Pulverized Coal Firing of Aluminum Melting Furnaces

MASTER

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Aluminum Company of America
Alcoa Laboratories
Alcoa Center, Pennsylvania 15069

Work Performed Under
Contract EM-78-C-01-4203

Quarterly Technical Report for
Period 1979 July 1 - September 30

1980 September

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PULVERIZED COAL FIRING OF ALUMINUM MELTING FURNACES

QUARTERLY TECHNICAL PROGRESS REPORT
FOR PERIOD 1979 JULY 01 - SEPTEMBER 30

CHARLES E. WEST

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ALCOA LABORATORIES
ALCOA CENTER, PA 15069

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DEPARTMENT OF ENERGY
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CONSERVATION AND SOLAR APPLICATIONS
DIVISION OF INDUSTRIAL ENERGY CONSERVATION
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FORWARD

This quarterly technical progress report is submitted in accordance with the requirements of Contract No. EM-78-C-01-4203, a 5-1/2 year cost sharing agreement between the Department of Energy and Alcoa. The report describes work performed in the first quarter of the second year of the program.

ABSTRACT

Phase I of the subject 5-1/2 year, two phase contract was started in May of 1978. At the end of the 6th Quarter, the program for Phase I is estimated to be 26% completed with 25% of the funding expended.

The ultimate objective of this program is the commercial demonstration of an efficient, environmentally acceptable coal firing process suitable for implementation on melting furnaces throughout the aluminum industry. To achieve this goal, the program has been divided into two phases.

- 1) Phase I has begun with the design and construction of a 350 pound (coal) per hour staged slagging cyclone combustor (SSCC) attached to a 7-ft diameter aluminum melting ladle furnace. Process development will culminate with a 1000 pph prototype SSCC firing a 40,000 pound capacity open hearth melting furnace at the Alcoa Laboratories.
- 2) Phase II implementation is currently planned for Alcoa's Lafayette, IN, Works, where two of the ingot plant's five open hearth melting furnaces will be converted to utilize coal. In addition to confirmation of data gathered in Phase I, the effect of extended production schedule operation on equipment and efficiencies will be determined. This work would begin in 1982 pursuant to technical and economic evaluation of the process development at that time.

DISCUSSION

Most activity this quarter focused on design and test tasks in the previous and now expanded subcontract with General Electric Space Science Laboratories. The technical highlight of the period is the evaluation of the qualification test run at General Electric on 1979 June 07 wherein combustion stability was obtained under strongly reducing (0.650) conditions. This test (the results of which are included as appendix A of this report) confirms the validity of the two stage combustor approach under development in this program.

Mechanical design continues both at Alcoa and at General Electric, and electrical control design will begin next quarter.

SUBCONTRACT EXTENSION - ADDITIONAL TASKS

As a result of ongoing relationships with General Electric Space Sciences Laboratories, it was deemed effective to broaden G.E.'s effort to include the following three additional tasks already within the scope of the Alcoa/DOE contract:

<u>Proposed Tasks</u>	<u>Objectives</u>	<u>Deliberables</u>
1. Pilot burner design	Engineering design of the pilot burner for the first stage combustor Detailed design of the pilot burner	Fabrication drawing Operation Specifications
2. 2nd Stage burner design	Engineering design of a burner to complete combustion of the coal-gas-fuel produced by the first stage burner Detailed design of the 2nd stage burner	Fabrication drawing Operations Specifications
3. Combustor test at GE under reducing conditions	Substoichiometric combustion test at GE test facility to determine flammability limits.	Test Plan Test Data Joint post test analyses with Alcoa

Tasks 1 and 2 are under way and will be reported in the next quarter. Task 3 has been completed and is reported in Appendix A of this report.

PROGRESS

Phase I - Research and Development

Task No. 1 - "Computer Modeling"

No additional work is contemplated in this area until actual combustion tests indicate the specific area where modeling will be advantageous.

Task No. 2 - "Design Burner A"

Design work has progressed on a cyclonic, slagging two-stage coal combustor with substoichiometric combustion in the first stage, the first prototype of which is called Burner "A". Alkali metal salt additives will be fed to the unit with up to 350 lb/hr of pulverized coal in order to suppress the slag fusion temperature and maximize sulfur capture in the molten slag.

Under the terms of a subcontract negotiated earlier in the contract, General Electric Space Science Laboratory agreed to provide the detailed design of the coal/gas injector and the conceptual design of the combustion unit, based on the successful operations of the GE/DOE closed cycle MHD coal combustor.

During the report period, the specified design work was completed by GE and transmitted to Alcoa; a cross-sectional view of the unit is shown in Figure 2.1. Detailed design for the combustion unit, including design of molds and mandrels for refractory installation, has progressed at Alcoa.

This task is 70% complete.

During the next quarter, the design of the combustion unit should be essentially completed.

Alcoa/GE 2-Stage Combustor-Cross Section

Figure 2.1

Task No. 5 - "Process Equipment Design and Layout"

Mechanical and electrical process design for the initial coal combustion pilot have continued. Revised process flow diagrams and equipment layout are shown in Figures 5.1, 5.2 and 5.3, respectively. The initial draft of the coal combustion unit process description is also included. The drawings and description are necessary because personnel from several divisions at Alcoa Technical Center are currently working on the project; they will be periodically updated as the design work progresses.

A review of applicable NFPA Codes and literature pertaining to pulverized coal handling and flame safety was completed during the report period. Several design modifications, including the use of N_2 to inert the atmosphere in the coal hopper and fluid bed mixer, reflect information obtained in the safety review. System safety considerations will again be reviewed following completion of this task.

Specifications have been established for several major equipment items, including the coal feeder and hopper and a combined cooling and combustion air blower. A blower of sufficient capacity (2100 scfm air at 15 psig outlet pressure) for the cooling air requirements of future burner prototypes will be purchased; the unit is of sufficient size to provide combustion air needs for the initial installation.

Electrical and instrumentation system design has progressed during the report period. The use of a Gould Modicon programmable controller for relay logic and PID control is presently being evaluated; indications are that its use would be cost effective and provide maximum flexibility.

This task is 55% complete.

In the next quarter, mechanical and electrical design work should be essentially completed.

A-306138-ED

ALUMINUM COMPANY OF AMERICA			
PRODUCTION EQUIPMENT LABORATORY			
PROCESS FLOW DIAGRAM			
MELTING FURNACE COAL COMBUSTOR			
PART 1			
DESIGNED BY	D. STEWART	CHECKED BY	S. GLOZIK
DATE	ED	DATE	ED
A-306138-ED

Figure 5.2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	5
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A-306494-ED

-11-

Figure 5.3

ALUMINUM COMPANY OF AMERICA PRODUCTION EQUIPMENT LABORATORY	
EQUIPMENT LAYOUT FOR MELTING FURNACE	
DESIGNED BY D. STEWART	CHECKED BY J. M. EDI
DATE 11-1-58	SCALE 1/4" = 1'-0"
A-306494-ED	

CONTROL VALVE SUMMARY

CV Name	Number	Fluid	Temperature °F		Flow, SCFM			Pressure, Psig	
			Min	Max	Min	Design	Max	Upstream	Downstream
Burner Air - Low Flow	FCV-1	Air	65	100	7	-	70	A.R.	1-2
Burner Air - High Flow	FCV-2	Air	65	100	45	-	450	A.R.	1-2
Gas - Low Flow	FCV-3	N.G.	60	85	0.75	-	7.50		1-2
Gas - High Flow	FCV-4	N.G.	60	85	4.2	-	42		1-2
Vert. Trans. N ₂ Flow	FCV-5	N ₂	60	85		10		A.R.	20-40
Coal Primary Air Flow	FCV-6	Air	60	85		33		A.R.	10-20
Cooling Air Flow	FCV-7	Air	65	100	100	320	550	5-15	Max.
Coal Secondary Air Flow	FCV-8	Air	600	1000	50	320	385	A.R.	1-2
Coal Tertiary Air Flow	FCV-9	Air	70	300	100	385	440	A.R.	1-2
D.I. Water Temperature	TCV-1	Water	135	180					
Tertiary Air Temperature	TCV-2	Air	65	100	100	385	440	A.R.	1-2
Air System Pressure	PCV-1	Air	90	225				5-15	Atmos.
Coal Air Pressure	PCV-2	Air	90	225	100	400	500	5-15	1-2
Gas Burner Air Pressure	PCV-3	Air	65	100	7	400	450	5-15	1-2
Cooling Air Back Pressure	PCV-4	Air	400	600	100	420	550	1-2	Atmos.
Air Trim Valve	PCV-5	Air	600	1000	50	400	150	ΔP ≈ 1 psi	

SOLENOID VALVE SUMMARY

Name	Number	Fluid	Max. Temp, °F	Max. Pres., psig	Size, In. (Phase I)	Size, In. (Phase II)	Type
Low Burner Air Shutoff Valve	SV-1	Air	100	2-3	1-1/2	3	
High Burner Air Shutoff Valve	SV-2	Air	100	2-3	4	8	
Low Gas Shutoff Valve	SV-3	N.G.	100	2-3	1/2	1	
High Gas Shutoff Valve	SV-4	N.G.	100	2-3	1-1/4	2-1/2	
Burner Vane Cooling Air Shutoff Valve	SV-5	Air	100	2-3	1/2	1/2	
Low Water Level Shutoff Valve	SV-6	Water	150	4			Pinch
Water Level Control Valve	SV-7	Water	150	4			Pinch
High Water Level Shutoff Valve	SV-8	Water	80	100			
Fixed Orifice Bypass Valve	SV-9	P.O.C.		1-2			
Emergency C.W. Inlet Valve	SV-10	Water	80	100			3-way
Emergency C.W. Drain Valve	SV-11	Water	180	100			3-way
Hot Tertiary Air Shutoff Valve	SV-12	Air	225	2-3			
Cold Tertiary Air Shutoff Valve	SV-13	Air	100	2-3			
Gas Safety Shutoff Valve	SV-14	N.G.	100	2-3	1-1/4	2-1/2	Safety
Gas Safety Shutoff Valve (#2)	SV-15	N.G.	100	2-3	1-1/4	2-1/2	
Gas Vent Valve	SV-16	N.G.	100	2-3	3/4	1-1/4	

PROCESS DESCRIPTION - COAL COMBUSTOR PILOT PLANT

The Alcoa/GE coal combustor is a two-stage, slagging cyclonic unit designed to direct fire an aluminum melting furnace at a rate of approximately 4.4 mm Btu/hr (300 lb coal/hr). The coal and an additive to trap sulfur compounds in the slag, is burned substoichiometrically in the first stage at 0.55 ϕ (55% of stoichiometric air) in the design case. Gaseous products leaving the first stage pass through a short analysis section and into the second stage, where sufficient air to complete combustion (total air = 10% excess) is injected. The hot ($>3000^{\circ}\text{F}$) products of combustion pass directly into a melting furnace, which will be a 7-foot diameter ladle for the first combustor (Burner A), and to the stack. In future tests, an energy cascading system, where hot gas leaving the melting furnace pass through a holding furnace, will be evaluated.

The pilot system consists of the following subsystems:

- 1) gas burner system
- 2) coal and additive feed system
- 3) coal combustion air system
- 4) cooling air system
- 5) slag handling system
- 6) deionized water cooling system

The gas burner system (Figure 5.2) is designed to control the flow of combustion air and natural gas to the combustor during startup operations, and is equipped with the mandated safety features. Air from the Schwitzer blower enters the burner system and is controlled through one of two flow control systems. For low flows (7-70 scfm), FCV-1 (enabled by SV-1) is used, while an equivalent, larger system (SV-2 and FCV-2) is used for higher flows (45-450 scfm). The duplicate system (primary flow element and control valve) is necessary because of the large design turndown ratio. A bypass around the automatic flow control systems, consisting of SV-5 and a manual valve and rotometer, allows a small air purge through the swirl valves when the natural gas system is off. A low pressure switch on inlet air and a prepurge rate flow signal on the high air rate system are interlocked through the flame control unit with the gas safety valving.

Natural gas enters the system from an upstream pressure regulator (not shown) through the required manual and dual vented safety valve system. Low and high pressure switches are interlocked through the flame safety control unit with the safety shutoff valving. As with the air system, a duplicate primary flow element/control valve system is required for flow control of gas to the burner. The low flow system, consisting of SV-3, FCV-3 and an appropriate flow element, is used to control from 0.75 to 7.50 scfm gas by ratio control with the low air flow (FCV-1 controller) system. High firing rates (4.2 - 42 scfm gas) are controlled (SV-4 and FCV-4) by ratio with the high air rate (FCV-2) system.

The firing rate, or BTU input, of the natural gas system as designed is entirely determined by reactant (gas and air) flow control. The downstream temperature will be monitored, but will not be a control variable. The final element in the gas burner safety system is a flame monitoring device (probably UV), which will shut the system down on loss of flame (5 second delay). In order to control flame shape and intensity at high firing rates, it may be necessary to inject part of the natural gas combustion air through the secondary air system (Figure 5.1). In this case, either the ratio control driving FCV-4 will be adjusted or the flow element used by the FCV-2 flow controller will be located immediately downstream of the air blower.

The coal and additive feed system is designed to safely transport 50-350 lb coal/hr and 3.5-25 lb additive/hr with primary air to the combustor. Approximately one ton of coal, which is sufficient for six hours of operation, will be batch pulverized in the existing Riley Stoker Co. Attrita coal pulverized at rates of 1000 - 4000 lb/hr. The pulverized coal (average particle size: 50 μ) will be transported to the cyclone above the coal hopper with about 60,000 scfh air, where 97-99% of the coal will be separated from the transport gas. The dust-laden air passes on to either a small filter baghouse for final dust removal or to a hot flue, where the remaining dust will be consumed.

The coal hopper, a Vibrascrew LBB-4-50 50 cu ft live bottom bin, will be suspended on a load cell in order to monitor charge and discharge rates. The hopper will be purged with N₂ at a low rate during charging and at a rate sufficient to inert the atmosphere in the vessel thereafter, as determined by an O₂ sensor and alarm in the head space. The types of coal to be utilized in the combustion experiments require inerting to ~15-17% O₂ to be non-explosive; the O₂ alarm set-point will be significantly lower to provide a large safety factor. The coal feeder, a Vibrascrew 2" screw feeder, is designed for accurate control of 90-900 lb coal/hr.

The additive hopper/feeder is an existing integral BIF Model 25-06 screw feeder with 3/4" screw. This unit will be manually charged with various additives from bags or small drums. Suspension from a load cell will provide indication of discharge rates.

During operation, coal and additive will be metered by the two screw feeders and transported by N₂ or gravity to the fluid bed mixer. The mixer is designed to thoroughly mix the solid components and provide a means of assuring a predictable constant feed to the combustor. The bed is fluidized with N₂, which passes overhead with transport N₂ to the baghouse for dust removal. Solids are conveyed vertically from the unit through two dip-tubes with N₂ flows controlled by FCV-5A and 5B. Downstream of the fluid bed mixer, primary air controlled by FCV-6A and 6B is injected at a design rate of 150 lb/hr into each of the lines, which then split into four 3/8" tubes to provide feed to the 8 combustor injection ports.

A Schwitzer Model 7108 Air Power Unit will provide up to 2100 scfm air at 15 psig (max) for the coal combustion and cooling air systems, in addition to the natural gas combustion air discussed previously. Excess air exiting the positive displacement compressor will be vented through PCV-1 in order to avoid over-pressurizing the air system. The pressure controller driving PCV-1 will be set slightly (<1 psig) above the highest downstream pressure requirement, which will normally be the cooling air system. Cooling air and natural gas combustion air at 200-225°F are cooled to <100°F in the air cooler, a water cooled shell-and-tube heat exchanger. Immediately downstream of the cooler, gas combustion air passes through PCV-3 (outlet pressure ~2 psig) and on to the burner system described above. Controls on the cooling air system are minimal: flow control with FCV-7 (100-550 scfm) on the cold air and back-pressure control at ~1 psig with PCV-4 on the hot air exiting the combustor. The temperature of air entering and exiting the unit is monitored; high temperature alarms on both will be provided.

Coal combustion air exiting the compressor passes through PCV-2 (outlet pressure ~2 psig) to the air heater, an electric resistance heater controlled on exit gas temperature. The unit is sufficiently large to preheat secondary air to 1000°F. Protection for the heater is provided by a low flow alarm on the inlet air and a high temperature shutdown switch on the last heating element. Flow of hot secondary air (50-382 scfm) to the combustor is controlled with FCV-8.

Flow of tertiary air, which is injected into the second stage is the combustor, is controlled with FCV-9 (100-440 scfm). The temperature of the tertiary air is controlled (Ambient-300°F) with ECV-2 by varying bypass flow around the heater. In order to provide good control, an air trim valve (PCV-5) is provided, which operates via a position controller in the control room.

The slag handling system (Figure 5.1) is designed to quench and filter slag leaving the first stage of the combustor. In order to keep the slag tap open, approximately 1% of the hot stage one gas exits through the tap and leaves the slag quench pipe near the top after a 180° flow reversal. The gas is cooled (jacketed pipe section) and passes through a fixed orifice which determines the flow rate to the stack. If the slag tap appears to be closing (visually determined by closed circuit television focused on the port), the amount of gas exiting via the tap can be increased by opening SV-9.

In the quench pipe, molten slag droplets fall into water which is maintained at depth of 15 to 25 inches. Water enters the unit through two tangential ports somewhat below the lowest water level. Water is fed at a constant rate through SV-8 (automatic shut-off valve), a manual flow control valve and a rotometer. Water and slag exit the pipe through SV-7, the water level control valve, and SV-6, the low level shutoff valve. The level is controlled by a control unit, equipped with high and low audible alarms. that opens SV-7 at the high control point and closes the valve at the low point. An additional high level switch closes SV-8 (inlet

water shut-off; automatic reset), while a low level switch closes SV-6 (outlet shut-off; manual reset). Water leaving the unit is screened and filtered for slag collection and analysis prior to entering the drain system.

The D.I. Water system (Figure 5.1) is a totally enclosed cooling water system for the injector and view ports. Water is pumped (100 gpm and 100 psig: design conditions) from the base of the D.I. water surge tank through a filter and heat exchanger to a manifold serving the cooling water users. The filter is a standard dual cartridge unit with 3-way valves to allow filter changes during operation. The temperature of the cooling water (135°F design) is controlled by TCV-1, which allows a variable bypass around the city water cooled shell-and-tube exchanger. Each of the D.I. cooling water users is equipped with a manual flow control valve, rotometer, and high temperature alarm (audible) on the outlet. Standard procedure will be to increase the flow to an area when the exit temperature becomes excessive. A low flow into the exit manifold from the inlet manifold is maintained by a manual flow control valve and pressure gauge. In case of cooling system failure, a time-delayed control system to start city water cooling with SV-10 and SV-11 (3-way valves) has been specified.

Task No. 7 - "Purchase Process Equipment"

Quotations have been solicited on major equipment items for which specifications (Task No. 5) have been established and purchase orders have been issued on some items.

This task is 25% complete.

As progress continues in the design phase of the project (Task No. 5), specified equipment will be purchased.

Task No. 8 - Fabricate Burner "A"

Quotations have been solicited on the coal/gas injector following receipt of the detailed drawings from General Electric Space Science Laboratory.

This task is 10% complete.

A purchase order for the injector unit will be issued following evaluation of vendor quotations.

STATUS REPORT ON PHASE I DATA DELIVERABLES

As of SEPT 30, 1979.

A. Theoretical Combustion Reactions

1. Provide Abstracts
2. Use CEP to investigate reactions
3. Bench Scale verification of (2)
4. Recommendations of Initial Test reaction.

COMPLETED	IN PROGRESS	NEXT QUARTER	NOT APPLICABLE
X			
X			
			X
X			

B. Design Burner "A"

1. Provide abstracts on important lit.refs.
2. Summarize mass & heat balance equations.
3. Provide schematic diagram of process.
4. Provide design dwgs. of key elements.
5. Specify range of fuel and additive compositions.

X			
X			
X			
X			
X			

C. Purchase Stack Gas Sampling Instrumentation

1. Obtain info & quotations from manufacturers.
2. Specify and select appropriate equipment.

X			
X			

D. Slag Chemistry Bench Scale investigation

1. Laboratory investigation
 - a) Literature search
 - b) Slag Development
2. Combustion Tests
3. Refractory Selection
 - a) Test for slag corrosion resistance - static
 - b) Test for slag corrosion resistance - dynamic

X			
X			
X			
X			

Status Report of Phase I Data Deliverables

E. Design Coal Handling Equipment

1. Coal and additive bunkers.
2. Conveyors.
3. Feeders.

COMPLETED	IN PROGRESS	NEXT QUARTER	NOT APPLICABLE
X			
X			
X			

F. Design Heat Recuperation Equipment

1. Calculate heat transfer potential.
2. Design furnace ducting.
3. Specify heat transfer device.
4. Design mechanical and electrical controls.

X			
X			
X			

G. Install Stack Gas Sampling Equipment, Coal Handling Equipment & Recuperation Equipment.

1. Specify site location and logistics.
2. Tabulate material flow specifications.
3. Tabulate hardware and materials items requisitioned.

H. Test Burner "A"

1. List combustion parameters to be monitored.
2. List operating conditions of tests.
3. Outline scope of test period showing expected test durations and milestones.
4. Tabulate results.

I. List additional design parameters to be investigated.

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J. Design Slag Handling System

1. Provide design drawings and specify materials.

--	--	--	--

Status Report on Phase I Data Deliverables

K. Test Burner "B"

1. List parameters to be monitored in addition to those from Burner "A".
2. List operating conditions for tests.
3. Outline scope of test period showing expected test durations and milestones.
4. Tabulate results.

COMPLETED	IN PROGRESS	NEXT QUARTER	NOT APPLICABLE

L. Design and Operate Burner "C"

1. Provide design drawing of the prototype combustor.
2. Specify all material to construction.
3. Outline scope of test period showing expected test durations and milestones.
4. Tabulate results.

M. Cast Ingot and Examine for Quality Assurance.

1. Extract bath samples and analyze composition to assess impact of contamination from coal combustion.
2. Cast product and monitor its quality through various fabrication processes.

AMENDMENT/MODIFICATION TO CONTRACT

To date, the following Amendment/Modifications have been issued by DOE:

<u>Amend/ Mod No.</u>	<u>Effective Date</u>	<u>Description</u>
A001	1979 Sept.25	<p>In order to increase the fund allotted for obligation from \$850,000, by \$560,000, to \$1,410,000, ARTICLE 3.2 - LIMITATION OF FUNDS is hereby deleted in its entirety and the following is substituted in lieu thereof:</p> <p>"Pursuant to Clause 3.2.4, Limitation of Funds, total funds in the amount of \$1,410,000 have been allotted for obligation and are available for payment of allowable costs to be incurred from the effective date of this contract through the period estimated to end September 30, 1978."</p>
A002	1979 March 19	<p>The purpose of this modification is to change the Contract Administration office noted in Block 6.</p> <p>DCASMA, Pittsburgh Attn: Contract Management Office 1610 S. Federal Bldg. 1000 Liberty Ave Pittsburgh, PA 15222</p> <p>All other terms and conditions of the contract remain unchanged.</p>
A003	1979 April 06	<p>In order to increase the fund allotted for obligation from \$1,410,000 by \$100,000 to \$1,510,000, ARTICLE 3.2 - LIMITATION OF FUNDS is hereby deleted in its entirety and the following is substituted in lieu thereof:</p> <p>"Pursuant to Clause 3.2.4, limitation of Funds, total funds in the amount of \$1,510,000 have been allotted for obligation and are available for payment of allowable costs to be incurred from the effective date of this contract through the period estimated to end September 30, 1979.</p>
A004	1979 Sept.29	<p>In order to increase the fund allotted for obligation from \$1,510,000 by \$1,700,000 to \$3,210,000. ARTICLE 3.2 - LIMITATION OF FUNDS is hereby deleted in its entirety and the following is substituted in lieu thereof:</p>

A004

1979 Sept 29

Cont'd

"Pursuant to Clause 3.2.4, limitation of Funds, total funds in the amount of \$3,210,000 have been allotted for obligation and are available for payment of allowable costs to be incurred from the effective date of this contract through the period estimated to end September 30, 1980.

COST SUMMARY

During this quarter, expenditures totaled \$161,021. Cumulative spending to date is \$484,006. This expenditure rate is below the projected rate but is expected to increase at a more rapid rate when fabrication, purchase and construction costs occur over the next several months.

JOINT ALCOA/GE COAL GASIFICATION TEST

SUBMITTED: SEPTEMBER 10, 1979

CONTRACT No.: TC 621001TC

TO: Dr. C. E. West
Ingot Casting Division
Alcoa Laboratories
Aluminum Company of America
Alcoa Center, PA 15069

FROM: Dr. S. Omori
Dr. E. S. Fleming
Mr. K. Dickinson
MHD Programs Section
General Electric Space Sciences Laboratory
King of Prussia, PA 19406

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SECTION I. GENERAL DESCRIPTION OF COAL GASIFICATION TEST

As a preliminary investigation of Alcoa's coal gasification program, an Alcoa/GE joint test was conducted at the General Electric coal combustor test facility on June 7, 1979. Although the General Electric Space Sciences Laboratory's coal combustor was originally developed as a heat source for a Closed Cycle MHD system utilizing a single stage, excess air, and having approximately 60 msec gas residence time, the combustor could be operated under quite different conditions.

The combustor, shown in Figure 1, is an air cooled cyclone coal combustor with axial swirl injection of pulverized coal and combustion air. The combustor inner diameter is 12 inches and the inner length is 24 inches. The normal operating conditions of the combustor for the MHD system include a coal feed rate of 90 lbm/hr, combustion air of 900 lbm/hr, combustion pressure of 2 psig, and a preheated secondary air temperature of 1050 F. As Figure 1 shows, dried, pulverized coal is injected with primary air into the combustor through eight axial swirl injection ports at room temperature. The preheated secondary air enters the combustor through the secondary air swirl vanes at high velocity, creating a high cyclonic flow field that centrifuges the coal and ash particles. The coal combustion takes place mainly on or in the vicinity of the slagging wall. The molten slag average temperature and viscosity are controlled by the cooling air flow rate.

In order to retain these combustion characteristics, it is important to maintain the high cyclonic flow field even for off-design operating conditions such as reducing or substoichiometric operation. Therefore, it was decided for the test that the secondary air temperature and flow rate would be at normal operating values, while the coal feed rate would be increased to meet the specified test condition of 0.65 ϕ .

For efficient coal gasification, a longer gas residence time is generally required than for single staged, excess air coal combustion. For example, compared with the GE combustor's nominal gas residence time of 60 msec for excess air combustion, Alcoa's bench scale gasifier has been designed to allow approximately 300 msec gas residence time at a 0.55 ϕ operating condition.

Whether the residence time in the GE combustor was enough for efficient gasification was not of prime importance. Of major importance was whether a stable flame with partial gasification at 0.65 ϕ could be obtained based on the GE cyclone concept. The test results indicated a very stable flame and confirmed the validity of adopting the GE Cyclone concept to the Alcoa bench scale gasifier.

Although the pulverized coal was sieved before loading into the two pressurized coal feed tanks, to remove large pieces which might cause blockage of the coal feed lines, unfortunately two small strip pieces caused trouble on two occasions during the test by blocking the coal lines. The first time, by depressurizing the appropriate coal feed tank in order to purge the plugged line, we could resume the scheduled test. But shortly thereafter the other feed tank exhibited the same problem. However, we were able to continue the test by using only one of the feed tanks and obtained the 0.65 ϕ reducing condition for approximately 30 minutes.

At the end of this period we accidentally lost the shop air which supplied pressure for valve controls because of shop air compressor failure. Although efforts were made to continue the test by manual operation of the valves, a significant increase in the sulfur-containing product gases escaping from the combustor into the laboratory forced a shutdown.

In spite of the somewhat limited 30 minute reducing condition test, the

main objectives of the test were well accomplished as the details in Sections II and III show. That is:

1. The 0.65 Ø condition was tested at 2 psig.
2. Combustion/gasification was stable.
3. Gas sampling and analyses were made. *6 Samples*
4. All required data were reduced and analyzed.
5. Carbon conversion rates of approximately 80% were obtained in spite of the short gas residence time. *60% see*
6. Measured gas compositions agree with CCE results.
7. Gasification temperature estimated is approximately 3400 F.

REGENERATIVELY AIR COOLED COAL COMBUSTOR

Figure 1. GE Regeneratively Air Cooled Coal Combustor Developed for MHD

SECTION II. GASIFIER PRODUCT ANALYSIS* OF ALCOA/GE JOINT TEST

1. Introduction

As a preliminary simulation test of the Alcoa slagging coal gasifier the General Electric Cyclone Combustor was fired substoichiometrically with fuel enthalpy inputs up to 1.66×10^6 Btu/hr (139 lb/hr of Illinois #6 pulverized coal) with 744 K (880 F) air preheat. The coal composition and screen analysis are presented in Tables 1 and 2 while the coal ash analysis is on Table 3. The resultant hot, product gas stream, which contains unburnt fuel, would then be fired on a second stage with sufficient air to complete combustion. The incoming stream at the second stage should be relatively ash free and desulfurized to permit use in Alcoa's aluminum remelting furnaces without harmful effects on the process and without violating EPA emissions standards.

2. Results and Discussion

During the combustion tests six first-stage product gas samples were extracted at different times during the run by allowing the 2 psig gas to expand into six evacuated stainless steel lecture bottles. These samples were later analyzed on a dry basis by gas chromatography and detector tube colorimetry. The results of these analyses as well as the actual heat pick-up by the combustor cooling air are given in Table 4. Samples 2 and 3 were apparently diluted by air leakage into the sample bottles, thereby giving

* By E. S. Fleming

TESTER WHEELER DEVELOPMENT CORPORATION

FUEL ANALYSIS

SAMPLE DESCRIPTION Coal, Freeburg, Ill., River Wing Mines, Ill. No.6

CHARGE NO. 9-61-5521 DATE 6-11-79 LAB. REF. NO. 79-0695

AIR DRY LOSS, % 5.72 EQUILIBRIUM MOISTURE, %

	AS REC'D	DRY
FIXED CARBON	41.54	47.24
VL. MATTER	35.30	40.13
ASH	11.11	12.63
MOISTURE	12.05	---
TOTAL	100.00	100.00

CARBON	59.40	67.54
HYDROGEN	4.59	5.22
CHLORINE	8.53	9.70
NITROGEN	0.84	0.95
SULFUR	3.48	3.96
ASH	11.11	12.63
MOISTURE	12.05	---
TOTAL	100.00	---

H.H.V., BTU/LB	10,670	12,132
SULFATE S	0.02	0.02
PYRITIC S	1.19	1.35
ORGANIC S	2.27	2.59

REACTIVITY INDEX, °C

ACTIVATION ENERGY, CAL/G-MOL

HARDGROVE INDEX

FREE SWELLING INDEX

SPECIFIC GRAVITY

VISCOSITY

ASH FUSION TEMPERATURE, °F

	RED.	OXID.
INITIAL DEFORM.	2060	2340
SOFT. TEMP. SPH.	2200	2460
SOFT. TEMP. HEM.	2240	2520
FLUID TEMP.	2340	2620

REMARKS: B. P.

Table 1. Illinois #6 Coal Analysis

Alfred Forrester
ANALYTICAL LABORATORY

Screen Analysis

TO: <u>J. Rickenbach</u>	DATE <u>7/24/79</u>	CHARGE NO. <u>9-61-5549</u>	LAB. REF. NO.
--------------------------	------------------------	--------------------------------	---------------

SAMPLE DESCRIPTION:

SAMPLE DESCRIPTION	RUN 11 COAL PRIMARY SAMPLE		RUN 11 COAL SECONDARY SAMPLE					
SAMPLE #	790942		790943					
SCREEN	% on	% thru	% on	% thru	% on	% thru	% on	% thru
3" Round								
2-1/2" "	MOISTURE		MOISTURE					
2" "	1.31	%	1.35	%				
1-1/2" "								
1-1/4" "								
1" "								
3/4" "								
1/2" "								
3/8" "								
No. 4 square (4.76mm)								
No. 6 square (3.35mm)								
No. 8 square (2.38mm)								
No. 10 square (1.70mm)								
No. 14 square (1.40mm)		100.00						
No. 16 square (1.19mm)	0.01	99.99						
No. 18 square (1.00 mm)	0.01	99.98						
No. 20 square (850μ)	0.01	99.97						
No. 25 square (710μ)	0.05	99.92						
No. 30 square (595μ)	0.10	99.82						
No. 50 square (297μ)	1.94	97.88						
No. 60 square (250μ)	14.88	83.00						
No. 70 square (210μ)	14.73	68.27						
No. 80 square (175μ)	18.31	49.96						
No. 100 square (149μ)	30.95	19.01						

Analyst J.S.

Supervisor MMF / d

MMF/af

Table 2. Coal Screen and Moisture Analysis

M.M. Fornoff
ANALYTICAL LABORATORIES

FOSTER WHEELER DEVELOPMENT CORPORATION

J. Rickenbach (G.E.)

ASH/DEPOSIT ANALYSIS

SAMPLE DESCRIPTION Coal from Freeburg Ill. River King Mines

CHARGE NO. 9-61-5521

DATE 6/14/79

LAB. REF. NO. 790695

ANALYTE	AS ELEMENT	X FACTOR	OXIDE	ANALYT. METHOD
SILICON	SI	2.140	SiO ₂ 52.8	X-Ray
ALUMINUM	AL	1.090	Al ₂ O ₃ 19.5	X-Ray
TITANIUM	TI	1.668	TiO ₂ 1.0	X-Ray
IRON	FE	1.430	Fe ₂ O ₃ 14.8	X-Ray
CALCIUM	CA	1.399	CaO 4.1	X-Ray
MAGNESIUM	MG	1.658	MgO 1.2	X-Ray
SODIUM	NA	1.348	Na ₂ O 0.9	X-Ray
POTASSIUM	K	1.205	K ₂ O 2.1	X-Ray
SULFUR	S	2.500	SO ₂ 2.4	X-Ray
PHOSPHORUS	P	2.291	P ₂ O ₅ 0.2	X-Ray
MANGANESE	MN	1.583	MnO ₂	
NICKEL	NI	1.273	NiO	
VANADIUM	V	1.785	V ₂ O ₅	
CHROMIUM	CR	1.461	Cr ₂ O ₃	
MOLYBDENUM	MO	1.500	MoO ₃	
ZINC	ZN	1.245	ZnO	
LEAD	PB	1.077	PbO	
TIN	SN	1.270	SnO ₂	
COPPER	CU	1.252	CuO	
SILVER	AG	1.074	Ag ₂ O	
ANTIMONY	SB	1.197	Sb ₂ O ₃	
[CHLORIDE]	CL	1.0	CL	

REMARKS:

Table 3. Coal Ash Analysis

Table 4. Results of Gasifier Product Analysis

SAMPLE NO.	EQUIVALENCE* RATIO, ϕ	GAS SPECIES							HEAT TRANSFER TO COOLING AIR % of HHV
		CO ₂	CO %, DRY	H ₂	N ₂	H ₂ S	COS PPM	SO ₂	
1	0.94	17.0	1.2	1.3	80.5	< 5	Trace	17	6.45
2 ^ξ	0.97	5.7	0	0	94.3	< 5	Trace	5	7.37
3 ^{+,ξ}	0.83	11.7	1.0	0	87.4	< 5	0	16	4.38
4	0.85	15.6	2.7	0	81.7	< 5	7	14	4.69
5	0.65	11.8	11.2	2.8	74.1	< 5	134	7	5.02
6	0.65	13.5	9.2	1.9	75.4	< 5	86	4	5.39

* Calculated from measured air and coal flow rates and coal composition. For stoichiometric combustion 9.24 lb air/lb. coal is required.

⁺ Coal flow shutdown during sampling.

^ξ Sample bottle apparently leaked in air after sample taken.

NO₂, Methane & Ammonia absent

spuriously low values for CO_2 , CO , and H_2 and will therefore be excluded from subsequent analysis. The remaining samples essentially retained their integrity and the analyses generally conform with the corresponding equivalence ratios^{*}, i.e. at near stoichiometric conditions (e.g., $\phi = 0.94$) relatively little unburnt fuel exists as H_2 or CO while at fuel-rich conditions the amount of unburnt fuel increases as expected.

Comparison of the measured gas compositions for samples 5 and 6 (cf Table 4) shows considerable variation even though both samples were taken nominally under the same conditions. This lack of reproducibility is possibly due to local fluctuations in species concentrations (as well as temperature) normally occurring in turbulent flow systems, and points out one of the limitations of batch sampling, i.e. the measurements may not be time averaged.

Although water is one of the main products of fossil fuel combustion its quantitative measurement by techniques suitable for "permanent" gases is difficult since water exists as a pure vapor only at relatively high temperatures. In ambient gas analysis small amounts of liquid water can adversely affect the measurements of trace species such as NO_x , SO_x and NH_3 owing to the likelihood of dissolution and/or reaction. Because of this, the concentrations of trace species listed in Table 4 should be considered

* Equivalence ratio is ordinarily defined as the actual amount of fuel expressed as a decimal ratio of the stoichiometrically correct amount of fuel. In the text equivalence ratio (ϕ) is defined as the inverse or reciprocal of the ordinary definition.

qualitative only. Even so, one trend suggested by the data is an increase in the SO_2/COS ratio with increasing air (increasing equivalence ratio, ϕ) as one would expect. Trace gas species tested for but not found were CH_4 , NO_2 , and NH_3 . Of these, NO_2 and NH_3 could have been present in the flame gases but were subsequently lost by interactions in the sampling bottle.

For the gas samples not contaminated by leakage (viz. samples 1, 4, 5, and 6) there is generally poor agreement between the measured species concentrations and those predicted by General Electric's CCE equilibrium program except for sample number 1 where the measured and CCE values agree on the average to within $\pm 1.1\%$ - units^{*}. The remaining samples, nos. 4, 5, and 6, show the progressively worse agreement, viz. ± 2.4 , ± 3.0 , and $\pm 4.5\%$ - units respectively. A comparison of measured and CCE values is given in Table 5. Using the actual heat transfer into the cooling air of $\sim 5.5\%$ at sample point 6 (instead of 10%) raises the equilibrium flame temperature to 1999 K but affects the CCE species concentrations by only 0.3% - units at most, indicating that temperature changes on the order of 100 K do not greatly affect major species concentrations under fuel rich conditions. This would not be true as the equivalence ratio approached 1.0.

The basic disagreement between the measured and CCE calculated gas composition (except for sample number 1) implies that overall equilibrium

* The method chosen to evaluate the agreement (or lack of same) between the measured and CCE calculated gas species composition for each sample is the average of the unsigned absolute error (absolute difference between measured value and CCE value) for each species. This form of expression was used instead of the often encountered percent error since at very low concentrations a small absolute error would yield a large percent error. For example, if the CCE calculated values for N_2 and H_2 concentration both differed by 1.0% - units from the measured values then the absolute error for each is 1.0% - units as is the average for the two. However, if the measured values of N_2 and H_2 were 75% and 0.2% respectively then the absolute % - errors for a 1.0% - unit difference would be 1.3% and 500%.

Table 5. Comparison of Measured and CCE Equilibrium⁺
Calculated Major Gas Species Concentrations^{*}

SAMPLE NO..	EQUIVALENCE RATIO, ϕ	% ^E , DRY								EQUILIBRIUM FLAME TEMPERATURE (K)
		CO ₂		CO		H ₂		N ₂		
		MEAS.	CCE	MEAS.	CCE	MEAS.	CCE	MEAS.	CCE	
1	0.94	17.0	15.9	1.2	3.1	1.3	0.3	80.5	80.7	2305
4	0.85	15.6	14.1	2.7	6.5	0	0.9	31.7	78.5	2232
5	0.65	11.8	8.6	11.2	15.9	2.8	4.1	74.1	71.4	1877
6	0.65	13.5	8.6	9.2	15.9	1.9	4.1	75.4	71.4	1877

⁺ CCE concentrations and temperatures for 10% heat loss.

^{*} CCE concentrations at equilibrium temperature of nearest 100 to equilibrium flame temperature.

^{ξ} CCE concentrations normalized to 100%.

was not closely approached in the GE combustor except for sample number 1. This, along with the visual observation of a luminous, optically thick stream at fuel-rich conditions, suggests that fuel conversion to gaseous products (primarily CO and H_2) is significantly less than 100%. No direct analysis of the gasifier product stream for unburnt fuel was possible since this stream was "flared" by dilution air downstream of the diagnostic section. This was done to prevent combustible mixtures from entering the exhaust system and to thereby preclude potentially explosive conditions. However, analysis of the fly ash in the flared stream revealed more carbon than previously encountered during excess air testing, implying that the unflared stream initially had even more carbon. Slag analysis showed that little carbon was present in this component.

Assuming that fuel-hydrogen is completely converted to H_2 or H_2O and that unburnt fuel is carbon only, a stoichiometric mass balance at each sampling point was performed utilizing the measured equivalence ratio and gas analysis as well as atom conservation. The results of this analysis are presented in Table 6. The salient feature of this analysis is that it permits an estimation of fuel conversion at a given equivalence ratio in the GE combustor. As expected, the amount of unconverted fuel, as unburnt carbon, increases with decreasing equivalence ratio. It should be emphasized that for a given fuel at a given equivalence ratio the amount of unburnt carbon will vary with combustor design. In an uncatalyzed

Table 6. Results of Stoichiometric Mass Balance Analysis

SAMPLE NO.	%, DRY								CALCULATED UNBURNT CARBON WT. % of C INPUT
	CO ₂		CO		H ₂		N ₂		
	MEAS.	CALC.	MEAS.	CALC.	MEAS.	CALC.	MEAS.	CALC.	
1	17.0	17.0	1.2	1.2	1.3	1.3	80.5	80.5	2.1
4	15.6	15.6	2.7	2.6	0	0	81.7	81.7	11.1
5	11.8	11.8	11.2	11.3	2.3	2.9	74.1	74.1	15.5
6	13.5	13.4	9.2	9.2	1.9	1.9	75.4	75.3	22.2

gasification process unburnt fuel reacts with steam and combustion products to produce the final, equilibrium mixture. These endothermic reactions are relatively slow and therefore require sufficient residence time (as well as temperature and mixing) to go to practical completion.

In any case, the results of the stoichiometric mass balance permitted the original coal analysis to be modified for each sample number to account for unburnt carbon. Using the resultant modified coal analysis, the measured equivalence ratio for the original coal, and species conservation, an effective equivalence ratio (ϕ_{EFF}) was derived for each sample number. This approach in effect, treated unburnt carbon as an inert and re-determined a new equivalence ratio (ϕ_{EFF}) for the modified coal composition from the original coal's measured equivalence ratio. Also, using the modified coal analysis (plus a modified HHV and the actual heat loss from Table 4) as input to the CCE should give best agreement between measured and CCE gas species concentrations at $\phi_{EFF} \approx \phi_{CCE}$ if the estimation of unburnt carbon is essentially valid. The results of such an approach are shown in Table 7. The measured and CCE calculated species concentrations for samples 1, 4, 5, and 6 show good agreement, viz. to within an average of ± 1.0 , ± 0.2 , ± 0.9 , and $\pm 1.1\%$ - units, respectively.

This agreement, along with the results on Table 5, suggests that the current CCE program cannot be used in systems where fuel conversion is substantially less than 100%, i.e. in fuel rich conditions with relatively short residence times. However, independently accounting for unburnt

Table 7. Comparison of Measured and Modified Coal CCE Equilibrium
Calculated Major Gas Species Concentrations

SAMPLE NO.	MODIFIED COAL EQUIVALENCE RATIOS		_____, DRY _____								EQUILIBRIUM FLAME TEMPERATURE (K)	
			MEAS. CCE		MEAS. CCE		MEAS. CCE		MEAS. CCE			
	ϕ_{EFF}	ϕ_{CCE}	CO_2		CO		H_2		N_2			
1	0.96	0.95	17.0	16.0	1.2	3.1	1.3	0.3	80.5	80.6	2345	
4	0.94	1.00	15.6	15.1	2.7	2.9	0	0.3	81.7	81.7	2361	
5	0.75	0.75	11.8	10.7	11.2	11.2	2.8	2.2	74.1	75.9	2182	
6	0.80	0.80	13.5	12.1	9.2	8.7	1.9	1.7	75.4	77.5	2241	

* Gas concentrations normalized to 100%. CCE concentrations at equilibrium temperature of nearest 100 to equilibrium flame temperature.

fuel allows the use of a modified coal CCE that adequately scopes the gas phase. This kind of modification will probably be unique to each combustor and set of operating conditions and requires for implementation detailed product gas analysis. The measurement of unburnt fuel carryover would also be valuable.

The equilibrium flame temperatures listed in Table 7 should be considered as upper limits of the actual flame temperatures since the modified coal CCE does not account for the sensible heat of the unburnt fuel stream. Conversely, optical pyrometer measurements of the slag surface temperature may be considered as lower limits of the actual flame temperatures inasmuch as the slag surface was obscured by the luminous stream (probably hot carbon particles), especially at the lowest equivalence ratios. This resulted in temperature measurements which were averaged over the gas stream, assuming that the luminous particles were at temperatures close to those of the gas.

A rough estimate of the actual flame temperatures can be made by correcting the modified coal CCE flame temperatures for unburnt carbon's sensible heat content. This was done from the mass balance analysis and averaged specific heats for the gas species as well as for unburnt carbon as graphite. It should be emphasized that such a correction is somewhat crude and that the resulting temperatures may be only slightly more accurate than the upper limit modified coal CCE temperatures. Estimated flame temperatures are presented in Table 8 along with the modified coal CCE and optical pyrometer temperatures for comparison.

Table 8. Comparison of Estimated Flame Temperatures with Optical Pyrometer (Lower Limit) and Modified Coal CCE (Upper Limit) Temperatures

SAMPLE NO.	OPTICAL PYROMETER* TEMPERATURE, K (F)		MODIFIED COAL CCE TEMPERATURE, K (F)		ESTIMATED FLAME TEMPERATURE, K (F)	
1	1662	(2532)	2345	(3762)	2341	(3754)
4	1842	(2856)	2361	(3790)	2336	(3745)
5	1903	(2966)	2182	(3468)	2139	(3391)
6	1964	(3076)	2241	(3574)	2175	(3456)

* Slag surface temperature normally ~ 2700 F under oxidizing conditions.

3. Conclusions and Recommendations

Substoichiometric combustion of pulverized coal results in a hot product stream consisting of the usual combustion products plus CO and H₂ as well as unburnt fuel particles. For a given combustor and set of operating conditions equilibrium estimates of product stream composition based on the input coal composition can be highly misleading owing to the dependence of fuel burnout on residence time in the combustor. Accounting for fuel conversion by some independent method permits the use of CCE equilibrium calculations to reasonably predict the gaseous composition. Resultant CCE equilibrium flame temperatures are probably upper limits and should converge to the actual temperature as fuel conversion approaches 100%.

Table 9 presents a more complete picture of the "best fit" results of the modified coal CCE to the measured gas concentrations for Alcoa's substoichiometric test on GE's combustor. Depending upon the operating conditions of Alcoa's gasifier which has approximately 300 msec residence time, the amount of unburnt carbon and, hence, the gas phase composition and flame temperature can differ considerably from the values listed in Table 9, even for identical stoichiometry and firing density.

If 100% of the coal sulfur (3.96 wt. %, dry coal) is eventually oxidized to SO₂ and exhausted to the atmosphere the pollution rate would roughly be 6 lbs. SO₂/million Btu, greatly exceeding the Federal EPA limit of 1.2 lbs. SO₂/million Btu. Owing to the longer residence time of ALCOA's gasifier fuel conversion should be greater than that obtained in the GE combustor for similar conditions. This implies that gasifier product gas composition and temperature should more closely approach the CCE values shown on Table 5.

Table 9. Summary of Best Fit CCE Results Based on Best Agreement Between Measured and Modified Coal CCE Concentrations

SAMPLE NO.	ORIGINAL COAL EQUIVALENCE RATIO	UNBURNT CARBON WT. %	FLAME TEMPERATURE, K (F)						SO _x ⁺ ppm	NO _x ^ξ
				CO ₂	CO	H ₂ %*	H ₂ O	N ₂		
1	0.94	2.1	2341 (3754)	14.2	3.1	0.3	9.3	73.1	3800	2516
4	0.85	11.1	2336 (3745)	14.2	2.1	0.2	9.7	73.8	3919	3481
5	0.65	15.1	2139 (3391)	9.7	9.9	2.1	10.3	68.0	5117	91
6	0.65	22.2	2175 (3456)	10.8	7.7	1.5	11.0	69.0	5166	141

* Major gas species concentration normalized to 100%.

⁺SO_x = SO₂ + COS + H₂S + S + SO + 2S₂

^ξNO_x = NO + NO₂

September 17, 1979

ADDENDA

(To be added to Section III, Test Data)

JOINT ALCOA/GE
COAL GASIFICATION TEST

September 10, 1979

CONTRACT NO.: TC 621001TC

As a result of the Technical Review Meeting held at Alcoa on 10 September 1979 it was decided that further, detailed analysis of rejected slag and downstream filter samples might be of some use in getting a semi-quantitative idea of slag rejection rates, fireside sulfur capture as well as other phenomena as a function of equivalence ratio, even though thermal equilibrium was not completely obtained in the test run and was only approached during the latter stages. Also, flaring of the gasifier product stream as well as the trapping of solid residue (during the non-thermal equilibrium stage) throughout the combustor system precluded any authoritative mass balance. It is cautioned therefore, that interpretation of the data should be made with a good understanding of the test conditions and constraints described in the main report and this addenda, including the troubles encountered with coal feed as well as the relative smallness of the GE combustor for gasification purposes.

Analysis of slag and filtrate were paired into three so-called sets, corresponding to roughly steady-state flow conditions for coal and air, and having comparable run times. According to Figure 8 the following three sets were obtained: set #1 is slag sample #2 and filter Sample #1; set #2 is slag sample #3 and filter sample #2; and set #3 is slag sample #5 and filter sample #3. For these sets the combined slag and filter mass rejection rates for ash, carbon, hydrogen, and sulfur were determined from the data on Table 10. These in turn were compared to the appropriate coal mass-fraction input rates shown in Addenda Table I. The following subsections

Table I. Coal Component Input Rates

Set No.	Run Time* (Min.)	lbm/hr				
		Coal	Ash	C	H	S
I	71	92	11.47	61.33	4.74	3.60
II	135	131	16.33	87.33	6.75	5.12
III	163	140	17.45	93.33	7.21	5.47

* Average of slag and filter sample run times

individually deal with each fuel component of interest.

Ash

The results of the ash analysis are shown in Addenda Table II. Rejection of ash as slag apparently fell off as the equivalence ratio dropped to the 0.650 operating condition, implying a lowering of the cyclone collection efficiency as previously noted. The slag rejection rate determined for set #1 at $\phi = 0.94$ is unexpectedly low on the basis of previous GE tests conducted at thermally equilibrated, excess air (near-stoichiometric) conditions and is probably attributable to several factors, the most important of which is that at this relatively early run time (~ 71 min.) the combustor had not yet come up to operating temperature (this is illustrated in Figure A84) owing primarily to the irregular coal feed history, shown in Figure 6. This, along with the higher ash fluid temperatures associated with the stronger oxidative condition at $\phi = 0.94$, and the need to build up a slag layer on the walls prior to achieving steady-state slag rejection, likely accounts for the unexpected low slag rejection measured for set #1. It should further be noted, as Figure 6 indicates, only four of the eight coal swirl injection ports (corresponding to only one coal feed tank) were in use for the majority of the test run because of coal line blockage. This off-design operation would have altered somewhat the combustor flow pattern and is suspected therefore, to be another factor in reducing the cyclonic collection efficiency.

Table II. Slag/Filter Ash Analysis

Set No.	Approximate Equivalence Ratio	Ash, lbm/hr			—% of Coal-Ash Input—		
		Coal-Ash Input	Slag*	Filter [‡]	Slag	Filter	Total
I	0.94	11.47	6.75 ⁺	0.83	59	7	66
II	0.87	16.33	9.62 ⁺	1.78	59	11	70
III	0.65	17.45	8.57	3.09	49	18	67

* Based on ash weight of slag calculated by difference from values on Table 10.

⁺ Assumes that "bag" analyses for slag sample #'s 2 and 3 are the same as "bag" slag sample #5.

[‡] Based on ash weight of filter sample calculated by difference from values on Table 10.

The amount of ash collected in the flyash filters (cf., Figure 1 for location) increased as the equivalence ratio decreased, suggesting that proportionately more ash was carried over as fuel richness increased. The amount of coal-ash unaccounted for is ~ 30 to 34% of the amount fed in and is likely to be found in the solid residues throughout the combustor system, especially in the anti-swirl and main sump sections (shown in Figure 9) and tabulated in Table 10.

Carbon

Addenda Table III summarizes the results of the carbon analysis performed on the sets of slag and filter data. The amount of carbon rejected with the slag is 1.6% or less, implying that even under reducing conditions the amount of carbon rejected with the slag (and therefore lost to further combustion) is relatively small. It might be expected, however, that in Alcoa's gasifier the carbon carried in the slag could be even less owing to the designed longer residence time and stronger cyclonic flow fields.

Because the carbon in the filter sample is the flared remainder of that initially in the gasifier product stream, as noted in Section II of the main report, the amount of carbon blowby (as percent of input coal-carbon) is probably a lower limit to the amount of unburnt carbon in the unflared gasifier product stream. Treating the total carbon found in the slag and fly-ash filters as lower limits to unburnt carbon and comparing these to the

Table III. Slag/Filter Carbon Analysis

Set No.	Approximate Equivalence Ratio	Carbon, lbm/hr			— % of Coal - Carbon Input—		
		Coal-Carbon Input	Carried in Slag	Blowby to Filter	Carried in Slag	Blowby to Filter	Total
I	0.94	61.33	0.99*	1.44	1.6	2.3	3.9
II	0.87	87.33	0.64*	2.46	0.7	2.8	3.5
III	0.65	93.33	0.99	4.78	1.1	5.1	6.2

* Assumes that "Bag" analysis for slag sample #'s 2 and 3 is the same as that for Bag slag sample #5.

percents of unburnt carbon derived in Section II, at comparable equivalence ratios, we find some inconsistency only at $\phi = 0.94$: the slag/filter analysis yielding a value of 3.9% while the stoichiometric mass balance gave 2.1%. Owing to the indirect nature of the unburnt carbon calculation techniques, employed in the stoichiometric mass balance of Section II, and the time variations in flow of coal and air, as Figure 8 shows, during the slag and filter samplings as well as the unknown partitioning of unburnt carbon between the filtered and main sump fraction this inconsistency is not considered too bad.

At the equivalence ratios of 0.87 and 0.65 the amounts of unburnt carbon derived from the slag/filter analysis (viz. 3.5 and 6.2%), although attenuated by flaring, qualitatively fit in with the values from Section II (viz. 11.5 and 15.1/22.2%).

Hydrogen

The relatively low amounts of hydrogen retained in the slag and filter samples, shown in Addenda Table IV, indicate that hydrogen burnout is more extensive than carbon burnout,

Sulfur

As Addenda Table V shows, the amounts of coal-sulfur rejected with the slag are quite small ($\approx 1.4\%$). Even with perfect (100%) ash rejection as slag the amount of trapped sulfur would be at most $\sim 3\%$ of the coal-sulfur input, assuming constant slag composition. This indicates that efficient fireside removal of sulfur would definitely require the use of chemical additives.

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Table IV. Slag/Filter Hydrogen Analysis

Set No.	Approximate Equivalence Ratio	Hydrogen, lbm/hr			— % of Coal - Hydrogen Input —		
		Coal-Hydrogen Input	Slag	Filter	Slag	Filter	Total
I	0.94	4.74	0.018*	0.026	0.4	0.6	1.0
II	0.87	6.75	0.024*	0.034	0.4	0.5	0.9
III	0.65	7.21	0.018	0.062	0.2	0.9	1.1

* Assumes that "Bag" analysis for slag sample #'s 2 and 3 is the same as for Bas slag sample #5.

Table V. Slag/Filter Sulfur Analysis

Set No.	Approximate Equivalence Ratio	Sulfur, lbm/hr			% of Coal - Sulfur Input		
		Coal-Sulfur Input	Slag	Filter	Slag	Filter	Total
I	0.94	3.60	0.050	0.028	1.4	0.8	2.2
II	0.87	5.12	0.034	0.053	0.7	1.0	1.7
III	0.65	5.47	0.061	0.106	1.1	1.9	3.0

Compliance would require ~ 80%

sulfur capture either fireside or in the stack. Based on the modified coal and CCE "best fit" values for NO_x in Table 9, NO_x pollution rates vary from ~ 0.008 (sample point 5) to ~ 3.8 lb. NO_2 /million Btu. The Federal EPA limit is 0.7 lb. NO_x /million Btu (mid-1974) for coal firing. However, NO_x formation is highly sensitive to the combustion temperatures so that an evaluation of NO_x formation should be made "in situ," although it is fair to say that substoichiometric combustion usually reduces NO_x (as compared to normal, excess air combustion) due to generally lower temperatures. In any case both SO_x and NO_x pollutant formation must be evaluated for the overall combustion process, including second stage product and exhaust stream analysis.

DETAILED DESIGN OF ALCOA COAL GASIFIER'S INTEGRATED INJECTOR

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SECTION I. GENERAL DESCRIPTION OF INTEGRATED AXIAL SWIRL INJECTOR ASSEMBLY

A part of the ALCOA/DOE project "Pulverized Coal Firing of Aluminum Remelting Furnaces" is to design, fabricate, and test coal gasifier/combustor systems. To this end General Electric has designed an integrated axial swirl injector unit for coal and natural gas combustion. In order to positively and independently control the combustion gas flow field apart from the slagging wall phenomena, and to permit easy maintenance of the gasifier as well as flexibility in changing the tangential wall gas velocity (by modifying swirl characteristics), the axial swirl injection concept has been adopted.

As the conceptual sketch on Figure I.1 shows the integrated axial swirl injector unit which is to be installed in the air cooled cyclone coal gasifier is composed of a natural gas pilot burner, located at the center, a preheated secondary air swirl vane assembly, and a pulverized coal injection section.

The natural gas pilot burner assembly consists of the natural gas swirl injector, the pilot air swirling vanes and the water cooled cylindrical jacket. The rotational direction of the central natural gas swirl is counter-clockwise facing the injector, while that for the pilot air swirl is clockwise just as the swirls for the secondary air and the primary coal/air injection. Ignition of the natural gas will be initiated by a pair of electrode igniters as shown in the detailed drawing, 1217-340, in Section IV.

The pilot burner is used to gradually heat up the system in order to avoid thermal shock to the refractories and has been designed to provide a maximum of 2.5 MMBtu/hr natural gas at which firing rate the pilot air should provide about 50% to 60% of the stoichiometric air, while the rest is supplied through

Figure I.1 INTEGRATED AXIAL SWIRL INJECTOR CONCEPT

This document describes and for the time being, as the best
 as known, available and intended to provide the General
 Electric Company with information of General Electric Company
 design and of the design and to describe the general
 of the design. The General Electric Company is providing
 an application for patent, with the design, will describe the
 of the General Electric Company. In the design, the design
 and the design shall be used only for the purpose
 of providing the data required under the design of the
 design and shall not be disclosed outside of the design of the
 design.

the secondary air swirl ports. The minimum coolant water flow rate should be ~15 GPM at 135 F (this temperature water condensation on the metal surface) For the low-fire operation of the pilot burner, or for cooling water flow rates of approximately 25 GPM, the pilot burner can be operated with the pilot air supplying all the necessary air. However, to protect the secondary air swirl vanes from overheating due to radiative and convective heat transfer from the combustion process, at least ~200 lb_m/hr of air should always be introduced through the secondary air swirl vanes irregardless of air preheat temperature.

When switching from the natural gas pilot to the coal combustion/gasification process, the natural gas supply rate should be gradually decreased while the coal feed rate is gradually increased such that the total thermal input remains approximately constant in order to minimize thermal shock to the refractories.

The nominal design conditions for operating the injector unit for coal gasification include:

GASIFICATION = 0.55 Ø BASED ON ALCOAL W.VA. COAL

$\dot{W}_{\text{Coal}} = 300 \text{ lb}_m/\text{hr}$

$\dot{W}_{\text{Primary Air}} = 300 \text{ lb}_m/\text{hr}$ at 80 F

$\dot{W}_{\text{Secondary Air}} = 1,447 \text{ lb}_m/\text{hr}$ at 705 F and 1 psig

$\bar{T}_{\text{Air}} = 600 \text{ F}$

Coal Injection Velocity = 300 ft/sec

Secondary Air Injection Velocity = 615 ft/sec

For gasification conditions ($\dot{W}_{\text{Coal}} = 300 \text{ lb}_m/\text{hr}$ and 0.550, 1447 lb_m/hr of preheated air enters the combustor through the secondary air swirl vanes. During coal only operation, a small amount of air should be introduced through the pilot burner air swirlers to protect the vanes from radiation heat.

Pulverized coal is injected with primary air through eight primary injection swirl ports, which are water cooled. The primary injection component is surrounded by a water jacket in order to minimize the thermal expansion gap between the primary injection and its surrounding cylinders during operation.

The relationship among the secondary air preheat temperature, injection velocity, and wall tangential velocity are tabulated below for the off-design conditions:

TABLE I.1 PREHEAT AIR TEMPERATURE VS. INJECTION VELOCITY

$T_{\text{2nd Air}}$ (F)	$\left[\dot{W}_{\text{inj, 2nd Air}} \right]^*$ (FT/SEC)	$\dot{W}_{T_2}$ (FT/SEC)
800	665	324
750	640	312
705	615	300
650	586	286
600	560	273
550	533	260
500	507	247
450	480	234
400	454	221

* Boundary Layer Effects included

Based on the ALCOA coal size distribution shown in Figure I.2, the effect of the wall tangential velocity on the cyclone collection efficiency is presented in Table I.2 and Figure I.3. It is noted that the wall tangential velocity, U'_{T_2} , in Table I.1, is a single secondary air tangential velocity and the velocity U_{T_2} , in Table I.2 and Figure I.3 is a real wall tangential velocity which was created by both the primary and secondary air injections. Due to the smaller injection velocity of the primary air/coal mix, the real wall tangential velocity, U_{T_2} , is smaller than U'_{T_2} . It is cautioned not to reduce the real wall tangential velocity, U_{T_2} , below 100 ft/sec because of the exponential reduction of the cyclone collection efficiency. Because of this coupling effect of primary and secondary air injection on real wall tangential velocity, preheat temperature should be kept above about 350 F. This low temperature limit also arises from the necessity of maintaining stable coal combustion/gasification operation.

The cooling water flow rates for the primary injector and the injector outer water jacket should be nominally 8 GPM and 10 GPM, respectively.

Figure I.2 - ALCOA COAL SIZE DISTRIBUTION

TABLE I.2 CYCLONE COLLECTION EFFICIENCY*

WALL TANGENTIAL VELOCITY, U_{T2} (FT/SEC)	WITH COAL BURNING (%)	WITHOUT BURNING (%)
300	99.06609	99.95728
250	98.91097	99.93331
200	98.51776	99.89281
150	98.13488	99.81017
100	97.44295	99.61365
50	86.35274	98.87041

* BASED ON ALCOA COAL SIZE DISTRIBUTION

Figure I.3 CYCLONE COLLECTION EFFICIENCY

SECTION II. NATURAL GAS PILOT BURNER

1. General Considerations

The natural gas pilot burner is of the nozzle mix or forward flame burner type and will be primarily used to gradually bring the gasifier/combustor refractories up to temperature prior to coal firing without subjecting the refractories to thermal shock. For this application a moderate flame of intermediate combustion intensity (ratio of fuel enthalpy input to the flame volume) is preferable to either a short, intense flame or a long, lazy flame. The former will transfer a significant amount of its heat to the pilot burner's water-cooled jacket, leaving less for heating the combustor refractory and therefore requiring longer heat-up time, while the latter may have a flame length exceeding the combustor system dimensions and impinge on the experimental furnace backwall.

Flame characteristics such as flame length and combustion intensity, as well as flame stability, are mainly controlled on this kind of burner by fuel-air mixing. Good initial mixing yields short, intense flames while poor mixing gives rise to longer flames of lower intensity. The method of introducing the fuel and air at the burner mainly determines the mixedness of the combustion gases. Examples of conventional parameters that affect mixing at the burner are relative fuel-air momentum, number of fuel and

air jets, angle of fuel and air injection, and swirl strength.

The natural gas pilot burner has been designed to deliver sufficient fuel and air to fire a maximum of around 2.5MM Btu/hr for fuel and air pressures and temperatures of approximately 1 psig and 80 F at $\phi = 1.0$ (stoichiometric air-fuel ratio). Significant variations in the fuel and/or air inlet conditions, especially pressure, from the above values may to some extent result in off-stoichiometric combustion, flame instability, and/or changes in maximum firing rate. In any case both fuel and air inputs should be measured independently and monitored continuously during a run.

Air for the pilot can vary from 100% of required stoichiometric air to a few percent necessary to keep the air swirling vanes cool and to prevent back-diffusion of combustible mixtures into the air line. When air at the pilot is less than required the remainder should be added through the surrounding secondary air swirl ports that normally supply preheated secondary air in the coal combustion mode. This partitioning of pilot air will affect flame characteristics by varying the combustion flow pattern.

2. Natural Gas Pilot Operation

When the natural gas pilot is to be fired the following general procedure should be followed:

- a. Turn on pilot air to a low flow rate¹ and allow it to purge the system for approximately two minutes.
- b. Turn on ignition electrodes.
- c. Turn on natural gas to a minimum flow rate for ignition.
- d. Verify ignition within about 5 seconds. If no ignition, turn off natural gas, return to step (a) and repeat sequence.
- e. If ignition occurs at step (d) go to desired higher flow rates².

During first-time use of the gasifier an extensive low-fire versus time program is necessary to cure the "green" refractory. Also some "bake-out" at low fire might be necessary after prolonged shutdown or if the combustor system refractory ever gets wet due to water leaks or repairs.

3. Suggested Safety Features

The following enumeration of safety considerations is by no means complete but is intended to merely highlight potential trouble areas. For further details of the hardware requirements it is recommended that the appropriate vendors and/or safety engineer be contacted.

As noted in Section 2 the use of fuel-air ratio controls can prevent

-
1. The low firing rate should never be less than $\sim 30,000$ Btu/hr = 1.35 lb/hr at $\phi = 1.0$ due to the possibility of flashback or, in the present case,^m combustion taking place entirely within the water-cooled jacket. The burning velocity of methane is ~ 1.5 ft/sec at $\phi \approx 1.0$; Alcoa natural gas is 95.46% methane.
 2. When changing inputs of fuel or air the increments should be such that the fuel-air ratio does not fall outside the flammability limits. The low limit for methane is 5% by volume in air or $\phi = 0.47$, while the high limit is 15% or $\phi = 1.65$. Instead of manual control, use of an air-follow regulator or some other fuel-air ratio control would obviate this potential problem.

inadvertant introduction of non-flammable mixtures of air and natural gas into the combustor. This latter eventuality can arise with manual air and fuel flow control if operating personnel are untrained or careless.

Step (d) in the start-up procedure in Subsection 2 implies the presence of some flame monitoring device, e.g., a UV flame "detector." Flame failure should activate within 5 seconds a fuel shut-off valve. Loss of fuel or air pressure at the burner as well as high pressure limits should also be incorporated into a safety network.

One of the potentially most damaging failures is loss of cooling water to the pilot jacket. Provision should be made to allow switching to city water or for fuel shut-off with cooling water recycle in the event of water loss.

4. Shakedown Tests

The following is a list (incomplete and subject to revision) of suggested tests for shakedown operation of the natural gas pilot.

- (a) Determine the ideal axial position for swirl vanes inside water jacket. Want to minimize heat to water jacket but still be stable. Perform at high fire and $\phi = 1.0$. No secondary air.
- (b) Validate fuel and air inlet design at $\phi = 1.0$ with no secondary air and examine:
 1. Turndown
 - i) high-fire maximum, i.e., blowoff
 - ii) low-fire minimum, i.e., flashback or retreat of flame inside water jacket.

2. Heat pickup by water jacket at various firing rates.

- i) Temperature of inlet water
- ii) Temperature of outlet water
- iii) Water flow through jacket

3. Flame Shape - measure length and width

4. Stability

(c) Test partitioning of air between pilot and coal-combustion secondary air swirl ports after pilot fully scoped.

5. Natural Gas Properties

The following is a list of pertinent natural gas properties.

(a) Composition

<u>Species</u>	<u>Vol. %</u>
CO ₂	0.02
N ₂	0.46
CH ₄	95.46
C ₂ H ₆	3.22
C ₃ H ₈	0.52
i - C ₄ H ₁₀	0.09
n - C ₄ H ₁₀	0.14
C ₅ H ₁₂	0.09

(b) Other properties

HHV = 23,634 Btu/lb_m (1047 Btu/SCF)

Specific gravity = 0.5826

Density_{STP} = 0.0443 lb_m/ft³

Stoichiometric Ratio = 17.24 lbs air/lb fuel
(9.905 SCF air/SCF fuel)

Molecular Weight = 16.80

SECTION III. HEAT TRANSFER ANALYSIS OF PILOT BURNER WATER JACKET

1. Introduction

The main purpose of the heat-transfer analysis is to determine design specifications for the natural gas pilot's water-cooled jacket as shown in Figure III.1 at anticipated operating conditions, the major criterion being to keep the inner wall of the water-cooled jacket at as low a temperature as possible within constraints.

The analysis often incorporates models and/or assumptions that give so-called "worst" case conditions, i.e., situations where the heat-transfer from the combustion process is maximized so as to severely tax the jacket's cooling ability. This is a conservative design approach, attempting to "overdesign" the system and ensure safe, continuous, and durable operation over a wide range of conditions.

The pilot's water-cooled jacket will absorb heat convectively and radiatively from any combustion process occurring within the jacket itself or in the gasifier. This would include pilot operation as well as coal gasification. Although there are a large number of possible firing conditions only a limited number of cases could be analyzed owing to practical considerations. Of the several types of operation anticipated, the one which would probably demand the most of the water-cooled jacket is the case where the pilot (at 2.5 MM Btu/hr and $\phi = 1.0$), retracted 10 inches inside the jacket, has a flame entirely within the jacket, transmitting heat by convection and radiation.

Figure III.1. NG PILOT BURNER WATER JACKET

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The bulk of the heat-transfer analysis relates to this situation. It should be noted that such a situation is not only undesirable from an operational efficiency standpoint but is, in actuality, impossible owing to mixing and burning velocity considerations. However, using this configuration as a limiting, "worst" case to determine design specifications, ensures adequate cooling of the pilot's water jacket for normal operating conditions.

The ability of the cooling-jacket to dissipate heat depends primarily on the volume of cooling water available and on the annular area for water flow, i.e., water flow velocity in the jacket. Figure III.1 is a cross-sectional view of the natural gas pilot and water jacket showing the annular water flow path in the jacket as well as the positioning of the pilot burner within the jacket. The water inlet temperature is also of some importance in determining jacket-wall temperature and, hence, total water requirements.

2. Basic Heat Transfer Equations

For steady-state operation the heat transferred from the combustion process or flame to the water-cooled jacket will be fixed for a given system design and set of operating conditions. Further, the heat or enthalpy flux (Btu/hr) associated with the various types of heat transfer must be equal, i.e.

$$Q_F \equiv Q_M \equiv Q_W \quad (1)$$

where Q_F = heat flux from the combustion process, Q_M = heat flux through the jacket wall, and Q_W = heat flux carried out by the cooling water.

The primary mechanisms of heat transfer from the natural gas pilot flame to the metal, water-cooled jacket are radiation and convection while thermal conduction controls the heat transfer rate through the jacket's metal wall. Convection governs the heat pick-up by the cooling water from the jacket wall. The governing equations are listed below: the terms are defined in a glossary at the end of this section.

$$Q_F = A \sigma F_e F_a (T_F^4 - T_{MH}^4) + h_{CF} A (T_F - T_{MH}) \quad (2)$$

$$Q_M = (k_M/L) A (T_{MH} - T_{MW}) \quad (3)$$

$$Q_W = h_{CW} A (T_{MW} - T_W) \quad (4)$$

3. Results of Heat Transfer Analysis

Using Equations (2) through (4) along with several assumptions, e.g. inviscid water flow, and specified operating parameters as well as system design configurations, sets of calculated water-jacket wall temperatures can be generated for the various cases.

Table III.1 is a summary of the parametric effects of several crucial operating variables on jacket wall temperatures for natural gas firing at 2.5 MM Btu/hr (105.8 lb/hr) and $\phi = 1.0$. As can be seen for an annular water flow opening of $\sim 13/64$ " (0.201"), the value selected for the final

Table III.1 Alcoa Natural Gas Pilot Cooling Water Jacket Heat-Transfer
Results (NG at 2.5 MM Btu/hr, $\phi = 1.0$)

Case	Water Volume (gal/min)	Water Temp. (F)	Annular Opening (in.)	Water Velocity (ft/sec)	Jacket Temp. Hot-Side (F)	Jacket Temp. Water-Side (F)	Fuel Enthalpy to Jacket (%)
Ia	15	60	0.36 (~ 3/8)	1.2	650	535	3.3
Ib	15	150	0.36	1.2	550	431	3.3
IIa	25	60	0.25	3.0	400	276	3.4
IIb	25	150	0.25	3.0	400	276	3.3
IIIa	25	60	0.201*	4.1	350	224	3.5
IIIb	25	150	0.201*	4.1	375	250	3.6
"Ideal" a	41	60	0.201*	6.6	300	170	3.5
"Ideal" b	15	60	0.072	6.6	300	170	3.5
"Ideal" c	25	60	0.119	6.6	300	170	3.5
IV	15	150	0.201*	2.4	410	286 ⁺	3.2

⁺Calculations suggest that T_{MW} could be reduced to ~ 200 F for NG Pilot firing at $\phi \sim 0.35$.

*Fabrication dimension of jacket as designed.

fabrication design, the inner wall (or water side) jacket temperature can vary from 224 to 286 F for various inlet flows and temperatures. For good jacket operation the inner wall temperature should not exceed the boiling point of water (e.g., 307 F at 60 psig) so as to avoid or at least minimize localized boiling. It should be reemphasized however that these calculated jacket wall temperatures are limiting, upper values based on "worst" case assumptions, and that for real operation they are likely to be significantly lower.

4. Low-Fire Option

Another approach for keeping the natural gas pilot's water-cooled jacket wall temperature at a minimum is to fire the pilot substoichiometrically, allowing the coal's secondary air swirl ports to supply the remaining requisite air in the gasifier proper. This mode of operation will limit heat transfer to the jacket by lowering the gas flame temperature and velocity.

Figure III.2 is a plot of adiabatic, equilibrium flame temperature for ALCOA's natural gas and for methane versus equivalence ratio. This figure, along with equations (2) through (4) and the specification of other operating conditions as in case IV on Table III.1 (except jacket wall temperatures), suggests that acceptable jacket temperatures can be achieved by going to fuel-rich combustion at the pilot, viz. $\phi \sim 0.35$. This option should supply some degree of flexibility by allowing continued pilot operation in situations where jacket cooling water flow is reduced below desired values.

Figure III.2. FLAME TEMPERATURE, F.

5. Conclusions and Recommendations

For safe operation of the natural gas pilot's water-cooled jacket the following operating conditions are recommended. The flow of cooling water should not be less than 15 gallons/minute, in any case the maximum flow rate is desirable. Cooling water inlet temperature should not exceed ~ 150 F. ^{or < 135°F}
(for condensation)
Since the cooling effect of the water is coupled to both flow and temperature, any decrease in the former must be compensated by a decrease in the latter to get the same cooling effect. Inlet and outlet water temperatures as well as volume flow should be monitored.

In instances where cooling water flow and/or temperature do not correspond to minimum requirements, the natural gas pilot can be fired fuel-rich with the rest of the air being supplied by the coal's secondary air swirl ports. In any case the adjustment of operating parameters should be dictated by the requirement to minimize the cooling water outlet temperature. This final parameter is of prime importance and, in a sense, is the only indication of the natural gas pilot's water-cooled jacket efficiency.

Glossary of Terms

- A = inside area of water-cooled jacket exposed to flame gases, ft^2 .
- σ = Stefan-Boltzman constant, $0.1713 \times 10^{-8} \text{ Btu/ft}^2 \text{ hr } ^\circ\text{R}^4$.
- F_e = emissivity factor, dependent on flame and metal jacket emittances as well as system geometry, dimensionless.
- F_a = arrangement factor, dependent on system geometry, dimensionless.
- T_F = flame gas temperature, $^\circ\text{R}$.
- T_{MH} = metal jacket wall temperature on flame or hot side, $^\circ\text{R}$.
- k_{CF} = flame gas film coefficient for convective heat transfer, $\text{Btu/ft}^2 \text{ hr } ^\circ\text{R}$.
- L = metal jacket's wall thickness, ft.
- T_{MW} = metal jacket wall temperature on water side, $^\circ\text{R}$.
- h_{CW} = water film coefficient for convective heat transfer, $\text{Btu/ft}^2 \text{ hr } ^\circ\text{R}$.
- T_W = water temperature inside jacket, $^\circ\text{R}$.