CELL AND STACK DESIGN ALTERNATIVES

FIRST QUARTERLY REPORT

August 1, 1978 - October 31, 1978

Contract No. ET-78-C-03-2031

D. Q. Hoover
Program Manager

January, 1979

Prepared for:

Department of Energy
20 Massachusetts Avenue NW
Washington, DC 20545

Technical Manager
NASA-Lewis Research Center
Robert B. King
Fuel Cell Project Office

MASTER

Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

-NOTICE-

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report or represents that its use by such third party would not infringe privately owned rights.

TABLE OF CONTENTS

	<u>Page</u>
Abstract	VIII
List of Figures	V
List of Tables	VII
 1. Study of System Design Alternatives	 1
1.1 Application	1
1.1.1 Application Selection	1
1.1.2 Building Characterization	3
1.1.3 Load Patterns	9
1.2 Study Site	18
1.3 Abbreviated Weather Data	20
1.3.1 Model Reference	20
1.3.2 Construction of Abbreviated model	20
1.3.3 Solar Loading	23
1.4 Thermal Load Calculation	29
1.4.1 Dynamic Model	29
1.4.2 Results	36
 2. Fuel Cell Design Alternatives	 44
2.1 Fuel Cell Analysis	44
2.1.1 Simplified Lumped Model	44
2.1.2 Detailed Functional Model	51
2.2 Westinghouse Stack Test Facility	53
2.3 Fuel Cell Design and Fabrication	58
2.4 Cell and Stack Experiments	58
 3. Methane Conditioner Study	 59
3.1 Technology Assessment	59
3.2 Mathematical Model	59

TABLE OF CONTENTS (Cont'd)

4. Management and Documentation	68
4.1 Supervision and Coordination	68
4.2 Documentation and Reporting	69
4.3 Planning	70
Appendix A	71
Distribution List	83

LIST OF FIGURES

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
1	Resource Saving by Building Type	2
2	Relative Life Cycle Costs	4
3	Sixteen Unit Apartment Building	6
4	Building zones analyzed	10
5	Electrical load per apartment	13
6	Peak demand pattern for 48 unit apt. complex	14
7	Composite weekday-weekend occupancy pattern	15
8	Domestic hot water consumption per apt. unit	17
9	S. E. zone normalized solar temperature increment	26
10	Maximum solar incremental temperature vs month of the year	27
11	Equivalent network representation of sensible heat flow	30
12	The superposition principle applied to $T_{sa}(t)$	33
13	Introductory Page of Calculation Output - Important Input Parameters	37
14	Thermal Load Components for 4th Day of February	38
15	Thermal Load Components for 1st and 2nd Day of July	39
16	Dynamic sensible building load Albany - February 4	41
17	Dynamic sensible building load Albany - July 2	42
18	Distribution of current density (i) in 12" x 17" cell at 350°F	52
19	Lab Layout	54
20	Gas Utilization Based on 15 kW Electrical Output	55

LIST OF FIGURES (cont'd)

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
21	Blending Scheme	56
22	Air Circulation	57

LIST OF TABLES

<u>Table Number</u>	<u>Title</u>	<u>Page</u>
I	New Multifamily Residential Construction	5
II	Building Characteristics	8
III	Projected Electrical Consumption - 1980	11
IV	Ten Representative Northeastern Cities and Heating Degree Days	19
V	Comparison - Ave. Year with Abbreviated Model Year	22
VI	Albany 1973-1974 Insolation Data	24
VII	Heat Gains from Human Beings	35
VIII	Methane Conditioner Bibliography	60
IX	Information Required for Methane Conditioner Subsystem Design	61

Abstract

This report summarizes the first-quarter progress on the four Tasks of the Cell and Stack Design Alternatives contract.

An apartment house in Albany, New York with HUD minimum insulation was selected as the application to be used in evaluating various system configurations. Methods for calculating the static and dynamic thermal loads for a simulated season were developed. Computer models of some major subsystems are now being developed.

Finite element models of the electrochemistry, thermodynamics and heat transfer relationships for fuel cells were developed and have been used to calculate current density and temperature distributions for sets of large cells and cooling plates. The results obtained led to several innovative ideas for advanced stack designs. A single lump model of a fuel cell stack was developed for use in the systems study.

The available information on methane conditioning was collected and reviewed and a plan for attaining the missing design data has been developed. Simple models of reformer and water-gas shift reactors were developed for use in the systems study.

The lines of communication among technical tasks were established, required documentation of plans and progress was prepared and delivered and the monthly review meetings were held as planned.

1. STUDY OF SYSTEM DESIGN ALTERNATIVES

1.1 Application

1.1.1 Application Selection

On-site Fuel Cell Total Energy Systems that can provide electrical and thermal energy to an integrated load have a potential for conserving significant quantities of "convenience" fuels and at the same time operate in an environmentally acceptable manner. Since the thrust of this program is at the intermediate sized fuel cells, those applications of potential interest fall into the commercial category as contrasted to industrial or single family residential categories. Included in commercial would be multifamily residential projects.

As a part of the on-going DOE program in fuel cells, United Technologies-Power Systems Division has conducted a study⁽¹⁾ on commercial and multifamily applications. The principal factors considered were resource conservation and life cycle cost.

The building types considered included: retail stores, office buildings, restaurants, nursing homes and apartment buildings. Detailed analyses of these buildings were made for Detroit, Washington, D.C. and Phoenix. Assessments of national resource conservation and range of relative life cycle costs were made. The results of both of these analyses can be used to rationally select an application type which takes into account both resource conservation and potential commercial viability.

Figure 1 shows the summary results (insofar as resource conservation is concerned) from reference (1). As can be seen, both the apartment building and nursing home have significantly better potential than any of the others. They are the only applications that are above the mean for all application types.

(1) Information supplied by NASA technical manager from DOE Contract No. EY-76-C-03-1264 (On-Site Fuel Cell Resource Conservation in Commercial and Multifamily Buildings).

Figure 1. Resource Savings by Building Type

While potential conservation of resources is important per se, the ability of the fuel cell TES to penetrate the market is essential in order to successfully achieve that potential. Therefore the results of the study of reference 1 shown in Figure 2 are an important input toward arriving at an application decision.

The numbers in Figure 2 that lie under the columns labeled 0.7 to 1.2 are the cumulative percentage of the potential total market in that building category that have cost/benefit ratios less than or equal to the column heading. For example under the column heading of 1.0, 57% of the apartment market as measured in square footage would have a life-cycle cost/benefit ratio of one or less. Thus, since apartments represented 28% of the total building market considered, 57% of the 28%, or 16%, of this market would be viable by the measure of life-cycle cost/benefit ratio. The last column labeled Viable-% shows this calculation for all building types considered. Since the apartment building application represents almost 75% of all viable square footage of construction and since it also shows either the best (or possibly second best) potential for resource conservation, we have recommended that an apartment building or apartment complex application form the bases of system analyses.

1.1.2 Building Characterization

In a recent study⁽²⁾ conducted for EPRI by Westinghouse on heat pump improvement in northern climates, a portion of the study involved a heat pump application in a 16 unit, two story garden type apartment building. This type of building was chosen by the architectural consultant in the program as being representative of current apartment construction. Further confirmation of that judgement was obtained by

(2) "An Investigation of Methods to Improve Heat Pump Performance and Reliability in a Northern Climate," Report No. EPRI EM-319, Project 544-1, January 1977, Westinghouse Electric Corporation, Pittsburgh, PA 15235.

NATIONAL COMMERCIAL BUILDING MARKET BREAKDOWN BY RELATIVE LIFE CYCLE COST

	PERCENT OF TOTAL MARKET (SQ. FT.)	RELATIVE COST*** LESS THAN						VIABLE %
		0.7	0.8	0.9	1.0	1.1	1.2	
APARTMENT	28	14*	30	46	57**	67	75	16.0
NURSING HOME	3	7	24	40	57	71	82	1.7
RESTAURANT	1	1	4	11	22	37	51	0.2
OFFICE BUILDING	14	1	5	12	17	26	36	2.4
RETAIL STORE	13	1	3	5	10	19	28	1.3
TOTAL	100	6	15	25	38	47	57	21.6

- PERCENT OF MARKET (BASED ON FLOOR AREA)
- ** RANGE OF RESULTS FOR INDIVIDUAL BUILDINGS STUDIED
- *** FUEL CELL SYSTEM LIFE CYCLE COST LESS EXPENSIVE THAN CONVENTIONAL SYSTEM FOR VALUES LESS THAN 1

Figure 2. Relative Life Cycle Costs

referring to statistics from reference (3). The reference cited contains statistics for the years 1973 through 1977 regarding the patterns of construction of multifamily buildings during that period. The table below shows the statistical distribution of both numbers of housing units and numbers of buildings by building size (as measured by the number of units in the building). As can be seen the 16 unit building being considered falls at the peak of the "unit" distribution and would represent a type of unit of relatively high potential impact insofar as TES application is concerned.

Table I
New Multifamily Residential Construction

1973 - 1977 Construction				
Bldg. Size	Units-Thous.	Percent	Bldgs.-Thous.	Percent
2 to 4 units	453	15.8	167	51.4
5 to 9 units	568	19.8	80	24.6
10 to 19 units	681	23.7	52	16.0
20 to 29 units	331	11.5	14	4.3
30 to 49 units	284	9.9	7	2.2
50 units or more	556	19.3	5	1.5
TOTALS	2873	100%	325	100%

Figure 3 shows plans and elevations of the building forming the basis of the study. The walls of the building are of conventional frame construction with 1" of stucco exterior and 3/4" of polystyrene sheathing board over the studs. The walls are insulated with R-11 fiberglass and the interior finished with 1/2" gypsum board. The second floor ceiling is insulated with R-19 fiberglass with 1/2" gypsum board applied to the ceiling joints. The gypsum board has acoustical tile cemented to it.

(3) U.S. Bureau of the Census, Construction Report - Series C25
Characteristics of New Housing 1977
U.S. Department of Commerce, Washington D.C. 1978

Figure 3. Sixteen Unit Apartment Building

The attic space is ventilated at the rate of 1 cfm/sq foot of floor area and the sum of infiltration and air ventilation in the occupied portion of the building is 0.70 air changes per hour. The roof is asphalt shingle on plywood and for solar loading a light to medium colored wall and roof surface was assumed. The building was assumed to be slab mounted with a perimeter insulation leading to a heat loss of 31 Btu per hour at design temperature. The glazing was assumed to be double with good quality windows to reduce infiltration. Light control was to be achieved with venetian blinds, which with double glazing results in a shading coefficient of 0.25. The overall philosophy, with respect to building design, was to achieve or exceed HUD, 1973 minimum property standards for multifamily dwellings. Partial confirmation of this philosophy as being a reasonable one is contained in reference (4) in which it was stated that the wall and roof U factors for the apartment buildings being studied were selected as being typical of the construction in the location being studied (Washington D.C.). In the study cited, they used U factors for the walls and roof of 0.07 and 0.05 respectively which are in conformity with HUD minimum standards. The cited study included single glazed windows, which while appropriate for Washington D.C. would not be appropriate for more northern climates.

The building characteristics and sensible loads are shown in Table II. The winter sensible design load is based upon a 70° interior temperature and a 97 1/2% design temperature of 2° (appropriate to Albany, New York). The summer sensible design load is based upon an interior temperature of 75° and a 2 1/2% design temperature of 88° (also appropriate to Albany, New York). The static building load line of 3690 Btu/°F applies to the entire building as an entity. Under dynamic conditions of exterior temperature variations, the sensible portion of the building load will tend to follow a slope that is less than the static

(4) "Preliminary Design Study of a Baseline MIUS,"
Report No. NASA TM X-58193, April 1977,
L.B.J. Space Center, Houston, Texas 77058

Table II
Building Characteristics

INSULATION

Walls - R-11	Attic Ventilation - 1 cfm/ft ²
Ceiling - R-19	Glazing - double
Slab - R-3.75	Infiltr. & Vent. - 0.7 air ch./hr.
Light Control - Venetian Blinds - S. C. = 0.25	

PERFORMANCE

	<u>U Factors</u>	
	<u>Design</u>	<u>HUD Min. Stds.</u>
Walls	0.069	0.070
Ceiling/Roof	0.047	0.050
Glazing	Double	Double

Static Building Load Line - 3690 Btu/°F

Dynamic Building Load Line - 2828 Btu/°F

Winter Design Load* (70°/2°) - 251,000 Btu/hr.

Summer Design Load* (75°/88°) - 48,000 Btu/hr.

* Not including effects of internal sources, solar loading or building dynamics.

load line because of sensible energy storage in the walls, ceiling and roof of the building. For extremely rapid fluctuations in exterior temperature, the building load will tend to follow a slope of 2828 Btu/°F. For normal diurnal type variations, the slope will fall in between the two above values. There is further discussion of this effect in section 1.4.2.

Because solar loading effects are directional and time dependent, the building loads are calculated for four zones as shown in Figure 4. Although a load calculation is made for each zone, there is no implication that HVAC system control will be imposed on a zone basis.

1.1.3 Load Patterns

In the analysis of the fuel cell TES, a knowledge of complete electrical and thermal loads will be necessary during every hour of the analysis period. These loads are listed below:

Thermal Loads

- Building sensible load (environmental)
- Internal appliance sensible load
- Internal lighting sensible load
- Internal occupancy sensible load
- Domestic hot water load
- Building latent infiltration load
- Internal appliance latent load
- Internal occupancy latent load
- Solar loads

Electrical Loads

- Appliance loads
- HVAC system electrical loads
- Lighting loads (internal and external)
- TES auxiliaries electrical loads

Fig. 4 – Building zones analyzed

Some of these loads will be dependent upon the type of system configuration being analyzed.

The methodology for calculating both the building sensible load and the load due to latent infiltration will be described in a later section. Also the solar loading effects will be described later.

Appliance and Lighting Loads

The appliance loads within the units of the building will consist of the following, with an estimate of the annual kWhr consumption using reference (5).

Table III
Projected Electrical Consumption - 1980

<u>Contributor to Load</u>	<u>All Electric</u>	<u>Gas Cooking & Drying</u>
Clothes Dryer	1000 kWhrs.	75 kWhrs.
Clothes Washer	100 kWhrs.	100 kWhrs.
Range	1200 kWhrs.	--
Refrigerator	1600 kWhrs.	1600 kWhrs.
Television	440 kWhrs.	440 kWhrs.
Dishwasher	360 kWhrs.	360 kWhrs.
Misc. Appliances	1200 kWhrs.	1200 kWhrs.
Lighting	850 kWhrs.	850 kWhrs.
Total	6750 kWhrs.	4625 kWhrs.
Ave. Demand	0.770 kW	0.528 kW

This table does not include any allowance for domestic hot water needs or HVAC needs as they will be considered separately during the system analysis. References (1), (2) and (4) along with unpublished (proprietary)

(5) "Residential Consumption of Electricity: 1950-1970"
ORNL-NSF-EP-51, July 1973, Oak Ridge National Laboratory,
Oak Ridge, Tennessee 37830

data from a large eastern utility were used to develop an average (diversified) diurnal pattern of kW demand for each unit of the apartment building (based on an all-electric apartment). This load pattern is shown in Figure 5. Also included in Figure 5 is an allowance for area lighting pro-rated across each apartment to allow for lighting of hallways, parking lots, etc. These lights are assumed to be on a timer that shuts them off at 7:00 a.m. and turns them on at 5:00 p.m. The data from the large eastern utility was analyzed using reference 6 to determine the effect of diversity. Figure 6 was prepared from that data to determine the deviation from average peak for a complex consisting of three 16 unit apartment buildings. The 100% peak demand corresponds to the peak value (not including area lighting) on Figure 5.

Occupancy Pattern

References 1, 2, and 4 have in them occupancy patterns for multifamily residences. In some cases these patterns are for both weekday and weekend occupancy. The available data from these sources were compared and found to be similar enough to justify averaging them. Also the weekday/weekend patterns were coalesced into one pattern that represents the weighted average of both patterns. The results of this analysis are shown in Figure 7. The 100% value of 56 persons applies to one 16 unit apartment building in the complex. In section 1.4 this occupancy pattern is translated into both sensible and latent interval sources by considering activity levels and person heat releases appropriate to the time of day.

(6) "Electric Utility Engineering Reference Book-Distribution Systems" Vol. 3, published by Westinghouse Electric Corporation, 1959, East Pittsburgh, PA

Curve 713678-A

Fig. 5 — Electrical load per apt. (not including T.E. auxiliaries)

Fig. 6 — Peak demand pattern for 48 unit apt. complex

Fig. 7 — Composite weekday - weekend occupancy pattern

Domestic Hot Water Consumption

The pattern of domestic hot water consumption has been derived from an evaluation of references (1), (2), and (4). Also an analysis of the energy consumption pattern of electric domestic hot water heaters as supplied by a large eastern utility has been performed to arrive at a consumption pattern. The coalescence of all four sources of information is shown as Figure 8, on a unit basis. The actual thermal demand on the TES will depend upon the size of the storage available for D.H.W. This sizing (and its impact) will be accomplished in the system studies.

Fig. 8 — Domestic hot water consumption per apt. unit

1.2 Study Site

This section deals with the selection of the site which will form the basis of the system evaluation and a definition of the concomitant environmental inputs.

Site Selection

In accordance with the proposal leading to this study effort, attention has been confined to the Northeastern United States. The rationale for this selection was that near term commercial penetration of fuel cell total energy systems would be most likely in areas where there were high sustained thermal loads that could be served by the reject heat from the fuel cell and its associated fuel conditioning equipment. From such locales, penetration into warmer climates would ensue as "learning" effects brought the cost of equipment down. For the purposes of making a selection, the northeastern region considered included a band of cities lying between the 40th and 43rd parallels and extending from the coast to the western shore of Lake Michigan. By and large population density falls off quite rapidly above the 43rd parallel. In assessing possible sites, Philadelphia and New York were eliminated as being too warm (due to moderation of their climates by the Gulf Streams). Table IV shows a list of 10 representative cities in this area ranked in accordance with their heating degree days (HDD). The average HDD among these 10 is 6400 which corresponds to Detroit. It should be noted that Detroit was one of the cities studied by U.T.C. in reference (1). Since it was felt that higher than average thermal loads would help in early penetration of this type of system into the marketplace, there was an opting for a city somewhat colder than Detroit.

Table IV
Ten Representative Northeastern Cities
 and Heating Degree Days

<u>Choice of City</u>		
Milwaukee	7205 H.D.D.	
Albany	6888	"
Buffalo	6838	"
Syracuse	6520	"
Detroit	Average → 6404	"
Chicago	6310	"
Providence	6125	"
Cleveland	6006	"
Pittsburgh	5905	"
Boston	5790	"

Among those colder than Detroit, Albany was selected for the following reasons:

- Westinghouse has edited weather tape for Albany.
- Westinghouse has had experience using these data in the study of reference (3).
- While Albany is colder than average N.E. city, it is not too deviant from the average.
- Westinghouse has summary solar data for Albany with which to estimate solar loading effects.

On the basis of this evaluation of Northeastern sites, a decision has been made to continue the system evaluation using climatology characteristic of Albany.

1.3 Abbreviated Weather Data

In the interest of reducing the cost of computer analyses of the large number of systems to be considered, it was originally proposed to develop abbreviated seasonal representations of the weather as an input to system models. This original intent has been modified to the extent that abbreviated monthly weather models have been developed instead of seasonal models.

1.3.1 Model Reference

As a reference against which to gauge the weather model to be developed, the heating and cooling degree day data (representing 30 year averages) of reference (7) were used. In matching the model to these data, the heating degree days during the months September through May were considered to be the prime determiner and the cooling degree days during the months of June, July and August were likewise considered the prime determiner of a match.

1.3.2 Construction of Abbreviated Model

Since the Albany weather tape used in reference (3) was the year 1961, this same year was chosen as a basis to develop the abbreviated model. The 1961 tape contains, on an hour by hour basis for the entire year, both the dry bulb temperature and the corresponding dew-point temperature. For each month considered, the thirty year average degree hours were computed from reference (7) on the basis of a four day representation of that month. For example the month of February has a heating

(7) "Daily Normals of Temperature and Heating and Cooling Degree Days 1941-1970," Climatology of the United States, No. 84, U. S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Center, Asheville, NC.

degree day figure of 1162. This would correspond to 27,888 degree hours for a 28 day month or 3984 degree hours for a 4 day representation.

From the weather tape, totals of heating degree hours and cooling degree hours were calculated for all possible contiguous (or serial) 4-day periods starting with 1-1-61 through 1-4-61 and ending with 12-28-61 through 12-31-61. These degree hours (heating or cooling as the case may be) were compared to the desired monthly representation based upon NOAA thirty year average data and the closest match determined. In some cases secondary criteria were employed such as average maximum and average minimum temperatures during the periods being evaluated. For example the period 2-6-61 through 2-9-61 had a HD hr of 4006 while the period 2-10-61 through 2-13-61 had a HD hr of 3956. In February the average maximum temperature is 32.7°F and the average minimum is 14.3°F. In the first period being considered, the average maximum temperature was 35.2°F and the average minimum was 8.5°F whereas for the second period the corresponding temperatures were 32.5°F and 14.2°F respectively. Therefore the second period (namely 2-10-61 through 2-13-61) was chosen as being more representative of February than the first. Thus by this procedure the serial correlation of temperatures in February was for the most part representative.

This procedure was repeated for all 12 months. Since month to month transitions are not contiguous, some smoothing of the temperature transitions at these points was introduced so as to reduce the abruptness (in some cases) of the temperature change. When this smoothing was taken into account the final heating degree hours for February became 3964 instead of the 3956 previously found. These 3964 HD hrs (for a 4 day period) are equivalent to 1156 HDD on a full month basis. The results of this procedure are tabulated in Table V with a comparison with the 1941-1970 averages.

Table V
COMPARISON

AVE. YEAR WITH ABBREVIATED MODEL YEAR

MONTH	HEATING DEGREE DAYS		COOLING DEGREE DAYS	
	1941-1970 AVE.	MODEL	1941-1970 AVE.	MODEL
JAN	1349	1349	0	0
FEB	1162	1156	0	0
MAR	980	962	0	0
APR	543	545	0	0
MAY	253	262	27	39
JUNE	39	25	114	111
JULY	9	22	226	211
AUG	22	26	165	165
SEPT	135	166	42	64
OCT	422	458	0	0
NOV	762	764	0	0
DEC	1212	1295	0	0
TOTALS	6888	7030	574	593

HEATING SEASON:

97 1/2 PERCENT TEMP. 2°F
97 1/2 PERCENT TEMP. (ABBREV. MODEL) 3°F

COOLING SEASON:

2 1/2 PERCENT TEMP. 88°F
2 1/2 PERCENT TEMP. (ABBREV. MODEL) 83.5°F

AVERAGE ANNUAL TEMPERATURE (1941 - 1970) 47.7°F

AVERAGE ANNUAL TEMPERATURE (ABBREV. MODEL) 47.4°F

Also shown at the bottom of this table are 97 1/2% and 2 1/2% temperatures in comparison with those from reference (8).

1.3.3 Solar Loading

Solar loading of the building is caused by two contributions. The first is the net absorption (or radiation in the case of nighttime) of solar radiation on the surfaces of the building. The second source of loading is the transmission of solar radiation directly through the glazing into the interior of the building. There are highly refined methods⁽⁹⁾ of calculating these effects. However such methods were not used in the modeling of the solar effects because of the following reasons:

- 1) Only one site was being considered in this project and it was decided that computerization of the methodology would be more costly than simple hand calculations for that site;
- 2) There was some question as to the availability of the cloud cover data required to implement the ASHRAE methodology.

In estimating the solar loading effects reference (10) was used to supply summary solar data for Albany.

(8) Handbook of Air Conditioning, Heating, and Ventilating, Clifford Strock and Richard L. Koral, Industrial Press, Inc., 200 Madison Avenue, New York, NY 10016, 1965.

(9) "Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations-Alogrithms for Building Heat Transfer Subroutines" Copyright 1975, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., 345 East 47th St., New York, NY 10017.

(10) "Solar Energy Atlas for New York State," Atmospheric Sciences Research Center, State University of New York at Albany, March 1975.

The monthly statistics with regard to average, maximum and minimum total daily insolation on a horizontal surface at Albany are shown in Table VI. Using the approximation that the hour by hour insolation tends to follow the lobe of a sinusoid between sunrise and sunset, the equivalent mid-day peak insolation has also been tabulated.

Table VI
Albany 1973-1974 Insolation Data

Month	Daily Total $\frac{\text{Btu}}{\text{Ft}^2}$			Equivalent Mid Day Peak $\frac{\text{Btu/hr}}{\text{Ft}^2}$		
	Max.	Mean	Min.	Max.	Mean	Min.
Jan	905	515	85	154	88	14
Feb	1501	898	221	227	136	33
Mar	2017	994	169	270	141	23
Apr	2484	1321	247	295	157	29
May	2635	1428	275	286	155	30
June	2650	1700	442	275	177	46
July	2605	1961	534	276	208	56
Aug	2399	1601	224	274	182	26
Sept	2042	1222	158	260	155	20
Oct	1524	953	144	219	137	20
Nov	975	467	63	160	76	10
Dec	791	339	52	140	60	9

Sol-Air Temperature

The temperature which must be used to compute the transmission of sensible energy through the walls and roof of a building will in general not be equal to the ambient dry bulb temperature. The equivalent surface temperature of any of the exposed surfaces will depend upon the amount of insolation falling on that surface, the absorptance and emittance of the surface, the coefficient of heat transfer (by convection and long wave radiation) of the surface and the difference between long

wave radiation received from the sky and that emitted by the surface. In reference (11) a methodology has been developed for taking these factors into account (in summer months) called the Sol-Air temperature method. Table 2, p. 25.5 of reference (11) gives the total Sol-Air (or equivalent surface temperature) in mid July (at a 40° N latitude). This table gives the equivalent surface temperature as a function of time of day for an assumed variation in ambient temperature and two values of absorptional to heat transfer ratios. The table also includes the effect of orientation of the vertical surfaces as well as for a horizontal surface. The difference between the Sol-Air temperature and ambient temperature can be looked at as a solar increment to temperature which is essentially proportional to insolation falling on that surface. The insolation falling on each of these surfaces (to a gross approximation) can be considered proportional to the insolation values tabulated in Table VI. For an absorptance over heat transfer ratio of 0.15, the solar increment to temperature was calculated for each of the four zones into which the building was divided, weighting the contribution to incremental solar temperature in accordance with relative total heat transmission (UA) of each surface of the zone. This was done for four months of the year (representative of the four seasons). An example of this calculation is shown in normalized form in Figure 9, along with a functional curve fit to the data. The reason the normalized solar increment to temperature drops to a negative value near sunrise and sunset is because of night radiation to the sky. For the southeast zone, the variation in actual maximum solar temperature increment on a seasonal basis is shown in Figure 10. The incremental temperature calculated using Figures 9 and 10 on an hour by hour basis are for an extremely bright day with no cloud cover. The actual day solar incremental temperature has been taken as that computed for an extremely clear day multiplied by the ratio of average monthly insolation to maximum monthly insolation and by the ratio

(11) 1977 ASHRAE Handbook of Fundamentals Published by American Society of Heating, Refrigerating and Air-Conditioning Engineers, 345 East 47th Street, New York, NY 10017.

Curve 713704-A

Fig. 9 — S.E. zone normalized solar temperature increment

Curve 713703-A

Fig. 10 - Maximum solar incremental temperature vs month of year

of peak daily temperature to the average of the daily peak temperatures for that month. The latter correction assumes that on a short term basis, insolation correlates well with ambient temperature. This methodology has been applied to all four zones of the building.

Since the solar effects are a small part (but not a negligible contributor) of building load, the methodology, while coarse, should not lead to gross errors in building load. The calculations used are both site specific and building specific in the interest of conserving on computer time and because the intent of the project was not to be concerned with site variations and building variations. To that extent the computer model for load calculations cannot be applied in a general manner.

Solar Gain Through Glazing

A similar approach was used to obtain the solar gain through the glazing of the four zones into which the building was divided. The solar heat gain factors from Table 22, chapter 26 of reference (11) were used for the appropriate orientations of the glazing, time of day and month of year. These heat gain factors (Btu/hr ft^2) are for double strength single glazing with no attempt at light control. For double glazing with venetian blinds for light control, these heat gain factors would be multiplied by a shading coefficient of 0.25. These heat gain factors are for extremely clear days and in the loading model they are multiplied by a factor to account for an estimate of daily insolation (relative to maximum possible) taking into account the ratio of the average monthly insolation of Table VI, and an assumed correlation of insolation with maximum daily temperature. As stated with regard to Sol-Air temperature these solar gains through glazing estimates are both site and building specific.

1.4 Thermal Load Calculations

1.4.1 Dynamic Model

As a basis for the calculation of the building dynamic thermal load, an RC equivalent network was set up which represents the differential equations describing sensible heat flow in the structure (Figure 11).

For a perfect (0° dead band) thermostat capable of holding the interior temperature, T_i , absolutely constant at a given set point temperature, the dynamic building load, Q_{DL} , can be calculated, in its time response to exterior sol-air temperature, T_{SA} , from the figure. The resistance R_o , which represents the stagnant air envelope or "film" surrounding the structure, is shown as dotted, and its value is neglected in computations since its effect is negligible compared to the resistances R_1 and R_2 . Also, capacitances C_1 and C_3 will not influence the results: C_1 because it is directly influenced by exterior temperature (since film impedance is neglected), and C_3 because it is at constant temperature, therefore experiencing no heat flow. The remaining network parameters have been calculated to meet the HUD minimum standards (according to the building design as described in section 1.1.2):

$$R_1 = 0.0005801 \text{ } ^\circ\text{F-hr/Btu}$$

$$R_2 = 0.0003536 \text{ } ^\circ\text{F-hr/Btu}$$

$$C_2 = 27,515 \text{ Btu/}^\circ\text{F}$$

Dynamic Sensible Building Load

The dynamic sensible building load is found as a function of sol-air temperature by applying the method of the Laplace Transform to the solution of the representative circuit. For constant interior temperature, T_i (at the set point):

$$Q_{DL}(S) = -(G_o \frac{1 + S\tau_2}{1 + S\tau_1}) T_{SA}(S)$$

- R_0 - Film Impedance
- $2R_1$ - Wall and Roof Thermal Impedance
- R_2 - Fenestration and Infiltration Equivalent Impedance
- C_1 - Exterior Brick and Roof Thermal Capacitance
- C_2 - Exterior Wall Thermal Capacitance (Excluding Exterior Brick and Interior Plaster)
- C_3 - Interior Partitions Plus Interior Plaster on Exterior Walls-Thermal Capacitance
- T_{sa} - Exterior Sol-air Temperature
- T_i - Interior Temperature
- Q_{DL} - Sensible Dynamic Thermal Load
- ΔQ - Sensible Heat Sources (Solar Gain through Glazing and Interior)
- Q_{HVAC} - HVAC System Thermal Input

Fig. 11—Equivalent network representation of sensible heat flow

$$\text{where } G_o = \frac{1}{R_2} + \frac{1}{2R_1}$$

$$\tau_1 = \frac{R_1 C_2}{2}$$

$$\tau_2 = \frac{\tau_1}{(1 + R_2/2R_1)}$$

and S is the generalized complex frequency of the Laplace Transform.

This is of the form

$$H(S) = G(S) * F(S)$$

where $H(S)$ is the response transform, $G(S)$ is the transform of the system function, and $F(S)$ is that of the driving function. In the actual time system, the temperature input $T_{SA}(t)$ is a succession of degree hours each of which may be described as a unit impulse driving function. Solving for the response to one unit impulse, in the notation of the Laplace Transform, let

$$T_{SA}(t) = \delta(t) \text{ degree hours}$$

Its transform is unity:

$$T_{SA}(S) = 1; \text{ therefore,}$$

$$Q_{DL}(S) = -G_o \frac{1 + S\tau_2}{1 + S\tau_1}$$

Taking the inverse Laplace of this, $Q_{DLI}(t)$ represents the real-time impulse response due to the unit impulse $\delta(t)$:

$$Q_{DLI}(t) = -\left(G_o \frac{\tau_2}{\tau_1}\right) \cdot \delta(t) - \left(G_o \frac{(\tau_1 - \tau_2)}{\tau_1^2}\right) e^{-\frac{t}{\tau_1}} \cdot U(t)$$

where $U(t)$ is the unit step function.

However, since the driving function $T_{SA}(t)$ can be represented as a continuous series of unit impulses, the actual response function at any time t is the superposition of the responses to all past impulse functions. This is shown graphically in Figure 12 in which $T_{SA}(t)$ is represented as a succession of rectangular pulses which approximate the unit impulse driving function as $d\lambda$ approaches zero.

As a result, the dynamic load response takes the form of a superposition integral, and, with the inclusion of a term which expresses the constant heat input required to maintain the set point temperature T_{SP} , the dynamic sensible load response due to varying exterior sol-air temperature is:

$$Q_{DL}(t) = G_o T_{SP} - G_o \frac{\tau_2}{\tau_1} T_{SA}(t) - G_o \frac{(\tau_1 - \tau_2)}{\tau_1^2} \int_0^t T_{SA}(\lambda) e^{-\frac{(t-\lambda)}{\tau_1}} d\lambda$$

For the entire building, substitution yields:

$$Q_{DL}(t) = 3690. \cdot T_{SP} - 2828.1 \cdot T_{SA}(t) - 108.0 \int_0^t T_{SA}(\lambda) e^{-0.1253(t-\lambda)} d\lambda$$

For each of the four zones into which the building was divided the coefficients were scaled by a factor of four and the sol-air temperature appropriate for the direction of exposure was input.

It was determined that the effect of a temperature input was negligible 48 hours from its introduction; therefore, the integral was replaced by a summation over the past 48 hours in the computer program.

The response at any time t' to a varying input $T_{sa}(t)$ may be represented as the sum of the responses to all individual inputs into which T_{sa} is decomposed. ($T_{sa}(t)$ as an impulse driving function is approximated as $d\lambda$ approaches zero)

Fig. 12 – The superposition principle applied to $T_{sa}(t)$

The building set point temperature was chosen to be 70°F for the heating season (September-May) and 75°F for the cooling season (June-August). Also, nightly temperature setbacks were an available option in the computations.

Sources of Heat Gain

The dynamic sensible building load (Q_{DL}) is the amount of heat required to maintain the internal temperature at the building set point. In addition to the heat to be supplied by the HVAC system, contributions to the satisfaction of the sensible building load come from several sources: solar heat gain through glazing, occupants, and other internal sources. In addition, comfort requirements in the cooling season necessitate dehumidification, hence the latent heat sources: latent infiltration and latent heat due to internal sources (people, lighting and appliances) should also be considered.

Diagrammatically, these heat sources may be described as inputs into the RC network representation of the structure at ΔQ in Figure 11. Therefore the total load to be supplied by the HVAC system would be determined from:

$$Q_{HVAC} = Q_{DL} - Q_{SOLGG} - Q_{PS} - Q_{INTS} - \underbrace{Q_{LATIN} - Q_{PL} - Q_{INTL}}_{\text{(only in cooling season)}}$$

Sensible Heat Contributions - The calculation of solar sensible heat gain through glazing has been discussed in section 1.3. Heat gains due to occupants were developed following the occupancy profile described in section 1.1.3. Taken from reference (8), Table VII shows average sensible and latent heat emission per person for various levels of physical activity.

Table VII
Heat Gains from Human Beings

<u>Activity</u>	Average Emission, Btu/hr per person		
	<u>Sensible</u>	<u>Latent</u>	<u>Total</u>
Lying in bed	150	110	260
Sitting down	195	205	400
Standing	240	360	600
Brisk Activity	390	910	1300

From this, both sensible and latent hourly heat gains could be determined by estimating approximate activity levels for time of day and applying the building occupancy as a factor.

Other major internal sources of heat are appliances and lighting. Their electrical consumption has been jointly defined in the kWh-electrical demand profile described in section 1.1; therefore, their heat input into the structure was expressed as a linear function of hourly electrical demand. Heat energy, as a byproduct of conversion processes, comprises a very large percentage of the original energy input to both the mechanical processes of appliances and especially the incandescent lighting standard in residences. A factor (of .75) was chosen to represent that percentage of total electrical demand which is converted entirely into a thermal load. The value chosen assumed that the clothes dryer was vented to the outside and provided some allowance for occasional venting of the range as well as for the wide range of rates of heat gain from typical household appliances, as seen in reference (12). From this heat gain, an appropriate split into sensible and latent heat contributions to thermal load was determined as a rough approximation to the data of the same reference.

(12) 1972 ASHRAE Handbook of Fundamentals Published by American Society of Heating, Refrigerating and Air-Conditioning Engineers, 345 East 47th Street, New York, NY 10017.

Latent Heat Calculations - The net sensible heat load, Q_{DL} - sensible ΔQ , determines the mode of HVAC operation: when the net sensible load is positive, a heating mode is entered, when negative, cooling. Since latent heat gains are only recognized as loads on the air conditioning equipment, their calculation was suppressed when a heating situation was defined by the sensible loads.

Latent Infiltration - A significant contribution to latent heat gain in the cooling season is due to infiltration. Both hourly dry bulb and dewpoint temperatures were available from Albany weather tape data. From data of the psychrometric table of reference (8), a curve-fit was established between dewpoint temperature and grains of moisture per pound of dry air. The cooling season interior space air conditioning requirements of 75°F/relative humidity of 50% represented a design point of 65 grains water vapor per pound of dry air. The latent heat load per pound of dry air was then calculated with the assumption of 45°F exit temperature of water vapor from the chiller. The total building rate of infiltration was calculated to be 7870 lbs./hr. from the design specifications as described in section 1.2. Since latent heat gain from infiltration also is a load in the cooling season only, its calculation was performed only for dewpoints above 55°F.

1.4.2 Results

HVAC Thermal Loads - Computer printouts from typical HVAC thermal load calculations are reproduced in Figures 13, 14, and 15. Figure 13 shows an introductory page which displays the significant input parameters incorporated. It should be restated that although the load calculations are performed on a building zone basis, the final HVAC system control will be determined from the system studies. Calculations by zone served to better simulate the influence from solar heat gains, which often define

ALBANY, NEW YORK

HOURLY THERMAL LOADS FOR ONE OF FOUR ZONES
OF A 16-UNIT APARTMENT BUILDING
AS REPRESENTED BY A 48-DAY ABBREVIATED YEAR

WINTER SET POINT IS: 70.0 DEGREES F
SUMMER SET POINT IS: 75.0 DEGREES F
NO NIGHTLY TEMPERATURE SET BACKS
PERCENTAGE OF TOTAL ELECTRICAL DEMAND
CONTRIBUTING TO THERMAL LOAD IS
75 % OF THIS
70 % CONTRIBUTES TO SENSIBLE,
30 % CONTRIBUTES TO LATENT.

Figure 13. Introductory Page of Calculation
Output - Important Input Parameters

SOUTHEAST ZONE

THERMAL LOADS: BTU / HOUR													
HOUR	MO/DAY/HR	AMBIENT TEMP	SOL-AIR TEMP	DYNAMIC BUILDING	SOLAR GAIN GLAZING	SENS.HEAT ELECTRIC	SENS.HEAT PEOPLE	LAT.HEAT PEOPLE	LAT.HEAT ELECTRIC	LATENT INFILTR.	TOTAL SENSIBLE	TOTAL LATENT	TOTAL
169	2/ 4 / 0	14.0	12.5	51281.	0.	2007.	2025.	0.	0.	0.	47249.	0.	47249.
170	2/ 4 / 1	12.0	10.5	52925.	0.	1218.	2025.	0.	0.	0.	49681.	0.	49681.
171	2/ 4 / 2	9.0	7.5	55295.	0.	1218.	2025.	0.	0.	0.	52052.	0.	52052.
172	2/ 4 / 3	8.0	6.5	56294.	0.	1218.	2025.	0.	0.	0.	53051.	0.	53051.
173	2/ 4 / 4	4.0	2.5	59404.	0.	1218.	2025.	0.	0.	0.	56160.	0.	56160.
174	2/ 4 / 5	3.0	1.5	60454.	0.	1218.	2025.	0.	0.	0.	57211.	0.	57211.
175	2/ 4 / 6	0.	-1.5	62902.	0.	2222.	2062.	0.	0.	0.	58617.	0.	58617.
176	2/ 4 / 7	0.	-6	62638.	497.	8099.	1706.	0.	0.	0.	52336.	0.	52336.
177	2/ 4 / 8	2.0	6.1	58177.	3114.	8457.	1330.	0.	0.	0.	45276.	0.	45276.
178	2/ 4 / 9	10.0	18.1	49775.	5127.	8099.	1000.	0.	0.	0.	35549.	0.	35549.
179	2/ 4 / 10	15.0	26.0	44014.	6200.	8099.	1075.	0.	0.	0.	28640.	0.	28640.
180	2/ 4 / 11	18.0	30.5	40502.	6253.	8242.	1020.	0.	0.	0.	24987.	0.	24987.
181	2/ 4 / 12	20.0	32.5	38649.	5457.	8744.	1020.	0.	0.	0.	23428.	0.	23428.
182	2/ 4 / 13	24.0	35.2	36287.	4163.	7597.	840.	0.	0.	0.	23687.	0.	23687.
183	2/ 4 / 14	30.0	39.0	33200.	2767.	7597.	822.	0.	0.	0.	22014.	0.	22014.
184	2/ 4 / 15	30.0	36.0	34803.	1574.	7597.	977.	0.	0.	0.	24654.	0.	24654.
185	2/ 4 / 16	30.0	32.7	36821.	709.	9102.	1237.	0.	0.	0.	25772.	0.	25772.
186	2/ 4 / 17	30.0	29.1	39095.	98.	7669.	1870.	0.	0.	0.	29458.	0.	29458.
187	2/ 4 / 18	30.0	28.5	39433.	0.	9748.	2096.	0.	0.	0.	27589.	0.	27589.
188	2/ 4 / 19	31.0	29.5	38637.	0.	9748.	2047.	0.	0.	0.	26842.	0.	26842.
189	2/ 4 / 20	30.0	28.5	39242.	0.	7454.	2127.	0.	0.	0.	29660.	0.	29660.
190	2/ 4 / 21	30.0	28.5	39175.	0.	6881.	2250.	0.	0.	0.	30044.	0.	30044.
191	2/ 4 / 22	29.0	27.5	39823.	0.	5160.	2584.	0.	0.	0.	32079.	0.	32079.
192	2/ 4 / 23	26.0	29.5	41916.	0.	3154.	2295.	0.	0.	0.	36467.	0.	36467.

Figure 14. Thermal Load Components for 4th Day of February,
as Calculated with Parameters of Figure 13

SOUTHWEST ZONE

THERMAL LOADS: BTU / HOUR

HOURL	MO/DAY/HR	AMBIENT TEMP	SOL-AIR TEMP	DYNAMIC BUILDING	SOLAR GLAZING	GAIN	SENS. HEAT ELECTRIC	SENS. HEAT PEOPLE	LAT. HEAT PEOPLE	LAT. HEAT ELECTRIC	LATENT INFILTR.	TOTAL SENSIBLE	TOTAL LATENT	TOTAL
577	7/ 1 / 0	62.0	59.4	11540.	0.	0.	1218.	2025.	1485.	522.	2271.	8296.	0.	8296.
578	7/ 1 / 1	58.0	55.4	14799.	0.	0.	1218.	2025.	1485.	522.	0.	11556.	0.	11556.
579	7/ 1 / 2	55.0	52.4	17395.	0.	0.	1218.	2025.	1485.	522.	0.	14152.	0.	14152.
580	7/ 1 / 3	56.0	53.4	17179.	0.	0.	1218.	2025.	1485.	522.	0.	13936.	0.	13936.
581	7/ 1 / 4	55.0	52.4	18296.	0.	0.	1218.	2025.	1485.	522.	0.	15052.	0.	15052.
582	7/ 1 / 5	54.0	53.2	18112.	190.	2222.	2062.	1812.	1812.	952.	0.	13637.	0.	13637.
583	7/ 1 / 6	59.0	62.5	11887.	687.	8099.	1706.	1755.	3471.	0.	0.	1395.	0.	1395.
584	7/ 1 / 7	61.0	68.6	7618.	1315.	8457.	1330.	1505.	3625.	0.	0.	-3485.	-5130.	-8614.
585	7/ 1 / 8	65.0	76.5	1955.	2130.	8099.	1000.	1250.	3471.	733.	733.	-9274.	-5454.	-14728.
586	7/ 1 / 9	68.0	83.0	-2906.	3134.	8099.	1075.	1425.	3471.	0.	0.	-15215.	-4896.	-20111.
587	7/ 1 / 10	71.0	88.9	-7502.	4273.	8242.	1020.	1360.	3532.	737.	737.	-21038.	-5630.	-26667.
588	7/ 1 / 11	73.0	93.1	-10970.	5436.	8744.	1020.	1530.	3747.	738.	738.	-26170.	-6016.	-32185.
589	7/ 1 / 12	70.0	91.4	-10299.	6473.	7597.	840.	1260.	3256.	3944.	3944.	-25210.	-8460.	-33670.
590	7/ 1 / 13	75.0	96.7	-14423.	7222.	7597.	822.	1207.	3256.	3116.	3116.	-30065.	-7580.	-37645.
591	7/ 1 / 14	78.0	98.7	-16369.	7531.	7597.	977.	1381.	3256.	2304.	2304.	-32474.	-6941.	-39416.
592	7/ 1 / 15	80.0	98.5	-16732.	7288.	9102.	1237.	1705.	3901.	2308.	2308.	-34360.	-7914.	-42274.
593	7/ 1 / 16	78.0	93.2	-13371.	6446.	7669.	1870.	2465.	3287.	5753.	5753.	-29356.	-11505.	-40861.
594	7/ 1 / 17	76.0	86.8	-9099.	5031.	9748.	2096.	2681.	4178.	3119.	3119.	-25974.	-9978.	-35952.
595	7/ 1 / 18	77.0	82.6	-6196.	3147.	9748.	2047.	2486.	4178.	2302.	2302.	-21137.	-8966.	-30103.
596	7/ 1 / 19	75.0	74.9	-707.	959.	7454.	2127.	2520.	3195.	1506.	1506.	-11248.	-7221.	-18469.
597	7/ 1 / 20	72.0	69.4	3373.	0.	6881.	2250.	2475.	2949.	3108.	3108.	-5757.	-8532.	-14289.
598	7/ 1 / 21	71.0	68.4	4402.	0.	5160.	2584.	2716.	2212.	3947.	3947.	-3342.	-8875.	-12217.
599	7/ 1 / 22	69.0	66.4	6124.	0.	3154.	2295.	2160.	1352.	4809.	4809.	675.	0.	675.
600	7/ 1 / 23	66.0	63.4	8564.	0.	2007.	2025.	1485.	860.	4796.	4796.	4532.	0.	4532.
601	7/ 2 / 0	66.0	63.2	9075.	0.	1218.	2025.	1485.	522.	4796.	4796.	5831.	0.	5831.
602	7/ 2 / 1	65.0	62.2	10099.	0.	1218.	2025.	1485.	522.	3088.	3088.	6855.	0.	6855.
603	7/ 2 / 2	65.0	62.2	10402.	0.	1218.	2025.	1485.	522.	3088.	3088.	7158.	0.	7158.
604	7/ 2 / 3	63.0	60.2	12083.	0.	1218.	2025.	1485.	522.	3082.	3082.	8840.	0.	8840.
605	7/ 2 / 4	62.0	59.2	13074.	0.	1218.	2025.	1485.	522.	3079.	3079.	9830.	0.	9830.
606	7/ 2 / 5	62.0	61.1	11961.	207.	2222.	2062.	1812.	952.	3079.	3079.	7470.	0.	7470.
607	7/ 2 / 6	66.0	69.8	6058.	746.	8099.	1706.	1755.	3471.	5690.	5690.	-4494.	-10916.	-15410.
608	7/ 2 / 7	68.0	76.3	1441.	1429.	8457.	1330.	1505.	3625.	5701.	5701.	-9776.	-10830.	-20606.
609	7/ 2 / 8	73.0	85.5	-5259.	2314.	8099.	1000.	1250.	3471.	5727.	5727.	-16673.	-10448.	-27121.
610	7/ 2 / 9	78.0	94.3	-11862.	3406.	8099.	1075.	1425.	3471.	4849.	4849.	-24442.	-9745.	-34187.
611	7/ 2 / 10	81.0	100.5	-16794.	4643.	8242.	1020.	1360.	3532.	4862.	4862.	-30699.	-9754.	-40453.
612	7/ 2 / 11	83.0	104.9	-20539.	5906.	8744.	1020.	1530.	3747.	6718.	6718.	-36209.	-11996.	-48205.
613	7/ 2 / 12	85.0	108.3	-23614.	7033.	7597.	840.	1260.	3256.	14220.	14220.	-39084.	-18736.	-57820.
614	7/ 2 / 13	87.0	110.5	-25867.	7847.	7597.	822.	1207.	3256.	5801.	5801.	-42134.	-10264.	-52398.
615	7/ 2 / 14	85.0	107.5	-24358.	8182.	7597.	977.	1381.	3256.	3998.	3998.	-41114.	-8635.	-49750.
616	7/ 2 / 15	86.0	106.1	-23881.	7918.	9102.	1237.	1705.	3901.	8712.	8712.	-42139.	-14318.	-56457.
617	7/ 2 / 16	84.0	100.5	-20287.	7003.	7669.	1870.	2465.	3287.	6724.	6724.	-36829.	-12476.	-49305.
618	7/ 2 / 17	75.0	86.7	-10765.	5466.	9748.	2096.	2681.	4178.	9650.	9650.	-28075.	-16509.	-44584.
619	7/ 2 / 18	78.0	84.1	-8754.	3419.	9748.	2047.	2486.	4178.	7653.	7653.	-23968.	-14316.	-38284.
620	7/ 2 / 19	77.0	76.9	-3481.	1042.	7454.	2127.	2520.	3195.	8641.	8641.	-14105.	-14355.	-28460.
621	7/ 2 / 20	73.0	70.2	1572.	0.	6881.	2250.	2475.	2949.	10689.	10689.	-7559.	-16113.	-23671.
622	7/ 2 / 21	70.0	67.2	4144.	0.	5160.	2584.	2716.	2212.	10659.	10659.	-3600.	-15587.	-19187.
623	7/ 2 / 22	71.0	68.2	3906.	0.	3154.	2295.	2160.	1352.	8593.	8593.	-1542.	-12105.	-13647.
624	7/ 2 / 23	70.0	67.2	5004.	0.	2007.	2025.	1485.	860.	7597.	7597.	972.	0.	972.

Figure 15. Thermal Load Components for 1st and 2nd Day of July

heating and cooling situations to exist simultaneously within a multi-unit structure.

In Figure 14 is presented the thermal load components for the SE zone on the 4th day of February, for which the highest zone heating load of the season occurred at 8:00 a.m. The greatest zone cooling load of the year occurred on day 2, July at 1:00 p.m. for the SW zone, shown in Figure 15. Here, the "total" load, seen by the HVAC system, of course includes the significant latent heat contributions to such a cooling load. The repression of latent heat contributions in the heating season is exemplified in the former figure.

Dynamic Sensible Building Load Results - Dynamic sensible loads for the building as a whole are presented graphically in the "Lissajous" Figures 16 and 17. These results were obtained by summing the four zoned calculations. Figure 16 shows hourly load versus sol-air temperature for day 4, February. The (solid) static load line, with a slope of -3690, gives the linear relationship which would hold between any given sol-air temperature and its load if that temperature were absolutely constant. The slope is derivable from the previous dynamic load calculations ($= -G_o$) and represents the steady heat input necessary to maintain the building set point against heat flow through walls, roof, windows, and sensible infiltration. (Note that the static load line will pass through 0 Btu/hr at the building set point temperature). The dynamic load line gives the slope of the ellipse tracing the diurnal load pattern. Under normally varying exterior temperatures, the slope of the actual load response differs from the static case. Using phasor notation, the first relationship presented in section 1.4.1 is:

$$\frac{\Delta Q_{DL}}{\Delta T_{SA}} (j\omega) = -3690 \frac{1 + j 6.117 \omega}{1 + j 7.981 \omega}$$

Fig. 16— Dynamic sensible building load Albany - Feb 4th

Fig. 17— Dynamic sensible building load Albany — July 2nd

Letting the time frequency ($f = \frac{\omega}{2\pi}$) vary from $f = 0$, representing no cycles of temperature fluctuation (per hour), i.e., constant exterior temperature, gives slopes for the load response ranging from -3690 to -2828 at $f = \infty$. The latter figure reflects the sensible energy storage capability of the materials of the structure itself in the extreme situation of very rapidly fluctuating exterior temperature. For the frequency of a diurnal cycle, $f = 1/24$ per hour, a slope of -3008 is derived which is most practical for the time variation model incorporated. Since past temperature histories influence the dynamic sensible load, the slopes of the final ellipses also vary from the theoretical, for example, on 4 February where this slope is -2910.

In Figure 17 is presented the sensible dynamic load characteristic of the hottest day of the abbreviated year, 2 July. Note that the range for dynamic sensible building load is $\sim -100,000$ to $250,000$ Btu/hr over the year for this structure.

2. FUEL CELL DESIGN ALTERNATIVES

2.1 Fuel Cell Analysis

2.1.1 Simplified Lumped Model

The simulation model for the Total Energy System requires a simple model of the relationships between fuel cell voltage, current, heat generation and the various reactant flow rates, compositions and temperatures. These relations have been developed and coded for the DIGAS concept.

Flow Relations for DIGAS

In the DIGAS system, a fraction, λ , of the cathode gas flows through process channels in the bipolar plates and the fraction $1 - \lambda$ flows through channels in cooling plates that are placed between groups (3 - 6) of cells. The makeup air contains α moles of N_2 per mole of O_2 (where $\alpha = 3.76$) and w moles of water vapor per mole of dry air. Thus the moles of makeup flow per mole of O_2 consumed is

$$N_i = X (1 + \alpha) (1 + w)$$

where X = makeup moles of O_2 per mole O_2 consumed.

Since each mole of consumed oxygen (O_2) reacts with hydrogen to form 2 moles of water vapor (H_2O), the bleed flow per mole of consumed O_2 (N_x) is greater, by one mole, than the make up flow;

$$N_x = 1 + N_i$$

The recirculation ratio, f , is defined as moles of gas recirculated per mole exhausted (or bled) from the flow system. Then the moles of stack flow per mole O_2 consumed is

$$N_s = N_i + f N_x$$

The makeup flow contains X moles O_2 , αX moles N_2 and $(1 + \alpha)Xw$ moles H_2O per mole O_2 consumed. The exit flow contains $X - 1$ moles O_2 , αX moles N_2 and $2 + (1 + \alpha)Xw$ moles H_2O per mole O_2 consumed. Using the definition of recirculation ratio, the stack flow contains $X + f(X - 1)$ moles O_2 , $(1 + f)\alpha X$ moles N_2 and $2f + (f + 1)(1 + \alpha)Xw$ moles H_2O . The stack inlet composition is then

$$Y_{p_i O_2} = \frac{X + f(X - 1)}{N_S}$$

$$Y_{p_i H_2O} = \frac{2f + (f + 1)(1 + \alpha)wX}{N_S}$$

where $Y_{p_i O_2}$ and $Y_{p_i H_2O}$ are mole fractions at process inlet of O_2 and H_2O respectively.

Since the fraction λ of the stack flow passes through process channels, the process moles of O_2 per mole O_2 consumed is

$$S = \lambda (X + f(X - 1))$$

The process exit compositions are

$$Y_{p_x O_2} = \frac{(S - 1) Y_{p_i O_2}}{S + Y_{p_i O_2}}$$

$$Y_{p_x H_2O} = \frac{S Y_{p_i H_2O} + 2 Y_{p_i O_2}}{S + Y_{p_i O_2}}$$

The process inlet and exit compositions are used to determine the mean for use in the voltage calculation.

The hydrogen concentration in the fuel inlet is given as Y_{fiH_2} . The exit hydrogen mole fraction is

$$Y_{fxH_2} = \frac{(1 - \eta_F) Y_{fiH_2}}{1 - \eta_F Y_{fiH_2}}$$

If $Y_{fi,J}$ is the inlet fuel mole fraction of component J, the exit concentration is

$$Y_{fx,J} = \frac{Y_{fi,J}}{1 - \eta_F Y_{fi,H_2}}$$

which applies for CO , CO_2 , H_2O and CH_4 when present in the inlet fuel.

Cell operation demands a value of S greater than 1.0. It is seen that S depends on X , λ and f . It has been decided that a reasonable design approach is to choose f such that the mean temperature rise of the total stack flow has a value consistent with the desired stack temperature level and uniformity and the recirculation stream temperature range (ΔT). Thus given X , f is obtained by a heat balance such that the temperature range (ΔT) is obtained. This heat balance is obtained as follows.

The cell heat generation is

$$Q = \left(\frac{-\Delta H}{2F} - V \right) I$$

where ΔH = enthalpy change for the reaction = -243,458 joules/mole H_2 at 450°K

The moles of O_2 consumed are

$$\dot{N}_{O_2} = \frac{I}{4F}$$

Thus the inlet mass flows to the stack are

$$\dot{m}_{O_2} = 32 \dot{N}_{O_2} (X + f(X - 1))$$

$$\dot{m}_{N_2} = 28 \dot{N}_{O_2} \alpha X (1 + f)$$

$$\dot{m}_{H_2O} = 18 \dot{N}_{O_2} [2f + (1 + f)(1 + \alpha)wX]$$

The energy balance is

$$Q = (\dot{m}_{O_2} C_{p_{O_2}} + \dot{m}_{N_2} C_{p_{N_2}} + \dot{m}_{H_2O} C_{p_{H_2O}}) \Delta T$$

The solution for f is

$$f = \frac{K_3 - K_1}{K_2}$$

where

$$K_3 = \frac{4F \left(\frac{-\Delta H}{2F} - V \right)}{\Delta T}$$

$$K_2 = 32 (X - 1) C_{p_{O_2}} + 18 (2 + wX (1 + \alpha)) C_{p_{H_2O}} + 28 \alpha X C_{p_{N_2}}$$

$$K_1 = X [32 C_{p_{O_2}} + 18 (1 + \alpha) w C_{p_{H_2O}} + 28 \alpha C_{p_{N_2}}]$$

For $w = 0.01$ the expression for f becomes

$$f = \frac{(1.2612 - V) \left(\frac{2718}{\Delta T} \right) - X}{X + 0.2981}$$

where appropriate values for specific heats have been used and where V is cell voltage and ΔT is the rise in °K.

This simulation model has been coded and debugged including calculation of all mass flow rates, specific heats, and temperatures for operation of the cell stack at specified temperature.

Voltage-Current Characteristics

The fuel cell model adopted to predict the current-voltage curve as a function of temperature and gas compositions is basically the same as one developed earlier by ERC. That model was modified to include the effect of CO and fitted to the performance data for cell stack #319 by making cell resistance a function of temperature.

The voltage equation is

$$V = E - \eta$$

where

V = cell voltage

E = Nernst potential (reversible open circuit E.M.F.)

η = overpotential

The reversible potential, E, at one atmosphere is given by the Nernst equation

$$E = E_o(T) + \frac{RT}{ZF} \ln \left(\frac{Y_{H_2} \sqrt{Y_{O_2}}}{Y_{H_2O}} \right)$$

with

$$E_o(T) = 1.2605 - 0.00025T$$

where

$E_o(T)$ = standard E.M.F. of the cell, volts

R = gas constant, 8.314 joules/(gm. mole - °K)

F = Faradays Constant, 96500 coulombs/mole - equivalent

Z = number of electrons transferred per mole of hydrogen, Z = 2.

T = temperature, °K

Y_{H_2} = mole fraction of hydrogen at anode

Y_{O_2} = mole fraction of oxygen at cathode

Y_{H_2O} = mole fraction of water vapor at cathode

The polarization term η consists of four components.

$$\eta = \eta_a + \eta_r + \eta_d + \eta_{CO}$$

where

η_a = activation polarization at cathode

η_r = resistance polarization

η_d = diffusion polarization

η_{CO} = activation polarization at anode due to CO.

The cathode activation polarization is given by the Tafel equation

$$\eta_a = \frac{RT}{\alpha ZF} \ln \frac{i}{i_o (SA)(CL)(CU)}$$

where

α = transfer coefficient, assumed to be 0.5

i = current density, A/cm²

i_o = exchange current density

SA = specific catalyst surface area, cm²/gm

CL = catalyst loading on cathode, gm/cm²

CU = catalyst utilization factor (Cu = 0.1 for stack #319)

The exchange current is a function of acid concentration, temperature, and partial pressure of oxygen. The acid concentration is a function of water vapor partial pressure which permits correlation of i_o as a function of Y_{O_2} , Y_{H_2O} , and T.

An empirical fit

$$i_o \cong 0.2327 Y_{O_2} Y_{H_2O}^{0.4377} \exp(-6652/T)$$

gives i_o within about 5 percent in the range of interest.

The resistance polarization is

$$\eta_r = ir$$

where r = specific cell resistance.

The stack #319 data appeared to show a relatively large change in cell resistance with temperature. A good fit was obtained by

$$r = r_o \exp \left(3650 \left(\frac{1}{T} - \frac{1}{450} \right) \right)$$

with $r_o = 0.44 \Omega - \text{cm}^2$ for stack #319.

The diffusion polarization was neglected. The effect of diffusion was estimated to effectively lower Y_{O_2} by about 0.004 at $i = 0.15 \text{ A/cm}^2$. The potential change due to this concentration gradient is negligible.

The data of stack #319 and reference (1) were used to formulate an expression for η_{CO} . The form of the expression was chosen to have strong temperature dependence (doubling every 15°K), be directly proportional to Y_{CO} and have a logarithmic dependence on i , i_{Ao} and catalyst effective area. The constants were set to give about 7 mv voltage drop with 1 percent CO in the fuel supply, a cell operating temperature of 450°K and a current density of 0.2 A/cm^2 . The resulting expression is

$$\eta_{CO} = 0.0782 Y_{CO} \exp \left(9190 \left(\frac{1}{T} - \frac{1}{450} \right) \right) \cdot \ln \left(\frac{i}{CL_a \cdot SA \cdot CU \cdot i_{Ao}} \right)$$

where

CL_a = anode catalyst loading

i_{Ao} = anode exchange current, assumed to be $5.3 \times 10^{-5} \text{ A/cm}^2$.

The equations presented here apply to the average performance of a cell when appropriate values are used for the variables. The geometric mean of inlet and outlet mole fractions were selected for the gas composition.

For example, this gives

$$Y_{H_2} = \sqrt{\left(Y_{H_2} \right)_{in} \left(Y_{H_2} \right)_{out}}$$

and similar expressions for other reactants and products.

A subroutine was coded to perform the calculations including an iterative solution for i when V is given. This iterative form of the equation is required when determining local current density distribution for the more detailed finite element model.

2.1.2 Detailed Functional Model

Current Density Distribution

A detailed model of the cell has been developed to obtain the current density distribution in a large cell with cross flow geometry of the reactants. Inputs include cell geometry, catalyst loading, cell temperature, fuel composition supplied, total cell current, etc. The electrochemical and thermodynamic relations described in the previous section are applied to finite elements of a rectangular grid. The reactants consumed and the currents produced in each element are calculated for a fixed voltage by iteration. The reactant compositions are recalculated as hydrogen is consumed and water vapor generated and appropriate inlet values used for each element. The result is iterated until the voltage is consistent with the specified total current.

An example result is shown in Figure 18 for an isothermal cell. Note that there is a significant variation in current density over the cell which arises due to depletion of H_2 and O_2 as flow proceeds through the cell. The code is presently being combined with the thermal analysis code to obtain the effect of local cell temperature variation on current density and local heat generation.

Cell Thermal Analysis

A cell stack temperature distribution analysis has been developed which determines temperature distribution within a set of process and cooling plates in a strip in the air flow direction. The analysis includes the cooling effect of process flow, local heat transfer coefficients calculated for developing laminar flow, effect of channel cross-section aspect ratio, conduction within bipolar plates, conduction between plates and temperature change of air along all flow channels. The local heat generation is based on results from the current density distribution analysis. Sample cases have been run to verify the code is performing as intended. Detailed results are expected to be available by the next report period.

Fig.18—Distribution of current density (i) in 12" $\times$ 17" cell at 350°F

2.2 Westinghouse Stack Test Facility

It was decided that the fuel cell testing laboratory should be designed to service fuel cell stacks capable of producing 15 KW of electrical energy. The laboratory will incorporate three test plinths each able to accept a stack of 7.5 KW output and it is anticipated that two test plinths may be operative at one time. Support facilities will include one control module, one electrical module and one gas blending module for each plinth as illustration in Figure 19.

The flow rates of CO , CO_2 , H_2 , and H_2O (vapor) required to synthesize reformed and shift converted natural gas for two 7.5 KWe stacks were determined. Methods of storing the gas were decided upon after consultations with prospective suppliers and Westinghouse Research facilities personnel. Figure 20 illustrates the gas supply scheme.

A scheme for continuous blending of the gases is illustrated in Figure 21. Foxboro, Wagh, Air Products and Flow Media Inc. have been asked to produce detailed proposals for the supply of a blending system based on this scheme or any other scheme they consider more suitable. The stack air circulation problem has received attention and the current scheme is illustrated by Figure 22. Additional effort has been directed towards specifying combustible gas leak detectors.

Figure 19
LAB' LAYOUT.

Figure 20

Gas Utilization Based on 15 KW Electrical Output

Gas		H ₂	CO	CO ₂	H ₂ O A
Hourly Cons'	lb/hr	3.75	.75	22.5	22.5 30
Monthly Cons'	lb/m	1875	375	11250	11250
at 500 hr/m	tons/m			5.125	
	scf/m	3.58×10^5	4.33×10^3		
<u>Storage Method</u>		H ₂	CO	CO ₂	H ₂ O
		Trailer Cluster	Frame Cluster	Liquid Bulk/ Gass Accum'	Steam Generator

Capacity	scf	1.4×10^5	3×10^3		
	Tons			6.0	
	lb/hr				50.0
Turnover	Days	11 to 12	20	24	N/A.
Location		Outdoors	Outdoors	Outdoors	Indoors.

Figure 21

2.3 Fuel Cell Design and Fabrication

The cell components were fabricated for the two state-of-the-art 2-KW stacks and the stack components for one were fabricated and it is now being assembled.

A three cell stack was designed and fabricated with the cells and current collectors divided into two sections. The currents in these sections will be measured separately to verify the calculated effect of air depletion on current density.

More detailed discussions of this work are given in Appendix A.

2.4 Cell and Stack Experiments

Tests to measure the effects of fuel and oxidant utilization and fuel composition and humidity on cell performance have been initiated

The flow distribution (ratio of process air to cooling air) for a DIGAS stack was determined using a combination of flow and electrochemical measurements and cross-checked by an energy balance.

These tests are described in more detail in Appendix A.

3. METHANE CONDITIONER STUDY

3.1 Technology Assessment

To avoid duplicative efforts in developing the detailed data base that is needed to design a reasonably optimized, and integrated small scale methane conditioning system, the available information was collected and studied to determine its adequacy. The sources of this information included the open literature, specifications for reformers from the files of program personnel, technical data provided by catalyst manufacturers and information provided by Mr. Voecks of the Jet Propulsion Laboratory. The attached bibliography (Table VIII) is a list of those sources which can be meaningfully referenced.

At this time, the type of information (listed in Table IX) needed to begin a serious effort to design a system does not appear to be available. Therefore, a detailed plan to develop this information "in house" was written. This plan calls for a joint ERC-Westinghouse effort with ERC doing the electrochemical experiments and Westinghouse developing appropriate combustors and designing the system. The literature indicates that the fuel processing equipment is a critical subsystem in phosphoric acid fuel cell systems and an early start on the development of this data base appears to be imperative for timely installation of the proof-of-concept versions of the OS/IES.

3.2 Mathematical Model

A preliminary mathematical model for use in the system study has been developed for the methane fuel conditioner. This model describes the functional performances of both the reformer and the shift converter, as influenced by various design parameters. A computer program, REFORM, has been written in FORTRAN V. This program provides various algorithms for solving the basic equations used in the mathematical model.

Table VIII

Methane Conditioner Bibliography

1. EPRI EM-695, Vols. 1, 2 "Assessment of Fuels for Power Generation by Electric Utility Fuel Cells", Arthur D. Little, March 1978.
2. EPRI EM-696, Vol. 1 "An Assessment of the Fuel Cell's Role in Small Utilities", Burns & McDonnell Engrg. Co., February, 1978.
3. DOE and EPRI, "FCG-1 Module Demonstrator Semi-Annual Report No. 4", FCR-0969, UTC, August 1978.
4. EPRI 318 "Assessment of Fuels for Power Generation by Electric Utility Fuel Cells", Arthur D. Little, October 1975.
5. Meek, Baker, and Allen, "Hydrogen Generator Design", in Hydrocarbon Fuel Cell Technology edited by B. S. Baker, Academic Press, 1965.
6. Meek, Baker "Fuel Cell Systems" in Advances in Chemistry Series 47, 1965.
7. EPRI EM-576 "Advanced Fuel Cell Technology Program", UTC, November 1977.
8. EPRI EM-335 "Advanced Technology Fuel Cell Program", UTC, October 1976.
9. DOE & GRI, "On-Site 40-Kilowatt Fuel Cell Power Plant - Preliminary Model Specification", FCS-0937, UTC, July 1978.
10. DOE, "Venture Analysis Case Study for On-Site Fuel Cell Energy Systems, Final Report, Volume II", UTC, July 1978.
11. DOE, "Phase I, Improvement of Fuel Cell Technology Base, Final Report", UTC, 1978.
12. Allen, Gerbard, Likins, "Kinetics of the Methane-Steam Reaction", Ind. Eng. Chem., Process Des. Dev. 14, 1975.
13. Dirksen, Riesy, "Equilibrium in the Steam Reforming of Natural Gas", Ind. Eng. Chem. 45, 1953.
14. Beam, Roskowski, "Modern Hydrogen Manufacture", Symp. on H₂d. Manuf. - Chem. & Cat. Techn., Div. of Petr. Chem, Inc., ACS, LA Mtg., 1971.

Table VIII (cont'd)

Methane Conditioner Bibliography (Cont)

15. Davis, "Fuel Cell Trials: Utilities Now, CPI Next?", Chemical Engineering, August 14, 1978.
16. NASA CR-135429 "Assessment of Industrial Applications for On-Site Fuel Cell Cogeneration Systems", A. D. Little, 1978.

Table IX

Information Required for Methane Conditioner Subsystem Design

- Equipment Design Information for the Reformer/Shift Reactor/Heat Exchangers
 - Configuration
 - Size
 - Materials of Construction
 - Instrument and Control Specifications and Installation Details
 - Provisions for Reliability
 - Maintenance Requirements
- Catalyst Specification and Performance Information
 - Forms (tablets, ribbons, etc.)
 - DP Through Beds
 - Capacity and Breakthrough
 - Life/Activity Data
 - Contamination Potential
 - Preconditioning Requirements
 - Limitations on Service
 - Costs and Availability
- Equipment Performance Information for the Reformer/Shift Reactor/Heat Exchangers
 - Exchanger Fouling Rates
 - Turndown/Startup Performance Data
 - Gas Composition versus Throughput and Temperature
 - Kinetic Relationships

The mathematical model is based on thermodynamic equilibrium being achieved in both the steam reforming and water gas shift reactions. Fundamental equilibrium data⁽¹⁾ has been internally included in REFORM. Incorporation of approaches to equilibrium as well as deviations from the assumed total thermal insulation of the conditioner system can be added to subsequent models which will be developed for thermally integrating the fuel conditioner into the overall fuel cell system. These are anticipated to be part of the (W) efforts in future phases of the program.

Computer Program Output

The REFORM computer program, which was written during this quarter, is currently being "debugged". Output from the program gives the following:

1. Pound moles of CH_4 , CO , H_2O , CO_2 and H_2 being discharged from both the reformer and the shift converter,
2. Volume percentages of CH_4 , CO , H_2O , CO_2 and H_2 , on both a wet and dry basis, in gases being discharged from the reformer and shift converter,
3. Equilibrium conversions of CH_4 and CO (pound moles) in both the reformer and shift converter,
4. Heats of reaction, sensible heat and total heat added or absorbed in the reformer and shift converter,
5. Inlet temperature to the shift converter, calculated to balance the heat of reaction with sensible heat of the feed.

Development of Mathematical Model

A number of basic equations were developed as part of the preliminary mathematical model for the methane fuel conditioner. These

(1) "Estimation of Coal and Gas Properties", US Department of the Interior, Office of Coal Research, R&D Report No. 22, Interim Report No. 7, 1971.

equations describe the functional performances of both the reformer and shift converter and serve as the basis for the preparation of the associated computer program, REFORM.

Reformer

Reactions which describe the performance of the reformer are as follows:

The model assumes that one pound mole of CH_4 and R_B pound moles of H_2O are present at the start. The maximum extent of conversion can be defined by thermodynamic relationships. Considering both Equations (A) and (B) at equilibrium at the same time, the following conversions are defined.

N_A = Number of pounds moles of CH_4 reacting in Equation (A)

N_C = Number of pound moles of CO reacting in Equation (B)

Various reactants and products present are then expressed as follows:

$$\text{Pound Moles of } \text{CH}_4 = 1 - N_A$$

$$\text{Pound Moles of } \text{H}_2\text{O} = (R_B - \frac{b}{a} N_A - \frac{b'}{c} N_C)$$

$$\text{Pound Moles of } \text{CO} = (\frac{c}{a} N_A - N_C)$$

$$\text{Pound Moles of } \text{H}_2 = (\frac{d}{a} N_A + \frac{d'}{c} N_C)$$

$$\text{Pound Moles of } \text{CO}_2 = \frac{e}{c} N_C$$

$$\text{Total pound moles, } N = 1 + R_B + N_A \frac{c+d-b-a}{a} + N_C \frac{d'+e-b'-c}{c}$$

At equilibrium the following expressions apply

$$(K_p)_A = \frac{(\frac{c}{a} N_A - N_C)^c (\frac{d}{a} N_A + \frac{d'}{c} N_C)^e}{(1 - N_A)^a (R_B - \frac{b}{a} N_A - \frac{b}{c} N_C)^b} p^{\Sigma n} N^{-\Sigma n} \quad (C)$$

$$(K_p)_B = \frac{(\frac{e}{c} N_C)^e (\frac{d}{a} N_A + \frac{d'}{c} N_C)^{d'}}{(\frac{c}{a} N_A - N_C)^c (R_B - \frac{b}{a} N_A - \frac{b'}{c} N_C)^{b'}} p^{\Sigma n} N^{-\Sigma n} \quad (D)$$

where

$a = 1$	$b' = 1$	$\Sigma n = 2$ for Equation (A)
$b = 1$	$e = 1$	$\Sigma n = 0$ for Equation (B)
$c = 1$	$d' = 1$	$(K_p)_A, (K_p)_B =$ Equilibrium constants for
$d = 3$		Equations (A) and (B)
		$p =$ Pressure in the reformer

Equations (C) and (D) are reduced to the following:

$$(K_p)_A = \frac{(N_A - N_C) (3 N_A + N_C)^3}{(1 - N_A) (R_B - N_A - N_C) (1 + R_B + 2 N_A)^2} p^2 \quad (E)$$

$$(K_p)_B = \frac{N_C (3 N_A + N_C)}{(N_A - N_C) (R_B - N_A - N_C)} \quad (F)$$

Equations (E) and (F) must be satisfied simultaneously in order to establish equilibrium compositions. Equilibrium constants for equations (A) and (B) are selected at the exit temperature from the reformer.

Shift Converter

Products and unreacted reactants from the reformer are passed directly to the shift converter. Reaction (B), shown above, describes what occurs in the shift converter. However, the reaction temperature in the shift converter is much lower; the water gas shift reaction is favored by the lower temperature.

An equation analogous to equation (F) applies to the reaction occurring in the shift converter. Terms are defined as follows:

N'_C = Number of pound moles of CO reacting in shift converter

Pound Moles of $CH_4 = 1 - N_A$

Pound Moles of $H_2O = R_B - N_A - N_C - N'_C$

Pound Moles of $CO = N_A - N_C - N'_C$

Pound Moles of $H_2 = 3 N_A + N_C + N'_C$

Pound Moles of $CO_2 = N_C + N'_C$

$(K_p)'_B$ = Equilibrium constant for Equation (B) in the shift converter.

$$(K_p)'_B = \frac{(N_C + N'_C) (3 N_A + N_C + N'_C)}{(N_A - N_C - N'_C) (R_B - N_C - N'_C)} \quad (G)$$

Defining constants as follows:

$R = N_C$

$S = 3 N_A + N_C$

$T = N_A - N_C$

$U = R_B - N_A - N_C$

also, $C = N'_C$ and $K = (K_p)'_B$

$$K = \frac{(R + C) (S + C)}{(T - C) (U - C)} \quad (H)$$

This yields a quadratic equation which can then be solved analytically

$$(K - 1) C^2 - [K (T + U) + R + S] C + KTU = 0 \quad (I)$$

$$C = \frac{[K (T + U) + R + S] \pm \sqrt{[K (T + U) + R + S]^2 - 4 (K - 1) (KTU)}}{2 (K - 1)} \quad (J)$$

The negative sign is normally used for those expressions within the square root.

Thermal Calculations

Heat requirements for the reformer and shift converter are calculated from the heats of reaction and the appropriate sensible heats of the reactants and products.

The two reformer reactions require a net input of heat for them to proceed. The model provides for this in addition to the sensible heat required to raise the CH_4 and H_2O reactants from the inlet temperature to the temperature where the reaction takes place, namely the exit temperature

$$Q_R = H_A N_A + H_B N_C + (T_2 - T_1) [(C_p)_m + (R_b) (C_p)_w]$$

Q_R = Total heat added to the reformer, BTU

H_A = Heat of reaction of the steam reforming equation at T_2 (A),
BTU/lb mole

H_B = Heat of reaction of the water gas shift equation at T_2 (B),
BTU/lb mole

N_A = Number of pound moles of CH_4 reacting in the reformer (Eqtn A)

N_C = Number of pound moles of CO reacting in the reformer (Eqtn B)

T_2 = Exit temperature from the reformer, $^{\circ}\text{F}$

T_1 = Entrance temperature to the reformer, $^{\circ}\text{F}$

$(C_p)_m, (C_p)_w$ = Specific heats of CH_4 and H_2O at T_{avg} , BTU/lb mole $^{\circ}\text{F}$

R_b = Pound moles of H_2O fed to the reformer

$T_{\text{avg}} = (T_1 + T_2)/2$, $^{\circ}\text{F}$

Note: Pound moles of $\text{CH}_4 = 1$

The shift converter reaction is exothermic, thereby requiring the removal of heat. Heat from the shift converter serves to heat its inlet stream. Accordingly, the inlet temperature is calculated so as to allow the outlet temperature to not exceed the selected value.

$$Q_S = H_C N'_C = - (T_4 - T_3) [M_1 (C_p)_1 + M_2 (C_p)_2 + M_3 (C_p)_3 + M_4 (C_p)_4 + M_5 (C_p)_5]$$

Q_S = Total heat released in the shift converter, BTU

H_C = Heat of reaction of the water gas shift reaction of T_4 , BTU/lb mole

N_C = Number of pound moles of CO reacting in the shift converter

T_4 = Exit temperature from the shift converter, °F

T_3 = Entrance temperature to the shift converter, °F

M_1 = Number of pound moles of CH_4 fed to the shift converter

M_2 = Number of pound moles of CO fed to the shift converter

M_3 = Number of pound moles of H_2O fed to the shift converter

M_4 = Number of pound moles of CO_2 fed to the shift converter

M_5 = Number of pound moles of H_2 fed to the shift converter

$(Cp)_1$ = Specific heat of CH_4 at T_A , BTU/lb mole °F

$(Cp)_2$ = Specific heat of CO at T_A , BTU/lb mole °F

$(Cp)_3$ = Specific heat of H_2O at T_A , BTU/lb mole °F

$(Cp)_4$ = Specific heat of CO_2 at T_A , BTU/lb mole °F

$(Cp)_5$ = Specific heat of H_2 at T_A , BTU/lb mole °F

$T_A = (T_3 + T_4)/2$, °F

4. MANAGEMENT AND DOCUMENTATION

4.1 Supervision and Coordination

The proposed contract was received from DOE San Francisco Operations Office on July 28 and work began immediately. The contract was executed by Westinghouse on August 2 and by the DOE Contracting Officer on August 3.

The proposed ERC subcontract, which had been prepared earlier from the proposal work statement, was forwarded to DOE for approval. A purchase order authorizing ERC to commit funds in the interim was issued on July 31. DOE approval of the subcontract was received on October 18 and the subcontract was forwarded to ERC for their execution.

The Westinghouse task leaders were informed that work should begin and funds could be committed. On August 10, the first of four weekly meetings of Westinghouse key personnel was held. The purposes of these meetings were 1) discuss the task descriptions to ensure that they were understood, 2) establish intertask lines of communication to ensure that the need for close interaction would be recognized 3) define the system modeling task so that the function of the mathematical models of fuel cells and methane conditioner were clarified and 4) discuss planned effort levels for each task and establish limits of authority and funding.

The contract required the preparation of 1) management plan 2) milestone plan and management report 3) cost plan 4) manpower plan and 5) energy RD&D work in progress reports. These were prepared, delivered and corrections directed by the Government Technical Manager were made during this quarter.

Two groups of Westinghouse key people (a design group and a test group) visited ERC to view their facilities, discuss available information and establish the working level interfaces during the second week of September.

4.2 Documentation and Reporting

The first monthly review meeting was held at the ERC location on September 19 in conjunction with a review of the ERC technology contract and a tour of ERC facilities. Mr. King and Mr. Simons of NASA-LERC represented the government. Dr. Maru, Dr. Chang, Dr. Baker and Mr. Christner of ERC reported on their plans for fabricating the fuel cell stacks for testing on this contract and reported on the work being done under their technology contract and conducted the tour of their facilities. Dr. Kirschbaum and Mr. Hoover represented Westinghouse R&D at this meeting. Dr. Kirschbaum discussed the selection of an apartment complex in Albany, New York for the TES application, explained his method of representing a typical year by 12 four day periods and described the shape and causes of diurnal load variations. The latter resulted in a useful discussion of ways to reduce peak load and thus, reduce the fuel cell capacity (also fuel processor and power conditioner) required.

A more extensive review was held on October 19 & 20 at the Westinghouse R&D center. The government representatives of this meeting were Drs. Fordyce and Warshay and Messrs. King, Simons, Presler and Bollenbacher of NASA-LERC and Voecks of JPL. Drs. Kothmann and Kirschbaum of Westinghouse and Maru of ERC and Messrs. Draper, Sammarone and Vidt of Westinghouse presented talks on the technical progress of Phase I and plans for Phase II. Drs. Veyo and Stewart, Messrs. Cyphers, Makiel and Hoover and Ms. Habron of Westinghouse and Drs. Baker and Chi and Mr. Christner of ERC also participated in the meetings.

As a result of Dr. Kothmann's presentation on fuel cell analysis, a question of the proper method of formally advising the Government Technical Manager of patent disclosures arose. Dr. Angello of our patent committee has agreed that these should be included with identification in the pre-patent clearance copies of reports (see discussion below) which are sent to the Government Technical Manager and the DOE Patent Group.

At the close of the October review meeting several action items were specifically agreed on and these were summarized in a letter written by the Government Technical Manager. Two of these items (approval of Albany and 16-unit apartment) have been resolved.

The monthly Milestone Plan and Management Reports, Contract Management Summary Reports, Technical Status Reports and Cost Management Reports were prepared and delivered as required by the contract. The procedure for submitting the Technical Status Reports for patent clearance and the format of the cover page have been clarified through discussions with the Government Technical Manager. These procedures will also be followed in submitting quarterly and final reports.

4.3 Planning

A detailed work statement for Phase II was developed and submitted to the Government Technical Manager for comment and consideration. The preparation of this document was a cooperative effort by ERC and Westinghouse and it reflects the close cooperation between the two groups during the current program and anticipates an even closer relationship during Phase II.

Appendix A

ERC Quarterly Technical Progress Report

PROGRAM TO DEVELOP AND TEST FUEL CELL
DRIVEN TOTAL ENERGY SYSTEMS

Subcontract 34-JP-76802-A
(DOE Contract No. ET-78-C-03-2031)

TECHNICAL PROGRESS REPORT NO. 3

Quarterly Report for
August to October, 1978

TASK 2.1 FUEL CELL ANALYSIS

The purpose of this task is to compile data on operating characteristics of ERC's phosphoric acid fuel cells. The data on heat recovery and power conditioning requirements, failure modes and protection requirements, and control requirements will be compiled. Whenever a data gap exists, such data will be generated in specific laboratory experiments.

For the effect of gas compositions and temperature, the data on two typical 5 in. x 15 in. cells has already been compiled. Additional data with the present state-of-the-art components is being compiled both on 5 in. x 15 in. cell stacks as well as on 12 in. x 17 in. cell stacks.

2.1.A.1 Performance as a Function of Fuel and Oxidant Utilization:

Testing has been initiated to gather the following data points:

	<u>H₂ (Pure) Conversion</u>	<u>O₂ (in Air) Conversion</u>
1.	80%	75%
	80%	50%
	80%	25%
	80%	10%
2.	50%	50%
	20%	50%

As indicated above, the base line conditions will be 80% H₂ and 50% O₂ utilization. The 80% H₂ conversion is the present operating condition of ERC fuel cells and 50% O₂ conversion corresponds to twice the stoichiometric amount of flow through the cathode channels.

2.1.A.2 Effect of Fuel Composition and Humidity

The effect of carbon dioxide and carbon monoxide on the cell performance will be determined at a constant utilization, H₂ at 80% and O₂ (in air) at 50%, varying the fuel compositions as follows:

100% H₂

75% H₂ + 25% CO₂

75% H₂ + 24% CO₂ + 1% CO

75% H₂ + 22% CO₂ + 3% CO

Also, the effect of humidity will be obtained by humidifying the inlet fuel to cells to simulate the fuel composition from a reformer.

2.1.A.3 Effect of Temperature

Data from 2 in. x 2 in. cells are being compiled to map the effect of temperature on cell performance.

2.1.A.4 Heat Recovery Requirements

The electricity production in the phosphoric acid fuel cells is accompanied by approximately equal amounts of heat generation. Thus, an effective means of heat removal is very important because of its exothermic nature of reactions and the strong dependence of performance on temperature.

In this system, a ~ 100% H_3PO_4 is used as electrolyte and the cells operate at 300 to 400°F. The reactions at anode and cathode are -

$$\Delta G_{350\text{F}} = -52,940 \text{ cal/gmol}$$

$$\Delta H_{350\text{F}} = -58,160 \text{ cal/gmol}$$

In an operating cell, heat is generated because of

- Changes in entropy resulting from electrochemical reactions at the anode and cathode.
- Irreversibilities resulting from overpotential and ohmic effects.

If the anodic and cathodic reactions are fully reversible, a minimum amount of heat is liberated,

$$\left(- \frac{dQ}{dt} \right)_{\text{rev}} = - \frac{T\Delta S}{nF} \cdot I \quad (4)$$

subscript "rev" signifies the heat generated when the reactions are reversible. Equation 4 represents an overall reversible heat generation, but the heat effects at the anode and cathode could be different in nature as is recently shown for molten carbonate fuel cell system (1). Although single electrode heat effects are not studied for phosphoric acid fuel cells, qualitatively it can be stated that if a gaseous reaction takes place with a decrease in the number of moles, then heat is evolved (2). Under this assumption, we expect the heat to be evolved at the anode and absorbed at the cathode. Because Reaction 3 is exothermic, there will be a net generation of

heat, but at the individual electrodes the signs of heat generation may be opposite. Therefore, the magnitude of heat absorption or generation at each electrode could be greater than the net "reversible" heat generation. This is even more important in porous electrodes because the current density distribution in a pore is nonuniform, and these heat effects may create local temperature gradients which may in turn affect local catalyst sintering, corrosion, and electrolyte loss.

Because of the irreversibility resulting from activation, concentration, and ohmic overpotentials, an additional heat is generated in the fuel cell. This heat generation,

$$\left(- \frac{dQ}{dt} \right)_{\text{irrev}}, \text{ can be represented as } \left(- \frac{dQ}{dt} \right)_{\text{irrev}} = (\epsilon - V) I \quad (5)$$

or, the total heat generated because of contribution of reversible effects is given as

$$- \frac{dQ}{dt} = \left(- \frac{T\Delta S}{nF} + \epsilon - V \right) I \quad (6)$$

As an example, at 350°F, with $\epsilon = 1.2V$ and $V = 0.65 V$ (design operating voltage), approximately 50% of the input enthalpy shows up as heat (Equation 6) and 50% as electrical energy. Of the heat produced, approximately 17% heat is reversible heat (Equation 4) and 83% is related to irreversibility. Because a majority of the irreversibility in the phosphoric acid fuel cell occurs at the cathode, a significant amount of heat is generated on the cathode side of the cell. This is an important consideration for temperature gradients across the cell, local hot spots, and heat removal schemes.

2.1.A.5 Power Conditioning Requirement

As presently envisioned, two 60 kW modules will be connected in a parallel circuit for redundancy requirement (Figure 1). Thus when one 60 kW unit is to be temporarily shut down for maintenance, the other unit can be overloaded and still provide the power needed for the short duration.

The inverter will draw 320 V and 375 A DC current and will deliver 220 V AC at 60 cycles.

2.1.D Fuel Cell Models

ERC's existing model for performance of PAFC as a function of gas compositions, platinum loading, and operating temperature is presently being revised.

FIGURE 1 ARRANGEMENT OF 120 kW POWERPLANT FOR TOTAL ENERGY SYSTEM

2.1.A.6 Phosphoric Acid Fuel Cell (PAFC) Maintenance and Failure Modes

The discussion presented here relates to maintenance and failure modes of test stacks as well as to stacks operating under actual conditions. In the latter case, of course, several additional controls can be installed to prevent certain failure modes.

The performance of PAFC stacks is controlled by several operating parameters, including resistive load, temperature, reactant flow rates and inlet temperatures, extent of heat removal, and the removal mode. These operating parameters must be balanced and adjusted to maintain an optimum temperature with respect to performance and life of the stack. It is important to note that there may be a time lag between adjustment of some operating parameters and their impact. Therefore, a stack must be monitored continuously after an adjustment until stable conditions are achieved. Should undesirable problems such as -

- Fuel supply cut-off
- Oxidant supply cut-off
- Stack temperature overshoot
- Load is too high or off
- Cross-leak
- Fuel/Air channel blockage, etc.

occur, corrective actions should be taken immediately to prevent serious and/or permanent damage to the stacks. Data on these failure modes and the maintenance are being compiled, and the standard procedures for corrective actions are being formulated.

TASK 2.2 CORROBORATING EXPERIMENTS

In parallel to the Westinghouse effort in the analytical cell model development, ERC has fabricated a 3-cell stack (5 in. x 15 in. cells) with specially designed current

collectors to verify the current density distribution obtained from the analytical model. In this stack, the flow of current through the active area of the cell is to be divided into two equal sections, and the stack has two equal size current collectors at two ends. The schematic of one side of the stack is shown in Figure 2. The current through the upper half of the stack near the air inlet will be collected by a pair of current collectors and that through the lower half near the air outlet will be collected by another pair. This design will be adequate to determine the current density distribution in these two sections.

TASK 2.3 FUEL CELL DESIGN AND FABRICATION

2.3.1 Flow Distribution in a Digas-Cooled Stack

In the design and development of integrated energy systems, it is important to know the reactant flow distribution within the fuel cell stack. In particular, the number of stoichiometric amounts of air passing through cells versus the number passing through the cooling members. For this purpose, a 11 in. x 14 in., 10-cell stack with a cooling plate incorporated between the 5th and 6th cells was used to verify our design concepts and to develop the experimental techniques to quantify the flow rates.

The total input flow rate was measured using a Velometer operating on the principle of measuring static and dynamic pressure difference. The results were further verified with the help of a hot wire anemometer.

To determine the flow split ratio into the cells (m_1) and the cooling plates (m_2), either m_1 or m_2 must be found. However, the small channels of the cells and cooling plates make it very difficult to perform direct measurements. Thus, an electrochemical approach was employed to determine the flow rate

FIGURE 2 SCHEMATIC OF 3-CELL STACK FOR CURRENT DENSITY STUDY

through the cells, m_1 . The flow rate m_1 could be obtained at a given blower setting and load by measuring the limiting current density (L.C.D.) at a given reactant (in this case, oxygen) flow rate. The flow rate of air through the cooling plates, m_2 is obtained by the difference between m_T and m_1 . Excellent agreement between the experimentally determined ratio of $m_1:m_2$ ($= 1:7.01$) and the design ration ($1:7$) was obtained. Table 1 presents the values of m_T , m_1 , and m_2 .

TABLE 1 AIR FLOW RATES IN THE DIGAS-COOLED STACK

	<u>lbm/hr</u>	<u>No. Stoichs</u>
Total Air, m_T	53.7	22.4
Cell Air, m_1	6.7	2.8
Cool. Plate Air, m_2	47.0	19.6
<hr/>		
m_2/m_1	7.01	

A cross-check on the flow distribution ratio was obtained by making an energy balance on the stack at a steady state, i.e., constant temperature, load, reactant flow rates and concentrations, and performance. A good agreement in the energy balance was obtained using the measured flow rates and temperatures.

The methodology developed will be useful for the testing of 2-kW stacks presently being assembled.

2.3.2 Stack Design and Fabrication

The first two 2-kW stacks have been designed to determine -

- Cell to cell performance reproducibility
- Cell to cell temperature distribution

- ⊙ Effect of heat removal by different air flow rates
- ⊙ Effect of simulated reformer fuel, etc

Fabrication of the cell and stack components (ERC's state-of-the-art 5 in. x 15 in. hardware) of the first 2kW stack has been completed and the stack is being assembled. A schematic of this stack with ducting is shown in Figure 3. Also, the subcomponent fabrication and cell subassembly of the second 2kW stack has been completed.

The test stand for these stacks has been designed, and the construction is expected to be completed by the end of December, 1978.

Short stacks of 5 in. x 15 in. and 12 in. x 17 in. cells are also being fabricated to obtain the necessary performance data for use in Task 1.2.1.

DISTRIBUTION LIST

Dr. Bernard S. Baker
Energy Research Corporation
3 Great Pasture Road
Danbury, CT 06810

Mr. Paul L. Blum (2)
Department of Energy
20 Massachusetts Avenue, NW
Washington, DC 20545

Mr. George Ciprios
Exxon Research & Engineering
Laboratories
P.O. Box 8
Linden, NJ 07036

Mr. John Cuttica
Department of Energy
20 Massachusetts Avenue, NW
Washington, DC 20545

Mr. Richard F. Dudley, Jr.
Department of Energy
20 Massachusetts Avenue, NW
Washington, DC 20545

Mr. Robert Dumke
Engelhard Industries Division
Engelhard Min. & Chemical Corp.
Menlo Park, Edison, NJ 08817

Mr. Arnold P. Fickett
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94304

Dr. V. Fiore
Gas Research Institute
3424 South State Street
Chicago, IL 60616

Mr. E. Gillis
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94304

Mr. Lawrence M. Handley,
Program Manager
United Technologies Corporation
Power Systems Division
P.O. Box 109
South Windsor, CT 16074

Mr. D. Q. Hoover
Westinghouse Electric Corporation
Research & Development Center
1310 Beulah Road
Pittsburgh, PA 15235

Mr. William Houghtby, Manager
United Technologies Corporation
Fuel Cell Technology
P.O. Box 109
South Windsor, CT 16074

Dr. John Houseman
Jet Propulsion Laboratory
4800 Oak Park Drive
Pasadena, CA 94720

Mr. J. Huff
DRDME-EC
Department of the Army
U.S. Army Mobility Equipment
Research and Development Command
Fort Belvoir, VA 22060

Mr. J. Joebstl
DRDME-EC
Department of the Army
U.S. Army Mobility Equipment
Research and Development Command
Fort Belvoir, VA 22060

Mr. Robert King (5)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Dr. Byron McCormick
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, NM 87545

DISTRIBUTION LIST
(Continued)

Mr. Leonard J. Rogers
Department of Energy
20 Massachusetts Avenue, NW
Washington, DC 20545

Dr. Arnold Schnyer, Program Manager
Energy Systems Division
Office of Energy Programs
NASA Headquarters, NE
Washington, DC 20546

Mr. Richard T. Sperberg
Gas Research Institute
3424 South State Street
Chicago, IL 60616

Dr. S. Srinivasan
Department of Applied Science
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, NY 11973

Dr. P. Stonehart
Stonehart Associates
34 Five Fields Road
Madison, CT 06443

Mr. Alan Streb
Department of Energy
20 Massachusetts Avenue, NW
Washington, DC 20545

W. Taschek
DRDME-EC
Department of the Army
U.S. Army Mobility Equipment
Research and Development Command
Fort Belvoir, VA 22060

Mr. Gary E. Voelker
Department of Energy
20 Massachusetts Avenue, NW
Washington, DC 20545

Mr. G. Walker
DRDME-EC
Department of the Army
U.S. Army Mobility Equipment
Research and Development Command
Fort Belvoir, VA 22060

Dr. Fraser Walsh
Eco-Control, Inc.
56 Rogers Street
Cambridge, MA 02142

Dr. Marvin Warshay
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Dr. Lawrence B. Welsh
Universal Oil Products
10 UOP Plaza
Des Plaines, IL 60016

Professor E. Yeager
Case Western Reserve
Electrochemistry Laboratory
University Circle
Cleveland, OH 44106

Mr. Martin Zlotnick
Department of Energy
20 Massachusetts Avenue, NW
Washington, DC 20545

Conservation Division/SAN (2)
Department of Energy
1333 Broadway
Oakland, CA 94612

California Patent Group/
Livermore Office
P.O. Box 808, L-376
Livermore, CA 94550