100 HOUR TEST OF THE PRESSURIZED WOODCHIP-FIRED
GRAVEL BED COMBUSTOR

by

Kenneth W. Ragland and Danny J. Aerts
University of Wisconsin-Madison
Department of Mechanical Engineering
Madison, WI 53706

August 1994

prepared for:

THE U.S. DEPARTMENT OF ENERGY
Under contract No. DE-FG02-85E4073

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I. TEST OBJECTIVES AND TEST PLAN

In this project a downdraft, packed bed combustor for a gas turbine cogeneration system using woodchips is being developed. The combustor is designed to promote intense combustion in a thin reaction zone and to control particulate growth by using high excess air. The combustor contains a magnesia and alumina gravel bed on top of which woodchips are fed. Previous work on this combustor are reported in references [1, 2].

The following test objectives were established for the 100 hr test:

- a) demonstrate preliminary durability of the combustor
- b) demonstrate steady operation of the system
- c) investigate combustor pressure drop
- d) investigate bed ash cake buildup
- e) expose metal alloy coupons for corrosion examination
- f) obtain closure within 10% on mass and energy balances
- g) obtain emissions data

The plan for the 100 hr test was to operate the combustor at the following conditions: day 1, 4 atm(absolute) pressure and 700-800°C outlet temperature; day 2, 4 atm pressure and 800-900°C outlet temperature; day 3, 5 atm pressure and 800-900°C outlet temperature; days 4 and 5, repeat day 3. The inlet air was not preheated.

The 100 hr test was conducted during the week of June 1. The first shift worked from 7 am to 7 pm and consisted of Ken Ragland, Ted Frey, Oscar Ohlsson and Brett Jebens. Roger Cole replaced Jebens on days 4 and 5. The second shift worked from 7 pm to 7 am and consisted of Danny Aerts, Mark Bryden, Richard Wilkening and Bo Hoffmann-Jorgensen.

II. TEST SETUP

The gravel bed combustor, shown in Fig. 1, has a 42 cm i.d. and is made of 0.95 cm thick carbon steel (SA-53) lined with insulation and refractory. The combustor is in the shape of a tee, and stands 109 cm high and 91 cm long. The hot section of the combustor is lined with 7.3 cm thick Kricon 28XR refractory and 2.5 cm of Ceraform 143 insulation. The combustor outlet has a 18 cm i.d. and was connected to a 7.6 cm i.d. stainless steel ball valve with an Automax E1200 electric actuator. The woodchips were augered into the upper side wall of the combustor, and the compressed air was supplied from three 4.1 cm i.d. jets in the upper side wall. The air jets were adjusted to give good distribution of the woodchips on the bed. Programmable controllers were used to actuate the compressed air valve, and the exhaust valve.

The gravel bed was configured in the following manner. The top 2 cm were 7-10 mm magnesia chips (Pyro-Mag KF-98 from National Refractory). The next 9 cm was a wedge shaped mixture of magnesia chips and 25 mm alumina balls (T-162 tabular alumina from Coastal Chemical). Finally, 25 mm alumina balls were used in the horizontal section. A set of eleven 1.3 cm dia. alumina rods held the bed material in place.

Woodchips were fed to the combustor by a conveyor to a slidegate-lockhopper chamber with a 26 L volume. The lockhopper was operated intermittently and supplied a horizontal auger which operated continuously. Fuel level in the lockhopper was sensed sonically, and in the combustor the fuel level was sensed optically with a laser. A video camera was mounted above the combustor and viewed the fuel bed through a 7.5 cm diam. quartz window on the top flange. Since the combustion is below the surface of the fuel bed, the video camera provides an excellent view of the fuel surface.

Figure 1. Schematic of test setup.

Instrumentation included inlet air and combustor exhaust temperature, combustor pressure before and after the fuel and gravel bed, and air flow rate. All data was sampled and stored on a hard disk every 6 s. The feed rate of woodchips was determined with an optical tachometer which measured the rotation rate of the horizontal fuel auger. A calibration of woodchip flow versus auger speed was used. Also, the weight of the fuel hopper was measured continuously with a load cell, and this was used as a check on the horizontal auger data.

Flue gas was sampled continuously for oxygen, carbon dioxide, carbon monoxide, and nitrogen oxide using non-dispersive infra red equipment. The gas was chilled and filtered before the gas measurement equipment. Particulates samples were taken with a sampling train which had a small cyclone ahead of the filter. Schleicher and Schuell binderless glass fiber no. 30 filters were used. Aldehydes were measured with a separate sampling train following EPA BIF Method 0011 [ref. 3]. An exhaust gas sample was passed for 20 min through impingers containing a solution of dinitrophenyl-hydrazine (DNPH) and the liquid sample was analyzed by high performance liquid chromatography at the Wisconsin Occupational Health Laboratory.

III. TEST RESULTS AND DISCUSSION

A. Fuel Characterization

Twenty green tons of aspen chips were purchased from Magnum Timber Co. in Hixton, WI, and dried by Tenneson Shavings Co. in Cedar Grove, WI. The dried chips were transported to Madison in a closed van which was parked at the US Forest Products Lab. The chips were screened to remove fines which unfortunately had been introduced by the drier. The screened chips were stored in boxes at the Forest Products Lab for daily delivery to the Engineering Research Building. At the ERB the chips were transferred to 90 lb barrels and brought to the basement test lab.

The fuel was sampled from the hopper every 3 hr. The average moisture content of the aspen chips was 16.6 % (as-received basis), and the standard deviation was 0.85 %, based on 27 grab samples. The highest moisture was 17.7 % and the lowest was 13.2 %. Also, samples of chips were taken from the auger stream every 6 min for 1 hr starting at hour 83; the average moisture content was 14.7 % with a standard deviation of 0.98 %. During this time the highest moisture was 16.5 % and the lowest was 13.2 %. The proximate analysis, ultimate analysis, and heating value of the aspen woodchips are given in Table 1. The lower heating value is 7883 Btu/lb on a dry basis, and for 16.6 % moisture chips the lower heating value is 6400 Btu/lb. Based on the ultimate analysis, the stoichiometric air to fuel ratio by weight is 6.38 (dry basis). The size distribution of the woodchips is given in Fig. 2. Approximately 90 % of the woodchips were less than 19 mm.

Table 1. Proximate and ultimate analysis and heating value of aspen woodchips (dry basis) [ref. 4]

volatiles	85.12 %	carbon	51.57 %	higher heating value
fixed carbon	13.66	hydrogen	6.24	8496 Btu/lb
ash	0.72	nitrogen	0.47	lower heating value
		sulfur	0.02	7883 Btu/lb
		oxygen	39.52

Figure 2. Size distribution of the aspen woodchips.

B. Combustor Performance

The combustor was started up at 9 am on June 1 and was operated through 1 pm June 5, 1992, for a total of 100 hours. A total of 6.65 tons of woodchips was burned during the test, and the overall average burning rate of the 16.6 % moisture aspen chips was 160 lb/hr. During the 100 hour period the combustor was operating for a total of 83 hours and was shut down for 17 hours. There were seven shutdowns of one to three hours duration each. The on/off periods of combustor operation are summarized in Table 2. The feed system worked well and there were no hopper jams. The slide gates worked well; the seals jammed with chips several times and had to be cleaned, but this did not necessitate system shutdown.

During the first shutdown the top of the combustor was removed and the bed was inspected. The ash cake was hard in the middle and softer around the edges to a depth of 2 cm. Water spray nozzles and gas

sampling lines were cleaned. During the second shutdown a hole in the bed surface at the elbow edge approximately 5 cm diam. was observed and was filled with magnesia gravel. Approximately 2 cm of the ash cake on the top of the bed was broken up with a rod and removed. The third shutdown was required to repair the same hole with MgO. The fourth shutdown was required because of a fire in the lockhopper. At this time the exhaust valve was worked back and forth with a wrench, the temperature probe at the bed outlet was replaced, the exhaust water spray nozzles were cleaned, the bed ash cake was broken up and a small amount removed. A small amount of MgO was added to the same spot on the bed. The fifth shutdown was required because more woodchips had to be screened at the Forest Products Lab. The sixth shutdown was necessary because the exhaust valve would not open wide enough to maintain the pressure at 4 atm with the air flow required to keep the temperature 900°C. The exhaust valve also had become difficult to operate with the actuator. The exhaust valve was removed and inspected, and the actuator positioning which had slipped out of position was reset. There were no major deposits on the valve, and fine grit which impeded the motion was partially removed. During the seventh shutdown the actuator on the exhaust valve was removed, and the exhaust valve was operated by a wrench on the valve stem.

Table 2. Summary of combustor on/off periods.

day	status	time	hour	on	off	comments
1	on	9am-6pm	0-21	21 hr		
	off	6pm-9pm	21-24		3 hr	inspect bed and system
2	on	9pm-3am	24-42	18		
	off	3am-5am	42-44		2	add bed material
3	on	5am-12pm	44-51	7		
	off	12pm-2pm	51-53		2	add bed material
	on	2pm-1am	53-64	11		
	off	1am-4am	64-67		3	work exhaust valve
	on	4am-7am	67-70	3		
4	off	7am-10am	70-73		3	screen woodchips
	on	10am-3pm	73-78	5		
	off	3pm-6pm	78-81		3	work exhaust valve
	on	6pm-2am	81-89	8		
	off	2am-3am	89-90		1	remove exhaust actuator
5	on	3am-1pm	90-100	10		

The video camera monitor showed that the fuel feed was generally well distributed, and the fuel bed height was typically about 10 cm deep. There was little burn-through of the combustion in the bed except for two brief episodes of upset in the combustion. The first upset occurred at 7 hr-38 min into the test. Apparently a change in air flow allowed the flame to

move upstream. The video tape showed a swirl of smoke in the combustor and then a flame suddenly igniting above the fuel layer. The viewing window went dark from smoke and was not completely clear until 4 min later. Combustion seemed to be normal within one minute of the ignition. The second upset started at 88 hr-05 min into the test when the slide gate valves would not seal and wood flow to the combustor was stopped. The fuel bed level became very low and radiant heat apparently ignited some fuel in the screw feeder/air manifold area. At 88 hr-11 min fuel flow was restored and operation seemed normal, but 4 min later burning woodchips started falling on the bed, as seen on the video tape, causing a surge in burning rate. The upset lasted for 6 min, at which time the system was shut down to check the bed, clean the slide gate valve seats, and work on the exhaust valve. No damage was observed during the inspection.

Figure 3 shows the record of the combustor pressure, combustor outlet temperature, air flow rate, fuel flow rate and bed pressure drop over the duration of the test. A pressure of 4 atm (abs.) was maintained for 46 hours and then raised to 5 atm, as planned. The bed outlet temperature was increased gradually from 600°C to 800°C during the first day, and the combustor temperature fluctuated between 800°C and 900°C during the second day. The air flow was adjusted manually to control the temperature, and as the pressure increased the fuel burned faster, thus requiring more air. This in turn typically required opening the exhaust valve to maintain the pressure. As noted before [1,2] the combustor is sensitive to each adjustment and to possible changes in fuel properties. The bed pressure drop fluctuated with air flow rate, pressure, temperature, and the ash buildup in the bed. During the first 50 hours the pressure drop across the bed gradually built up to about 0.26 atm and did not increase much beyond that level.

During the last 50 hours the pressure had more fluctuations due to the increasing difficulty in operating the exhaust control valve. During the last 50 hours the exhaust thermocouple recorded higher temperatures and then began to fail. A blank data record signifies that this data was inadvertently lost after the test. Post-run inspection showed that the combustor outlet thermocouple and the gas sampling tube were both burned off to the wall. Difficulty in moving the exhaust valve and intermittent operation of the exhaust thermocouple made the system more difficult to run during the last 24 hours.

Figure 3. Combustor pressure, outlet temperature, air flow rate, fuel flow rate and bed pressure drop versus time.

C. Mass and Energy Balance

The mass balance was calculated on the basis of the carbon flow in equals carbon flow out. The carbon flow in was the fuel feed rate times the percent carbon in the fuel, which was 51.6 % on a dry basis. The fuel flow rate was obtained from the speed of the horizontal feed auger and the hopper weight. The carbon flow out was obtained from the air flow plus fuel flow times the weight percent of carbon in the exhaust CO_2 and CO after correcting for the water vapor in the flue gas. The particulate carbon in the exhaust had negligible mass and, as Table 7 shows, this generally represents less than 0.5% of the fuel. The carbon mass balance was done by averaging over selected time periods as shown in Table 3. The carbon output is high during the first part of the test and low during the latter part of the test. The lack of closure may be due to non-uniform CO_2 concentration in the exhaust.

Table 3. Summary of mass balance based on carbon.

TEST TIME hr	FUEL dry basis lbm/hr	AIR lbm/hr	CO_2 dry %	CO dry %	CARBON IN lbm/hr	CARBON OUT lbm/hr
1-7	99	1866	10.2	0.07	51	78
8-16	112	1833	8.7	0.14	58	67
17-20	106	1739	7.3	0.16	55	56
25-30	135	1948	11.6	0.06	70	94
32-42	137	2099	10.6	0.01	71	91
47-50	154	1449	5.1	0.11	79	54
55-60	163	2420	4.5	0.15	84	47
74-78	157	2272	8.2	0.06	81	78
83-87	134	2325	4.3	0.10	69	43
90-94	135	2486	3.2	0.12	70	36

The energy balance is a statement that the energy input to the combustor equals the energy loss through the walls of the combustor plus the energy output in the exhaust. The energy input was the fuel feed rate times the lower heating value of the as-received fuel. The inlet air temperature was typically 25°C ; the air preheater was not used. An infrared temperature gun was used to measure combustor metal surface temperatures every four hours at five locations. Metal temperatures above the combustion zone remained essentially at room temperature. The average surface temperature on the blind flange on the end of the combustor was 71°C and the surface area was 0.519 m^2 . The combustor section below the combustion zone averaged 93°C and the area was 1.361 m^2 . The outlet section averaged 248°C and the area was 0.738 m^2 . Total heat loss was the sum of surface radiation and convection losses. An emissivity of 0.2 was used, the convective heat transfer coefficient was

0.00424 W/m² K for the blind flange, 0.0431 W/m² K for the vertical section, and 0.00752 W/m² K for the horizontal section. The energy loss was calculated to be less than 1% of the energy input. The energy flow in the exhaust was determined from the air flow plus fuel flow times the sum of the mass fraction times enthalpy increase for CO₂, CO, H₂O, O₂ and N₂ in the exhaust. The energy balance was done by averaging over selected 1 hr time periods as shown in Table 4. The lack of closure may be due to non-uniform CO₂ and temperature in the exhaust stream.

Table 4. Summary of operating conditions and energy balance.

HOUR	FUEL lb/hr	AIR scfm	A/F	O ₂ wt%	CO ₂ wt%	TEMP °C	PRES atm (abs.)	POWER OUT kW	POWER IN kW	OUT IN
2.2	58.8	404.4	31.0	12.9	13.9	582	4.0	148	132	1.12
4.4	117.7	424.7	16.2	12.7	17.5	733	4.1	215	264	0.81
8.4	137.2	420.8	13.8	13.6	9.9	874	3.9	263	308	0.85
10.4	95.7	429.3	20.2	13.6	14.4	690	4.0	196	215	0.91
15.1	88.0	384.7	19.7	13.3	10.9	560	4.0	140	198	0.71
19.4	109.3	378.7	15.6	14.6	12.3	674	4.2	174	245	0.71
24.4	135.0	355.7	11.9	10.5	9.2	655	3.4	165	303	0.54
26.9	127.2	438.3	15.5	11.1	17.6	706	4.0	213	286	0.74
29.1	144.8	440.6	13.7	8.6	16.5	676	3.9	208	325	0.64
31.8	198.7	444.3	10.1	10.6	20.7	800	4.0	266	447	0.60
34.4	132.7	455.0	15.4	12.3	16.9	826	4.0	261	298	0.88
36.6	140.9	466.1	14.9	11.4	16.5	873	4.0	287	317	0.91
41.6	133.2	476.6	16.1	14.0	10.7	786	4.0	257	299	0.86
47.0	172.5	551.9	14.4	15.7	8.1	887	4.9	346	388	0.89
49.5	151.8	532.6	15.8	15.9	7.7	904	4.8	336	341	0.99
55.4	161.3	528.6	14.7	16.3	6.5	976	4.5	368	363	1.01
57.6	150.4	549.9	16.5	17.0	5.8	976	4.4	375	338	1.11
74.1	122.4	493.3	18.1	16.1	8.2	839	3.7	281	276	1.02
76.6	200.1	534.2	12.0	14.2	11.1	1092	4.8	436	451	0.97
82.4	152.1	471.1	13.9	14.5	11.1	995	4.0	338	343	0.98
86.6	120.9	522.2	19.4	17.4	6.2	944	4.0	337	273	1.23
91.1	115.5	561.0	21.9	18.9	2.8	984	3.3	374	261	1.43

D. Emissions

Carbon monoxide and nitric oxide concentrations at the combustor outlet were measured continuously and are summarized for a few selected hours in Table 5. Carbon monoxide concentrations should decrease with higher temperatures, but are high because of the short residence time. Nitrogen oxide concentrations are relatively low because of the low temperature and short residence time. Post-run inspection showed that the sampling probe had burned off to the wall, and hence the measurements are difficult to interpret. The lowest readings in the table may indicate nonuniform flow in the exhaust.

Three aldehyde samples were taken, and the results are shown in Table 6. The first two samples may not be accurate because some liquid carried over to the desiccant. The third sample showed 141 ppm of formaldehyde, 8 ppm of acetaldehyde and 8 ppm of acrolein. Wood burning spreader-stokers typically have formaldehyde emissions of 1 ppm and 0.1 ppm of acetaldehyde [8], and the aldehyde emissions increase when the CO increases. Thus the aldehyde emissions during the tests were high due to the relatively low temperatures and short residence time.

Exhaust particulate data were taken approximately every four hours. The particulate data taken during the first two days were not valid because a valve was not opened wide enough and the data was only 10 % to 15 % isokinetic. As indicated in Table 7, a * means that the cyclone catch was not recovered due to water in the cyclone. The last three runs are probably not representative of normal combustor operation. Excluding these three runs, the cyclone catch, which collects particles greater than approximately 10 microns, averaged 261 ppm. The filter catch, which represents particulate primarily less than 10 microns, averaged 118 ppm(wt) and 61 % of this was carbon. This is higher than the previous measurements [1] which averaged 44 microns.

Table 5. Summary of CO and NO emissions data for selected hours.

HOUR	TEMP °C	PRESS atm	CO ppm	NO ppm
2.2	582	4.0	966	20
4.4	733	4.1	682	142
8.4	873	3.9	1426	244
10.4	690	4.0	860	233
15.1	560	4.0	1925	190
19.4	674	4.2	13	193
24.4	655	3.4	1419	226
26.9	706	4.0	198	198
29.1	676	3.9	357	87
31.8	800	4.0	42	61
34.4	826	4.0	4	67
36.6	873	4.0	-	33
41.6	786	4.0	349	23
47.0	887	4.9	809	8
49.5	904	4.8	709	5
55.4	976	4.5	1402	12
57.6	976	4.4	1658	11
74.1	839	4.7	1575	69
76.6	1092	4.8	377	28
82.4	995	4.0	343	33
86.6	944	4.0	1012	22
91.1	984	3.3	1015	195

Table 6. Summary of aldehyde data [ref. 5].

SAMPLE	TIME	TOTAL	ISOKIN.	FORMALD.	ACETALD.	ACROLEIN
	hour	mg	%	ppm	ppm	ppm
1*	13.8	81	80.0	86.2	5.4	0.0
2*	36.4	28	75.3	20.6	0.0	3.5
3	62.6	204	71.6	140.6	7.6	7.9

* wet desiccant

Table 7. Summary of particulate data.

TEST	ISOK.	FILTER	CYCLONE	TOTAL	FILTER	TOTAL	CARBON	UNBURNED
TIME				MASS			MASS	FUEL
hour	%	mg	mg	mg	ppm	ppm	%	%
48.3	53	40	10	50	157	197	60	0.54
54.4	65	38	140	178	123	575	74	0.34
56.7	81	41	80	121	115	363	68	0.23
60.4	71	20	*	-	53	-	85	0.16
68.2	-	67	*	-	-	-	48	-
74.8	80	50	100	150	155	464	52	0.18
82.8	75	42	*	-	129	-	-	-
87.0	72	32	*	-	94	-	69	0.16
94.9	68	107	20	128	385	457	52	0.76
98.9	78	118	60	178	357	539	46	0.51

* water in cyclone

E. Pressure Drop Across the Bed

The extent of ash deposition in the bed is reflected by the pressure drop across the bed when the change in upstream pressure, temperature and flow rate have been factored out. Using the relations $\Delta p = K \rho V^2$, $FLOW = K \rho V$, and $\rho = p / (R \cdot T)$, then $K = p \Delta p / (FLOW^2 \cdot T)$. If there is no deposition then K should be a constant. Table 8 shows that K gradually increased during the first 50 hours and then decreased a little.

Table 8. Average bed pressure drop.

TIME	Δp	p	FLOW	T	K*
hr	atm	atm	kg/s	°C	
1-7	0.03	4.10	0.24	678	2.48
8-16	0.04	4.15	0.23	642	3.46
17-20	0.05	4.09	0.22	627	4.87
25-30	0.06	4.04	0.25	713	4.37
32-42	0.16	4.05	0.26	826	8.23
47-50	0.24	4.76	0.31	880	10.47
55-60	0.23	4.19	0.30	985	8.39
74-78	0.15	4.39	0.29	1021	6.06
83-87	0.17	4.35	0.29	925	7.37
90-94	0.23	3.64	0.31	935	7.05

* $K = 1000 \cdot p \Delta p / (FLOW^2 \cdot T)$

Several days after the test run was completed the combustor was disassembled and inspected. The back flange was pulled and the lower part of the bed was removed. Approximately the upper half of the bed was fused together to a depth of 25 cm. The center was fused more than the edges. A hole in the bed, which was small at the top of the bed and expanded to about 6 cm diam. inside the bed, had developed along the inner elbow. Several of the rods had broken. Cold flow of air showed that part of the air flowed through the bed and part flowed through the hole.

F. Composition of Ash and Deposits

Mineral analysis of the wood ash, deposits on top of the bed, deposits after the bed but before the exhaust valve, the cyclone ash, the filter particulate, and from the bed deposits are given in Table 9. The ash on top of the bed is primarily calcium, magnesium and manganese. The cyclone catch is rich in iron, probably from the sampling probe itself. The filtered particulate is rich in potassium, and, to a lesser extent, sulfur, boron, and sodium. The bed deposits reflect the substrate, and the strongest deposits have the highest amount of potassium.

Table 9. Mineral analysis of ash deposits (ppm, wt) [ref. 6]

#	P	K	Ca	Mg	S	Zn	B	Mn	Na
0	11800	112500	211700	35500	7000	3400	500	1400	600
1	<43	<124	5837	1128	308	<2	895	<1	434
2	4465	1017	379000	151000	3230	39	200	10300	185
3	1160	799	332000	22800	3890	2380	34	709	137
4	5000	440	81800	27000	2750	2580	552	6710	2070
5	1022	124000	79600	14010	12500	2220	11600	184	6570
6	2416	<60	74500	533000	788	569	75	2058	85
7	1520	606	127000	1530	1330	14	23	341	282
8	4510	4530	142000	63300	1360	108	22	2270	613

#	Fe	Cu	Al
0	2600	300	1400
1	125	<5	3156
2	43400	61	7400
3	1580	1500	2090
4	213000	3000	12200
5	2100	2770	46100
6	31800	203	7200
7	7130	18	243000
8	8720	104	43500

Sample

0. Aspen ash prepared at 600°C	5. Particulate filters, average of six samples
1. Blank filter	6. Bed ash between magnesia chips
2. Top of bed, average of six samples	7. Bed ash between alumina balls, flaked off

3. Deposits before exhaust valve
4. Cyclone catch, average of two
8. Bed ash between alumina balls, hard

G. Metal Coupons

The metal coupons were 12 mm diam. disks cut from turbine blade material (Mar M509 alloy, see Table 10) provided by Allison. The coupons were mounted on an inconel rod which was inserted into the combustor exhaust before the exhaust valve. One coupon was in place during the entire 100 hr and other coupons were inserted for 24 hr. The 100 hr coupon had a 47 mg deposit; the 0-24 hr coupon had a 43 mg deposit; 24-48 hr coupon had a 90 mg deposit; the 48-72 hr coupon had a 110 mg deposit and the last coupon came off and was lost. The elemental composition of the deposits (Table 11), which were measured by the electron microscope, show high amounts of potassium, sodium and sulfur. These numbers are from a 6 mm² area, and the values vary somewhat from area to area on the coupon. The deposits are rich in potassium and sodium, and have a significant amount of sulfur considering that wood ash contains only a small amount of sulfur. The enrichment factors between the ash and the deposits are potassium: $30/11.25 = 2.67$; sodium: $18/0.06 = 300$; and sulfur: $12/0.7 = 17$. The coupon which was exposed for 100 hr weighed 2.591 g initially and 2.525 g after the deposits were removed by soaking in water and also a 10% hydrochloric acid solution. Thus the weight loss was 2.5 % per 100 hr. Electron microphotographs of the coupon taken before and after the 100 hr deposits were removed, shown in Fig. 4, also indicate that some corrosion has occurred.

Table 10. Elemental composition of clean metal coupon [ref. 7].

Element	Wt. %
Co	57.0
Cr	21.5
Ni	10.0
W	7.0
Ta	3.5
C	0.6
Ti	0.2
Mn	0.1
Si	0.1
B	0.01

Table 11. Elemental composition of 100 hr deposits on coupon.

Element	Wt. %
K	30
Na	18
S	12
Mg	11
Si	11
Ca	10
Al	7.2
P	0.57
Fe	0.55

Blank Turbine Coupon

Figure 4. Electron microphotograph(x1000) of metal coupon (a) before test
b) after 100 hr exposure in combustor.

IV. CONCLUSIONS AND RECOMMENDATIONS

The combustor was operated for 83 hr during the 100 hr test period at pressures of 4 atm to 5 atm (absolute) and 700°C to 900°C. The average fuel burning rate was 73 kg/hr. The operation was fairly steady except for two brief burn-backs. The bed pressure drop reached 0.06 atm after the first day, 0.24 atm after the second day, and decreased after that, probably due to a hole which developed in the bed. The mass and energy balance closure was greater than 10 % probably due to non-uniform flow in the exhaust. Emissions of CO, NO aldehydes, and particulates were measured. The coupon exhibited a mass loss of 2.5 % per 100 hr.

Deposits in the bed were severe. Previously we had found that magnesia bed material was much less prone to deposit buildup than alumina. However the magnesia was more prone to thermal cracking, and thus we used magnesia for the first 10 cm of bed and then used alumina for the remainder of the bed. After about 24 hours the pressure drop began to build up more rapidly probably due to deposition to the alumina. This caused local hot spots to develop which exacerbated the deposition in the magnesia. Previously we had found that if the exhaust temperature was below 900°C, then an ash layer built up on top of the bed which remained relatively soft and could be broken up with a rod and removed during a brief shutdown. During these longer tests the ash layer became stronger and denser probably due to altered gas flow caused by the deposits on the alumina deeper in the bed. The main recommendation is that the alumina bed material should be replaced with magnesia bed material throughout the bed. Effort must be made to find a magnesia based refractory which is not prone to thermal cracking. Water cooled probes should be used for gas sampling and thermocouples.

ACKNOWLEDGEMENTS

This project was sponsored by the U.S. Department of Energy under grant DE-FG02-85CE40735. Steve Waslo of DOE was the Program Manager. Ramish Jain from DOE witnessed the test. Andrew Baker with the USDA Forest Products Laboratory helped to supply the woodchips. Richard Wenglarz at the Allison Division of General Motors supplied the coupons. Tom Marciniak and Roger Cole at Argonne National Laboratory helped to plan the tests. Many thanks to the other test operators.

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