SOLAR-MEC®

DEVELOPMENT PROGRAM

Project 9103 Semiannual Progress Report
For the Period September 1, 1977, Through February 28, 1978

Jaroslav Wurm
Sanford A. Weil
Leslie R. Wright

MASTER

Prepared by

Institute of Gas Technology
IIT Center, 3424 S. State Street
Chicago, Illinois 60616

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or 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.

Date Published — January 1979

Prepared for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract No. EG-77-C-01-4495

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.

ABSTRACT

Progress on the development of the Solar-MEC® desiccant cooling system is reported. Specifically, the dynamic performance of a supported molecular-sieve, regenerative, heat and mass exchanger is reported, under input conditions typical of the operation of a solar-powered open desiccant cooling system. Comparisons of the above experimental data with a computer model describing the dynamic processes of air drying and desiccant regeneration of the Solar-MEC desiccant cooling system are reported. An account of the test setup, of the experimental program, and the results of diagnostic steps to evaluate air leakage rates within the Solar-MEC system and actions to minimize such leakage are reported. The test design and experimental approach to verify the performance of the rotary regenerative (sensible) heat exchanger are reported.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
1.1 Program Objectives	1
1.2 Overall Goals	1
1.3 Immediate Technical Goals	2
2. PROGRESS	4
2.1 Task 1A: Process Design Reevaluation, Desiccant Measurements	4
2.2 Task 1B: Process Design Reevaluation, Mathematical Model	5
2.3 Task 3A: Diagnostic Laboratory Tests, Leakage Evaluation	8
2.4 Task 3B: Diagnostic Laboratory Tests, Heat-Exchanger Wheel Performance	8
APPENDIX A. COMPARISON OF PERFORMANCE DATA FOR THE DESICCANT WHEEL	11
APPENDIX B. LEAK DETERMINATION	13
1. METHODOLOGY OF LEAK DETERMINATION	13
1.1 Steady-State Leak-Rate Determination	13
1.2 Transient Leak-Rate Determination	16
1.3 Cross-Leak	18
2. TESTING	19
2.1 Air Flow Measurements	19
2.1.1. ASME Nozzle Method	19
2.1.2. Pitot Traverse Method	19
2.2 Pressure Measurements	20
2.3 Tracer-Gas Concentration Measurements	20
2.4 Tracer-Gas Flow-Rate Measurements	20
2.5 Temperature and Dew-Point Measurements	27
2.6 Miscellaneous Instruments	27
2.6.1. Digital Multimeter	27
2.6.2. Recorder	27
3. DISCUSSION OF RESULTS	29
3.1 Evaluating Carry-Over	29
3.2 Leak Rates	29
3.3 Summary and Conclusions	34
3.4 Suggestions for Design Improvements	40

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1	Milestone Plan and Management Report	3
2	Comparison of Dryer Wheel Simulations With Munters Data for the Molecular Sieve Wheel	6
3	Comparison of Dryer Wheel Simulations With Cargocaire Data for the Molecular Sieve Wheel	7
4	Heat-Exchanger Performance Test Setup	9
B-1	Flow Test Loop Arrangement	14
B-2	Tracer Gas Mass Balance Diagram for Transient Leak Determination	16
B-3	Air and Tracer Gas Flow Schematic for Determining the Cross-Flow Leak	18
B-4	Pressure Sensing Technique With Related Sensors, Electronics, and Recorders	21
B-5	Pressure Indicating and Recording Setup	22
B-6	Zero Calibration of Hydrocarbon Analyzer and Recorder	23
B-7	Range Calibration of Hydrocarbon Analyzer and Recorder	24
B-8	Normal Operation of Hydrocarbon Analyzer and Recorder	25
B-9	Tracer-Gas Flow Measurement	26
B-10	Temperature and Dew-Point Sampling for Air-Flow Measurements	27
B-11	Calibrating Scheme for the Electronic Manometer and the Recorder	28
B-12	Process Air Flow Rate Versus Leak Rate	32
B-13	Process Air Flow Rate Versus Percent Leak	33
B-14	Location and Relative Amount of Dynamic Leak in the Solar-MEC	35
B-15	Portion of the Desiccant Wheel Relative to the Guide Block Showing Minimum Clearance	36
B-16	Portion of the Desiccant Wheel Relative to the Guide Block Showing Maximum Clearance	37
B-17	Portion of the Desiccant Wheel Relative to the Radial Seal Showing Minimum Clearance	38
B-18	Portion of the Desiccant Wheel Relative to the Radial Seal Showing Maximum Clearance	39

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
A-1	Cargocaire Engineering Corporation Data	12
B-1	Leak-Tests Summary	31

1. INTRODUCTION

This is the first semiannual report on the Solar-MEC® development program, funded by the Solar Heating and Cooling Research Branch of DOE. A substantial amount of development work was done before this contract, culminating in field tests of prototype Solar-MEC systems. The performance of these prototypes indicated sufficient promise for this device to warrant further development work and indicated the direction in which that development work should proceed. The objectives of the current program derive from the results of the field test program, which was jointly sponsored by the National Science Foundation and the American Gas Association, with additional support by Southern California Gas Co., Consolidated Natural Gas Service Corp., and ENSERCH, Inc.

1.1 Program Objectives

The objectives of this program are -

- To obtain necessary data on the dynamic performance of the desiccant wheel and to use this information to improve our ability to mathematically describe the Solar-MEC cooling process. This description will then be used to develop and evaluate design improvements for better seasonal energy efficiency.
- To obtain experimental data for evaluating and improving the previously developed Solar-MEC prototype. Areas to be investigated include air-seal leakage, possible deterioration in the rotary heat-exchange-wheel performance, the desiccant support matrix material, and the distribution of input energy.

1.2 Overall Goals

The purpose of the overall development program for the Solar-MEC is, of course, to achieve its commercialization. IGT's subsidiary, Gas Developments Corp. (GDC) owns the patent rights to the Solar-MEC for the United States and certain foreign countries. These rights are shared on a worldwide basis with AB Carl Munters, a Swedish corporation that has had a long-term interest in this process and that manufactures rotary regenerative heat- and moisture-exchange wheels.

Because IGT, GDC, and Munters are not manufacturers, the commercialization of the Solar-MEC will ultimately require manufacturing partners. GDC is currently in advanced negotiation with a firm specializing in the assembly

and installation of air-conditioning equipment in commercial and institutional buildings. This firm has explored the technical and financial aspects of Solar-MEC and has built one prototype. The firm is now engaged in a joint program with GDC to obtain funding needed to construct and install a commercial-size unit at its own manufacturing facility to obtain additional construction and operating-life experience.

GDC is also actively seeking potential manufacturers who are capable of the high-volume production necessary for commercialization of residential Solar-MEC equipment. Negotiations here are not as far advanced because it is accepted that the initial market entry of Solar-MEC should be commercial and institutional installations, for reasons of size, maintenance requirements, and the inherent advantage of the Solar-MEC in systems requiring fresh-air ventilation.

The above involvement of manufacturers is timely and necessary for smooth transition of Solar-MEC into the marketplace. However, as was shown in the field test programs mentioned above, there are certain technical problems that must also be solved. It is not expected that these solutions will entail major modification of the Solar-MEC concept, but changes in configuration, design variables, and components are called for. This work comprises the objectives of the current DOE program, as listed in Section 1.1 above. A more detailed discussion of these objectives and the technical reasons for selecting them is contained in the proposal for this project.

1.3 Immediate Technical Goals

The proposal for this project identified a series of work tasks aimed at answering the technical questions raised in the previous field test program. These tasks are summarized in Figure 1, the Milestone Plan and Management Report.

Task 1 is aimed at improving our quantitative understanding of the Solar-MEC process and the development of design improvements to match the open cycle desiccant process to the solar input in a cost- and energy-efficient manner. Briefly, it consists of detailed measurements of the desiccant wheel performance, incorporation of the data into a mathematical model of desiccant wheel behavior, incorporation of this model into a model of the overall Solar-MEC process, and evaluation of the performance of a well-designed Solar-MEC system on a seasonal basis, under a variety of climate and load conditions.

1. Contract Identification		2. Reporting Period 9/1/77 through 2/28/78		3. Contract Number EG-77-C-01-4493	
4. Contractor Name, address Solar-MEC Development Program Institute of Gas Technology 3624 South State Street Chicago, Illinois 60616		5. Contract Start Date 9/1/77		6. Contract Completion Date 8/31/78	

Task	Reporting Category (e.g., contract item number or work breakdown structure element)	7. Fiscal Year and Month												10. Percent Complete											
		1977					1978					1979													
		S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	
1A	Desiccant Measurements																								60
1B	Math Model																								50
1C	Design Alternatives																								
1D	Seasonal Load																								
3A	Leakage Tests																								100
3B	Heat Exchange Tests																								20
3C	Desiccant Structure																								
7D	Design Evaluation																								
	Quarterly Report Submittal																								
	Semi-Annual Report																								
	Annual Report																								
	Draft Final																								
	Final Report																								

11. Remarks
Contract received 30 days after official starting date.

12. Signature of Contractor's Project Manager and Date

13. Signature of Government Technical Representative and Date

9703094

LEGEND

- CRITICAL MILESTONE
REVISED MILESTONE
WORK INITIATED AHEAD OF SCHEDULE
 SOLID SYMBOL OR BAR SHOWS WORK DONE

Figure 1. MILESTONE PLAN AND MANAGEMENT REPORT

There is no Task 2 in this program. The original proposal contained a Task 2 whose purpose was to improve the strength of the desiccant support structure. However, the work intended for that task has been modified and incorporated into Task 3C.

Task 3 is aimed at finding ways to improve the prototype hardware performance. It includes evaluation of air leakage within the unit, verification of the performance of the rotary regenerative heat exchanger, tests of desiccant support structure stability, consideration of alternative support materials, and laboratory evaluation of design suggestions developed in Task 1C.

2. PROGRESS

This report actually covers the period September 1, 1977 through February 28, 1978. During this period, we worked on four tasks, as shown in Figure 1. Considerable progress was made on Tasks 1A (Desiccant Measurements) and 1B (Math Model). Task 3A (Leakage Tests) was completed, as planned. Work on Task 3B (Heat Exchange Tests) has begun.

2.1 Task 1A: Process Design Reevaluation, Desiccant Measurements

Task 1A consists of laboratory measurements of the dynamic performance of the present molecular sieve drying wheel over a selected range of conditions. The measured data are necessary in Task 1B to define values of the physical parameters for the computer model of the dynamic processes of air drying and desiccant regeneration.

To perform these measurements we have been negotiating with two companies: Cargocaire Engineering Corporation, Amesbury, Mass., and AB Carl Munters, of Sweden. The preliminary negotiations were described in the Project 9103 Quarterly Progress Report (September 1 through November 30, 1977) and subsequent monthly progress reports. First agreement was reached and, as a result, Cargocaire Corp. performed 33 tests and submitted the results for our evaluation on schedule. The detailed results from these tests are presented in Appendix A.

We have not yet been able to finalize arrangements for additional tests at high humidity levels. The present facilities of Cargocaire do not provide for high humidity levels, but preliminary agreement has been reached with another firm to perform this testing within our budget and schedule requirements. However, before we can finalize this agreement, we must obtain clearance from Munters, as part of the patent licensing agreement with this company. This clearance has not yet been obtained.

2.2 Task 1B: Process Design Reevaluation, Mathematical Model

As part of our earlier studies of the desiccant cooling process that led to the Solar-MEC, IGT developed a finite difference model to describe the dynamic behavior of the desiccant wheels. This model was tailored to the lithium chloride desiccant used in earlier prototypes. It has been necessary to adapt this model to the molecular-sieve-based desiccant formation used in the wheels currently available and to incorporate the results of this modeling into more general models of the Solar-MEC air conditioner.

The model is a two-dimensional description (time and distance along the flute that passes through the wheel) of the heat and mass transfer between the air stream and the desiccant structure that comprises the wheel. This model was found to give an adequate description of the performance of the lithium chloride wheels used previously.

A similar computer model for lithium chloride wheels was developed independently by AB Carl Munters in Sweden. We have examined their model and found that it rests on the same technical foundation as the IGT model, but it uses a more efficient computational technique and requires less computer time. We have, therefore, decided to use and modify, as necessary, the Carl Munters program. The modifications needed include a description of the desiccant properties of molecular sieves in combination with silica gel and the incorporation of nonuniform temperature distribution on the air inlet streams.

Because our application of the model will be semiempirical, based on the measured performance data from Task 1A, several adjustment factors have been incorporated into the model. The factors considered include a linear temperature-dependent factor to artificially change the equilibrium vapor pressure of the desiccant, a factor applied independently to the molecular sieve and silica gel to alter the moisture capacity of the solid phase, and the effective fraction of silica gel and molecular sieve desiccant in the new structure.

Our work to this point has included testing the desiccant wheel model against proprietary performance data and against the data provided by Cargocaire Corp. With only two exceptions (Figures 2 and 3), both the proprietary data and those supplied by Cargocaire are predicted by the model with fair accuracy. The two data points with very high humidity levels, which are not in agreement with the model, are presently considered by us to have been reported erroneously.

Figure 2. COMPARISON OF DRYER WHEEL SIMULATIONS WITH MUNTERS DATA FOR THE MOLECULAR SIEVE WHEEL

Figure 3. COMPARISON OF DRYER WHEEL SIMULATIONS WITH CARGOCAIRE DATA FOR THE MOLECULAR SIEVE WHEEL

The comparison of the performance data for the desiccant wheel, as given by the desiccant wheel model and by direct measurements, is discussed in Appendix A.

2.3 Task 3A: Diagnostic Laboratory Tests, Leakage Evaluation

This work was satisfactorily completed in January. Measurements were performed on a system (unit and ducts), after which the main points of leakage in the structure of the metal casing and ducts were located and sealed. Thus, the leak distribution corresponds to a tight, but still practical structure. Use of a tracer gas leak-detection method was verified as one providing the necessary level of accuracy. This confirms the reliability of measured data as well as of deduced test results.

In summary we have accomplished the following:

- We have identified leak rates in individual compartments as a function of pressure levels in these compartments.
- We have quantified external and internal leaks for a machine of our specific design.

The test results allowed us to draw the following conclusions:

- The leaks in our machine are primarily associated with the dynamic seals around the wheels, and mainly around the desiccant wheel where the pressure differences are greatest. It is the peripheral drive design, which uses relatively unsealed guide blocks and causes wobbling, that decreases the sealing performance of the otherwise sound sealing elements.
- Some external leaks are unavoidable. These leaks are not negligible.
- Design changes can be suggested to minimize both the internal and external leaks. These changes will not necessarily complicate the machine.

Appendix B contains the detailed discussion of the leakage test measurements and results.

2.4 Task 3B: Diagnostic Laboratory Tests, Heat-Exchanger Wheel Performance

A test loop similar to the one used for the leak detection tests is currently under construction. Its design scheme is given in Figure 4. A slight delay that we are experiencing in the construction of the loop is not expected to seriously delay our testing plan.

Figure 4. HEAT-EXCHANGER PERFORMANCE TEST SETUP

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX A. COMPARISON OF PERFORMANCE DATA FOR THE DESICCANT WHEEL

The computer program to simulate the performance of the dryer wheel of the MEC unit was evaluated with performance data supplied by Cargocaire Engineering Corp. The results of 33 runs are presented in Table A-1. The wheel used in this study was 380 mm in diameter and 200 mm deep. It was constructed of a paper made of approximately 50/50 weight mixture of 13x type molecular sieve and asbestos. A wheel of similar composition and dimensions had been studied by Munters. It was on the basis of the latter data only that the wheel thermodynamic properties were assigned. Between the two data bases, the range of conditions studied were—

Humidity:	7 to 22 lb/1000 lbs
Process Temperature:	75° to 95°F
Reactivation Temperature:	180° to 300°F
Air Velocity:	200 to 400 ft/min
Wheel Rotation:	7.5 to 15 rpm
Reactivation/Process Flows:	0.33 to 1.

Figures 1 and 2 are comparisons of the reported and calculated average moisture of the processed air stream. In both sets, the deviations are of the order of 0.5 lb/1000 lb. Possibly significant systematic deviations appear in those runs in which the processed air is dry (less than 2 lb/100 lb). For the Cargocaire data, the calculated values tend to be high by 0.4. For the Munters data, the calculated values tend to be low by a similar amount. For a typical run in this region, the bulk (about 80%) of the processed air is extremely dry (humidity about 0.2 to 0.4 ppt). The overall average is several times greater because the first 20% is extremely moist. (In these tests, no purge section was included as would be in actual operation.) A minor difference in placement of seals, it is felt, can account for the differences observed.

The two points with major deviation (much greater than 1 ppt) correspond to runs with very high humidities (22 ppt), although three other runs at comparable humidities showed better agreements. No reasonable modification of the system could account for these deviations, and we currently believe these to have been erroneously reported.

Table A-1. CARGOCAIRE ENGINEERING CORPORATION DATA

CARGOCAIRE ENGINEERING CORPORATION - JOB #28994

1-11-78

TABLE 1

ROW NO.	FAN SPEED RPM	SECTOR R/P	FACE VELOCITY SFPM	PROCESS SECTOR				REACT. SECTOR				PASS BALANCE R/P
				TEMP AIR IN °F	MOISTURE AIR IN LBS 1000 LBS	TEMP AIR OUT °F	MOISTURE AIR OUT LBS 1000 LBS	TEMP AIR IN °F	MOISTURE AIR IN LBS 1000 LBS	TEMP AIR OUT °F	MOISTURE AIR OUT LBS 1000 LBS	
1	7.5	1:1	200	75.0	7.14	121.5	1.86	180.0	9.43	119.3	14.86	1.01
2	10	"	"	75.5	6.64	124.8	1.53	178.0	8.00	114.4	12.86	.99
3	15	"	"	74.6	6.66	129.6	1.77	178.0	7.93	108.2	12.29	.90
4	15	"	"	75.6	7.07	140.8	1.45	210	8.39	123.0	14.14	1.01
5	10	"	"	75.0	7.57	136.0	1.31	209	9.29	126.6	15.29	.97
6	7.5	"	"	74.2	7.21	128.6	1.06	207	9.23	129.8	15.43	.99
7	7.5	"	"	75.4	7.86	141.4	0.46	259	9.14	160.8	17.00	1.04
8	10	"	"	75.2	7.43	145.0	0.82	260	9.21	157.8	15.71	1.01
9	15	"	"	73.8	7.07	154.5	1.31	260	9.23	146.8	14.93	.99
10	15	"	"	94.0	6.57	146.2	1.53	210	7.71	133.0	12.64	1.00
11	10	"	"	95.6	6.29	137.9	1.00	208	7.43	136.7	12.79	1.02
12	7.5	"	"	97.4	7.07	141.6	1.21	212	8.43	141.6	14.43	1.03
13	7.5	"	"	73.7	11.43	144.2	1.96	214	4.57	120.7	14.50	0.97
14	10	"	"	76.0	11.79	153.5	1.81	210	4.91	111.0	15.29	1.02
15	15	"	"	76.4	11.85	161.0	1.77	210	5.11	106.7	15.71	1.05
16	15	"	"	75.8	12.14	176.3	0.80	260	5.32	133.4	16.14	0.96
17	10	"	"	76.4	11.91	166.4	0.83	264	6.33	140.0	17.71	1.03
18	7.5	"	"	74.7	11.86	161.4	1.27	255	8.26	139.5	18.57	0.96
19	7.5	"	"	94.8	12.43	176.5	1.61	260	6.69	146.5	17.14	0.96
20	15	"	"	75	11.71	182.0	1.16	264	5.86	144.2	16.86	1.02
21	15	"	"	96	11.71	188.2	1.13	260	4.71	136.4	15.43	1.00
22	15	1:2	200	75.0	12.29	124.0	6.09	208	2.73	85	16.21	1.05
23	10	"	"	74.2	12.43	122.8	5.62	210	2.61	87	16.71	1.01
24	7.5	"	"	74.6	11.86	121.2	5.01	210	3.30	91.7	17.00	0.97
25	7.5	"	"	96.0	12.07	153.8	3.79	260	2.67	115.0	18.86	0.96
26	10	"	"	95.0	11.43	156.6	3.297	260	2.49	106.4	19.57	1.00
27	15	"	"	95.0	12.00	159.0	3.14	263	2.37	102.0	19.57	0.96
28	7.5	1:3	"	95.0	11.71	122.5	7.66	210	2.61	98.8	15.14	1.02
29	10	"	"	96.0	11.71	123.4	7.37	212	2.37	98.0	15.14	0.98
30	15	"	"	94.8	12.00	121.2	7.83	212	2.87	93.4	15.00	0.97
31	7.5	"	"	75.8	12.14	124.6	5.86	260	2.87	93.0	21.43	0.97
32	10	"	"	76.5	12.14	123.4	6.33	260	2.87	89.4	21.14	1.03
33	15	"	"	76.2	12.21	123.8	6.58	260	2.73	87.7	20.43	1.03

NOTES:

- ① Face Velocity Stated at Equivalent Standard Conditions of 70°F ± 29.92" Hg (.075 Lbs/Ft³)
- ② Mass Balance (R/P) = $\frac{\text{Lbs of Air/Hr} \times \Delta \text{ Lbs of Water/Lb of Air in Reactivation Circuit}}{\text{Lbs of Air/Hr} \times \Delta \text{ Lbs of Water/Lb of Air in Process Circuit}}$
- ③ Outlet Temperature Values Were Taken Approx. 6 Ft. after Wheel Face in Uninsulated Ducts.

APPENDIX B. LEAK DETERMINATION

1. METHODOLOGY OF LEAK DETERMINATION

In our measurements, we set out to determine the amount of air being forced out of the Solar-MEC unit to the atmosphere (external leaks) and the amount of air leaking from the process side to the regeneration side (internal leaks). This leakage loss process consists of leakage through the peripheral seals; leakage through radial seals; leaks through sensible heat wheel material layers; carry-over due to the rotation of the wheels; leakage through cracks, holes, or otherwise poorly sealed compartments; leaks through the compartments themselves to the atmosphere; and absorption of air or gas on the molecular sieve wheel.

To determine the air leak rates in the Solar-MEC, we used a gas-tracer leak detection method. We used methane as the tracer gas and applied the method in two ways. When used as a steady-state leak rate technique the tracer gas was continuously injected into the process air stream and allowed to come to a concentration equilibrium. In another way, the concentration in the closed loop due to leakage was allowed to reach a maximum, the tracer gas flow was discontinued, and the decay was recorded. This application of the gas-tracer leak detection method we refer to as the transient leak-rate determination. Of the two techniques, the steady-state leak rate measurements are primary measurements whereas the transient leak rate data are considered as backup results. The following is a description of the two approaches.

1.1 Steady-State Leak-Rate Determination

The closed loop was built and connected as shown in Figure B-1. The duct was sealed to minimize external leaks. The nozzle and/or baffle plate, in conjunction with an opening in the side of the duct, were adjusted to provide internal unit pressures equal to those experienced and/or expected in actual field operations.

Figure B-1. FLOW TEST LOOP ARRANGEMENT

For computation, we assume that steady-state mass balance is achieved, and therefore, that the leaks from the process side are equal to the air make-up from the room. We also denominate all measured quantities as -

C_p = concentration of tracer gas on the process side (measured in the Solar-MEC before the desiccant wheel), ppm

C_1 = concentration of tracer gas in the leaking air, ppm

C_{ap} = concentration of the tracer gas in the ambient air entering the process air stream before the blower, ppm

C_{ri} = concentration of tracer gas at the regeneration air stream inlet to the Solar-MEC, ppm

C_g = concentration of methane in tracer gas, ppm

F_g = the (constant) amount of tracer gas flowing into the process air stream, cfm

F_{ap} = makeup ambient air flow entering the process stream, CF/min

F_{cbr} = flow carry-back to process by wheel rotations, CF/min

The unknown quantity of total leaks, F_1 (cfm), is a value to be determined by the described method.

Then, the tracer gas mass balance equation will be expressed as -

$$F_g C_g + F_{ap} C_{ap} + F_{cbr} C_{ri} = F_1 C_1 \quad (B-1)$$

Assuming that all gases are thoroughly mixed at leak concentration C_1 and that leaks always flow from the process stream -

$$C_1 = C_p \quad (B-2)$$

For our case -

$$C_g = 10^6 \quad (B-3)$$

because the purity of our tracer gas is almost 100%.

Also -

$$C_{ri} \approx C_{ap} \quad (B-4)$$

because both of these are concentrations of air taken from the same room.

This also implies that the flow, F_{cbr} , can be considered a part of the ambient process air stream, F_{ap} .

Using the air flow mass balance, as -

$$F_g + F_{ap} = F_1 \quad (B-5)$$

our Equation B-1 will become -

$$10^6 F_g + (F_1 - F_g) C_{ap} = F_1 C_p \quad (B-6)$$

and -

$$F_1 = F_g \frac{10^6 - C_{ap}}{C_p - C_{ap}} \quad (B-7)$$

1.2 Transient Leak-Rate Determination

To describe the tracer-gas concentration decay approach to leak determination, three additional quantities have to be defined. These are -

V = total air volume of the investigated system, (process side of the Solar-MEC, the duct work, and fan), CF

t = time, min

A = adsorption rate of the tracer gas on the desiccant matrix, SCF/min

See Figure B-2.

A78030765

Figure B-2. TRACER GAS MASS BALANCE DIAGRAM FOR TRANSIENT LEAK DETERMINATION

Following the diagram in Figure B-2, the tracer gas mass balance is expressed as:

$$F_g C_g + F_1 C_p + A + \frac{dv}{dt} C_p \quad (B-8)$$

Since—

$$C_g = 10^6$$

we have—

$$F_g = \frac{F_1(C_p - C_{ap})}{10^6} + \frac{A}{10^6} + \frac{V}{10^6} \frac{dC_p}{dt} \quad (B-9)$$

Substituting—

$$C' = C_p - C_{ap} \quad (B-10)$$

and assuming—

$$C_{ap} = \text{const} \quad (B-11)$$

$$dC' = dC \quad (B-12)$$

We can now rearrange Equation B-9 to get—

$$\frac{dC'}{dt} + \frac{F_1 C'}{V} = (F_g) \frac{10^6}{V} \quad (B-13)$$

since A is negligible.

Solving this equation for C' , we get—

$$C' = ke^{-\frac{F_1 t}{V}} + \left(\frac{F_g}{F_1}\right) 10^6 \quad (B-14)$$

The boundary conditions give us—

$$\text{at } t = 0, C' = C_o, \text{ and therefore } k = C_o - \left(\frac{F_g}{F_1}\right) 10^6, \text{ and}$$

$$\text{at } t = \infty, C' = C_\infty, \text{ and also } C = \left(\frac{F_g}{F_1}\right) 10^6.$$

Using these results, the particular solution of our equation is—

$$\frac{C' - C_\infty}{C_o - C_\infty} = e^{-\frac{F_1 t}{V}} \quad (B-15)$$

Because we define—

$$C' = C_p - C_{ap} \text{ as concentration at } t = t,$$

$$C_o = C_o \text{ as initial concentration at } t = 0, \text{ and}$$

$$C_\infty = \text{room ambient final concentration at } t = \infty.$$

We can also identify $e^{-\frac{F_1 t}{V}}$ as $e^{-\frac{-F_1 t}{V}} = x$ and solve Equation 15 for a leak rate F_1 in a time interval Δt :

$$\frac{x_1}{x_2} = e^{-\frac{F_1 \Delta t}{V}} \quad (B-16)$$

$$\ln \left(\frac{x_1}{x_2} \right) = \frac{-F_1}{V} - (t_1 - t_2) \quad (\text{B-17})$$

Therefore—

$$F_1 = \frac{V(\ln x_1 - \ln x_2)}{t_1 - t_2} \quad (\text{B-18})$$

1.3 Cross-Leak

The process air which leaks to the regeneration side of the Solar-MEC is referred to as the cross-leak. This leak is determined by measuring the exhaust air flow and concentration, process air concentration, and ambient air concentration of tracer gas in those streams. See Figure B-3.

Figure B-3. AIR AND TRACER GAS FLOW SCHEMATIC FOR DETERMINING THE CROSS-FLOW LEAK

Defining the terms in Figure B-3 —

F_{ri} = regeneration inlet air flow

F_{ci} = regeneration compartment leaks

C_{ci} = regeneration compartment leaks tracer gas concentration

F_x = cross-leak (process to regeneration sections)

F_{pg} = purge air flow

C_{pg} = tracer-gas concentration of purge air flow

F_e = regeneration air flow exit

C_e = regeneration air flow exit tracer gas concentration

C_p = concentration of tracer gas on the process side (measured in the Solar-MEC before the desiccant wheel), ppm

The tracer gas mass balance is expressed as follows:

$$F_{ri}C_{ri} + F_{ci}C_{ci} + F_{pg}C_{pg} + F_xC_p = F_eC_e \quad (B-19)$$

The air flow mass balance is -

$$F_{ri} + F_{ci} + F_{pg} + F_x = F_e \quad (B-20)$$

Since -

$$C_{ri} = C_{ci} = C_{pg} = C_a = \text{ambient concentration} \quad (B-21)$$

Then -

$$C_a(F_{ri} + F_{ci} + F_{pg}) + F_xC_p = F_eC_e \quad (B-22)$$

The total ambient inlet air flow is -

$$F_a = F_{ri} + F_{ci} + F_{pg} \quad (B-23)$$

Combining the terms of Equations B-19 to B-23 yields -

$$F_x = F_e \frac{C_e - C_a}{C_p - C_a} \quad (B-24)$$

2. TESTING

2.1 Air Flow Measurements

To determine the air flows with sufficient accuracy for our leak-detection tests, we have combined two methods of measuring air flow rates: the ASME nozzle measurements and Pitot probe measurements.

2.1.1. ASME Nozzle Method

The rules for measuring air flow rates by using the nozzle method are fully described in the ASME Power Test Codes. For our evaluation, we used the Test Code for Compressors and Exhausters as approved in 1934.

2.1.2. Pitot Traverse Method

The procedure applied in this case is the one described in the Bulletin H-100, Air Velocity Instruments, Dwyer Instruments Inc., Michigan City, Ind.

The Pitot tube used was a Dwyer Model 166-12.

2.2 Pressure Measurements

To measure pressures — specifically, the Solar-MEC and air duct internal pressures, and the differential pressures across the nozzle and velocity heads — we used a Datametrics Barocel pressure sensor Model 570-D-10T-2A-VI, Serial No. 5183, range 0 to 10 torr. The electronic package (power and output) was a Datametrics Barocel electronic manometer Model 1173, Serial No. 347, Model 1173-A1A-10A1-A1.

Figures B-4a, B-4b, B-4c, and Figure B-5 show the arrangements of components in the pressure sensing system.

2.3 Tracer-Gas Concentration Measurements

The tracer-gas concentration is measured by a Beckman Model 400 hydrocarbon analyzer. The fuel is 40.15% hydrogen in nitrogen. Zero air is used for combustion and calibration. A gas mixture of 518 ppm methane in zero air is used to calibrate the gas analyzer.

The setups for calibrating the hydrocarbon analyzer are shown in Figure B-6 for the zero calibration and Figure B-7 for the range calibration. Normal operation when the instrument is used to take data is shown in Figure B-8.

2.4 Tracer-Gas Flow-Rate Measurements

The gas flow rate of the methane into the air stream was first measured by a rotameter (Matheson Model 220D, range 2 to 22 SCF/hr air). The reading was multiplied by a factor to obtain the correct flow for methane.

The rotameter was tested against a wet-test meter (Precision Scientific Co., precision wet-test meter, Serial No. 12-WG). As a result of the test, the rotameter was then used only for course adjustment of the gas flow, while the wet-test meter was used to obtain the exact gas-flow measurements. See Figures B-9a and B-9b for the arrangements of these instruments.

The tracer-gas flow measurements required timing for regular measurements and pressure measurement for calibration. The gas pressure was measured with a Dwyer magnahelic pressure gage, range 0 to 8 inches. Timing was done with a Heuer Model 320 microsplit quartz timer with LDC.

a. Static Pressure in Duct or Solar-MEC

b. Pitot Pressure for Air Flow

c. Nozzle ΔP for Air Flow

Figure B-4. PRESSURE SENSING TECHNIQUE WITH RELATED SENSORS, ELECTRONICS, AND RECORDERS

Figure B-5. PRESSURE INDICATING AND RECORDING SETUP

Figure B-6. ZERO CALIBRATION OF HYDROCARBON ANALYZER AND RECORDER

Figure B-7. RANGE CALIBRATION OF HYDROCARBON ANALYZER AND RECORDER

Figure B-8. NORMAL OPERATION OF HYDROCARBON ANALYZER AND RECORDER

a. Initial Test Setup (Rotameter Only)

b. Final Test Setup

Figure B-9. TRACER-GAS FLOW MEASUREMENT

2.5. Temperature and Dew-Point Measurements

The temperatures of the measured air streams were measured with a Taylor secondary reference thermometer No. 21011, Serial No. 63F2917. The thermometer was placed in the circulating loop, downstream of the nozzle.

The dew points of the air streams were measured with the EE&G Model 880 CI electric dew-point hygrometer, Serial No. 0884.

An example of a setup for these measurements is given in Figure B-10.

Figure B-10. TEMPERATURE AND DEW-POINT SAMPLING FOR AIR-FLOW MEASUREMENTS

2.6 Miscellaneous Instruments

2.6.1. Digital Multimeter

The various voltages from instrument outputs were measured by the recorder with reference to the Hewlett-Packard digital multimeter 3465A. The signal output of the sensor electronics combined with the DMM (Digital Multimeter) provided the means to calibrate the recorder. For setting the zero and span adjustments of the recorder, see Figure B-11.

2.6.2. Recorder

The analog recorder is a 2-channel strip chart recorder, manufactured by the MFE Corp. (Model No. 2125m) and used to record output from the electric manometer and gas analyzer.

Figure B-11. CALIBRATING SCHEME FOR THE ELECTRONIC MANOMETER AND THE RECORDER

3. DISCUSSION OF RESULTS

3.1 Evaluating Carry-Over

In order to determine the credibility of the tracer-gas testing procedure to detect leaks, it was necessary to determine the amount of adhesion that the gas would have to the molecular sieve surface. This adhesion would become part of the leak, known as the physical carry-over leak. This physical carry-over leak is due to an air and gas mixture being physically transferred from one side of the unit to the other because of the motion of the wheel. Also carried over would be the gas adhering to the molecular sieve wheel and being discharged on the other side. A test was set up in which the air flow would pass through the process side of the Solar-MEC with both fans on. The tracer gas would be injected into the process air stream at time equal zero, and the concentration would be observed both upstream and just downstream of the desiccant wheel, on the process side. With the tracer gas flow rate, wheel rotation, and regeneration air flow being the same, the output signals (the traces on a strip-chart recorder) of the tracer gas concentration (increase, steady-state, and decay) were identical in both the upstream and downstream tests once the traces were adjusted for the slight time difference due to the different placement of the probe in the Solar-MEC. This would indicate that there was no measurable carry-over or absorption carry-over on the desiccant wheel.

The physical carry-over of trapped gases in the matrix was calculated to be 32.6 CF/min with both wheels rotating in the cooling mode. Test results indicate that the experimental carry-over ranged between 33 and 23 CF/min, with the average experimental carry-over being over 28 CF/min. In the evaluation of the leak rates, we assumed no adsorption carry-over and 30 CF/min of air as being physically carried from one side to the other side by the sensible heat wheel matrix.

3.2 Leak Rates

To evaluate air leaks in the Solar-MEC machine, the test loop was set up so that the pressures inside the various compartments were equal to those experienced and/or expected during actual operation. The leak rates were measured by the previously described steady-state leak and transient

leak test methods, and all the data were recorded. The reduced data were then tabulated as shown in Table B-1. These tabulated results were then used for further analysis. The results of this analysis are presented in Figures B-12 and B-13. The relationships between the leak rates and the flow rates of the process air are plotted in these figures. The process air flows ranged between 400 and 1300 CF/min while the regeneration air flow rate was held constant at 800 CF/min.

Once the size of the leak was determined, our efforts were concentrated on identifying the mechanism of the leak.

The Solar-MEC center panels were meticulously sealed to eliminate static leaks and to ensure that the only leaks from the process side to the regeneration side were through the dynamic sealing surfaces. Leaks from the process side of the Solar-MEC to the ambient were detected by various leak-detecting methods, but could not be measured directly. We were, however, able to measure the cross-leaks (i.e., the leaks from the process side to the regeneration side). Thus, indirectly, we could determine the magnitude of the ambient leak by subtracting the cross-leak from the total leak. It was found that the cross leak was about 80% of the total leak, leaving about 20% as an ambient leak.

By subtracting the physical carry-over from the cross-leak, the total internal leaks due to the sealing surfaces were found. However, we wanted to know not only the amount of total internal leak, but also the contribution of the individual compartments to the total amount. The direct measurement of such a leak distribution pattern was found to be beyond our direct leak flow measuring capability, and we therefore determined the leak distribution indirectly. Knowing that the leaks across the sealing elements of the wheels must be directly proportional to the corresponding square root of the pressure difference, we have precisely measured the pressure field along and inside the unit and based our determination of the relative leak rates on relative pressure differentials. Interestingly, it was noted that the pressure differences between process and regeneration sides in the same compartments always had the same ratios in comparison with the other compartments; therefore, we can also conclude that the ratio of the leaks in

Table B-1. LEAK-TESTS SUMMARY

Test No.	Date	Leak Rates		Process Air										Regeneration Air					Comments
				Air Flow		Frequency				Inlets				"L" Wheel		Fan		Boiler and SWK	
		Steady State	Transient	Flow	Nozzle	"L" Wheel	"S" Wheel	Fan	Duct	Duct	Inlets	"L" Wheel	"S" Wheel	Fan	Boiler and SWK				
		CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min	CF/min			
24	01/05/78	--	--	476	682	0.286	0.161	1.059	0.363	0.184	0.85	Off	--	--	--	--	Wheels are not sealed, only process side fan on, no wheel rotation.		
25	01/05/78	98	96	--	--	--	--	--	--	--	--	Off	--	--	--	--			
26	01/06/78	114	100	--	--	--	--	--	--	--	--	On	--	--	--	--			
27	01/06/78	114	107	671	685	0.2866	0.164	1.022	0.297	0.282	0.79	On	0.611	--	1.06	--	Both fans on, no wheel rotation.		
28	01/09/78	139	123	672	687	0.334	0.161	1.12	0.297	0.273	0.845	On	0.648	--	1.135	--	Both fans on, both wheels rotating.		
29	01/09/78	126	126	678	679	0.329	0.153	1.130	0.313	0.278	0.8511	On	0.609	--	1.03	--	Both fans on, no sensible wheel rotation.		
30	01/11/78	107	101	387	389	0.184	0.099	0.489	0.060	0.126	0.363	On	0.534	--	1.028	--	Both fans on, both wheels rotating.		
31	01/11/78	119	114	510	513	0.252	0.113	0.773	0.161	-0.177	0.546	On	--	--	--	--	Both fans on, both wheels rotating.		
32	01/12/78	128	111	625	641	0.320	0.131	1.034	0.252	-0.260	0.771	On	--	0.296	1.044	--	Both fans on, both wheels rotating.		
33	01/12/78	145	124	730	733	0.369	0.143	1.260	0.348	-0.313	0.947	On	0.642	--	1.07	--	Both fans on, both wheels rotating.		
34	01/12/78	151	143	794	800	0.410	0.161	1.424	0.426	0.337	1.086	On	0.594	--	1.06	--	Both fans on, both wheels rotating.		
35	01/12/78	174	170	956	952	0.481	0.228	1.919	0.458	-0.474	1.445	On	0.610	--	1.076	--	Both fans on, both wheels rotating.		
36	01/12/78	191	176	1131	1130	0.629	0.265	2.643	0.948	-0.686	1.927	On	0.583	--	1.047	--	Both fans on, both wheels rotating.		
37R	01/13/78	149.7	--	--	803	--	--	--	--	--	--	1250/1385	0.578	0.274	1.052	0.117	Both fans on, both wheels rotating.		
38R	01/13/78	146.7	--	--	796	--	--	--	--	--	--	1050	0.464	0.222	0.827	0.002	Both fans on, both wheels rotating.		
39R	01/13/78	144.0	--	--	795	--	--	--	--	--	--	1179/1313Rv	0.392	0.180	0.678	0.067	Both fans on, both wheels rotating.		
40	01/19/78	111.0	91.12	791	796	0.392	0.143	1.395	0.524	-0.341	1.124	Off	--	--	--	--	Only process fan on, both wheels rotating.		
41	01/19/78	120.0	100.0	783	788	0.370	0.131	1.339	0.476	-0.243	1.040	Off	0.390	0.189	1.743	0.052	Both fans on, no wheel rotation.		
42	01/19/78	113.0	95.3	740	797	0.360	0.119	1.401	0.517	-0.379	1.130	Off	--	--	--	--	Only process fan on, both wheels rotating.		
43	01/19/78	150.0	123.9	792	797	0.372	0.139	1.798	0.463	-0.292	1.109	Off	0.365	0.189	1.577	0.064	Both fans on, both wheels rotating.		
44	01/20/78	80	70.0	584	591	0.246	0.135	0.832	0.293	-0.134	0.998	Off	--	--	--	--	Only process fan on, no wheel rotation.		
45	01/20/78	80	79	591	585	0.267	0.149	0.968	0.265	-0.166	0.702	Off	0.411	0.180	1.767	0.013	Both fans on, no wheel rotation.		
46	01/20/78	82	69	588	591	0.275	0.142	0.854	0.279	-0.133	0.721	Off	--	--	--	--	Only process fan on, both wheels rotating.		
47	01/20/78	121	115	585	599	0.271	0.135	0.889	0.269	-0.170	0.710	Off	0.366	0.180	1.658	0.058	Both fans on, both wheels rotating.		

Figure B-12. PROCESS AIR FLOW RATE VERSUS LEAK RATE

Figure B-13. PROCESS AIR FLOW RATE VERSUS PERCENT LEAK

any of the compartments to the total leak remains unchanged. (See Figure B-14.) For example, the leak around the desiccant wheel is about 60% of the cross-leak, and this will remain true over varying process air flows.

Observation revealed that the greatest leakage from the wheel sealing surfaces occurs at the guide blocks. The installation of guide blocks (used to keep the wheel straight during rotation) required breaks in the peripheral seal. This obviously reduces the effectiveness of the sealing elements considerably. (See Figure B-14 to B-17, which show the relative size of the clearances of the desiccant wheel sealing elements.)

3.3 Summary and Conclusions

We can summarize our findings in the following way:

1. The carry-over due to the adsorption of tracer gas (methane) and rotation of the desiccant wheel is negligible.
2. Physical carry-over on the sensible heat-exchange wheel is approximately 30 CF/min. The corresponding amount on the desiccant wheel is negligible.
3. At design conditions,* about 19% of the net flow is considered leakage.
4. About 20% of the total leak escapes to the ambient, and about 80% crosses the MEC and is exhausted from the regeneration side.
5. The relative amount of cross-over leaks has been identified.
6. By observation, most of the dynamic leaks** (estimated at 80% to 90%) come from the guide blocks.

We therefore concluded that, with a new design of a continuous true sealing surface, the leak rate could be cut from 20% to 10% of the net process air flow. We cannot foresee that decreasing the leak rates below 10% for the residential Solar-MEC design would be practical. Excluding the carry-over, the minimum possible leakage in the Solar-MEC would be about 5%. As stated above, this would be possible only with excellent continuous peripheral sealing and contact radial seals.

---

* 800 CF/min process and regeneration air flow rates.

** Dynamic leaks would be defined as cross-leaks without carry-over.

Figure B-14. LOCATION AND RELATIVE AMOUNT OF DYNAMIC LEAK IN THE SOLAR-MEC

Note that peripheral seal adheres well to desiccant wheel.

Figure B-15. PORTION OF THE DESICCANT WHEEL RELATIVE TO THE GUIDE BLOCK SHOWING MINIMUM CLEARANCE

Note that peripheral seal still adheres well to desiccant wheel.

Figure B-16. PORTION OF THE DESICCANT WHEEL RELATIVE TO
THE GUIDE BLOCK SHOWING MAXIMUM CLEARANCE

Figure B-17. PORTION OF THE DESICCANT WHEEL RELATIVE TO THE RADIAL SEAL SHOWING MINIMUM CLEARANCE

Figure B-18. PORTION OF THE DESICCANT WHEEL RELATIVE TO
THE RADIAL SEAL SHOWING MAXIMUM CLEARANCE

We can also conclude that the information developed in Task 3A is accurate enough to be used in the design and modeling studies to follow, as they are defined in Tasks 1C and 3D.

3.4. Suggestions for Design Improvements

The experimental and analytical work of Task 3A allowed us not only to quantify the air stream leaks associated with the current design of the machine, but also to evaluate possible improvements in sealing efficiency. We have prepared these suggestions using our technical judgement and the relative importance we feel the individual losses have on the performance of the machine. Thus, in the decreasing level of importance, the design suggestions that would improve the performance of the machine are -

1. Provide a continuous peripheral seal. This will eliminate the leaks through the guide blocks.
2. Insure that the wheel is fabricated with sufficient precision to prevent wobbling, which may cause gaps in the peripheral and radial seals.
3. Use a sliding radial seal. This is better than a controlled gap, which is now used. The contact (sliding) seal will ride on a metal screen and not on the surface of the wheel.
4. Use center support wheels. This will eliminate the need for guide blocks.
5. Provide a vented wheel compartment. This would prevent a buildup of pressure in the wheel compartment, if one side of the wheel was not sealed as well as the other.
6. Provide a wheel rotation velocity only as fast as needed to maintain proper performance. This will eliminate excess carry-over and needless air losses.
7. Provide a continuous surface gasket for all statically joined surfaces. This will go a long way in eliminating external (ambient) leaks.
8. Make seals of even more flexible rubber material.

JN/JL

RECEIVED

SEP 28 1979

CONTRACT ADMIN