DOE/CS/40008--79

**Brayton-Cycle Heat-Recovery-System
Characterization Program**

SUBATMOSPHERIC-SYSTEM TEST REPORT

81-17949

July 31, 1981

DO NOT MICROFILM
COVER

RECEIVED
APR 27 1982
DOE OFFICE OF PATENT
AND LEGAL AFFAIRS

Prepared for the
Department of Energy
Contract No. EC-77-C-03-1557

AIRESEARCH MANUFACTURING COMPANY

MASTER

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.

DOE/CS/40008--T9

Brayton-Cycle Heat-Recovery-System Characterization Program

SUBATMOSPHERIC-SYSTEM TEST REPORT

81-17949

July 31, 1981

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It
has been reproduced from the best available
copy to permit the broadest possible avail-
ability.

ACD3-77CS40008

DOE/CS/40008--T9

DE82 008644

Prepared by

Lyman Burgmeier and Shing Leung

DISCLAIMER

This book 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.

Prepared for the

Department of Energy

Contract No. EC-77-C-03-1557

AIRESEARCH MANUFACTURING COMPANY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

gls

CONTENTS

<u>Section</u>	<u>Page</u>
1. INTRODUCTION AND SUMMARY	1-1
1.1 Test Program	1-1
1.2 Results	1-4
1.3 Recommendations	1-6
2. SYSTEM DESCRIPTION	2-1
2.1 Test Setup	2-1
2.2 Test System Instrumentation	2-6
2.3 Data Acquisition	2-7
2.4 Controls	2-10
2.5 Flue Gas Simulation	2-10
3. TEST PROGRAM	3-1
3.1 Vaned Nozzle Tests	3-1
3.2 Vaneless Nozzle Tests	3-7
3.3 Dust Deposit Analysis	3-11
4. CONCLUSIONS	4-1
5. REFERENCES	5-1
 <u>Appendix</u>	
A FLUE GAS EVALUATION	A-1
B TRUESDAIL LABORATORIES, INC. REPORT 34532	B-1

1. INTRODUCTION AND SUMMARY

This document, prepared as part of Subtask 3.3.3 of the program plan (Reference 1)* summarizes the turbine tests and results for the Brayton cycle subatmospheric system (SAS).

The test program was conducted as outlined in the test plan (Reference 2). A scaled model turbine was operated in the same environment as that which a full-scale SAS machine would experience from the hot effluent flue gas from a glass container furnace. The objective of the testing was to evaluate the effects of a simulated furnace flue gas stream on the turbine nozzles and blades. The following specific areas were evaluated:

- Erosion of the turbine nozzles and blades from the dust in the flue gas
- Hot corrosion from alkali metal salts in the dust and acid vapor (sulfur trioxide and hydrogen chloride) in the flue gas
- Fouling and flow blockage due to deposition and/or condensation from the flue gas constituents

1.1 TEST PROGRAM

The SAS model test program was conducted at the AiResearch Torrance, California facility using natural gas combustion plus injected contaminant gases and particulates to simulate the actual flue gas. The particulate matter was furnace dust obtained from a production glass container furnace exhaust stack.

1.1.1 Flue Gas Simulation

The composition and concentration of the contaminant gases and particles in the simulated flue gas are shown in Table 1-1. Also tabulated in Table 1-1 are the baseline values obtained from a literature search and the values for those constituents found at the demonstration site furnace (Appendix A). The test dust satisfactorily simulated both the composition and concentration found in an operational container glass furnace.

1.1.2 Dynamic Modeling Tests

The full-scale SAS turbine design is a radial inflow configuration. This configuration was scaled in the model test program using a production Garrett T04B turbocharger.

*All references are presented in Section 5.

TABLE 1-1

CONTAMINANT GAS AND PARTICULATES COMPOSITION

Contaminant	SAS Model Tests	BSFG*	Demonstration Site
<u>Dust</u>			
Amount ppm (wt)	200	200	95.4
85 percent less than, microns	8	3	0.7
Na ₂ SO ₄ , percent	87	63	88
<u>Vapor</u>			
SO ₂ , ppm (wt)	200	200	231
SO ₃ , ppm (vol)	10	10	0.8
HCl, ppm (wt)	16	15.8	13.7

*Baseline simulated flue gas, derived from literature search

To provide dynamic similarity, the turbomachine was run at tip speeds as close to the full-scale machine as the physical limitations of the model would permit. Stress limitations restricted the tip speed to 93 percent of the full-scale machine, but the spouting velocity and turbine inlet temperature of the full-scale machine were duplicated, providing good simulation. New vaned nozzles were designed and fabricated to provide the required spouting velocity. New turbine wheels were cast from IN-792 to provide hot corrosion resistance and high strength equal to the full-scale machine.

Tests using only vaned nozzles were originally planned (Reference 2); however, after extensive fouling of the vaned nozzles was encountered during testing, a vaneless nozzle was evaluated. Although the vaneless nozzle would reduce the power output in the full-scale SAS machine by about ten percent, the vaneless nozzle concept was selected for testing because it reduced potential fouling to a minimum. The turbine tests are summarized in Table 1-2.

Tests 1 through 5 comprised the SAS model tests using vaned nozzles, an injected dust level of 200 ppm, and turbine inlet temperatures from 1250° to 1550°F. Testing at the lower inlet temperature (1250°F) was performed to determine if a reasonable threshold temperature exists where the dust would not deposit and cause fouling and flow reduction.

TABLE 1-2
MODEL SAS TESTS

Test No.	Purpose	Test Duration, hr	TIT,* °F	Dust Rate, ppm (wt)	SO ₂ , ppm (wt)	SO ₃ , ppm (vol)	HCl, ppm (wt)	Turbine Nozzle	Remarks
1	Evaluate components fouling with simulated baseline conditions	3.5	1550	200	200	0	16	Vaned	Nozzles plugged, suspected oil contamination from bearing oil lubrication system
2	Repeat Test 1, no oil present on nozzles	3.5	1550	200	0	0	0	Vaned	Nozzles plugged
3	Determine fouling at a lower TIT	5.5	1450	200	0	0	0	Vaned	Slight flow reduction; turbine erosion, rust particles found downstream
4	Repeat Test 3 with the absence of rust from ducting	4.75	1450	200	0	0	0	Vaned	Flow reduction, nozzles plugged and interference from deposits on shroud
5	Determine fouling at a minimum acceptable TIT	7.0	1250	200	0	0	0	Vaned	Flow reduction, nozzles plugged
6	Preliminary evaluation of a vaneless nozzle	24.0	1350	200	0	0	0	Vaneless 1.7 A/R**	No visible plug, slight flow reduction, insufficient pressure ratio
7	Evaluate fouling at the baseline test conditions	10.0+	1550	200	200	10	16	Vaneless 0.96 A/R	Flow reduction, large deposit in scroll

*Turbine inlet temperature

**A/R = nozzle area to scroll radius factor

The fouling characteristics of vaneless nozzles were investigated in Tests 6 and 7. Test 6 was run with an oversize nozzle area to check out the characteristics of a vaneless nozzle until a proper sized unit could be obtained. Turbine speed was only 65 percent of that desired and the pressure ratio was only 1.5:1. The over-sized nozzle caused the turbine to operate so far under the design condition that the results are not significant. In Test 7, a more representative nozzle was used, and the test was conducted at baseline conditions.

1.1.3 Test Results

The model SAS test program has been completed with the following results:

- (a) Operating with an inlet temperature range of 1250° to 1550°F, the turbine with vaned nozzles experienced significant flow reduction in only a few hours due to heavy fouling in the nozzle (Figure 1-1). The flow reduction degraded the turbine performance and caused the compressor to operate in surge.
- (b) The vaneless nozzle tests produced a significant flow reduction in 10 hr due to a large dust deposit in the turbine scroll (Figure 1-1).
- (c) The turbine blade tips were eroded in most of the tests.
- (d) No hot corrosion was evident during the short test period.

1.2 RESULTS

1.2.1 Dust Melt Characteristics

Extensive testing and analysis has been performed by AiResearch and Oak Ridge National Laboratory (ORNL) on the melting characteristics of the glass furnace dust. These tests indicated that the dust begins to soften at 1391°F, starts melting at 1550°F, and completes melting at 1638°F.

To efficiently produce power through an SAS radial inflow turbine, a design turbine inlet temperature (TIT) of 1550°F was selected. Moreover, to maintain a minimum net power output, a TIT not less than 1250°F is required. This operating temperature range is so close to the furnace dust particle melting point, that the dust particles tended to be "sticky". Microphotographs verify that agglomeration and sintering of the dust particles has indeed occurred at the turbine nozzles.

1.2.2 Nozzle Fouling

The nozzle fouling rate appears to be a function of the difference between the TIT and the dust melt temperature. At 1550°F a flow reduction of 25 percent occurred in 3.3 hr; at 1450°F a flow reduction of 8 percent occurred in 4.75 hr; and at 1250°F a flow reduction of 10.2 percent occurred in 7.0 hr. The bulk melting of the dust begins at 1550°F. Clearly the operating temperature is too near the dust melt temperature.

A-15638

Figure 1-1. Flow Reduction in Model SAS Tests

AIRESEARCH MANUFACTURING COMPANY

Velocity at the vane inlet was about 300 ft/sec, and velocity at the throat was about 2700 ft/sec. Using the bulk density of the powder (0.225 gm/cc), the maximum impact pressure range (assuming no elasticity) is 136 to 11,000 psi (actual particle density may be an order of magnitude greater). These potentially high impact pressures plus the stickiness due to the lower melting point temperature of various compounds or to eutectics in the dust could help cause the deposit/fouling problem found in the turbine.

In the heat exchanger tests, the deposits were light and fluffy on the hot side fin edge and were easily removed by an air lance in the plain fin configuration. The velocities were only 20 to 30 ft/sec, resulting in an impact pressure two orders of magnitude less than the vane entrance and four orders of magnitude less than in the nozzle vane throat, where the hardest deposits were found. Gas velocity thus appears to be a very important factor in the fouling deposition of the flue dust in the test range of 1250° to 1550°F.

Similar trends have been reported in the available literature. In the coal derived liquid fuel program (Reference 3), nozzle plugging rates of 3 to 14 percent per 100 hr occurred in large axial turbines at a 1950°F TIT with coal-doped fuel. In a PFB coal fired program (Reference 4), it was reported that the TIT should be approximately 400°F below the particulate melt temperature to avoid high nozzle fouling rates. Large axial turbines have lower work loading per stage; therefore, the gas acceleration is less than that of the radial inflow turbine. Since the lower acceleration rates of the axial machines should drop out less dust, the higher fouling rates experienced during this program are consistent with the results in the literature.

1.3 RECOMMENDATIONS

The following problems were identified as a result of the SAS test program:

- (a) For either the vaned or vaneless nozzle design, the fouling rates are unacceptably high, requiring some form of abrasive cleaning on a 2-to-10 times per 24-hr basis. The abrasive cleaning would add to the blade and vane erosion and is not an acceptable solution.
- (b) Erosion of blade tips is evident in test runs of less than 20 hr. Although studies have shown that the dust particle size and concentrations found in the glass furnace dust should not cause erosion, the agglomerated, sintered dust created is enough to cause erosion damage.
- (c) Test durations have not been long enough to cause corrosion damage; however, a thin coating of adherent dust did attach to the blades, and over a longer period of time, these deposits might have caused hot corrosion of the blade material. (The fouling problems outlined in (a) and (b) above precluded long time testing of the model SAS.)
- (d) Development of a gas conditioning device to remove the dust would be very difficult, since only a very small amount of the dust that flows through the system actually deposits on the nozzle and causes the high fouling rates experienced; therefore, a dust removal device

would have to be highly efficient. To be compatible with SAS operation, a high-temperature, low pressure drop device would have to be designed to contend with the stickiness of the dust. This would require a complex and costly development program with very high technical risks.

These problems coupled with the acid condensation found in the heat exchanger tests (Reference 5) present very severe problems to the development of the SAS concept. No additional SAS tests are planned. Testing will instead be directed toward evaluating the fouling and cleaning characteristics of a positive pressure heat exchanger. In the positive pressure system, only the heat exchanger is exposed to the furnace effluent. SAS heat exchanger test results indicate that if the cold side is elevated to approximately compressor discharge temperatures, cold end fouling and corrosion would not be a problem. These results will be confirmed by further heat exchanger tests.

2. SYSTEM DESCRIPTION

2.1 TEST SETUP

Figure 2-1 is a schematic of the SAS. A natural gas combustor with contaminant injector at the turbine inlet was used to simulate the actual flue gas environment.

The SAS model test setup used a modified T04B turbocharger and a heat exchanger (developed in the previous phase of the program) with appropriate manifolds and ducts in a single assembly. Figure 2-2 is a photograph of the assembly. The starter-ejector, used to start the SAS by initially drawing air through the turbine, was mounted directly on this assembly. When the turbine reached a self-sustaining speed, the ejector could be turned off. A heat exchanger cold-side fan, a lubrication cart, and an instrumentation console were also part of the test setup.

Facility air at approximately 60 lb/min was used to cool the expanded gas in the heat exchanger and prevent the aluminum compressor from overheating.

The bearing lubrication system was designed to provide up to 2 gpm of SAE 30 oil at 50 psig and 200° to 250°F. The lubrication system included a largeflow scavenge pump to provide suction at the sump to maintain the machine bearing cavity at a pressure below the subatmospheric compressor inlet pressure. The low bearing cavity pressure ensured that oil was not pumped into the gas path of the turbomachine.

The heat exchanger and manifolds (Figure 2-2) were used in the previous phase test program. The entry velocity at the design flow of 0.269 lb/sec was approximately 24 ft/sec, which is close to the planned velocity in the full-scale SAS. The unit was fabricated from 409 stainless steel with 5 fins per inch that are 0.145 in. high, 0.016 in. thick, and 0.178 in. offset. The heat exchanger was cleaned manually during testing.

A valve, installed between the compressor inlet and the discharge of the heat exchanger, was operated by the turbine speed control unit and was used to bleed air into the compressor inlet. As the turbine speed increased, the valve bled ambient air into the compressor inlet to increase the work of the compressor and to back pressure the turbine. This action maintained turbine speed at the desired level.

Figure 2-3 is a drawing of the modified turbocharger. The turbine scroll was replaced by a boilerplate torus to hold the IN-738 nozzle assembly (Figure 2-4). The turbine wheel is cast IN-792 (Figure 2-5). The shaft assembly has

79823-1

F-34850

Figure 2-2. Turbocharger and Heat Exchanger Assembly

AIRESEARCH MANUFACTURING COMPANY

Figure 2-3. Modified T04B Turbocompressor

Figure 2-4. Vaned Nozzle

Figure 2-5. Modified T04B Turbocompressor

F-34861

81-17949

Page 2-5

AIRESEARCH MANUFACTURING COMPANY

a carbon face seal incorporated at the compressor end to prevent oil leakage from the oil sump to the compressor.

A photograph of the test setup is shown in Figure 2-6.

2.2 TEST SYSTEM INSTRUMENTATION

Automatic data recording, turbine inlet gas temperature controls, and turbine speed controls were selected for use on the model test system in a manner consistent with industrial requirements and the operation of a full-sized system. In addition, system controls and safety shutdown operations were selected to ensure proper, safe system operation with minimal surveillance.

The instrumentation system for the model SAS measured the parameters shown in Table 2-1 and recorded most of the output in engineering units on printed paper using a data logger. The parameters were temperatures, pressures, turbo-compressor speed, and vibration level. The data logger sampled the data upon manual command or under programmed control; in the latter mode, it acquired data automatically with no need for monitoring. The system sensors were located in or near the test article, and the data logger subsystem was remotely located in a trailer.

2.2.1 Temperature Sensors

Chromel-alumel type K thermocouples were used to measure gas and air temperatures throughout the system. This type of thermocouple covered the complete range of test temperatures (70° to 2000°F+).

The measurement of gas temperatures at the turbine inlet required special techniques. The low velocity gas stream (approximately 25 ft/sec) and the significant difference between the gas and wall temperatures (approximately 200°F) would cause a standard unshielded thermocouple to give a low reading. There are two measurement approaches to handle this problem. The first is to use an aspirating thermocouple to increase the velocity at the point of measurement, thus increasing the convective energy input and reducing the radiation loss to an insignificant amount. The second is to use shielding to minimize the radiant heat loss from the thermocouple to the walls. By combining these two techniques in special shielded aspirated thermocouples, it was possible to obtain an accurate measurement.

2.2.2 Pressures

All pressures were measured as wall static. Three of the four recorded pressures were measured in terms of pounds per square inch absolute (psia), and the remaining one was the difference in pressure (psid) between the inlet and outlet plenums of the hot side of the heat exchanger. The wall static taps were of the proper geometry to provide a correct measurement but were provided with an enlarged hole size to preclude blockage caused by the simulated flue dust.

The sensors used were industrial grade process transducers. These transducers changed the pressure input to an electrical signal appropriate as an input to the data logger.

Figure 2-6. Model SAS Test Setup

2.2.3 Speed Measurement

The speed of the turbocompressor was measured by using a magnetized washer that rotated with the shaft in conjunction with a horseshoe shaped magnetic flux pickup coil.

2.3 DATA ACQUISITION

A 48-channel Kaye Digistrip recorder was used to log the parameters, to perform some data calculations, and to monitor several parameters for safety shutdown. The printout permitted rapid visual monitoring of data trends and were collected and stored for future reference. A typical printout is shown in Figure 2-7.

F-34848

AIRESEARCH MANUFACTURING COMPANY

TABLE 2-1
INSTRUMENTATION LIST

Facility Item	Data Logger		Description/Location	Parameter	Range	Accuracy Percent
	Item	Ident.				
1	101	Speed	Turbine speed	rpm/10	0 to 50,000	1
2	-	-	Calculated compressor outlet flow	W	0 to 20 lb/min	-
3	105	TBRN	Combustor outlet	T	0 to 2000°F	2
4	203	PT1	Turbine inlet	P	0 to 20 psia	2
5	113	TAMB	System inlet air	T	0 to 2000°F	2
6	201	TIT1	Turbine inlet	T	0 to 2000°F	2
7	202	TIT2	Turbine inlet (aspirating)	T	0 to 2000°F	2
8	306	TXINH3	Turbine exit	T	0 to 2000°F	2
9	-	-	Calculated dust injection rate	W	10 to 100 gm/hr	-
10	106 206	THXINH1 THXINH2	Heat exchanger, gas side inlet	T	0 to 2000°F	2
11	-	-	Heat exchanger gas side inlet	P	0 to 60 in. Hg.	1
12	107 108 109 207 208 209 307 308	THXOTH1 THXOTH4 THXOTH7 THXOTH2 THXOTH5 THXOTH8 THXOTH3 THXOTH6	Matrix across Heat exchanger Exit face	T	0 to 2000°F	2
13	103	PSCI	Compressor inlet	P	0 to 15 psia	2
14	204	DPHX	Heat exchanger hot side	ΔP	0 to 10 psid	2
15	-	-	Calculated cooling air to heat exchanger	W	0 to 100 lb/min	-
16	114	THXINC	Cooling air to heat exchanger	T	0 to 2000°F	2
17	-	-	Cooling air to heat exchanger	P	0 to 50 psia	2
18	304	THXOTC	Heat exchanger cooling side outlet	T	0 to 2000°F	2
19	302	TCIN	Compressor inlet	T	0 to 2000°F	2
20	112	TCPOT2	Compressor flow orifice	T	0 to 2000°F	2
21	301	TCOI	Compressor outlet	T	0 to 2000°F	2
22	102	PSCO	Compressor outlet	P	0 to 50 psia	2
23	-	-	Calculated compressor outlet orifice	W	0 to 20 lb/min	-
24	212	PORF	Compressor outlet orifice	P	0 to 50 psia	2
25	205	TOILIN	Bearing oil inlet	T	0 to 2000°F	2
26	-	-	Bearing oil inlet	P	0 to 100 psig	2
27	305	TOIOUT	Bearing oil outlet	T	0 to 2000°F	2
28	-	-	Bearing oil outlet	P	-30 to 0 in. Hg	1
29	-	-	Compressor housing accelerometer	V	0 to 50 g	5
30	312	DPSAS	Compressor outlet orifice	ΔP	0 to 100 in. H ₂ O	2
31	113	TAMB	Compressor speed control orifice	T	0 to 2000°F	2
32	213	PAMB	Compressor speed control orifice	P	0 to 30 psia	2
33	313	DPBLD	Compressor speed control orifice	ΔP	0 to 100 in. H ₂ O	2
34	-	-	Calculated compressor speed control orifice	W	0 to 4 lb/min	-
35	-	-	Cooling air to heat exchanger	ΔP	0 to 60 in. H ₂ O	2
36	104	RPC	Calculated compressor ratio (102 + 103)	-	-	-
37	-	-	SO ₂ flowmeter	W	0 to 500 liters/min	2
38	-	-	HCl/N ₂ flowmeter	W	0 to 10 liters/min	2
39	-	-	H ₂ SO ₄ flowmeter	W	0 to 50 cc/min	2

3400-250481-83-3801 BRAYTON CYCLE HEAT RECOVERY SYSTEM																
0108	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
100	SPEED	PSCD	PSCI	RPC	TBNR	THXINH1	THXOTH1	THXOTH4	THXOTH7			TCPDT2	TAMB	THXINC		
200	TIT1	TIT2	PTI	DPHX	TDILIN	THXINH2	THXOTH2	THXOTH5	THXOTH8			PDRF	PAMB			
300	TCOI	TCIN		THXOTC	TDICUT	THXINH3	THXOTH3	THXOTH6				DPAS5	DPBLD			
TIME																
08:50:07	12686 S	13.78P	4.91P	2.8065	1683.7F	OPEN F	68.1F	65.8F	70.8F			339.1F	56.9F	53.7F		
	1495.6F	1538.3F	14.75P	1.58P	216.6F	918.3F	70.4F	72.0F	70.8F			13.07P	14.69P			
	383.3F	68.6F		137.8F	250.1F	1133.2F	74.9F	71.9F				8.63P	2.91P			
08:55:08	12796 S	13.73P	4.92P	2.7967	1685.4F	OPEN F	68.0F	65.7F	70.2F			338.8F	57.3F	54.0F		
	1493.8F	1539.1F	14.76P	1.57P	223.6F	920.8F	70.3F	71.8F	71.5F			13.08P	14.69P			
	380.6F	68.3F		137.9F	256.8F	1132.1F	74.4F	71.4F				8.60P	3.08P			
09:05:00	12923 S	12.64P	4.76P	2.6555	1689.9F	OPEN F	66.9F	65.5F	69.3F			345.1F	57.7F	54.7F		
	1486.5F	1538.2F	14.78P	1.62P	237.3F	915.2F	69.4F	71.0F	70.5F			11.89P	14.69P			
	388.1F	67.6F		136.8F	268.7F	1121.2F	73.0F	70.6F				9.15P	3.21P			
09:09:07	12946 S	12.56P	4.70P	2.6723	1687.7F	OPEN F	66.9F	65.5F	68.2F			345.9F	57.9F	54.9F		
	1482.3F	1537.8F	14.78P	1.61P	240.7F	910.7F	69.4F	70.8F	70.5F			11.88P	14.69P			
	389.6F	67.7F		137.4F	271.6F	1119.7F	72.6F	70.2F				7.94P	2.83P			
09:15:00	12778 S	12.49P	4.70P	2.6574	1698.8F	OPEN F	67.1F	65.6F	68.5F			346.8F	58.6F	55.2F		
	1482.2F	1538.7F	14.79P	1.62P	245.5F	916.0F	69.5F	70.7F	70.5F			11.90P	14.69P			
	390.5F	67.7F		137.9F	276.0F	1117.3F	72.4F	70.0F				8.87P	2.55P			
09:25:00	13022 S	12.50P	4.67P	2.6767	1687.4F	OPEN F	67.1F	65.3F	69.1F			347.9F	59.3F	55.5F		
	1480.5F	1537.8F	14.83P	1.62P	251.1F	914.0F	69.6F	70.4F	69.7F			11.79P	14.69P			
	391.0F	68.0F		136.6F	280.9F	1111.0F	71.9F	70.0F				9.62P	2.60P			

Figure 2-7. Data Logger Output

2.4 CONTROLS

2.4.1 Turbine Inlet Gas Temperature

A thermocouple was used as the control feedback input for a three-mode (proportional, integral, derivative) controller that regulated the natural gas fuel feed valve to the combustor. A separate thermocouple was monitored by the data logger to initiate an alarm in the event of an overtemperature condition.

2.4.2 Turbine Speed Control

A controller was used to control the turbine speed. By regulating a valve to allow atmospheric air to bleed into the subatmospheric loop downstream of the heat exchanger, the load on the compressor acted as a brake on the turbine.

2.5 FLUE GAS SIMULATION

SAS testing was performed with simulated flue gas as discussed in Appendix A. The particulate injection rate was controlled using a modified AiResearch unit originally developed for sand and dust testing. The device uses a variable speed motor driving a dust laden belt under a fixed height gate. Dust moving past the gate is vacuumed into an injector and then flows to the inlet duct.

The gas contaminate simulation was accomplished by injecting SO_2 from a supply bottle and by injecting HCl plus an N_2 carrier gas from a second supply bottle into the hot gas duct upstream of the turbine. The two gases were added to approximate 200 ppm (wt) and 16 ppm (wt) at the design hot gas flow of 16 lb/min.

To obtain sulfur trioxide in the gas stream, a method of introducing and then evaporating a diluted sulfuric acid solution (0.1 weight percent) was developed. This method consisted of flowing the solution into the inlet duct through a cooled probe and then evaporating the acid in a ceramic dish located at the bottom of the duct. The calculated and measured acid dewpoint agreed to within 5°F .

The turbine inlet duct was a ceramic-lined atmospheric tunnel. The gas and solid contaminants were injected upstream of the turbine in a temperature zone that did not exceed 1650°F . At the design flow of 16 lb/min of combustion gases, the particulate injection rate was 0.19 lb/hr or 87 gm/hr. The gaseous flows were 0.19 lb/hr of SO_2 , 0.015 lb/hr of HCl , and 0.026 lb/hr of SO_3 .

3. TEST PROGRAM

The major objectives of the test program were to determine fouling, erosion, and corrosion on turbine components operating in a simulated flue gas environment with gas temperatures up to 1550°F. A modified Garrett T04B turbocharger was used to characterize the full-scale machine and was operated at a tip speed of 1780 ft/sec with a nozzle jet velocity of 2700 ft/sec, which is nearly identical to the values of the full-scale unit. The turbocharger was run at 130,000 rpm and at a maximum gas temperature of 1550°F. A heat exchanger from the test program of the previous phase was used. This heat exchanger contained offset fins and had a very high pressure drop (24 in. H₂O). Operating the turbomachine at the design pressure ratio (3:1), speed, and temperature required the compressor flow to be increased to prevent surge. This flow increase was accomplished by running the start ejector to reduce the compressor exit pressure. This lower exit pressure resulted in a lower compressor inlet pressure and a higher corrected flow, thereby moving the compressor operating point away from the surge line.

The test program was conducted in two series: (1) evaluation of turbine nozzle fouling and blade tip erosion using the higher efficiency, scaled, vaned nozzles; and (2) evaluation of fouling and flow reduction using a vaneless nozzle.

3.1 VANED NOZZLE TESTS

The baseline conditions used for Test 1 are summarized in Table 3-1. After 3.5 hr of running, the turbine flow had decreased 17 percent, from 15.0 to 12.5 lb/min (Figure 3-1). Temperatures at the dust injection point, turbine inlet, turbine outlet, and heat exchanger inlet are shown as a function of test duration in Figure 3-2. The system was shutdown after one hour to analyze the test data to ensure that the turbocompressor was operating properly. During the shutdown and restart, the turbine wheel and nozzles may have been wetted by the lubrication oil. It was suspected that the onset of nozzle throat plugging was related to the presence of oil. Disassembly and visual examination of the turbine nozzles after the test revealed fragile deposit layers on the stagnation side of the leading edge. As shown in Figure 3-3 and 3-4, there are discontinuities in the dust deposits that are likely caused by agglomerated particles breaking off into the high velocity gas stream. There are considerably more dust deposits at the nozzle leading edge stagnation point and on the suction side. The deposits in the throat area were hard.

In addition to the nozzle fouling, there were heavy deposits on the turbine wheel (Figure 3-5) and turbine shroud. The buildup on the shroud was periodically broken off by contact with the turbine blades. As the result of fouling and rubbing, dynamic instabilities of the machine occurred. The vibration measurement indicated a substantial change in the vibration level during the testing period; however, no evidence of bearing damage was found during the

TABLE 3-1

BASELINE TEST CONDITIONS

Turbine inlet temperature	1550°F
Turbine inlet pressure	14.7 psia
Turbine flow	15 lb/min
Turbine speed	130,000 rpm
Compressor pressure ratio	3.10:1
Maximum compressor outlet temperature	400°F
Flue Dust Contaminants:-	
Dust	200 ppm (wt)
SO ₂	200 ppm (wt)
HCL	16 ppm (wt)
SO ₃	10 ppm (vol)

● TEST 1

△ TEST 2

Figure 3-1. Model SAS Tests 1 and 2 Results

A-14845

AIRESEARCH MANUFACTURING COMPANY

Figure 3-2. Test 1 Temperatures

F-34016

Figure 3-3. Nozzle Fouling

AIRESEARCH MANUFACTURING COMPANY

84076-2

Figure 3-4. Nozzle Fouling

84119-3

Figure 3-5. Dust Deposits on Turbine Wheel

vaned nozzle tests. Erosion was also evident at the inlet blade tip (Figure 3-5). The disassembled unit was cleaned by a high-pressure water jet before the start of Test 2. Special care was taken to prevent oil contamination in the turbine by starting the oil lubrication system after the turbine was started.

Test 2 was the repeat of Test 1. The plugging and flow reduction characteristics were similar to the previous test (Figure 3-1). After 3.3 hr, the nozzle throat plugging resulted in a flow reduction of 25 percent. The nozzle fouling not only deteriorated the performance of the power turbine, but it also reduced the surge margin of the compressor. The measured dust injector temperature varied from 1650° to nearly 1800°F. The actual temperatures at the injector were probably 50°F higher because the measurements were made using a nonaspirating thermocouple; therefore, it was possible that the dust was partially melted when it impacted the nozzle assembly. Sintering of the dust had occurred as shown in Figure 3-4.

Test 3 was conducted with a 1450°F TIT to determine if the 100°F reduction in temperature would eliminate or reduce the nozzle fouling. In addition, the dust injection point was moved closer to the turbine so that the dust temperature would be lowered in order to reduce the potential for sintering. After 5.5 hr of running at this reduced temperature, the airflow had decreased from 16.25 to 15.75 lb/min (Figure 3-6). After disassembly, the nozzles again were found to have fouled, and erosion occurred at the turbine blade tips. Chemical analysis of the dust deposits showed heavy iron concentrations. The upstream ducting was disassembled and severe scaling was found on the inside wall with a layer of black iron oxide on the bottom of the duct. The outer insulation therefore was removed from the duct and a ceramic board insulation was attached to the inside walls to reduce metal temperature and prevent duct scaling.

Test 4 repeated the 1450°F turbine inlet conditions. Flow reduction and fouling again occurred (Figure 3-7); however, in the dust samples no iron was found on the nozzles or in the downstream ducts. There was some sintering of the dust collected from the nozzles, but it was less than that evidenced at the higher test temperature. A minor amount of erosion was evident.

Test 5 was conducted at a lower TIT (1250°F) to determine if at a minimum threshold temperature, the dust would no longer stick to the nozzle assembly. Nozzle fouling and a 10.2 percent flow reduction occurred (Figure 3-8). In all the tests, no more than 2 cu in. of dust was found deposited in the nozzle. This amount represents less than two percent of the dust that passed through the turbine; therefore, a small fraction of the dust in the gas stream reduced the flow by over ten percent in just a few hours. Since this problem was severe, a test was conducted using a turbine with a vaneless nozzle. A vaneless nozzle has a gradual transition section in the scroll to accelerate the gas from the low velocity at the scroll inlet to the high velocity required at the blades. Further, there is no specific leading edge and therefore no stagnation surface as on the vaned nozzle. This design minimizes the potential for fouling at the expense of aerodynamic efficiency.

3.2 VANELESS NOZZLE TESTS

Test 6 was an initial checkout test using a turbine scroll having an oversized nozzle area (the proper sized unit was not available). During a 24-hr

Figure 3-6. Test 3 Results

A-14846

Figure 3-7. Test 4 Results

A-14849

Figure 3-8. Test 5 Flow Reduction

test period, the turbine flow decreased 8 percent from 19.8 lb/min to 18.2 lb/min (Figure 3-9). Because the turbine was operated far from the design point, the turbine tip speed was only 65 percent of the design point and the pressure ratio was only 1.5:1. Post test inspection showed no significant deposits or plugging in the turbine nozzle area; however, there was dust buildup at the turbine scroll inlet and heavy deposits on the blades and shroud.

The flow reduction that occurred in Test 6 could be related to the fouling on the blades and the disturbance of the aerodynamic streamlines at the turbine inlet due to the dust buildup. There was no plugging in the scroll nozzle area and the fouling rate was lower. The test was terminated because the fouling rate was still too high for long term operation, and the operating point was so far from design limits that it could not be scaled to the full size machine.

In Test 7, a more representative nozzle was used that resulted in a pressure ratio of 2.5:1 and a turbine speed of 125,000 rpm. This SAS model test was conducted under simulated baseline conditions, which included a 1550°F TIT and a 200 ppm dust level. A flow reduction of 8.5 percent (17.5 lb/min to 16.0 lb/min) occurred in 10 hr (Figure 3-9). The machine was disassembled and the flow reduction was found to be caused by a large accumulation of sintered dust in the scroll (Figure 3-10). Pieces of the deposits (about 0.25 in. thick) are shown in Figure 3-11. In addition, heavy deposits were found on the turbine shroud (Figure 3-12), which caused dynamic unbalance of the rotating assemblies.

During an attempted restart after 10 hr of testing, a large piece of the sintered dust broke away from the main deposit and impacted the turbine wheel. The sudden impact at high speed (100,000 rpm) caused excessive loads that failed the turbine end bearing. Testing of the vaneless nozzle design therefore was terminated. The unit was disassembled and inspected. Again,

Figure 3-9. Test 6 and 7 Flow Reduction

erosion was evident (Figure 3-13) in the inlet blade tip area. The wheel shown in Figure 3-13 was used in Tests 4, 5, 6 and 7.

3.3 DUST DEPOSIT ANALYSIS

An extensive analysis was made of the flue gas dust from a glass container furnace (Appendix A). The dust obtained from an electrostatic precipitator at the stack (Sample 3 in Table 3-2) was used in the heat exchanger and turbo-compressor model test program. Sample 4 shown in Table 3-2 was obtained by trapping flue gas dust on a filter placed in the flue downstream of the reversal valve (Appendix B). In Table 3-2, the raw chemical analyses were normalized to the constituents listed in the table and adjusted so that the cumulative total of all constituents is 100 percent.

The major constituent (about 87 percent) was sodium sulfate, as expected. Other constituents in the 1- to 4-percent range were SiO_2 , CaO , MgO , Cr_2O_3 , K_2SO_4 , and Sn. The SiO_2 and CaO probably were carried through the furnace and checkers from the batch feed; the MgO and Cr_2O_3 probably came from the checker bricks; and the K_2SO_4 (like the Na_2SO_4) was from volatilization of the melt. The reason for the relatively large amount of tin found in the dust from the electrostatic precipitator is not known.

Figure 3-10. Dust Buildup at the Scroll Inlet

Figure 3-11. Sintered Dust Deposits

AIR RESEARCH MANUFACTURING COMPANY

81-17949
Page 3-14

84441-2

F-34754

Figure 3-12. Deposits on the Turbine Shroud

84842

F-34721

Figure 3-13. Turbine Blade Tip Erosion

AIRESEARCH MANUFACTURING COMPANY

TABLE 3-2
FLUE DUST ANALYSIS⁽¹⁾

Method	Initial Baseline Dust, Percent	Sample 3 ⁽²⁾ Electrostatic Precipitator, percent			Demonstration Site Sample 4, percent		
		Primarily by Atomic Absorption	Primarily Wet Chemistry	EDXA ⁽³⁾	Primarily by Atomic Absorption	EDXA ⁽³⁾	Single Particle EDXA
SiO ₂	11.4	1.87	2.80	2.72	<0.1	1.22	0.57
Al ₂ O ₃	9.2	0.038	<0.1	-	<0.02	-	-
Na ₂ O	30.6	38.1	38.89	21.48	38.45	20.50	0.70
K ₂ O	2.1	0.77	-	2.74	1.57	4.56	0.53
CaO	0.7	3.31	3.07	3.93	1.83	2.11	79.12
SO ₃	41.4	47.2	51.71	63.97	54.89	70.81	18.70
MgO	2.2	0.091	0.13	-	2.35	-	-
Fe ₂ O ₃	1.8	0.062	0.39	-	0.02	-	-
Cr ₂ O ₃	0.7	3.84	1.60	1.80	0.09	0.80	0.38
BaO	-	-	0.24	-	-	-	-
As ₂ O ₅	-	0.21	0.009	-	<0.2	-	-
B ₂ O ₃	-	0.19	0.007	-	0.009	-	-
Se	-	0.51	0.22	-	<0.002	-	-
Mo	-	-	0.02	-	-	-	-
Rb	-	-	0.02	-	-	-	-
Sn	-	2.0	0.98	3.35	<0.2	-	-
Cd	-	0.044	-	-	0.019	-	-
Zn	-	-	0.01	-	0.054	-	-
F	1.6 ppm	-	<2 ppm	-	<0.01	-	-
P	-	<1	-	-	<0.001	-	-
Cl	17.1 ppm	8 ppm	-	-	<0.1	-	-
H ₂ O	-	0.83	-	-	-	-	-
Cumulative Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

- (1) Weight percent or ppm (wt).
(2) Used in test program
(3) For reference only

Particles larger than a few microns were believed to be due to dust carryover from the batch feed. Confirmation of this was obtained from Sample 4 using an x-ray microprobe technique. A relatively large particle ($>10\text{ }\mu\text{m}$) was found in the sample; this particle was analyzed and found to contain 79 percent CaO (Table 3-2). In addition, scanning electron microscope (SEM) analysis and energy dispersive x-ray analysis (EDXA) of Sample 3 particles by ORNL found that the larger particles (2 to $7\text{ }\mu\text{m}$) were silicate glass or quartz (SiO_2). The smaller particles were found to be sodium sulfate (Type III) and minor amounts of alpha-quartz.

A differential thermal analysis (DTA) of the dust used for injection was made by ORNL. The DTA curve resembled phase transformation of impure materials or glass transitions. The DTA endothermic peak was not sharp but rather broad. Using the conventional method of defining the melting or transition point (intersection point of the tangent line at the onset of the peak with the peak), a 1550°F melting point was obtained (pure sodium sulfate melts at 1623°F). Using standard DTA conventions, softening occurred at 1391°F and complete melting occurred at 1638°F . In addition, there was a small endotherm at 1137°F .

About 5 percent of the injected dust (Sample 3 in Table 3-2) had a particle size less than $0.4\text{ }\mu\text{m}$. Transmission electron microscope (TEM) analysis of this dust by ORNL showed that 80.1 percent of the dust smaller than $0.4\text{ }\mu\text{m}$ were in the $0.058\text{--}0.163\text{ }\mu\text{m}$ size range. The ultrafine size of the sodium sulfate dust suggests a tendency toward sintering and, therefore, deposition near its melting point in the SAS turbine. The thermally activated sintering process of a compact powder is inversely proportional to the initial particle size and varies exponentially with temperature. In addition, the sintering process was probably further accelerated by other constituents in the dust and by the impact pressure.

Velocity at the vane inlet was about 300 ft/sec, and velocity at the throat was about 2700 ft/sec. Using the bulk density of the powder (0.225 gm/cc), the maximum impact pressure range (assuming no elasticity) is 136 to 11,000 psi (actual particle density may be an order of magnitude greater). These potentially high impact pressures plus the stickiness due to the lower melting point temperature of various compounds in the dust or to eutectics could help cause the deposit/fouling problem found in the turbine.

In the heat exchanger tests, the deposits were light and fluffy on the hot side fin edge and were easily removed by an air lance in the plain fin configuration. The velocities were only 20 to 30 ft/sec, resulting in an impact pressure two orders of magnitude less than in the vane entrance and four orders of magnitude less than in the nozzle vane throat, where the hardest deposits were found. Gas velocity thus appears to be a very important factor in fouling deposition in the flue dust in the test range of 1250° to 1550°F .

Direct observation of the melting behavior of the injected dust used in the SAS test was performed by ORNL using a hot-stage optical microscope. The temperature of the dust sample was raised from room temperature to 1760°F in about one hour. At 1110°F , the color of the dust changed to yellowish. It remained in an unsintered state up to 1470°F . At temperatures between 1470°F and 1500°F , sintering commenced. Sintering associated with dramatic shrinkages of agglomerates was obvious at 1510°F . Melting occurred at about 1540°F .

The sample mass was about 5 percent molten at 1560°F, 10 percent molten at 1620°F, and fully molten at 1650°F. The observed melting point (1540°F) agrees with that deduced from the DTA curve (1550°F).

Direct visual evidence of sintering of the dust was obtained by ORNL. The submicron particles of the dust used for injection into the test rig (Sample 3) were dispersed in xylene and analyzed with a TEM. As shown in Figure 3-14, the dust particles generally appear as small (in this photograph, 0.06 to 0.3 μm) individual spheres. After injection into the test setup, the dust that deposited on the nozzle in Test 3 (1450°F) was dispersed in xylene and also analyzed by TEM. Evidence of sintering and bonding between particles is clearly shown in Figure 3-15. In addition, the sintered particles are larger (0.2 to 0.9 μm) than the original dust particles.

Figure 3-14. Transmission Electron Micrograph (78,000 X)
of Original Dust Particles

F-33255

AIRESEARCH MANUFACTURING COMPANY

81-17949
Page 3-19

T-744

Figure 3-15. Transmission Electron Micrograph (58,500 X)
of Nozzle Deposit Dust

AIRESEARCH MANUFACTURING COMPANY

4. CONCLUSIONS

The model SAS test program has been completed with the following conclusions:

- (a) The T04B turbocharger used as a model turbine operated very close to the tip speed (1780 fps) and nozzle jet velocity (2700 fps) of the full-scale machine at the 1550°F design TIT; therefore, the dynamic simulation of the turbomachinery was successful.
- (b) The SAS test rig using injected furnace dust particles at 200 ppm loading and injected contaminant gases including SO₂ (200 ppm), HCl (16 ppm), and SO₃ (10 ppm) did simulate the flue gas from a glass-melting furnace.
- (c) The dust does not have a sharp melting point; softening occurs at 1391°F, melting starts at 1550°F, and melting is completed at 1638°F.
- (d) It was found that within the SAS turbine TIT range of 1250° to 1550°F, the particles have a tendency to sinter together, causing fouling and erosion of the turbine components.
- (e) The model test demonstrated that the fouling characteristics on turbine components results in rapid degradation of turbine performance, forcing the compressor into surge.
- (f) The deposit formed at the vaned nozzles was a fragile layer starting at the leading edge stagnation point, then building up on the stagnation side of the airfoil and decreasing in thickness in the throat area. A high-efficiency vaned nozzle design is not feasible for SAS operation due to the heavy nozzle fouling.
- (g) The test program verified that the vaneless nozzle turbine is not applicable for SAS operation. Turbine fouling and flow reduction problems remained due to the heavy dust buildup in the turbine scroll, and the more solid sintered dust could not pass through the turbine without causing damage.
- (h) The early study on turbine blade erosion based on information from the PFBC turbine tests suggested that SAS turbine blade erosion would not be a problem; however, the model test indicated that turbine blade erosion did occur after several hours of operation. It is believed that dust loading coupled with the sintering effects were responsible.

- (i) Separate testing to evaluate hot corrosion with long and short residence times was conducted using samples of IN-100 and IN-713LC (this test program will be documented in separate report). Results of this testing revealed that classical hot corrosion had occurred to depths of up to 0.010 in. after exposure to Na_2SO_4 at a 1400°F metal temperature for 45 hr. These results suggest that hot corrosion could occur on the blades and vanes of the SAS turbine.

5. REFERENCES

- (1) Brayton Cycle Heat Recovery System Characterization Program, Program Plan, AiResearch report 79-16411, Rev. 3, May 30, 1980.
- (2) Brayton Cycle Heat Recovery System Characterization Program, Sub-atmospheric System Test Plan, AiResearch report 80-17130, June 23, 1980.
- (3) High-Temperature Gas Turbine Engine Component Materials Testing Program - Monthly Progress report no. 26, Contract no. EX-76-C-01-1765, General Electric Company, Gas Turbine Division, Report FE-1765-36, September 14, 1977.
- (4) PFB Coal Fired Combined Cycle Development Program, Gas Cleanup Performance Requirements Report, Contract no. AC21-76ET10377, General Electric Company, Energy Systems Program Department, Report FE-2357-66, May 1980.

APPENDIX A
FLUE GAS EVALUATION

APPENDIX A

FLUE GAS EVALUATION

INTRODUCTION

A flue gas evaluation was conducted as part of program Subtask G1.3 (Gas Characterization Tests) and in support of the heat exchanger and turbocompressor test program. A preliminary flue gas characterization was conducted as part of program Subtask G1.1, Literature Search (Reference 1). This Appendix covers the following items:

- Initial baseline flue gas
- Flue dust samples used in the test program
- Demonstration furnace site flue gas analysis

INITIAL BASELINE FLUE GAS

As a result of the literature search (Reference 1), the initial baseline flue gas characterization was found as shown in Table 1. During a program coordination meeting at AiResearch on July 31, 1980 (Reference 2), the following baselines for the simulated flue gas for the AiResearch heat exchanger and turbocompressor model test program were agreed upon:

- (a) The dust collected from the demonstration site furnace would be used unless the analysis, which was being conducted, showed it to be unsuitable. A particle concentration of 200 ppm would be used.
- (b) Arsenic and boron would be added only if the gas analysis that was planned under program Subtask G1.3 showed it to be necessary. (The test, reported at the end of this Appendix, showed that an arsenic and boron addition was unnecessary.)
- (c) Contaminant gases should be controlled to the following values in the test gas:

SO ₂	200 ppm (wt)
HCl	16 ppm (wt)
HF	1.5 ppm (wt)
O ₂	5 percent (vol)

TABLE 1
INITIAL BASELINE FLUE GAS

Particulate concentration in gas stream: 200 ppm	
Particulate	
<u>Size, microns</u>	<u>Percentage</u>
Larger than 30	<1
30 to 10.7	1.7 to 3.4
10.7 to 3.1 k	4.3 to 8.6
3.1 to 0.3	94 to 86
Smaller than 0.3	<1
Particulate concentration in solid mixture	
<u>Constituent</u>	<u>Weight, percent</u>
SiO ₂	10.2
Al ₂ O ₃	8.3
Na ₂ SO ₄	63.0
K ₂ SO ₄	3.6
CaO	0.6
MgO	2.0
Fe ₂ O ₃	1.6
Cr ₂ O ₃	0.6
As ₂ O ₅	5.0
B ₂ O ₃	5.0
Vapors	
<u>Constituent</u>	<u>Parts per million, by wt in gas stream</u>
HCl	15.8
HF	1.5
CO	5.0
SO ₂	271
NO _x	375

* From Reference 1

During a later coordination meeting, these baselines were modified as follows:

- (a) HF was eliminated because of its low concentration and the problems associated with its use and control.
- (b) Oxygen was not controlled, since the effect of oxygen concentration in the range of interest was minor and would require an extensive modification of the test setup.
- (c) SO₃ at a level of 10 ppm (vol) was added to the list of contaminants when data became available on its level in the flue gas and its potential effect on the cold end of the heat exchanger.

TEST PROGRAM FLUE DUST SAMPLES

Dust samples used in the test program were collected from three different glass container plants:

- (a) The first sample was obtained from the flue duct floor at the reversing valve inlet. Only a small sample (insufficient for use in the test program) was obtained because the flue duct floor was below ground level and not readily accessible.
- (b) The second sample comprised a larger quantity of dust removed from the flue duct floor upstream of the reversing valve at the demonstration site furnace.
- (c) The third sample comprised a large quantity of flue dust obtained from an electrostatic precipitator at the stack of a third furnace.

Visual examination of the first two samples indicated that both samples were composed primarily of fine powder and clinkers. At 70X magnification, the clinkers appeared to be composed of fine powder particles sintered into a solid mass. The first flue dust sample was examined using emission spectroscopy to roughly determine the composition. No basic difference between the powder and clinkers was found. A more exact analysis was performed on the second and third samples; the results are shown in Table 2.

Samples 2 and 3 were examined for particle size. All sample 2 particles were larger than 100 μm ; therefore, this dust was unacceptable for use in the test. Two-thirds of the sample 3 particles were larger than 44 μm , and 94 percent were larger than 11 μm . The relatively large particle size of sample 3 dust was inconsistent with the method of collection. Prior experience with "in situ" furnace dust measurements showed that only particles smaller than about 10 μm will stay suspended in the flue gases beyond the checker exhaust; therefore, the electrostatic precipitator located in the stack should collect only fine particles. High-power electron microscope photographs showed the sample 3 dust to comprise clumps of submicron particles.

The Sample 3 dust agglomeration was believed to be due to water adsorption or low melting point constituents in the flue gas. A checkout test was conducted by injecting the dust into a 1170°F airstream in the test setup to determine if

TABLE 2
DUST ANALYSIS*

	Sample 1		Sample 2 As Received, percent	Sample 2 Sifted <320 Mesh Fines, percent	Sample 3 Electrostatic Precipitator, percent	Sample 4 Demonstration Site, percent	Initial Baseline Dust, percent
	Powder	Clinker					
SiO ₂	Low	Low	7.06	7.27	1.88	<0.1	10.2
Al ₂ O ₃	Trace	Trace	0.16	0.24	0.038	<0.2	8.3
Na ₂ O	Very high	Very high	18.3	24.1	38.4	39.3	27.5
K ₂ O	Moderate	Moderate	0.73	0.79	0.77	1.6	1.9
CaO	Moderate	Moderate	8.0	7.3	3.33	1.9	0.6
SO ₃	~41 percent	28 percent	35.6	40.2	47.5	56.1	37.2
MgO	Low	Low	1.42	2.57	0.091	2.4	2.0
Fe ₂ O ₃	Low	Low	13.9	5.28	0.062	0.02	1.6
Cr ₂ O ₃			0.92	2.10	3.84	0.09	0.6
As ₂ O ₅					0.21	<0.2	
B ₂ O ₃			0.02	0.045	0.19	0.09	
Se					0.51	<0.002	
Sn					2.0	<0.2	
Cd					0.044	0.019	
Zn						0.054	
F						<0.01	1.4 ppm
P			<1	<1	<1	<0.001	
Cl			80 ppm	80 ppm	8 ppm	<0.1	15.4 ppm
H ₂ O			0.13	0.16	0.84		
Acid Insoluble			12.8	8.27	Trace		
Cumulative total			87.2	91.1	100.7	102.2	

*Weight percent or ppm (wt)

the temperature would cause the particles to deagglomerate and to determine if the calculated injection rate device setting was satisfactory. The test was performed using an Andersen cascade impactor (Reference 3). The test showed that the particles do break up (Figure 1) satisfactorily simulating the dust found in the checker exhaust of an operational plant. In addition, the measured rate was 19 gm/hr compared with the calculated injector setting of 24 gm/hr. The measured rate is within experimental error. Since the dust size and chemical composition are in general agreement with the indicated values found during the literature search and with the dust obtained from the flue gas of the demonstration plant, dust sample 3 was selected for use in the AiResearch heat exchanger and turbocompressor model test program.

DEMONSTRATION FURNACE

An analysis of the flue gas at the demonstration site furnace was conducted on November 13, 1980. The test report from the analytical laboratory is included in Appendix B of this document. In addition to sampling and analyzing the solid and gaseous phases, oxygen and temperature measurements were made upstream and downstream of the reversal valve to obtain data on air in-leakage into the checkers and reversal valve.

The flue gas sampling location was in a flue duct between the reversing valve and stack; gas temperature at this point varied from about 835°F at the beginning of a checker cycle to 910°F at the end of the cycle. In addition to collecting solid material at the flue gas temperature and gases at the end of the sample train, a glass fiber filter was maintained at 160°F to collect any condensibles between 835°F and 160°F. No measurable condensibles were detected in the filter or in the washings from the probe located between the flue and glass fiber filter. The gaseous constituents found on a wet basis (i.e., including the water vapor in the flue gas) are shown in Table 3. Concentration of the particles in the flue gas was 95.4 ppm by weight, based on total flow (wet). The particle size distribution is shown in Figure 1.

As shown in Table 3, the gaseous contaminant levels used in the model tests, except for SO₃, closely agree with the levels found at the demonstration furnace site. For SO₃ the test level was over 12 times the measured value at the demonstration furnace.

A-10551-A

Figure A-1. Particle Size Distribution

AIRESEARCH MANUFACTURING COMPANY

TABLE 3
GASEOUS CONSTITUENTS

Constituent	Demonstration Site		Test Levels, ppm (wt)
	Volume	Weight	
SO ₂	104 ppm	231 ppm	200
SO ₃	0.8 ppm	2.2 ppm	27.6
NO _x	271 ppm	433 ppm*	--
HCl	10.8 ppm	13.7 ppm	16
HF	0.14 ppm	0.1 ppm	--
CO ₂	7.5 percent	11.5 percent	--
O ₂	9.3 percent	10.3 percent	--
CO	0.001 percent	0.001 percent	--

*As NO₂

REFERENCES

- (1) Brayton Cycle Heat Recovery System Characterization Program, Literature Search, AiResearch Report 80-16900, March 9, 1980
- (2) Program Coordination Meeting Minutes, AiResearch Memo No. 09312-25037-016, July 31, 1980.
- (3) Truesdail Laboratories, Inc., Report 34504, October 6, 1980.

APPENDIX B

TRUESDAIL LABORATORIES, INC. REPORT 34532

REPORT

TRUESDAIL LABORATORIES, INC.

CHEMISTS - MICROBIOLOGISTS - ENGINEERS
RESEARCH - DEVELOPMENT - TESTING

4101 N. FIGUEROA STREET
LOS ANGELES 90068
AREA CODE 213 • 228-1564
CABLE: TRUELABS

CLIENT AiResearch Manufacturing Company
 2525 West 190th Street
 Torrance, California 90509
 ATTENTION: Mr. Joe Ruder

SAMPLE Glass furnace emissions from a
 Demonstration Plant
 P. O. No: 418-110321-0

DATE January 9, 1981

RECEIVED October 14, 1980

LABORATORY NO. 34532

INVESTIGATION

Tests as indicated

RESULTS

On November 13, 1980, a representative of Truesdail Laboratories, Inc., collected flue gas samples from a Demonstration Glass Furnace exhaust. The samples were collected to determine the state and concentrations of the components existing in glass furnace exhaust gases at 900°F. An attempt to sample at a higher temperature was not possible due to the lack of sampling ports and short ducts. The flue gas samples were taken after the reverse valve in a duct between the valve and a stack.

The following tests were performed:

On site:

1. O₂ concentration in the ducts between the checkers and a reverse valve.
2. O₂ concentration at the sampling location (after the reverse valve).
3. Temperature difference before and after the reverse valve.
4. Particulate matter sample using glass fiber filter at the flue gas temperature (900°F).
5. Particulate matter sample using silver membrane filters at the flue gas temperature.
6. In both particulate matter trains the filters were followed by the glass fiber filter at 160°F, to collect particulate passing the hot filters. The impinger trains following the filters were set up to determine: SO₃, SO₂, HCl, HF.

A sampling train diagram is submitted in the appendix of this report.

This report applies only to the sample, or samples, investigated and is not necessarily indicative of the quality or condition of apparently identical or similar products. As a mutual protection to clients, the public and these Laboratories, this report is submitted and accepted for the exclusive use of the client to whom it is addressed and upon the condition that it is not to be used, in whole or in part, in any advertising or publicity matter without prior written authorization from these Laboratories.

AIRESEARCH MANUFACTURING COMPANY

81-17949

Page B-1

7. Particle size distribution was determined using Andersen Cascade impactors at the flue gas temperatures. The impinger solutions (following Andersen samplers) were used to determine HCl and HF concentrations.
8. Nitrogen oxides (NO_x) 4 grab sample flasks for each direction of firing. Determination by the Phenoldisulfonic acid (PDSA) method for NO_x and Orsat analysis for CO_2 and O_2 on the gas phase of each of the NO_x sample flasks. CO concentration was determined by gas chromatography.
9. The flue gas flow rate determination was not possible due to the location. The velocity measurements were made with an S-type Pitot tube at the sampling location, so that an isokinetic sampling rate could be calculated for particulate matter sampling.

Analysis:

The particulate matter collected on the Andersen impactor plates and on the hot filters were analyzed for constituents.

Practically all the hot collection was water soluble, therefore, the analysis was made using an atomic absorption technique for most of the elements. However, there were changes:

1. Boron (B) was determined by the curcumin method.
2. HF and F determinations were done by a specific ion sensitive electrode.
3. HCl (Cl^-) mercuric nitrate titration.
4. Phosphorus (as PO_4) by a molybdenum blue colorimetric method.
5. Soluble SiO_2 - colorimetric method.
6. Sulfate (SO_3) was determined by Ba^{++} titration.

The filters at 160°F (following the hot filters) did not collect any weighable amount of particulate.

The silver membrane filters in the flue gas were plugged quite rapidly.

The SO_3 (or sulfuric acid) was collected in the impinger following the filters. This impinger was charged with 80% isopropyl alcohol.

SO₂ gas was collected in the next two impingers following the isopropyl impinger. These two impingers were charged with 3% hydrogen peroxide to oxidize the SO₂ to sulfuric acid (H₂SO₄). The resulting acid was determined by a Ba⁺⁺ titration (EPA Method 8).

The Andersen impinger solutions contained water only. These solutions were analyzed for hydrochloric acid and hydrofluoric acid.

The analysis was checked also in regular filter collections. Isopropyl alcohol also contained a similar amount of both acids as the Andersen sampling train.

The results were as follows:

Oxygen (O₂) measurements on site using a Teledyne O₂ meter

Ahead of reversing valve

	<u>% O₂</u>	<u>Time</u>
North Duct		
North	5.8-6.0	0950
Middle	5.6-5.4	
South	7.8-8.0	0955
South Duct		
North	6.3	1000
Middle	5.3	----
South	6.7	----
Common Duct (After the reverse valve)		
North	11.0	1008
Middle	11.0	
South	10.5	

Temperature Measurements

Chromel-Alumel Thermocouple - Minimate

(1) After Rev. Valve, Sampling Point		
North Firing	890°F	
	903	
	910 (end of the cycle)	
South Firing	835°F	1035 am
	842	1037
South Duct	1145°F	1045
	1165	1051
Switch		1055

There appears to be a temperature drop across the valve of about 150°F due to the air dilution.

Particulate Matter

Filter at 900 - 910°F

Test No.

1

2

Testing Time: Start
Finish

1157
1254

1405
1430

Filter Material
Sample Collection, grams
Sample Volume, DSCF
Concentration, grains/DSCF

Glass fiber
0.0545
15.57
0.0540

Silver
0.0167
8.46
0.0521

Filter at 160 - 190°F

Sample Collection, grams

0.0001

0.0000

Water Vapor, % v/v

9.6

9.6

Gaseous Constituents (Dry) volume by volume

Sulfur oxides (SO_x):

Sulfur dioxide (SO₂), ppm
Sulfur Trioxide (SO₃), ppm

115
0.9

115
0.9

Nitrogen Oxides (NO_x), ppm

South Firing

North Firing

329
308
312
282
Average 308

272
277
317
303
292

Carbon Dioxide (CO₂), %
Oxygen (O₂), %
Carbon Monoxide (CO), %
Hydrochloric Acid (HCl)
Hydrofluoric Acid (HF)

8.2
10.3
<0.001
11.9
0.2

8.4
10.2
<0.001
12.0
0.1

Particle Size Distribution (by weight)
Andersen Impactors

Plate	Size, microns	Test #1			Test #2		
		Collection mg	%	Cum. %	Collection mg	%	Cum. %
1	>13.0	0.0	0.0	----	0.0	0.0	----
2	8.2	0.0	0.0	----	0.0	0.0	----
3	5.4	0.0	0.0	----	0.0	0.0	----
4	3.8	0.0	0.0	----	0.0	0.0	----
5	2.4	1.8	4.3	99.9	0.0	0.0	----
6	1.25	2.9	6.9	95.6	2.0	6.1	99.9
7	0.76	10.2	24.3	88.7	11.1	33.9	93.8
8	0.51	7.0	16.7	64.4	7.6	23.2	59.9
Back-Up Filter	0.1	20.0	47.7	47.7	12.0	36.7	36.7
Total		41.9	99.9	----	32.7	99.9	----

Sampling Time: Start	1059	1315
Finish	1132	1346

Firing Directions, North	1059 - 1114	1336 - 1346
South	1117 - 1132	1315 - 1330

Andersen Impactor, max. temp. °F	910	900
----------------------------------	-----	-----

Analysis of Particulate Matter

Water Insoluble: The glass fiber filter was extracted with water and then heated at 500°C (932°F) for 15 minutes, cooled and weighed. There was a loss in weight of 2.9 milligrams, which was equal to the blank filter treated the same way.

Water insoluble residue - none detected (less than 1%)

The water soluble portion was diluted to volume and analyzed for constituents. Also, the sample collected on Andersen sampler plates and back-up filter was extracted with water and analyzed for constituents. The results were as follows:

Sample Collection Mode	<u>Filter (Glass Fiber)</u>	<u>Andersen Impactor</u>
Sample Weight, milligrams	<u>54.5</u>	<u>33.1</u>
SO ₃ , %	55.8	56.1
Na ₂ O, %	39.4	39.3
K ₂ O, %	1.55	1.58
CaO, %	1.90	1.86
MgO, %	2.33	2.41
Al ₂ O ₃ , %	<0.02	<0.02
Fe ₂ O ₃ , %	<0.01	0.02
Cr ₂ O ₃ , %	0.12	0.09
As ₂ O ₅ , %	<0.2	<0.2
SiO ₂ , %	<0.1	<0.1
B ₂ O ₃ , %	0.02	0.09
Trace Elements:		
Sn	<0.2	<0.2
Se	<0.002	0.002
Cd	0.020	0.019
Zn	0.050	0.054
F ⁻	<0.01	<0.01
PO ₄ ⁼	<0.004	0.004
Cl ⁻	<0.1	<0.1

Discussion of the Results

It appears that the particulate matter collected is mostly sodium sulfate. The collections were placed in a desiccator while still hot, therefore, no water absorption was noted.

The silver membrane filter gave a blue tint to the collection. It is possible that HCl reacted with the silver, or there was enough molten sodium sulfate (possibly Na pyrosulfate) to react with a silver metal of this temperature. The unusually fast plugging of the filter indicated some kind of reaction.

The Andersen plate collections formed quite narrow cones under the orifices. The cones were harder than usually found in the collections made at the lower temperatures.

The absence of Se and As in the flue gas was also noted. Usually Se appears after the hot filter on cooler surfaces as a red deposit during the sampling (in the first impinger). No such occurrence was noted during sampling or later analysis. The impinger liquids were analyzed for As and Se by A. A. technique.

The residual samples of #2 Andersen sampler and one of silver filter collections are kept in a desiccator in case further questions would arise.

Respectfully submitted,

TRUESDAIL LABORATORIES, INC.

Ignas Bandziulis
Ignas Bandziulis, Supervisor
Air Pollution Testing

TRUESDAIL LABORATORIES, INC.

AiResearch Manufacturing Company

Laboratory No. 34532

APPENDIX

AIRESEARCH MANUFACTURING COMPANY

DATE :

Sampling Location: After Reversing valve.

Static Pressure, Ps: -1.2 /

Test No.: 7

Barometric Pressure: 29.9

[illegible]

A. AVERAGE VELOCITY (TRAVERSE) ft/sec _____

B. REFERENCE POINT VELOCITY (TRAVERSE) ft/sec _____

C. AVERAGE VELOCITY (REFERENCE PT.) ft/sec _____

D. FLUE FACTOR C/B _____

E. PITOT TUBE CORRECTION FACTOR 0.85

F. GAS DENSITY CORRECTION FACTOR 10

G. CORRECTED VELOCITY, $A_x E_x F$, ft/sec 20.0
or, $A_x D_x E_x F$, ft/sec

H. AREA OF FLUE, SQ. FT. _____

J. AVERAGE FLUE TEMPERATURE, °F 899

K. FLOW RATE, $G \times H \times 60$, CFM _____

$$L. \text{ FLOW RATE, K} \times \frac{520}{460 + J} \times \frac{BP + Ps/13.6}{29.9}, \text{ SCFM}$$

M. FLOW RATE, L x MOISTURE CORR., DSCTM

$$V = f \cdot 2.9 \cdot \sqrt{(460 + T_s) \times V_{II} \times \frac{29.9}{P_{II} + P_{ATM}}}$$

Lab. No. 34532

Test No. <u>1</u>	Filter Wt. After <u>0.3095</u> gm.	Date <u>Nov. 13, 80</u>
Sample Position <u>DUCT, AHEAD OF STACK</u>	Filter Wt. Before <u>0.2550</u> gm.	Filter No. <u>142</u>
	Weight Gain <u>0.0545</u> gm.	Barometric Pressure
		Inches Hg. <u>29.9</u>
		Static Pressure
		Inches H ₂ O

GLASS FIBER FILTERS

$$\begin{aligned} \text{Condensate: } & 0.00267 \times \frac{32}{29.9} \times \frac{533}{29.9} = \frac{1.52}{29.9} \text{ CF} \\ \text{Total Meter Volume} = & \frac{16.13}{29.9} + \frac{1.52}{29.9} = \frac{17.65}{29.9} \text{ CF} \\ \text{Meter Correction} & \frac{17.65}{29.9} \times \frac{520}{533} \times \frac{29.9}{29.9} = \frac{17.22}{29.9} \text{ SCF} \times 0.904 = \\ & \frac{15.57}{29.9} \text{ DSCF} \\ \text{Concentration} & \frac{0.0545 \text{ gm.} \times 15.43}{15.57 \text{ D.S. cu. ft.}} = \frac{0.0540}{15.57} \text{ Gr./SCFD} \end{aligned}$$
$$\text{Calculated Loss} = \frac{\text{Gr./SCF} \times \text{SCFM} \times 60}{7000} = \text{lbs./hr.}$$
[illegible]

AIRESEARCH MANUFACTURING COMPANY

81-17949
Page B-11

TRUESDAIL LABORATORIES, INC.

Sampling Station _____ Date 11-13-80

WATER VAPOR AND GAS DENSITY CALCULATIONS

Percent Water Vapor in Gases

A. Gas pressure at meter, In. Hg. (Absolute) 29.9

B. Vapor pressure of water at impinger temp., In. Hg. 0.248

C. Volume of metered gas, Cu. Ft. 16.13

D. Volume of water vapor metered, B X C/A, Cu. Ft. 0.13

E. Volume of water vapor condensed, Cu. Ft. 1.52

F. Total volume of water vapor in gas sample, D+E, Cu. Ft. 1.65

G. Total volume of gas sample, C+E, Cu. Ft. 17.22

H. Percent water vapor in sampled gas, 100 X F/G 9.6

Gas Density Correction Factor

Component	Volume Percent/100 x Moisture Correction x Mol. Wt. =	Wt./Mole Wet Basis
Water	1.0	18.0
Carbon Dioxide	Dry Basis	44.0
Carbon Monoxide	Dry Basis	28.0
Oxygen	Dry Basis	32.0
Nitrogen & Inerts	Dry Basis	28.2

Average Molecular Weight

J. Density of gas referred to air = $\frac{\text{Av. Mol. Wt.}}{28.95}$ = _____

K. Gas density correction factor = $\sqrt{\frac{1.00}{J}}$ = _____

AIRESEARCH MANUFACTURING COMPANY

Silver FILTER

PARTICULATE SAMPLING TRAIN DATA.

Date _____
Filter No. _____
Barometric Pressure _____
Inches Hg. _____
Static Pressure _____
Inches H₂O _____

$$\text{Meter Correction } \frac{8.86}{540} \times \frac{520}{29.9} \times \frac{29.9 - 0.25}{29.9} = \frac{8.46}{29.9} \text{ DSCF}$$
$$\text{Calculated Loss} = \frac{\text{Gr./SCF} \times \text{SCFM} \times 60}{7000} = \text{lbs/hr.}$$
[illegible]

*SAMPLING TRAIN
FOR PARTICULATES AND GASEOUS COMPONENTS*

1. STAINLESS STEEL PROBE
2. FILTER HOLDER IN AN OVEN WITH A DIAL THERMOMETER
3. HEAT GUN (FOR 160°F TO 190°F)
4. SMITH-GREENBURGH IMPINGERS IN AN ICE BATH
5. LEAKLESS VACUUM PUMP WITH TWO CONTROL VALVES
6. DRY GAS METER
7. DIAL THERMOMETER
8. ORIFICE WITH 2-INCH MAGNETIC GAUGE (FLOWMETER)
9. GELMAN FILTER HOLDER (STAINLESS STEEL) WITH A SAMPLING NOZZLE.

PARTICULATE MATTER SAMPLING TRAIN

DIAGRAM (ANDERSEN, PARTICLE SIZE DETERMINATION)

- 1 SAMPLING NOZZLE
- 2 ~~GELMAN FILTER HOLDER FOR GLASS FIBER FILTER~~ ANDERSEN IMPACTOR
- 3 SAMPLING PROBE
- 4 SMITH-GREENBURGH IMPINGERS IN AN ICE BATH
- 5 LEAKLESS VACUUM PUMP WITH TWO CONTROL VALVES
- 6 DIAL THERMOMETER
- 7 DRY GAS METER
- 8 ORIFICE WITH 2-INCH MAGNEHELIC DRAFT GAUGE (FLOWMETER)