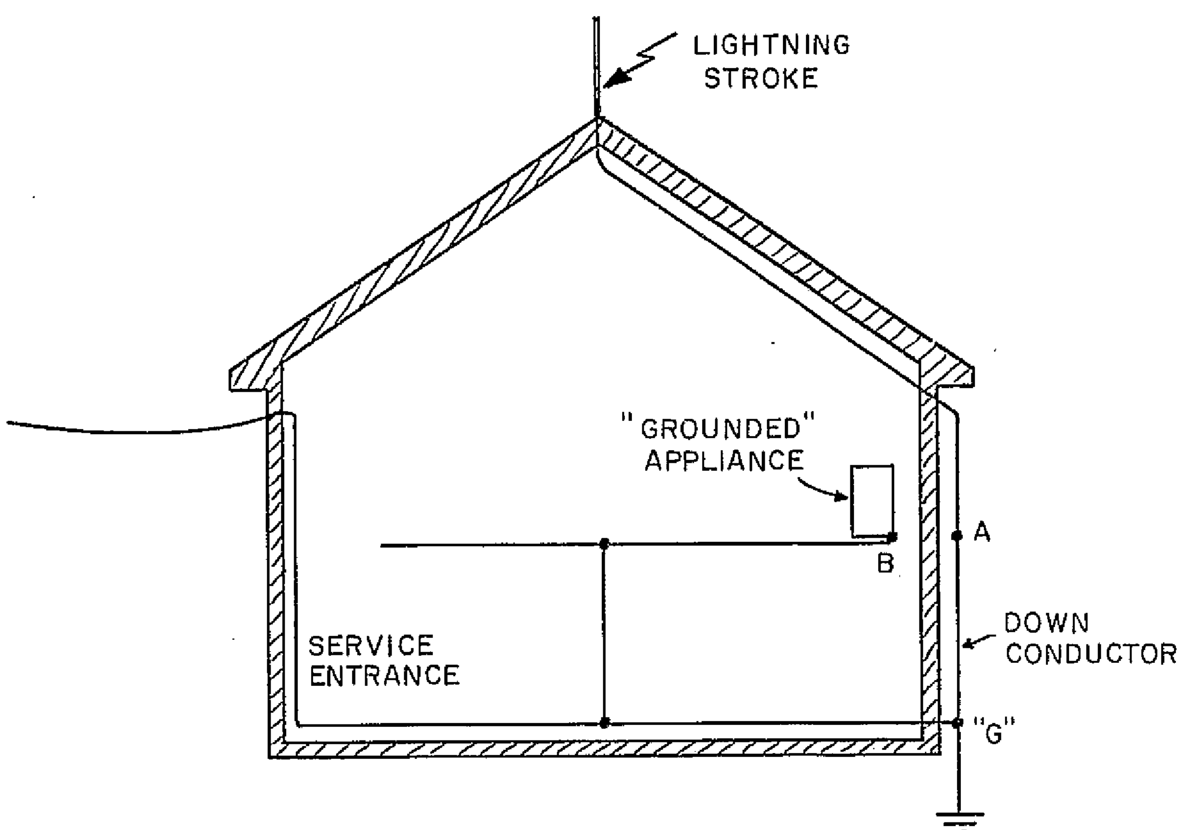


Figure B-13

Side flash problem on lightning conductors

3.2 Design of the air terminals

Protection of an experimental roof-top array is different from the protection to be provided, if any, for future mass-produced arrays. In the case of the experimental system, the high cost of a lightning strike should prevail over aesthetic considerations, so that the objective will be to maximize protection. Once the cost of the roof array is established as a commercial product, the trade off between economics and aesthetics will be quite different. In this discussion, however, we are addressing the case of the experimental house.

There are two basic approaches to providing sufficient protection: lightning masts, at some distance from the house, with sufficient height to provide an effective cone of protection, and lightning conductors above the roof. Neither can provide absolute protection against all possible strikes; however, the likelihood of a strike attaching to the roof-mounted array will be decreased by several orders of magnitude if a properly designed system is installed.

3.2.1 Lightning masts

The discussion of paragraph 2.4 above, and the possible exception to the protection expected for a strict interpretation of the cone of protection formula, give some guidance on the design of a mast system. For the experimental model, two masts at minimum are recommended, with four being even more effective. (In the case of a project involving a group of closely spaced houses, it may be possible to provide a common mast at each lot boundary. Figure B-14 shows how such a mast system can be implemented. One of the advantages would be complete independence of the power system and lightning system at all but one point.

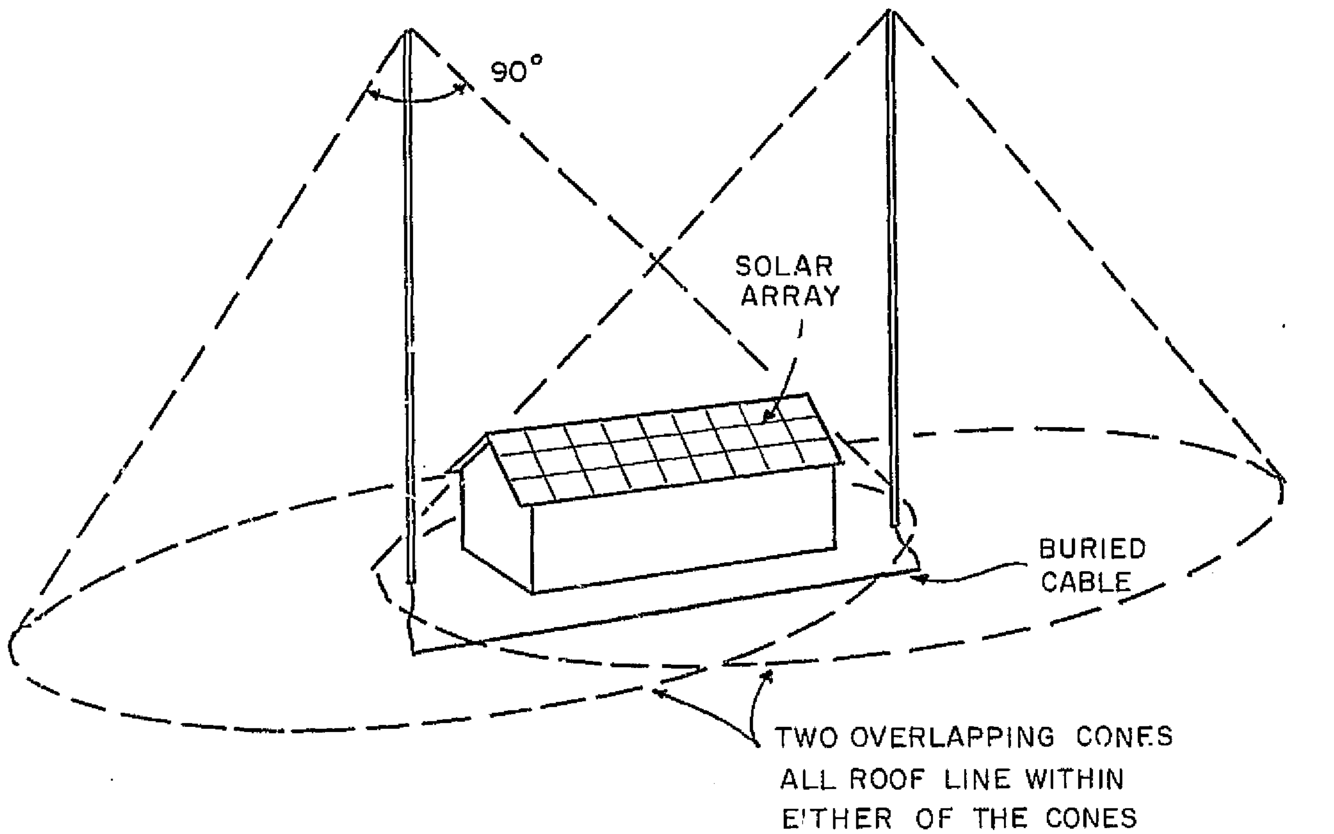


Figure B-14 Lightning protection using two masts

3.2.2 Lightning conductors

A possibly more effective protection can be expected from a lattice of lightning conductors strung some distance above the roof. The number of conductors, and the distance from the roof are in inverse proportions. Therefore, there is a possible trade-off between a few conductors high above the roof, and many conductors close to the roof. The boundaries of the trade-off correspond to the situation where the many conductors would be so close to the roof that side-flash becomes a problem, or where only a few, very distant conductors would allow a low-amplitude stroke, with attendent short striking distance, travel around the theoretical cone of protection, as discussed in paragraph 2.4.

In any case, the down conductors for the cable lattice have to be routed far enough away from the roof to prevent any side flash. Figure B-15 shows a possible arrangement for a cable lattice system.

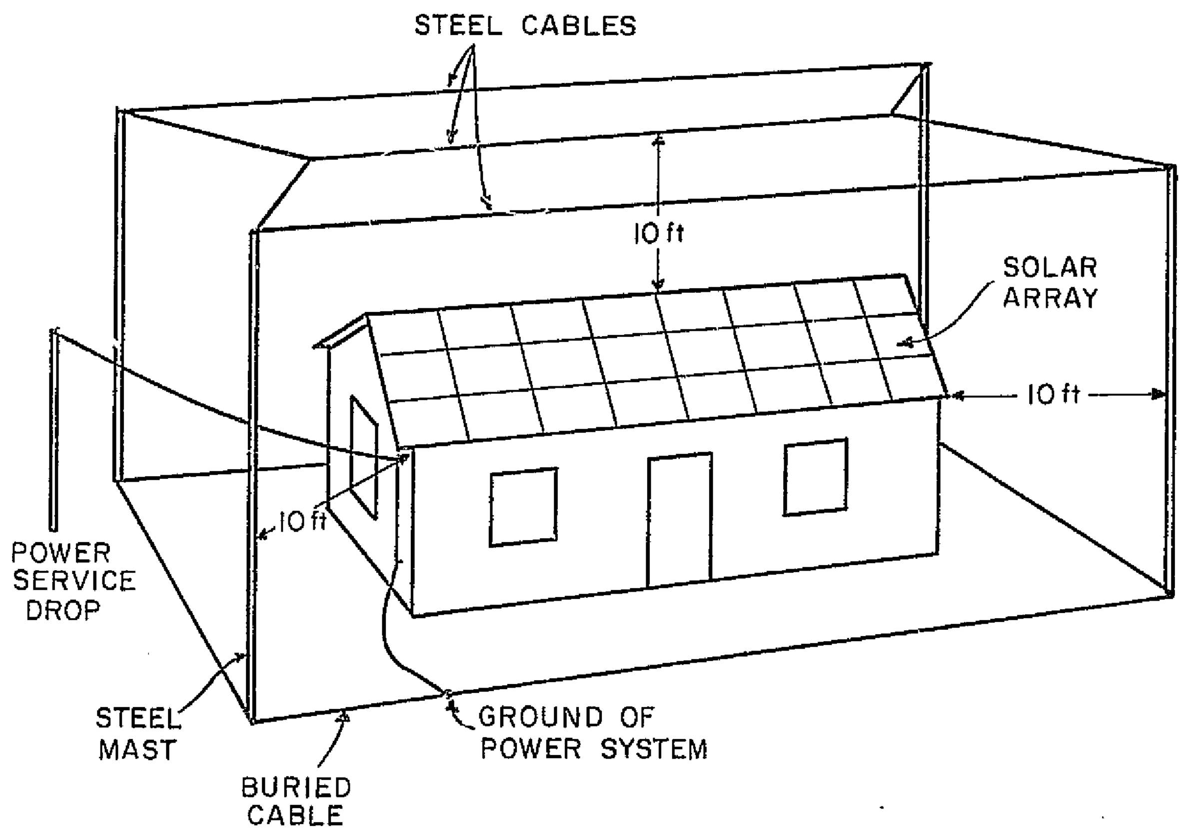


Figure B-15 Lightning protection using overhead cables

4.0 INDIRECT EFFECTS

4.1 Indirect voltages

The major indirect effect of lightning strokes for this project is the voltage induced on the power system by the rapidly changing magnetic flux associated with the high di/dt of the lightning current. A less important but still significant effect would be the voltage produced by electrostatic coupling between the roof array and the charges associated with atmospheric electricity.

Typical lightning strokes involve currents of 50 kA reaching crest in 1 microsecond. Thus, the $d\phi/dt$ near the lightning conductors will be quite high and capable of inducing destructive voltages in any loop which would link a substantial flux from the lightning current. Therefore, the power system, cell array and control circuits must be designed to minimize intrinsic coupling, or be suitably shielded.

4.2 Effect on incoming power system

There is a certain amount of information available from various sources on the magnitude of transient overvoltage entering a house wiring system by the route of the utility service. While not exhaustive, the data collected so far have indicated that transients up to 6 kV can occur, infrequently, but still often enough to cause concern for sensitive electronics. This problem of course is not unique to photo-voltaic systems, but is faced by every applicance manufacturer.

In the present case, recognition of the problem is all that is necessary since there is a wide variety of commercial devices available to suppress these surges.

5.0 FLASH INTERCEPTION RATE

The relationship between annual thunderstorm days and flash density has been defined by empirical formulæ and plotted by Cianos & Pierce. Table B-1 shows the computed ground flash density, obtained by multiplying the flash density by a factor relating the ground flashes to the total flashes. This factor depends on the latitude, as suggested by Cianos & Pierce.

Table B-1

Thunderstorm Days per year	FLASHES/km^2/YEAR Flash Density (total)	Ground Flash Density at 40° latitude
10	0.77	0.2
20	2.52	0.7
30	4.83	1.4
40	7.69	2.1

Using the cone of protection concept in reverse, we can estimate that the effective area of an object protruding over the ground surface, in attracting a strike, increases as its height increases. For a height h, a circle of radius 2h can be considered as candidate for flash interception. Thus, assuming a building of 45 feet (15m) x 30 ft (10m), with a height of 30 ft (10m), the effective area is indicated by the sketch of Figure B-16. The area corresponding to an elongated double cone originating from a roof antenna on one side and the peak of the roof on the other side, at a 2:1 angle, is approximately 50 m x 50 m = 2500 m^2 = 0.0025 km^2.

Applying the ground flash density of Table B-1 for an isokeraunic level of 40 (see map of Figure B-17), we obtain an estimated interception rate of 0.0025 x 2.1 = 0.005 flashes per year on the area covered by the house and its associated cones.

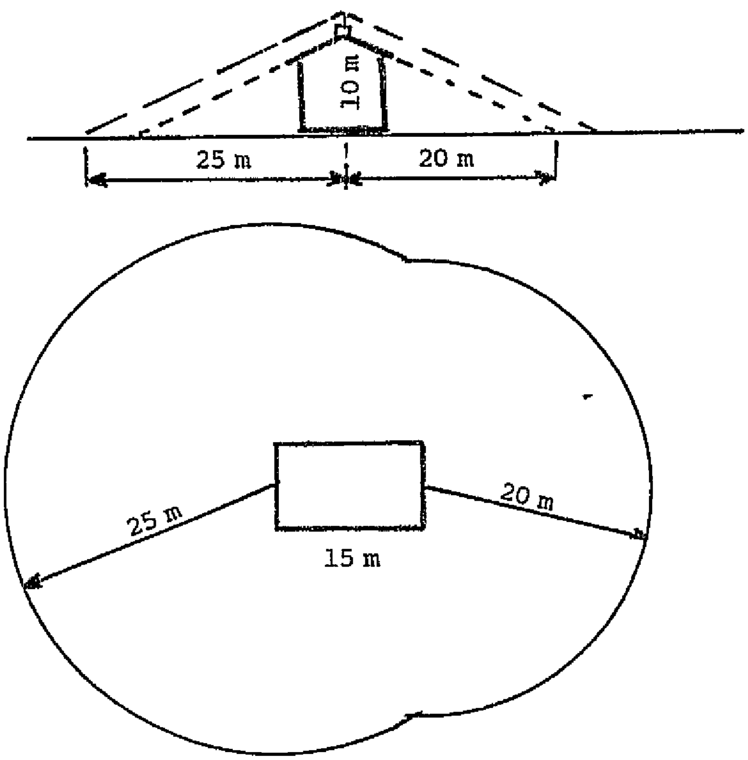


Figure B-16 Interception area of a typical house

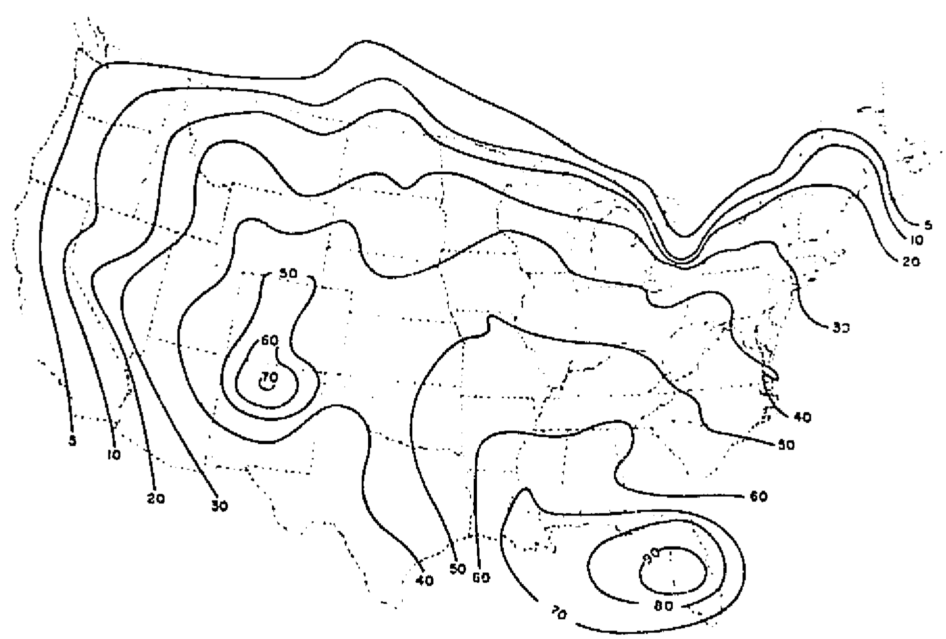


Figure B-17 Annual isokeraunic map (after Alexander)

In other words, the house in this example can be expected to intercept a lightning strike once every two hundred years. This prediction would be based on a house projecting above flat terrain, which we understand to be the case here. One must bear in mind that in the absence of adjacent, overlapping cones of protection from other buildings, trees or structures, the house and its cones can be treated as completely independant from the surroundings. On the other hand, hill tops and elevated details of the terrain can affect the local isokeraunic level upward, while depressed locations will affect it downward.

A simple trade-off based on economics would then consist in stating that for an estimated repair cost of say, $ 200 000, and a project life of two years, the break-even value of a lightning protection system is 200 000 x 0.005 x 2 = $ 2000. However, this trade-off undoubtedly would be modified to take into consideration the "utility" concept in a game plan. This concept introduces subjective factors which tend to magnify the perceived cost of a failure, but decrease the perceived cost of a desired event. Stated in other terms, a trade-off in this project must also take into consideration intangible factors such as delays in the study and the embarrassing situation of a major failure caused by a single lightning strike.

Therefore we submit that a well designed lightning protection system, at this time divorced from aesthetic considerations, would be a sound investment. This situation may change when the cost of the arrays will be lower, giving greater weight to aesthetics.

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Identification of potential Government liability from construction and operation of prototype photovoltaic homes

I. GENERAL.

General Electric Company ("GE") has a contract with the NASA Lewis Research Center (Contract NAS3-19769) for the definition of prototype residential photovoltaic systems. This involves selection of sites for possible construction of the prototypes and development of the conceptual design and a test program to acquire operating information. Task VI-1 requires GE to identify the potential "Legal liability of Prototype System Test(s) during and after installation."

The actual architectural design and construction of the prototypes will be done by other contractors, not by GE. The prototypes will be constructed on non-DOD federal property, with the first prototype to be built at the NASA Lewis Research Center. The sites for the other prototypes have not yet been selected.

The prototype homes will contain two conditions which make them potentially more hazardous than conventional residences. The first is the presence of a large lead-acid storage battery weighing about 5,000 pounds. This will contain a large quantity of acid. In addition, upon charging the battery will generate and release a significant quantity of hydrogen gas. This discharge of hydrogen gas will require forced ventilation of the chamber where the battery is located to prevent a build up of hydrogen gas. Presumably, however, the total amount of hydrogen is so small that it presents no hazard upon discharge into the ambient air.

The second hazard is the potential for electrical shock from the solar array on the roof and possibly from other major components of the electrical system, such as the battery. For the most part, the degree of risk is no greater than that in an ordinary home. The one exception would be in the situation where someone was on the roof of the prototype when the sun was shining.

No one will be living in the prototype homes once they are constructed. Instead, they will be periodically visited by various employees, either of NASA or of an independent contractor, for purposes of inspection, maintenance, testing and information gathering.

II. SCOPE OF REPORT.

The purpose of this report is to present in general terms the potential non-contractual liabilities of the United States Government arising from the construction, operation and maintenance of the prototype homes and steps which the Government can take to limit such liabilities. It will also cover, with respect to the prototype to be constructed at the NASA Lewis Research Center, the applicability of state and local regulatory requirements. This report is general in nature and outlines only the major general types of potential non-contractual liability; it is not intended to be exhaustive or to cover every conceivable event which might give rise to claims against the United States.*

III. DISCUSSION.

A. Potential Non-Contractual Liabilities of the United States.

1. General.

Any non-contractual liability of the United States (which would include claims against NASA-Lewis) to persons other than federal employees** based on the design, construction, operation or maintenance of the prototype homes would be by virtue of the Federal Tort Claims Act, the principal provisions of which are found in 28 U.S.C.A. §1346(b)*** and 28 U.S.C.A.

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* Any suit against NASA-Lewis for damages would be deemed a suit against the United States. Cf. 28 U.S.C.A. §2679(a). Apparently, however, a secondary concern is that if there be a claim against the United States, that it be based on the action or inaction of some federal agency or department other than NASA-Lewis. Since NASA-Lewis presumably cannot, and does not wish to, turn over its project responsibilities to another federal agency, any opportunities to so shift "responsibility" for potential claims is obviously limited. This issue is briefly covered in the Discussion, infra, but has not been considered a major portion of this evaluation.

** Liability for injuries to federal employees would be covered by 5 U.S.C.A., Chapter 81 ("Compensation for Work Injuries"). Such liability is not covered in this report.

*** "Subject to the provisions of chapter 171 of this title [28 U.S.C.A. §§2671-2680], the district courts, together with the United States District Court for the District of the Canal Zone and the District Court of the Virgin Islands, shall have exclusive jurisdiction of civil actions on claims against the United States, for money damages, accruing on and after January 1, 1945, for injury or loss of property, or personal injury or death caused by the negligent or wrongful act or omission of any employee of the Government while acting within the scope of his office or employment, under circumstances where the United States, if a private person, would be liable to the claimant in accordance with the law of the place where the act or omission occurred."

§§2671-2680.* Two important limitations to the Government's liability under the Tort Claims Act are now well established:

a. <u>No liability without fault</u>.

The United States is not liable under any strict liability or liability without fault theories and statutes. Any liability must be premised on some showing of negligence or fault** by an employee of the United States. Thus, for example, it might well be that in many states the operation of the lead-acid storage battery in the prototype homes would be considered "ultrahazardous" or "abnormally dangerous" or some other characterization which would mean that a private entity would be held liable for injury caused by the activity even in the absence of any showing of fault. Such a strict liability or liability without fault theory would not be applicable in suits against the United States based on any injury caused by the prototype homes.

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* In particular, 28 U.S.C.A. §2674 provides in pertinent part that: "The United States shall be liable, respecting the provisions of this title relating to tort claims, in the same manner and to the same extent as a private individual under like circumstances, but shall not be liable for interest prior to judgment or for punitive damages."

** While there must be some action or nonaction by a federal employee which can be characterized as negligent or at fault, the degree of care owed by the United States is determined by local law. Thus, under local law it may be that in carrying out certain functions the United States and its employees are required to exercise greater than ordinary care. See, e.g., <u>Ford v. United States</u>, 200 F.2d 272 (10th Cir. 1972) (applying Oklahoma law that persons having dangerous explosives in their possession and control are required to exercise the highest degree of care not to injure others); <u>Stewart v. United States</u>, 186 F.2d 627 (7th Cir. 1951), cert. denied, 341 U.S. 940 (1951) (applying Illinois law requiring highest degree of care in the handling and storage of explosives); cf. <u>Hess v. United States</u>, 316 U.S. 314 (1960) (case involving Oregon Employer's Liability Law which required those having charge of any dangerous work to use every precaution practicable without regard to cost).

b. No liability for negligence of independent contractors.

The United States cannot be held liable for negligence of its independent contractors, even where a private employer would be so liable. In particular, under state law, it is generally held that when one is undertaking an activity which is "abnormally dangerous" or "inherently dangerous" or "ultrahazardous", the duty of care is nondelegable and, therefore, if the undertaking miscarries, it is no defense that the injury was caused by the negligence of an independent contractor. In other words, the owner or initiator of the activity may be held vicariously liable for the negligence of his independent contractor if the injury is of the nature that falls within the scope of the hazard making the activity abnormally or inherently dangerous.* Thus, for example, it is the rule in Ohio that an employer is liable for injuries caused by failure of an independent contractor to exercise due care in performing work which is inherently or intrinsically dangerous. See, e.g., Massachusetts Bonding & Ins. Co. v. Dingle-Clark Co., 142 Ohio St. 346, 52 N.E.2d 340 (1943); Newcomb v. Dredge, 105 Ohio App. 417, 152 N.E.2d 801 (1957); Tedesco v. Cincinnati Gas & Elec. Co., 448 F.2d 332 (6th Cir. 1971), cert. denied, 405 U.S. 923 (1972).**

* For example, if X engages independent contractor Y to do blasting and Y negligently uses too much explosive and thereby damages Z's house, X may be liable for Y's negligence since the risk of damage from the explosion is what makes the activity abnormally or inherently dangerous. However, if one of Y's trucks while driving to or from the site strikes a pedestrian, X would presumably not be liable if Y is in fact an independent contractor.

** Of course, in some cases the employer may be entitled to indemnity from the independent contractor. See, e.g., Massachusetts Bonding & Ins. Co. v. Dingle-Clark Co., supra, 142 Ohio St. at 353.

Such theories of vicarious liability are not applicable in suits against the United States. The plaintiff must always point to some negligent action or failure to act by employees of the United States itself.

However, if employees of the United States have the authority to control, or in fact exercise control over, the physical activities of a contractor, it may be found that the contractor was not in fact an "independent" contractor. The United States might then be held liable for the negligence of the contractor's employees. However, merely having federal employees inspect the work of a contractor is not itself sufficient to destroy the contractor's independent status.

c. Duty of United States in undertaking an abnormally dangerous activity.

While it is generally held that the United States cannot be held vicariously liable for the negligence of its independent contractors, even when an abnormally dangerous activity is involved, the presence of such an activity is nevertheless material. This is so in two ways:

(1) The degree of care required by the United States will, under the applicable state law, undoubtedly be a function of the degree of danger involved in the activity. Hence, an act of a federal employee which might not be held negligent in the absence of an abnormally dangerous activity, may well be deemed negligent where the risk is great. For example, where the danger is that someone may fall into a readily visible excavation, clearly marking the danger area by means of say a sign and a rope around it may be sufficient. Where the danger is from hydrogen gas collecting in a lead-acid storage battery chamber, a sign warning of the danger might

not be sufficient. It might well be that the additional precaution of keeping the chamber secured, with only specifically authorized persons being given the means of entry, would also be required. As a practical matter, the more dangerous the activity and the more serious the injury giving rise to the claim, the more likely it is that a court using hindsight will find some negligent act or omission.

(2) Normally, in projects not involving any unusual degree of risk, the United States can probably delegate complete responsibility for safety to its independent contractors. In other words, it could substantially limit its liability to that for acts of its own employees to the exclusion of liability for mere failure to act. However, where an abnormally dangerous activity is involved, it may well be held that the United States has a nondelegable duty to see that the independent contractor uses appropriate methods and takes appropriate precautions. It is easily seen that this creates a potential "damned if you do, damned if you don't" situation. The Government cannot simply rely upon the contractor to take the necessary precautions; yet, to the degree it actively participates in ensuring safety, it risks a finding of negligence arising from that very activity. Thus, the risk cannot be completely eliminated.

d. Authority of NASA to settle claims.

Section 2675(a) of 28 United States Code provides that:

"An action shall not be instituted upon a claim against the United States for money damages for injury or loss of property or personal injury

> or death caused by the negligent or wrongful act or omission of any employee of the Government *** unless the claimant shall have first presented the claim to the appropriate Federal agency and his claim shall have been finally denied by the Agency in writing ***."

Complementing this provision, 28 U.S.C.A. §2672 authorizes the head of each federal agency or his designee, in accordance with regulations prescribed by the Attorney General of the United States (see 28 C.F.R. Subparts 14.1-14.11), to settle any claims for money damages against the United States where the United States would be liable under the Federal Tort Claims Act, provided that any settlement in excess of $25,000 can be made only with the prior written approval of the Attorney General. NASA regulations relating to such claims are in 14 C.F.R. Subpart 9.

In addition to this authority to settle claims where the United States would be subject to liability under the Federal Tort Claims Act, 42 U.S.C.A. §2473(c)(13)(A) authorizes NASA to settle and pay any claim for $5000 or less for bodily injury, death, or damage to or loss of real or personal property resulting from the performance of its functions, with no limitation that such claims be ones for which the United States would be liable under the Federal Torts Claim Act. Section 2473(c)(13)(B) provides that claims in excess of $5000 which NASA considers meritorious may be reported to Congress for its consideration. As reflected in 14 C.F.R. §1204.901(b), this authority to pay and settle claims extends to those which the United States would not be legally required to pay.

2. Potential liability arising from the design and construction of the prototype homes.

As indicated by the above general statements as to the scope of the Government's liability, the potential liabilities arising from design and construction of the prototypes can be largely eliminated through the use of independent contractors (as is apparently already intended), provided that NASA-Lewis exercises due care in selecting competent contractors to perform the work and does not exercise such a degree of supervision and control as to destroy the contractors' "independent" status. Certainly, by using independent contractors, liability for ordinary work-related accidents, e.g., workers falling off ladders, etc., can be avoided.* To accomplish this, the contracts should leave the contracting companies free to control the details of the work and the construction contractor should have control over the immediate work site. The contract with the architect should contain, if possible, language to the effect that adequate safety features will be incorporated and NASA-Lewis should probably require GE to review the blueprints and specifications as to their adequacy and safety. The contract with the construction contractor should provide that he will meet all applicable safety codes and regulations and that he will take such reasonable measures as are necessary or required by law to ensure the safety of the worksite and of workers and third-parties.

* A distinction must be made between two types of accidents here. NASA-Lewis might well be liable for any injuries resulting from a nonobvious pre-existing defect in the premises, e.g., if a ladder fell because a pre-existing concrete strip gave way under it (assuming NASA-Lewis knew or should have known of the defect). However, barring some negligent act by a NASA employee having a direct causal relationship, it should not be liable for most ordinary types of work-related injuries.

One possibility is to have the contractor and NASA-Lewis prepare safety procedures and regulations that will be followed by the contractor and its employees. In addition, NASA-Lewis may wish to insist upon an indemnity agreement from its contractors and that they obtain liability insurance naming NASA-Lewis as an additional insured.

Since the work on the initial prototype will be performed at the NASA-Lewis Research Center, even if control of the immediate worksite is given to the construction contractor, the construction workers will be making use of some property under NASA-Lewis ownership and control. Injuries arising from such use, e.g., a worker falling because of disrepair of a sidewalk, could lead to liability since NASA-Lewis as possessor of the property has the duty either to keep it in reasonably safe condition for the third-parties it allows in or else to warn such third-parties of any dangerous conditions which may exist.* To minimize such potential liability, the areas accessable to the construction contractor and subcontractors and their employees should be strictly limited and these

* Such a duty is also imposed by the Ohio "safe place of employment" statute, Ohio Revised Code §§4101.01, 4101.11 and 4101.12. Section 4101.11 requires that "Every employer * * * shall furnish a place of employment which shall be safe for the employees therein and frequenters thereof, shall furnish and use safety devices and safeguards, shall adopt and use methods and processes * * * reasonably adequate to render such employment and places of employment safe, and shall do every other thing reasonably necessary to protect the life, health, safety, and welfare of such employees and frequenters." Section 4101.12 is substantially similar. The statute defines employer as any entity "having control or custody of any employment, place of employment, or employee" (Ohio Rev. Code § 4101.01(C)) and "frequenter" as any person in a place of employment other than an employee or a trespasser (Ohio Rev. Code (4101.01(E)). Hence, the employees of NASA-Lewis' independent contractors and subcontractors, as "frequenters" of premises under NASA-Lewis' custody and control, would be entitled to the protection of the statute.

limitations should be made completely clear to all those engaged in the work. This is absolutely necessary with respect to any areas where hazardous work is being performed or hazardous conditions exist. If workers or other non-NASA employees must pass near or through such areas, a careful review should be made to ensure that necessary warnings have been made and precautions taken. It may well be that additional warning signs, etc. will have to be posted to convey adequately to non-NASA personnel the presence and scope of possible hazards.

Finally, as noted above, it is possible that the design and construction of the solar-array and storage-battery related aspects of the prototype will be deemed an abnormally hazardous activity. Therefore, special care should be taken that the design includes safety features for at least any readily perceivable hazards resulting from the installation and operation of the solar array and of the battery. During and subsequent to installation, access to the roof of the prototype and to the battery should be strictly limited and readily visible warning signs posted.

3. Potential liability arising from the operation, maintenance and testing of the prototype homes.

Apparently in some cases NASA employees will be "operating" the prototype homes after construction is completed. In others, such work may be done by an independent contractor. Potential liability will be minimized to the greatest extent if all work is done by independent contractors. Again, if independent contractors are used, a statement of testing procedures and safety precautions to be followed by the contractor could be prepared by NASA-Lewis or the contractor.

As noted above, the Government cannot be held liable unless there is some negligent act or omission by a federal employee. Hence, any injury arising without such negligence, e.g., from an explosion of hydrogen from the lead-storage battery, will not result in liability. However, NASA-Lewis will have to ensure that it carries out any nondelegable duties it may have to ensure that its contractors use proper procedures and take adequate precautions.

To minimize its liability, access to the prototypes, and particularly to the roof and battery room, should be strictly limited. Any access by "visitors", e.g., members of the public, visiting Congressmen, etc., should be under close supervision. If such visitors are to be allowed it is especially important that readily visible warnings be posted and that any dangerous equipment be secured and made as tamper-proof as possible. (This is doubly true if children are going to be allowed entry.) What may be adequate precautions where a technician thoroughly familiar with the prototype is concerned, obviously may not be in other situations.

In this connection, as long as the actual possession and control of the prototypes is vested in NASA-Lewis, a conveyance of the ownership of a prototype to the department or agency owning the real estate on which it is built will probably in no way decrease the responsibilities of NASA-Lewis. Moreover, such a division of ownership and possession broadens the potential liability of the United States since it introduces another federal agency which may owe duties of care to third persons. If not only ownership, but control over the prototypes is passed to another agency, this should not affect the potential liability of the Government (assuming the other agency will be as safety conscious and alert as NASA-Lewis) but will limit the responsibilities of NASA-Lewis itself.

4. Applicability of zoning restrictions and other limitations.

According to information received from NASA-Lewis, the Research Center lies within three different political subdivisions -- the cities of Cleveland and Brook Park and Riveredge Township. The proposed site for the prototype at the Research Center is within a part of the City of Brook Park zoned single-family residential. It is generally recognized that federal agencies and federal installations are not subject to state or local regulation unless there is a federal statute or executive order authorizing such regulation. See Curtis v. Toledo Metropolitan Housing Authority, 36 Ohio Ops. 423, 78 N.E.2d 676 (Lucas County Com. Pl. 1947) (temporary housing for veterans under Lanham Act);* 1949 Ohio Atty. Gen. Ops. 728, 731 (No. 1084) ("It has been decided in Ohio and elsewhere that the Federal Government is not bound by municipal zoning ordinances and building

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* The Lanham Act included an express provision that the Federal Works Administrator could act "without regard to * * * any Federal, State, or municipal laws, ordinances, rules, or regulations relating to plans and specifications * * *." Thus, these cases are distinguishable in that there was express statutory authority for disregarding local ordinances.

codes."); United States v. City of Chester, 144 F.2d 415 (3d Cir. 1944) (housing project under Lanham Act); United States v. City of Philadelphia, 147 F.2d 291 (3d Cir. 1945), aff'g per curiam 56 F. Supp. 862 (E.D. Pa. 1944), cert. denied, 325 U.S. 870 (194_) (same); Crivello v. Board of Adjustment, 183 F. Supp. 326 (D.N.J. 1960) (Postmaster General not required to comply with local ordinance in construction of post office); Town of Groton v. Laird, 353 F. Supp. 344 (D. Conn. 1972) (Navy exempt from local zoning ordinances); Tim v. City of Long Branch, 135 N.J.L. 549, 53 A.2d 64 (Ct. Er. & App. 1947) (another Lanham Act case); State v. Stonybrook, Inc., 149 Conn. 492, 181 A.2d 601, 604 (1962) ("as long as the government operated these housing units [constructed under the Lanham Act] through its agents it was immune from the effects of the building code"); 58 Ohio Jur. 2d, Zoning §76 ("The federal government is not subject to zoning ordinances adopted by the political subdivisions of the state."); 8 McQuillin, Municipal Corporations §25.16; 2 Metzenbaum, Zoning, 1285-1288, 1290-1292 (2d ed.); 3 Williams, American Land Planning Law §81.01; 1 Yokley, Zoning Law and Practice §2-25; Annot., Applicability of Zoning Regulations to Governmental Projects or Activities; 61 A.L.R.2d 970. This is particularly clear with respect to zoning restrictions. Moreover, the Building Department of the City of Brook Park has acknowledged that NASA-Lewis is not required to comply with its zoning restrictions or to receive a zoning certificate prior to construction and use of facilities.*

However, the Brook Park Building Department has informally taken the position that NASA-Lewis is required to obtain a city building permit. According to informal information from NASA-Lewis, sometimes it does provide information about proposed construction to the city as part of maintaining friendly relations; however, it does not always do this and does not believe it is obligated to do so. As noted above, the case law strongly indicates that NASA cannot legally be required to obtain such building permits. NASA-Lewis' attorneys should probably approach the Brook Park Building Department and/or City Attorney before proceeding without such a permit and ascertain with more certainty what the City's official position is.

A second matter of concern with regard to obtaining permits is the release of hydrogen gas from the storage battery. While the Ohio

* There is no general exemption of federal contractors from state and local requirements and regulations, particularly insofar as these relate to safety. See James Stewart & Co. v. Sadrakula, 309 U.S. 94 (1940) (until Congress otherwise provides, state statute relating to safe place to work applies to contractor constructing post office for United States on federal property); DeKalb County v. Henry C. Beck Co., 382 F.2d 992 (5th Cir. 1967) (hearing necessary on whether contractor engaged to construct government hospital on government property required to pay permit fee to county); Public Housing Administration v. Bristol Township, 146 F. Supp. 859 (E.D. Pa. 1957) (contractor engaged to do electrical work in federal housing project required to obtain township building permits); Annot., State and Municipal Regulation of Building and Construction Contractors as Applicable to Contractor Engaged in Construction for Federal Government, 1 L. Ed. 2d 1729; Annot., Applicability of State Statutes or Municipal Regulations to Contracts for Performance of Work on Land Owned or Leased by the Federal Government, 91 A.L.R. 779, supplemented, 115 A.L.R. 371, 127 A.L.R. 827. In particular, applicable state workmen's compensation laws apply to such contractors. See 40 U.S.C.A. §290; Roelofs v. United States, 501 F.2d 87 (5th Cir. 1974), cert. denied, 96 S. Ct. 49 (1975). Moreover, Government contractors are not entitled to any general immunity from liability by virtue of their relationship with the Government. See Whitaker v. Harvell-Kilgore Corp., 418 F.2d 1010 (5th Cir. 1969); Foster v. Day & Zimmermann, Inc., 502 F.2d 867 (8th Cir. 1974).

EPA has no emission limitations applicable to hydrogen, there is a general requirement that a permit to install be obtained before the installation of a new source of "air pollutants." Ohio EPA Regulation § EP-30-02. "Air pollutants" are defined broadly to include "particulate matter, dust, fumes, gas mist [sic], smoke, vapor or odorous substances, or any combination thereof." Ohio EPA Regulation §AP-2-01(C), which in turn is merely a restatement of the definition of "air contaminant" set forth in Ohio Revised Code §3704.01(A). Taken literally, this definition seems broad enough to include the escape of hydrogen from the storage battery. However, it would undoubtedly be of such a nature that even if it were from a private source, it would be given "registration" status. This is a practice whereby the Agency merely files permit applications for certain insignificant sources and neither issues nor denies a permit.

An additional matter is presented since this is a source which will be federally operated on a federal installation. The United States Court of Appeals for the Sixth Circuit (which includes Ohio) has held that under the Clean Air Act, while federal installations must comply with the substantive provisions of a state's implementation plan, they need not apply for nor obtain a permit from the state. _Commonwealth of Kentucky ex rel. Hancock v. Ruckelshaus_, 497 F.2d 1172 (6th Cir. 1974), cert. granted, _sub nom. Hancock v. Train_, 420 U.S. 971 (March 17, 1975) (No. 74-220). This case was argued before the United States Supreme Court on January 13, 1976 and is now awaiting decision by that Court. The Fifth Circuit has reached the opposite conclusion. State of Alabama v. Seeber, 502 F.2d 1238 (5th Cir. 1974), petition for cert. filed, 44 U.S.L.W. 3031 (U.S. No. 74-851). In an analogous case, the Ninth Circuit has held that federal facilities are required by the Federal Water Pollution Control Act Amendments of 1972 to obtain state water pollution permits. State of California ex rel. State Water Resources Control Bd. v. EPA, 511 F.2d 963 (9th Cir. 1975), cert. granted, 422 U.S. 1041 (June 23, 1975) (No. 74-1435) (argued with Hancock v. Train).

Therefore, at the present time, since Ohio is in the Sixth Circuit, no application for an air permit from the Ohio EPA or from the City of Brook Park is necessary. However, this could well change once the United States Supreme Court rules on this issue. According to the Cleveland Division of Air Pollution Control, which is the agent for the Ohio EPA in Cuyahoga County (where NASA-Lewis Research Center is located), it has no jurisdiction to require permits from sources at the center. However, for informational purposes they would prefer that NASA-Lewis register the source with them. Whether NASA-Lewis wishes to so oblige the Cleveland Division of Air Pollution Control is a matter beyond the scope of this report.