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PULVERIZED COAL FIRING OF ALUMINUM MELTING
FURNACES

First Annual Technical Progress Report for May 1978—June 1979

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October 1979

Work Performed Under Contract No. EM-78-C-01-4203

Aluminum Company of America
Alcoa Center, Pennsylvania

U. S. DEPARTMENT OF ENERGY

Division of Industrial Energy Conservation

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PULVERIZED COAL FIRING OF ALUMINUM MELTING FURNACES

FIRST ANNUAL TECHNICAL PROGRESS REPORT
FOR PERIOD 1978 MAY THROUGH 1979 JUNE

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PREPARED FOR THE
DEPARTMENT OF ENERGY
OFFICE OF THE ASSISTANT SECRETARY FOR
CONSERVATION AND SOLAR APPLICATIONS
DIVISION OF INDUSTRIAL ENERGY CONSERVATION
UNDER CONTRACT EM-78-C-01-4203

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FORWARD

This is the first annual technical progress report 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 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 this first year, the program for Phase I is estimated to be 21% completed with 18% 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.

A major design subcontract placed with General Electric Space Science Labs for assistance in the design of the SSCC is 80% completed. Purchasing of major system components will begin in the next Quarter, and construction will proceed through the first Quarter of 1980. Operational testing will begin April 1980.

PROGRESS

Phase I - Research & Development

Task No. 1 - "Computer Modeling"

The purpose of this task is to provide the air/fuel (coal) ratio, additive level and combustion gas temperature information needed for the first-stage combustor design. The approach taken in this task is to assume that in the combustor there is sufficient time to completely gasify the coal particles and that transport processes are rapid enough that chemical equilibrium is reached in the combustor. The standard scheme of Gibbs free energy minimization (Ref. 1) is used to determine the equilibrium states in the combustor at combustion temperature and pressure. The computation scheme is adopted from Chavez (Ref. 2). The set of equations used in the computation is presented as follows. The requirement for chemical equilibrium of a system at a given temperature, T and pressure, P is:

$$dG_{T,P} = \sum_{\alpha=1}^q \sum_{i=1}^N n_i^{\alpha} \left(G_i^{\alpha} / RT + \ln \frac{n_i^{\alpha}}{n^{\alpha}} \right) = 0$$

$$d^2 G_{T,P} > 0 \quad \dots \dots \dots (1)$$

where $G_{T,P}$ = system Gibbs free energy at temperature, T and pressure, P .

G_i^{α} = Gibbs free energy of pure specie i in phase α

α = number of phases.

i = number of species in phase α

n_i^{α} = number of moles of specie i in phase α

R = gas constant

$\frac{1}{n^{\alpha}} = \sum_i n_i^{\alpha}$

N = number of species present

q = number of phases present

In addition, to the minimum Gibbs free energy criterion,

$$n_i^{\alpha} \geq 0 \quad \dots \dots \dots (2)$$

since negative mole number is physically impossible.

From the conservation of atoms, one obtains

$$\sum_{\alpha=1}^q \sum_{i=1}^N a_{ij} n_i^{\alpha} = b_j^0, \quad j = 1, 2, \dots, M \quad \dots \dots \dots (3)$$

where M = number of elements present

a_{ij} = number of atoms of element j in specie i

b_j^0 = total number of atoms of element j originally present in the mixture.

Since the combustor temperature is unknown, it has to be determined from the energy balance of the combustor. For a flow system at steady-state with no mechanical work, the following is obtained.

$$\sum_{\alpha} \sum_i (n_i^{\alpha})_{\text{prod}} (H_i^{\alpha})_{T_r} - \sum_{\alpha} \sum_i (n_i^{\alpha})_{\text{reac}} (T_i)_{T_r} + Q_{\text{lost}} = 0 \quad (4)$$

where $(n_i^{\alpha})_{\text{prod}} \equiv$ number of moles of specie i in phase α in the combustion product.

$(H_i^{\alpha}) \equiv$ enthalpy of specie i in phase α at combustion temperature and pressure.

$(n_i^{\alpha}) \equiv$ number of moles of specie i in phase α in the combustion feed.

$(H_i^{\alpha})_{T_r} \equiv$ enthalpy of specie i in phase α at feed temperature and pressure

$Q_{\text{lost}} \equiv$ heat loss from the combustor

Equations (1) to (4) provide the system of equations needed for solving the combustion product composition and temperature when the feed temperature, composition and pressure and combustor heat loss are known.

In order to use equation (1), the Gibbs free energy of the pure species has to be determined from the standard enthalpy and standard entropy of the constituents at the combustor temperature, T and pressure, P . The reference standard enthalpy $(H'_{298})_i^{\alpha}$ is taken as the standard enthalpy change of formation of component i from its elements at 298°K and 1 atm .

$$(H'_{298})_i^{\alpha} = (\Delta H'_{298})_i^{\alpha} \quad (5)$$

The reference standard entropy $(S'_{298})_i^{\alpha}$ is taken as the standard entropy content of component i at 298°K and 1 atm with respect to 0°K and 1 atm .

$$(S'_{298})_i^{\alpha} = (S'_i 1_0^{298})^{\alpha} \quad (6)$$

The standard enthalpy and standard entropy of component i at 1 atm and the combustor temperature, T are determined by:

$$(H'_i)^{\alpha} = (H'_{298})_i^{\alpha} + \int_{298}^T C_{p_i}^{\alpha} dT \quad (7)$$

$$(S'_i)^{\alpha} = (S'_{298})_i^{\alpha} + \int_{298}^T C_{p_i}^{\alpha} \frac{dT}{T} \quad (8)$$

where $C_{p_i}^{\alpha} \equiv$ heat capacity of specie i in phase α at 1 atm .

Values of the reference enthalpy, reference entropy and heat capacity are obtained from the Joint Army Navy Air Force tables (Ref. 3). The heat capacity is represented in the form

$$C_{P_i}^{\alpha} = A + B \ln T + CT + DT^2 \dots (9)$$

where A, B, C, D are constants.

With the known values of standard enthalpy and standard entropy at 1 atm and combustor temperature, the Gibbs free energy of the pure component i under the same conditions is obtained from

$$(G_i')^{\alpha}/RT = [(H_i')^{\alpha} + T (S_i')^{\alpha}]/RT \dots (10)$$

where $(G_i')^{\alpha} \equiv$ Gibbs free energy of pure component i in phase α at 1 atm and combustor temperature T.

To get the Gibbs free energy for each pure specie i at the combustor temperature, T and pressure, P, ideal gas is assumed in the gas phase. For the gas phase

$$G_i^{\alpha}/RT = (G_i')^{\alpha}/RT + \ln P \dots (11)$$

and for the condensed phases, it is known that pressure has a negligible effect upon them. Therefore, for the condensed phases

$$G_i^{\alpha}/RT = (G_i')^{\alpha}/RT \dots (12)$$

For coal combustion, the energy balance equation, equation (4), can be written as

$$\sum_{\alpha} \sum_i n_i^{\alpha} \int_{298}^T C_{P_i}^{\alpha} dT + Q_{lost} = \sum_{\alpha} \sum_i n_i^{\alpha} (\Delta H_{fp})_i^{\alpha} - \sum_{\alpha} \sum_i (n_i^{\alpha})_{react} (\Delta H_{fr})_i^{\alpha}$$

where $(\Delta H_{fp})_i^{\alpha} \equiv$ heat of formation of specie i in phase α in the combustion product.

$(\Delta H_{fr})_i^{\alpha} \equiv$ heat of formation of specie i in phase α in the combustion feed.

The heat of formation of coal is determined from the coal heating value and analysis. The basic equations for the determination of the chemical equilibrium are now expressed in handier quantities.

A computer program was purchased from the University of Arizona. The computer program does the described calculations with one simplification. That is, the condensed phases are assumed to be pure components. The minimization of the system Gibbs free energy subject to the constraints of conservation of atoms is accomplished by the method of Lagrange multipliers (Ref. 4). The numerical technique used is the second order method of steepest descent. Detail description of the computer program can be found in Reference 2.

Chemical equilibrium calculations were made for the West Virginia Loveridge coal. The chemical analysis of the coal is listed in Table I. 600°F preheated air with 60% relative humidity at 70°F was used in the calculations. Combustion gas temperature and composition were calculated as functions of excess combustion air % under the condition of 4% and heat loss. Values of relevant species of the combustion gas and combustion gas temperatures are presented in Figures 1.1 to 1-4. An experimental combustion trial of the West Virginia Loveridge coal was carried out in the G.E. combustor on 1979 June 6. The validity of the computer model will be tested with the experimental results generated from the combustion trial.

This task is 30% complete.

Future plan of the chemical equilibrium calculation is to include sulfur removal additives in the calculation. The objective is to provide some insight in optimal air/fuel ratio and additive dosage for sulfur removal.

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1. Smoot, L.D. and Pratt, D.T., "Pulverized - Coal Combustion and Gasification - Theory and Application for Continuous Flow Processes", Plenum Press, New York, N.Y., 1979.
2. Chaves, R.M.C., "A Computer Program for the Calculation of Complex Chemical Equilibria", M. S. Thesis, The University of Arizona, 1976.
3. Stull, D.R. and Prophet, H., "JANAF Thermochemical Tables", Second Edition; U.S. Department of Commerce, 1971.
4. Sokolnikoff, I.S. and Redheffer, R.M., "Mathematics of Physics and Modern Engineering", Second Edition, 1966.

Figure 1.1

**Combustion Gas Temp.
Vs. % Stoichiometric Air
(W. Va. Loveridge Coal)**

Figure 1.2

**Mole Fraction Of O₂, CO, & CO₂
Vs. % Stoichiometric Air
(W. Va. Loveridge Coal)**

Figure 1.3

**Mole Fraction Of H₂ & H₂O
Vs. % Stoichiometric Air
(W. Va. Loveridge Coal)**

Figure 1.4

**Mole Fraction Of H₂S, SO₂, & SO₃
Vs. % Stoichiometric Air
(W. Va. Loveridge Coal)**

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.

A subcontract has been negotiated with General Electric Space Science Laboratory to design the initial test unit (Burner "A"), modeling the unit after the successfully operating GE/DOE closed cycle MHD coal combustor.

The design of the unit by GE is essentially complete; a cross-section is shown in Figure 2.1. GE has completed the detailed design of the coal and gas injector unit, which imparts an axial swirl to the incoming reactants to cause the cyclonic action. Detailed design of the balance of the combustor, including design of molds and mandrels where necessary, is in progress at Alcoa.

Figure 2.2 shows the proposed installation of Burner "A" in a 7-foot diameter ladle-type furnace. Installation in the ladle, rather than in the previously proposed 40,000 lb melting furnace, will allow better access and combustion control and the collection of better experimental data.

This task is 50% complete.

During the next quarter, the bulk of the design of Burner "A" should be completed.

Figure 2.1 Alcoa/GE 2 Stage Combustor-Cross Section

Figure 2.2 Revised Arnold Plant Layout

Task No. 3 - "Purchase Stack Gas Sampling Instrumentation"

An integrated stack gas analysis system has been ordered from Mine Safety Appliances Company, with delivery expected by December of this year. The system will automatically withdraw, condition (cool, dry and filter), analyze, and record gaseous samples from stage 1 product gas (partially combusted) or stack gas, or both on a preset timed cycle. Gaseous components determined by the system, range of concentrations and method of analysis are as follows:

- a) Reducing atmosphere (sample point G_1 in Figure 2.2)
 - 1) CO by Infra-red; 0-25%
 - 2) CO_2 by Infra-red; 0-10%
 - 3) CH_4 by Infra-red; 0-2%
 - 4) H_2 by Thermal Conductivity; 0-20%
- b) Oxidizing atmosphere (sample point G_2 in Figure 2.2)
 - 1) CO by Infra-red; 0-2000 ppm
 - 2) CO_2 by Infra-red; 0-20%
 - 3) SO_2 by Infra-red; 0-5000 ppm
 - 4) NO_x by Infra-red; 0-2000 ppm
 - 5) O_2 by Paramagnetic Analysis; 0-25%

This task is 95% complete.

Efforts under this task number will be directed toward any necessary expedition of the purchase order.

Task No. 4 - "Glass Chemistry Bench Scale Investigation"

INTRODUCTION

The following deliverables are now expected from this phase of the investigation:

- I. Laboratory Investigation
 - a) Literature search - report on slag characteristics, coal ash chemistries, leachability, effect of additives on coal ash properties and sulfur retention, and finally on the resistance of different refractories to coal ash slag corrosion.
 - b) Slag development - select a representative low fusion coal and investigate sulfur retainment and ash softening as influenced by additives. Test slags for chemical durability.
- II. Refractory Selection
 - a) Select refractories based on slag corrosion resistance by use of static cup tests. Refractory classes to be examined are: 1) high alumina phosphate-bonded plastics, 2) high alumina castables, 3) fused cast alumina or chromia materials, 4) alumina-chromia ramming mixes, and 5) silicon carbide.
- III. Combustion Investigation
 - a) Analyze natural and altered coal slags during coal combustion in GE's combustor and Alcoa's burner "A" as outlined in total program.
 - b) Dynamic slag resistance of refractories will be determined from actual performance of post-mortem examination from the combustion lining.

WORK ACCOMPLISHED THIS PERIOD

- I. Laboratory Investigations

Literature work is nearly completed on slag chemistries, refractory corrosion, as well as environmental pollution control. To date, two reviews have been compiled on slags and refractories. Other references surveyed in addition to those mentioned in the first quarterly report are:

Environmental

1. Yang, R.T. et al., Environmental Science & Technology, Vol. 12, 915, 1978.
2. Yang, R.T. and Shan, M., DOE, Contract No. EY-76-C-02-0016 1978.
3. Friedman, S. and Warzinski, R.P., Engineering for Power, Vol. 99, No. 3, 1977.
4. Abelson, P.H., Science, Vol. 189, 253, 1975.
5. Vogel, R.F., Mitchell, B.R., and Massoth, F.E., Environmental Science Technology, Vol. 8, 432, 1974.

Refractory-Slag Corrosion

1. Bonae, J.A., Kennedy, C.R., and Swaeoop, R. submitted to the Journal of the American Ceramic Society.
2. Vojnovich, T. et al., EPRI, Contract No. RP625-1, 1977.

Laboratory investigations have proceeded by choosing a low fusion high volatile bituminous coal for preliminary testing. The coal is a Loveridge Spreader Stocker variety supplied by the Consolidation Coal Company. The chemical analyses and physical characteristics are given in Table I below:

TABLE I

ANALYSES OF LOVERIDGE SPREADER STOKER COAL

<u>Oxide</u>	<u>Chemical Wt%</u>
Al_2O_3	20.5
SiO_2	37.0
Fe_2O_3	19.6
CaO	6.8
MgO	1.3
Na_2O	1.1
K_2O	1.2
TiO_2	1.0
SO_3	7.3
Moisture	4.5%
Volatile Matter	37.2%
Fixed Carbon	50.3%
Ash	8.0%
Sulfur	2.6%
BTU	13,310

It was concluded that a low fusion coal, although resulting in a heavy slag buildup, could be best handled in the intended first-stage combustion chamber and would allow better reaction between additive and sulfur occurring in the partially combusted coal particles.

Although no single test has yet been devised which will provide a reliable index of the behavior of coal ash, ash fusibility has been recognized as a tool for measuring the deposit buildup and slagging performance of coals and is perhaps the most basic single means for predicting coal ash performance. In the ASTM cone test, ANSI-ASTM D 1857-68, the measure of the fusibility of the finely pulverized ash is the temperature at which the cone deforms to specified shapes when the temperature is raised at a specified rate under stated atmospheric conditions, these shapes being spherical for the softening temperature and spreading to a flat layer for the fluid temperature.

A picture of the Bickley PCE test furnace is shown in Figure 4.1. The furnace is specifically designed for pyrometric cone equivalent determinations. It is equipped with an air/oxygen/gas combustion system and is suitable well above those temperatures considered for fusion. The combustion system is controlled by a single valve. Direct reading flowmeters assure accurate gas, oxygen, and air flow. The furnace meets all the specified requirements.

In this study, the Loveridge coal was ashed with different additives according to the standard. The softening temperatures of thirteen different additive combinations under stoichiometric 10%, 20% and 30% reducing conditions are reported in Table II. The neat Loveridge coal with no additives had a softening temperature of 1255°C as reported by Consolidation Coal Company. Upon reducing the oxygen/gas ratio to 20% below stoichiometric, however, the fusion point decreases to 1100°C. This effect is basically due to the effect of iron on the ash behavior. (The lower oxidized forms of iron can significantly reduce melting points. This phenomenon is well supported). Six different chemicals were next evaluated as to their influence on lowering the fusion. 1.36 wt.% of Colemanite, CaB_2O_7 , to the coal provided the lowest melting, 1085°C, followed by additives of Li_2CO_3 (1130°C), CaCO_3 (1197°C) and red mud (1200°C). (red mud is a by-product of bauxite refining. A typical composition may contain 33-45% Fe_2O_3 , 6-10% TiO_2 , 14-25% Al_2O_3 , 4-10% Na_2O , 10-18% CaO and 9-15% SiO_2). These tests all support that lowering the oxygen/gas ratio does have a marked influence on melting. (See Figure 4.2). It is found that a slight reducing atmosphere lowers fusion, but beyond approximately 10% melting is influenced very little by atmosphere. This result suggests that the degree to which the combustion atmosphere is made, reducing will impact mainly on sulfur entrapment and not ash slagging characteristics.

Along with the cone tests, the ash was also analyzed for sulfur. Measurements were determined spectrographically and the preliminary results are listed in Table III. Experimentally, the coal with and without additives was first pulverized to pass a 250mm sieve. It was then coked in a muffled furnace, after which it was ignited in a stream of oxygen for 1-1/2 hours at 800 to 850°C to ensure complete and uniform oxidation of the ash. The resulting sulfur level in the ash from the neat coal was 1.51% compared to a percentage of 2.63% sulfur originally detected in the coal. Sulfur reported is recognized as sulfate sulfur, pyritic sulfur, and organic sulfur. The effect of various additives were again examined. Before coking they were thoroughly blended in a ball mill for 1 hour. As seen in the table, Na_2CO_3 , K_2CO_3 , and colemanite had very little absorption capacity for sulfur. CaCO_3 , Li_2CO_3 , red mud, and a combination of Li_2CO_3 and red mud, on the other hand, had better retention with CaCO_3 having the highest retention. Results are also given at the 20wt% and 30wt% ash level of some additives. More sulfur is trapped with Li_2CO_3 , red mud, and the combination of these two materials.

The sulfur analyses provide a relative comparison of various additives under a specific set of conditions. These values should not be misinterpreted. Tests were run under oxidizing conditions. Under a reducing atmosphere sulfur retention is expected thermodynamically to increase, and the order of absorption capacities of the materials listed may change. For example, in the case of red mud, the change in oxidation state of the iron will enhance the formation of Fe_2S . Under the limitations of our existing equipment, testing under reducing conditions is not planned. Observations and analyses will be obtained through combustor runs.

During this period, it was determined that the best procedure to determine the immediate surface washing and the time-dependent diffusion-controlled leaching from waste was to use the proposed ASTM standard, D19.12. In this test ashed samples are added to an aqueous solution and subjected to a shake test for 48 hours before analyzing the solution for leachable materials. Two extraction solutions are employed - Method A - a water extraction and Method B - a sodium acetate extraction. Shaking consists of agitating a known weight of waste with water or an acidic buffer on a reciprocating platform operated at 60-70 one inch strokes per minute. Once allowed to disperse for 48 hours, the aqueous phase is separated and submitted for analyses. Samples are being pulverized and blended at Alcoa, transferred to the Bureau of Mines in Pittsburgh, and then ground and tested by Alcoa's Environmental group. The neat coal alone and with additives of Na_2CO_3 , CaCO_3 , Li_2CO_3 , and Li_2CO_3 + red mud, are being prepared initially.

TABLE II

COAL ASH FUSION

<u>Composition</u>	<u>Stoich</u>	<u>Softening Temperatures</u>		
		<u>10% Reducing</u>	<u>20% Reducing</u>	<u>40% Reducing</u>
1. Loveridge Coal Ash	1255°C		1100°C	1100°C
2. 10wt% Na ₂ CO ₃	1208°C			
3. 10wt% K ₂ CO ₃	1256°C			
4. 10wt% Colemanite	1085°C			
5. 10wt% CaCO ₃	1197°C		1146°C	
6. 10wt% Li ₂ CO ₃	1130°C	1033°C	1025°C	1015°C
7. 10wt% Red Mud	1200°C		1145°C	1138°C
8. 10wt% (Li ₂ CO ₃ + Red Mud)	1130°C		1060°C	1055°C
9. 20wt% Li ₂ CO ₃	1065°C		968°C	
10. 20wt% Red Mud	1255°C		1163°C	
11. 20wt% (Li ₂ CO ₃ + Red Mud)	1056°C		1010°C	
12. 30wt% Li ₂ CO ₃	1105°C		945°C	
13. 30wt% Red Mud	1268°C		1176°C	

TABLE III

SULFUR ANALYSES DATA

<u>Composition</u>	<u>% Sulfur Retention</u>
Coal	2.63
Coal Ash	1.51
10wt% Na_2CO_3	1.57
10wt% K_2CO_3	1.79
10wt% Colemanite	1.20
10wt% CaCO_3	3.95
10wt% Li_2CO_3	2.12
10wt% Red Mud	2.30
10wt% Li_2CO_3 + Red Mud	2.43
20wt% Li_2CO_3	4.79
20wt% Red Mud	2.74
20wt% Li_2CO_3 + Red Mud	3.16
30wt% Li_2CO_3	6.90

II. Refractory Selection

Background

The design criteria for refractory liner selected by GE was as follows:

1. Compatibility with coal slag at or near the slag fusion temperature in an oxidizing environment.
2. Thickness was dictated by heat transfer and the desired air coolant flow rate and slag wall temperature.
3. Ease of fabrication including external air cooling slots, machinability.
4. Less than fully dense refractory material in order to prevent small crack propagation.
5. Refractory must be commercially available, with vendors having fabrication experiences. Concerns were expressed to have better temperature control of the average combustor wall slag layer temperature and therefore provide control of the slag layer thickness and flow characteristics. Air cooling was considered a desirable feature. Without the close control of the local refractory surface temperature, it was felt that premature failure of the refractory lining under average conditions which the material should have survived.
6. Structural integrity and gas stream isolation during start-up, operation, and shutdown.
7. Ease of modification (replacement).

However, to provide close control, no air gaps between the refractory and the steel are allowed.

Experiments conducted by GE in cooperation with Combustion-Engineering Refractories showed that a rammed plastic, Emerald Ram (alumina-chromia refractory) could be installed and fired successfully without leaving an air gap.

Progress

To select refractories for Alcoa's burner A, consideration is being given initially to (1) Emerald Ram (an alumina-chromia plastic manufactured by CE Refractories which was used in GE combustor, (2) Shamrock 88 Plastic, a similar material by Didier Taylor Refractories, (3) fused cast alumina-chromia, and (4) fused cast chromia materials. Manufacturer data sheets are supplied in Tables IV and V.

TABLE IV

TECHNICAL DATA ON ALUMINA CHROME PLASTICS

<u>Chemical Analyses %</u>	<u>CE Refractories Emerald Ram</u>	<u>Didier Taylor Refractories Shamrock 888</u>
Al_2O_3	84.6	85.2
Cr_2O_3	9.6	9.7
P_2O_5	3.0	2.3
SiO_2	2.3	1.9
Fe_2O_3	0.3	0.5
Na_2O	0.1	0.4

Physical Properties

Bulk Density	203	210
Linear Firing Change:		
110°C (230°F)	0.0	0.0
540°C (1000°F)	-0.14	-0.03
1090°C (2000°F)	-0.05	-0.03
1370°C (2550°F)	-0.33	-0.04
Modulus of Rupture:		
540°C (1000°F)	2010	2063
1090°C (2000°F)	3010	2170
1370°C (2550°F)	4450	2591

TABLE V

TECHNICAL DATA
FUSED CAST REFRACTORIES

<u>Chemical Analyses, %</u>	<u>Carborundum Monofrax K-3</u>	<u>Carborundum Monofrax E</u>
Al ₂ O ₃	60.40	4.7
SiO ₂	1.77	1.3
Cr ₂ O ₃	27.26	79.7
MgO	6.05	8.1
Fe ₂ O ₃	4.21	6.1
Na ₂ O	0.31	-

Physical Properties

Bulk Density	3.90	4.09
% Apparent Porosity	4.23	-
Reheat-% Linear Change (2550°F)	+0.17	-
Modulus of Rupture	7950	-

Because of the increased alkali's in coal slag to enhance sulfur entrapment within Alcoa's burner, fused cast refractories may make the best liner. To support this theory, refractories from GE combustor lining are being analyzed petrographically. Mechanisms of coal ash attack will be determined. Additionally, static cup tests with a low fusion chemistry slag will be conducted to examine Emerald Ram and Shamrock 88 plastics.

The cup test is conducted by heating a known quantity of a specified ash into a cup-like depression made in a fired refractory. The sample is then placed in a furnace for 72 hours at 1100°C (2000°F). At the end of 72 hours, the refractory is cut in half and the depth of metal attack in the refractory recorded. The corroded product is analyzed petrographically.

A parametric study of the heat transfer with the gasifier, using two different designs employing fused cast refractories and plastic ram, has been completed by GE. In one case, the hot face material is an alumina-chromia plastic wall and the other material is a fused cast alumina-chromia backed by plastic (See Figure 4.3). Identical parameters were used:

Outer Metal Shell OD = 30.00 inches
Inner Metal Shell ID = 29.00 inches
Total Cooling Air = Secondary Air = 1,800 LBM/hr
Combustion (Gasification) = 0.550
Pressure = Psig
Gas Temperature = 2,600°F
Gas Mean Molecular Weight = 26.926
Gas and Particle Emissivity = 0.170
Slag Emissivity = 0.90
Wall Tangential Velocity = 300 ft/sq
Combustor Inner Diameter = 23.50 inches at front
 Est. = 24.00 inches at exit
Coal Feed Rate = 300 LBM/hr
Primary Air = 300 LBM/hr
Slag Layer Thickness = 2mm
Slag Thermal Conductivity = 1.734 Btu/ft/F/hr
Emerald Ram Averaged Thermal Conductivity = 2.250 Btu/ft/F/hr
Fused Cast Alumina-Chromia = 2.250 Btu/hr/ft/F
Steel Thermal Conductivity = 29.0 Btu/ft/F/hr
Combustor Inner Length = 4.5ft

The next four Figures 4.4 - 4.7 show temperature and heat flux distributions.

The refractory concept in either case is a good one. Temperatures at each of the indicated interfaces are nearly the same. The total heat flow difference is only 11,797 Btu/hr.

III. Combustion Investigation

Slags from actual combustion runs have not as yet been analyzed. Slags to be studied from GE's combustor have been collected from an Illinois #6 coal. Although this coal is somewhat different from the Pittsburgh West Virginia Loveridge selected for Alcoa burner "A", initial tests on both are high volatile bituminous coals (See typical ash content and ash fusion temperature in Table VI). Ash fusibility values are similar. The Illinois No. 6 coal does however, have a higher ash and sulfur content.

During this year's period, several GE runs were observed. All except one was under oxidizing conditions. Generally, when the atmosphere was oxidizing, the slag did not collect uniformly in the combustion chamber. Stalactite formation was observed. When subjected to a very lean combustion of 35% reducing, a very clean and open channel resulted. This result shows good slag flow and combustion is very promising.

As discussed previously, the slag-refractory interactions from GE's runs are being analyzed.

This task is 60% complete.

TABLE VI

ASH CONTENT AND ASH FUSION TEMPERATURES
OF PITTSBURGH WEST VIRGINIA AND
NO. 6 ILLINOIS COALS

<u>Seam & Location</u>	<u>Pittsburgh W. Virginia</u>	<u>No. 6 Illinois</u>
Ash, Dry Basis %	10.9	17.36
Sulfur, Dry Basis %	3.5	4.17
Analysis of Ash % by Wt:		
SiO ₂	37.6	47.5
Al ₂ O ₃	20.1	17.9
TiO ₂	0.8	0.8
Fe ₂ O ₃	29.3	20.1
CaO	4.3	5.8
MgO	1.3	1.0
Na ₂ O	0.8	0.4
K ₂ O	<u>1.6</u>	<u>1.8</u>
Total	95.7	95.2
<u>Ash Fusibility</u>		
Initial Deformation Temp. °F:		
Reducing	2030	2000
Oxidizing	2265	2300
Softening Temperature, °F:		
Reducing	2175	2160
Oxidizing	2385	2430
Hemispherical Temperature, °F:		
Reducing	2225	2180
Oxidizing	2450	2450
Fluid Temperature, °F:		
Reducing	2370	2320
Oxidizing	2540	2610

Figure 4.1
PCE Test Furnace Set-up

**Effect Of Oxygen/Gas Ratio
On Ash Fusion Temperatures
Figure 4.2**

1

2

(To Be Installed
After Fused Cast
Refractory For
Good Heat Transfer)

**Alterations: Combustor Refractory Liners
Figure 4.3**

RA = 0.350	IN	T1 = 2600.000	F
EEI = 0.150	IN	PREC= 1.000	PSIG
EEF = 0.150	IN	PREH= 1.000	PSIG
R2I = 11.750	IN	WC = 0.611	LBM/SEC = 2200 lb _m /hr
R2F = 12.000	IN	XK23= 1.333	BTU/HR/FT/F
TH = 2600.000	F	XMM = 26.926	
TL = 4.500	FT	NG = 120.000	
EG = 0.170		EW = 0.900	
VISH= 0.38542	*E-4	HLAM= 0.0442	
R3 = 1.208	FT	R5 = 1.2500	FT
R4 = 1.2492	FT	DD = 0.0363	FT
UT2 = 300.000	FT/SEC	UAX = 119.400	FT/SEC

Figure 4.4

Heat Flux Predicted Using an Alumina-Chromia Plastic Refractory Combustor Liner

AR = 0.350	IN	T1 = 2600.000	F
EE1 = 0.150	IN	PREC= 1.000	PSIG
EEF = 0.150	IN	PREH= -1.000	PSIG
R2I = 11.750	IN	WC = 0.611	LBM/SEC
R2F = 12.000	IN	XK23= 1.333	BTU/HR/FT/F
TH = 2600.000	F	XMM = 26.926	
TL = 4.500	FT	NG = 120.000	
EG = 0.170		EW = 0.900	
VISH= 0.38542	*E-4	HLAM= 0.0442	
R3 = 1.208	FT	R5 = 1.2500	FT
R4 = 1.2492	FT	DD = 0.0363	FT
UT2 = 300.000	FT/SEC	UAX = 119.400	FT/SEC

Q TOTAL = 303.064 * (1000.) BTU/HR

Figure 4.5

Thermal Distribution of a Fused Cast Alumina Liner
Backed by an Alumina-Chromia Plastic Refractory

RA = 0.350	IN	T1 = 2500.000	F
EEI = 0.150	IN	PREC= 1.000	PSIG
EEF = 0.150	IN	PREH= 1.000	PSIG
R2I = 10.750	IN	WC = 0.611	LBM/SEC = 2200 LBM/HR
R2F = 11.000	IN	XK23= 2.250	BTU/HR/FT/F
TH = 2600.000	F	XMM = 26.926	
TL = 4.500	FT	NG = 120.000	
EG = 0.170		EW = 0.900	
VISH= 0.38542	*E-4	HLAM= 0.0442	
R3 = 1.167	FT	R5 = 1.2500	FT
R4 = 1.2083	FT	OD = 0.0363	FT
UT2 = 300.000	FT/SEC	URX = 119.400	FT/SEC

Figure 4.6

Heat Flux Predicted Using a Fused Cast Alumina Liner
Backed by an Alumina-Chromia Plastic Refractory

RA = 0.350	IN	T1 = 2600.000	F
EE1 = 0.150	IN	PREC= 1.000	PSIG
EEF = 0.150	IN	PREH= 1.000	PSIG
R2I = 10.750	IN	WC = 0.611	LBM/SEC
R2F = 11.000	IN	XK23= 2.250	BTU/HR/FT/F
TH = 2600.000	F	XMM = 26.926	
TL = 4.500	FT	NG = 120.000	
EG = 0.170		EW = 0.900	
VISH= 0.38542	$\times E-4$	HLAM= 0.0442	
R3 = 1.167	FT	R5 = 1.2500	FT
R4 = 1.2083	FT	OD = 0.0363	FT
UT2 = 300.000	FT/SEC	URX = 119.400	FT/SEC

Q TOTAL = 314.861 $\times$ (1000.) BTU/HR

Figure 4.7

Figure 5.1
Process Flow Diagram

ALUMINUM COMPANY OF AMERICA									
<div style="display: flex; justify-content: space-between;"> <div> <p>DATE: _____</p> <p>BY: _____</p> <p>REVISION: _____</p> </div> <div> <p>PROJECT: _____</p> <p>DESIGN: _____</p> <p>CONSTRUCTION: _____</p> </div> </div>									
<p>APPROVED: _____</p> <p>DATE: _____</p>									

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

A process flow diagram and equipment layout drawing for the Phase I combustion system are shown in Figures 5.1 and 2.2, respectively. Initial plans to test the Phase I combustor in a 40,000 lb melting furnace have been revised; the unit will be installed in a 7-foot diameter ladle-type furnace in order to obtain improved combustion data. An additional 7-foot diameter ladle will be used in the heat recuperation phase of the project.

Sufficient coal for up to six hours of operation (2100 lb) will be batch pulverized in the existing Riley Stoker Atrita Unit and transported pneumatically to the coal feed bin, where the fine coal will be disengaged in the coal transport cyclone. During actual combustion, coal at rates to 350 lb/hr and additive at rates of 3.5 to 70 lb/hr (1 - 20 wt % of the coal rate) will be metered using appropriately sized screw feeders and transported pneumatically to the fluid bed mixer. The solid feed to the combustor (coal + additive) will be conveyed by primary air through a dip-pipe extending into the fluidized bed. The fluid bed should eliminate pulsations frequently experienced with screw feeders, in addition to thoroughly mixing the two solids.

Additional major equipment items shown on the PFD include the low-pressure combustion air (secondary and tertiary) blower, high-pressure cooling air blower, combustion air heater, deionized cooling water system and slag handling system.

Evaluation of existing equipment and design of new equipment items have begun, with long lead time units receiving priority. Anticipated process requirements indicate that available equipment can be used for the coal pulverizer, additive feeder, and combustion air blower and heater. Specifications have been established for the coal transport cyclone, coal feeder and bin, and the cooling air blower. The design of the deionized cooling water system, slag handling system and fluid bed mixer off-gas filter should be completed within two months. The design of the fluid bed mixer, which will be constructed and tested in-house, is approximately 75% complete.

This task is 25% complete.

In the next quarter, most of the mechanical design and 75% of the electrical design (including instrumentation) should be completed.

Task No. 6 - "Design Heat Recuperation Equipment"

Calculations have been performed which indicate that sufficient heat will be available in the products of combustion (POC's) leaving the 7-foot diameter ladle-type furnace, when fired with Burner "A", to maintain temperature in a second ladle functioning as a holding furnace. In later Burner "A" tests, this concept will be verified by actual testing. The duct leaving the melting ladle will be relocated, as shown by Item 10 in Figure 2.2, to allow part of the waste heat leaving the unit to be utilized in holding the second vessel at the temperature of molten aluminum.

This task is 5% complete.

The design of the ducting to test the heat recuperation concept will be started in the next quarter.

Task No. 7 - "Purchase Process Equipment"

Quotations have been solicited on the cooling air blower, coal transport cyclone and coal bin and feeder. As the design of other process equipment (Task No. 5) is completed, purchasing procedures will be started.

This task is 5% complete.

During the next quarter, mechanical and electrical equipment will be purchased as design work is completed. Long lead-time items will be given priority.

COST SUMMARY

In the first year the funds expended totaled \$322,985. The revised Baseline Cost Plan issued in 1978, October, called for first year expenditures of \$733,400. The primary reason for underspending during the first year was the decision to thoroughly survey the state-of-the-art in combustors of the type and size appropriate to this contract. A revised Baseline Cost Plan is now being developed.

PROGRAM MANAGEMENT

In 1978, October, Dr. G. K. Turnbull accepted a new assignment at Alcoa Laboratories necessitating his replacement as Program Manager of this contract. Mr. C. E. West was at that time identified as Program Manager and currently continues in that function.

In the third quarter of FY79, Mr. John E. Kuhn resigned from Alcoa to secure other employment. Mr. Donald L. Stewart, Jr. has become a member of the contract team and will coordinate system design, engineering and construction activities.

During this first year a subcontractual relationship was established with General Electric Company's Space Sciences Laboratory wherein the subcontractor will provide concept definition, review and assistance, engineering analysis, detailed design drawings, fabrication, installation and test operating experience and data evaluation resulting in the operation-ready Burner "A" test facility at the Alcoa Laboratories. The basis for such an arrangement is the GE laboratory experience in design and successful test operation of a novel, air cooled, horizontal, cyclone coal combustor as a potential heat source for closed cycle MHD power generation. This combustor concept, developed under DOE contract number EX-76-C-01-2238, is particularly suitable for direct application to the ALCOA combustor program in terms of its potential for thermal control of slag flow, low system heat loss and experimental design flexibility. The subcontract allows immediate transfer of DOE developed combustor technology benefiting another DOE program and will allow scaling and sulfur oxide removal data to be obtained to the benefit of both programs.