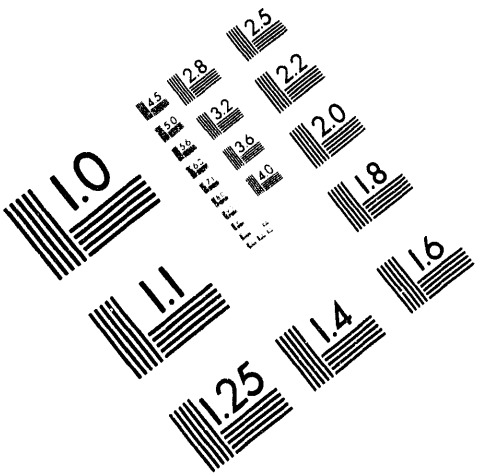
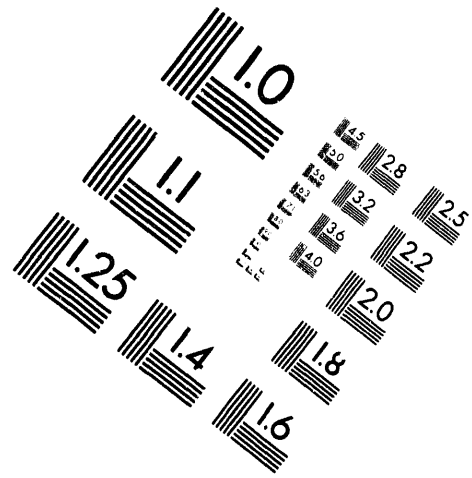
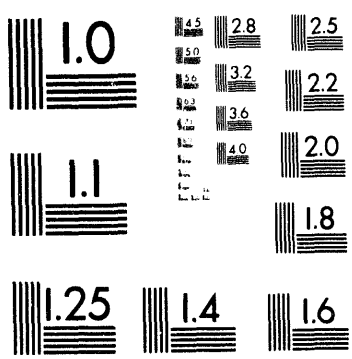


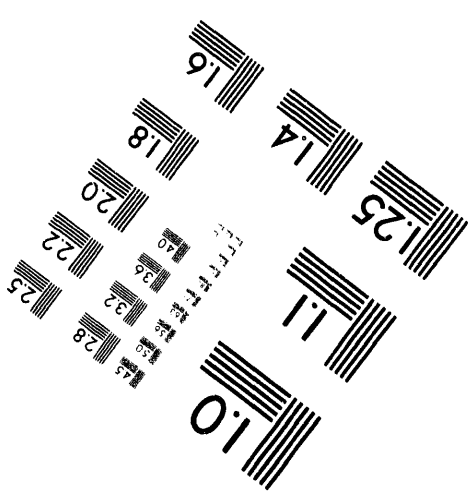
Association for Information and Image Management
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

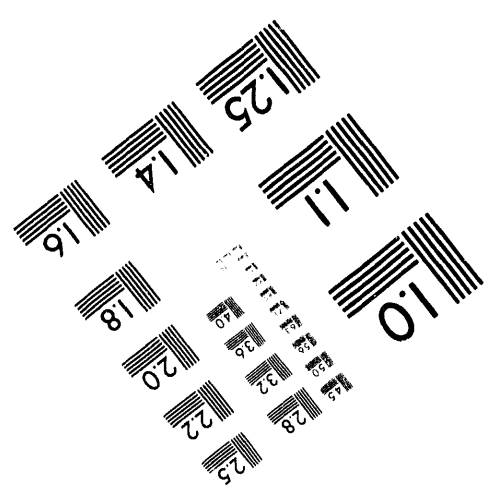


Centimeter

Inches







MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 3

DOE/MC/27259-3797
(DE94004149)

Moving Granular-Bed Filter Development Program

Topical Report

R. A. Newby
W. C. Yang
E. E. Smeltzer
T. E. Lippert

April 1994

Work Performed Under Contract No.: DE-AC21-91MC27259

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Westinghouse Electric Corporation
Science and Technology Center
Pittsburgh, Pennsylvania

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, 175 Oak Ridge Turnpike, Oak Ridge, TN 37831; prices available at (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

DOE/MC/27259-3797
(DE94004149)
Distribution Category UC-106, 117

Moving Granular-Bed Filter Development Program

Topical Report

R. A. Newby
W. C. Yang
E. E. Smeltzer
T. E. Lippert

Work Performed Under Contract No.: DE-AC21-91MC27259

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Westinghouse Electric Corporation
Science and Technology Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235-5098

April 1994

Table of Contents

1. Introduction 1

2. Summary 11

3. Conclusions and Recommendations 18

4. SMGBF Cold Model Testing 20
   4.1 Cold Model Test Facility 20
   4.2 Pellet and Fly Ash Materials 26
   4.3 Gas Flow Test Results 27
   4.4 Flyash Removal Test Results 31
      4.4.1 Exploratory Tests With a Constant Diameter Standleg 31
      4.4.2 Tests With a Flared Skirt 32
      4.4.3 Tests With a Bed Outside of a Flared Skirt 32
      4.4.4 Development of a Core Sampling Technique 38
   4.5 Interpretation For HTHP Conditions 42
   4.6 Cold Model Test Conclusions 44

5. PELLETIZATION STUDIES 47
   5.1 Pelletization Background 47
   5.2 Power Plant Waste Pelletization Experience 48
   5.3 Power Plant Waste Materials Tested 52
   5.4 Pellet Vendors and Techniques Used 53
   5.5 Pellet Vendor Results 56
   5.6 Pellet Durability Testing 57
   5.7 Pelletization Conclusions 71

6. SMGBF HTHP TESTING 72
   6.1 HTHP Facility 72
   6.2 Test Results 78
   6.3 Test Conclusions 84

7. EVALUATION FOR INTEGRATED GASIFICATION COMBINED-CYCLE APPLICATIONS 86
   7.1 IGCC, SMGBF Design and Evaluation Basis 86
   7.2 IGCC, SMGBF Process Description and Options 90
      7.2.1 Once-Through SMGBF 90
      7.2.2 Recycle SMGBF 95
   7.3 Design, Performance, and Cost Of Once-Through SMGBF 97
      7.3.1 Once-Through SMGBF Material and Energy Balances 97
      7.3.2 Once-Through SMGBF Equipment Sizing and Arrangement 102

7.3.3 IGCC, Once-Through SMGBF System Performance 109
7.3.4 Once-Through SMGBF System Cost 111
7.4 Design, Performance, and Cost of Recycle SMGBF 113
7.4.1 Recycle SMGBF Material and Energy Balances 113
7.4.2 Recycle SMGBF Equipment Sizing and Arrangement 113
7.4.3 Recycle SMGBF System Performance 119
7.4.4 Recycle SMGBF System Cost 126
7.5 SMGBF Comparison With Ceramic Barrier Filter System 129

8. EVALUATION FOR ADVANCED-PFBC APPLICATION 131
8.1 APFBC Process Basis and Description 131
8.2 APFBC SMGBF Process Description and Options 132
8.2.1 APFBC, Once-Through SMGBF 132
8.2.2 APFBC, Recycle SMGBF 136
8.3 Design, Performance, and Cost Of SMGBF 138
8.3.1 SMGBF Material and Energy Balances 138
8.3.2 SMGBF Equipment Sizing and Arrangement 141
8.3.3 SMGBF System Performance 141
8.3.4 SMGBF System Cost and Impact on Plant Cost 150
8.4 SMGBF Comparison With Ceramic Barrier Filter System 150

9. REFERENCES 156

Appendix A A List of Pelletization Equipment Vendors and Their Capability

Appendix B Vendors' Reports on Pelletization Results

Appendix C SMGBF HTHP Test Data Plots

Abstract

An advanced, moving granular bed filter has been conceived, and early development activities performed by the Westinghouse Electric Corporation, Science & Technology Center. This document reports on the Base Contract tasks performed to resolve the barrier technical issues for this technology. The concept, the Standleg Moving Granular Bed Filter (SMGBF) has a cocurrent downward, gas and bed media flow configuration that results in simplified features and improved scaleup feasibility compared to alternative designs. Two modes of bed media operation were assessed in the program: "once-through" using pelletized power plant waste as bed media, and "recycle" of bed media via standleg and pneumatic transport techniques. Cold model testing; high-temperature, high-pressure testing; and pelletization testing using advanced power plant wastes, have been conducted in the program. A commercial, economic assessment of the SMGBF technology was performed for IGCC and Advanced-PFBC applications. The evaluation shows that the barrier technical issues can be resolved, and that the technology is potentially competitive with ceramic barrier filters.

1. Introduction

Advanced, coal-based, power plants, such as IGCC and Advanced-PFBC, are currently nearing commercial demonstration. These power plant technologies require hot gas filtration as part of their gas cleaning trains. Ceramic barrier filters are the major filter candidates being developed for these hot gas cleaning applications. While ceramic barrier filters achieve high levels of particle removal, concerns exist for their reliability and operability in these applications.

An alternative hot gas filtration technology is the moving granular bed filter. These systems are at a lower state of development than ceramic barrier filters, and may have some inherent disadvantages compared to ceramic barrier filters. The current, moving granular-bed filter technologies are relatively large, complex, and costly systems in terms of their capital investment, their operating and maintenance cost, and their impact on the power plant efficiency. They are not easily and effectively integrated into advanced power plant environments. In addition, their effectiveness as filters is still in question. Their apparent attributes, relative to ceramic barrier filter systems, result from their much less severe mechanical design and materials constraints, and the potential for more reliable, failure-free particle removal operation.

The Westinghouse Science & Technology Center has proposed a novel moving granular-bed filter concept, the Standleg Moving Granular-Bed Filter (SMGBF) system, that may overcome the inherent deficiencies of the current state-of-the-art moving granular-bed filter technology. The SMGBF system combines unique features that make it highly effective for use in advanced coal-fueled power plants. The SMGBF is a compact unit that uses cocurrent gas-pellet contacting in an arrangement that greatly simplifies and enhances the distribution of dirty, process gas to the moving bed and allows effective disengagement of clean gas from the moving bed.

The SMGBF vessel concept is elucidated in Figure 1.1. Dirty process gas is introduced into the top chamber of the filter vessel through a tangential entry. The moving bed media is introduced into the same chamber through a single, vertical dipleg pipe, where it spills from the base of the dipleg pipe to form a free surface having the normal media angle of repose. The dirty process gas enters the moving bed media through this free surface. Cocurrent flow of gas and bed media through the short, vertical standleg promotes intimate contact between the flowing gas stream and the moving bed media, resulting in excellent separation of flyash particles. The cocurrent gas/solids operation also prevents fluidization at the bottom of the standleg and permits high flow throughput (3 to 6 ft/s through the standleg), with relatively small ratios of bed media-to-flyash (mass ratio of about 10). The cleaned gas is then allowed to flow out through the free surface of the bed formed naturally below the standleg. Special design features are built into the region at the base of the standleg to permit disengagement of the cleaned gas from the moving bed media without significant flyash re-entrainment. The bed media and captured flyash withdrawal from the filter vessel is controlled by a water-cooled, rotary valve or screw conveyor located below the vessel. The SMGBF vessel design is relatively simple, and it employs well-known standpipe design technology, making it cost effective, reliable, and easy to scaleup.

Two approaches for bed media flow can be used, "continuous" flow or "on-off" flow. In the continuous flow approach, the media conveyor operates continuously and the filter bed reaches and remains at a relatively steady condition with the filter bed having a constant pressure drop. In the on-off flow mode, the media conveyor remains off until the filter bed pressure drop reaches a trigger value. At the trigger pressure drop, the media conveyor is activated and media flows through the SMGBF at a relatively high rate until the bed pressure drop is reduced to a baseline value. While the net media use rate is about the same for the two techniques, there may be particle removal efficiency advantages with the on-off technique compared to the

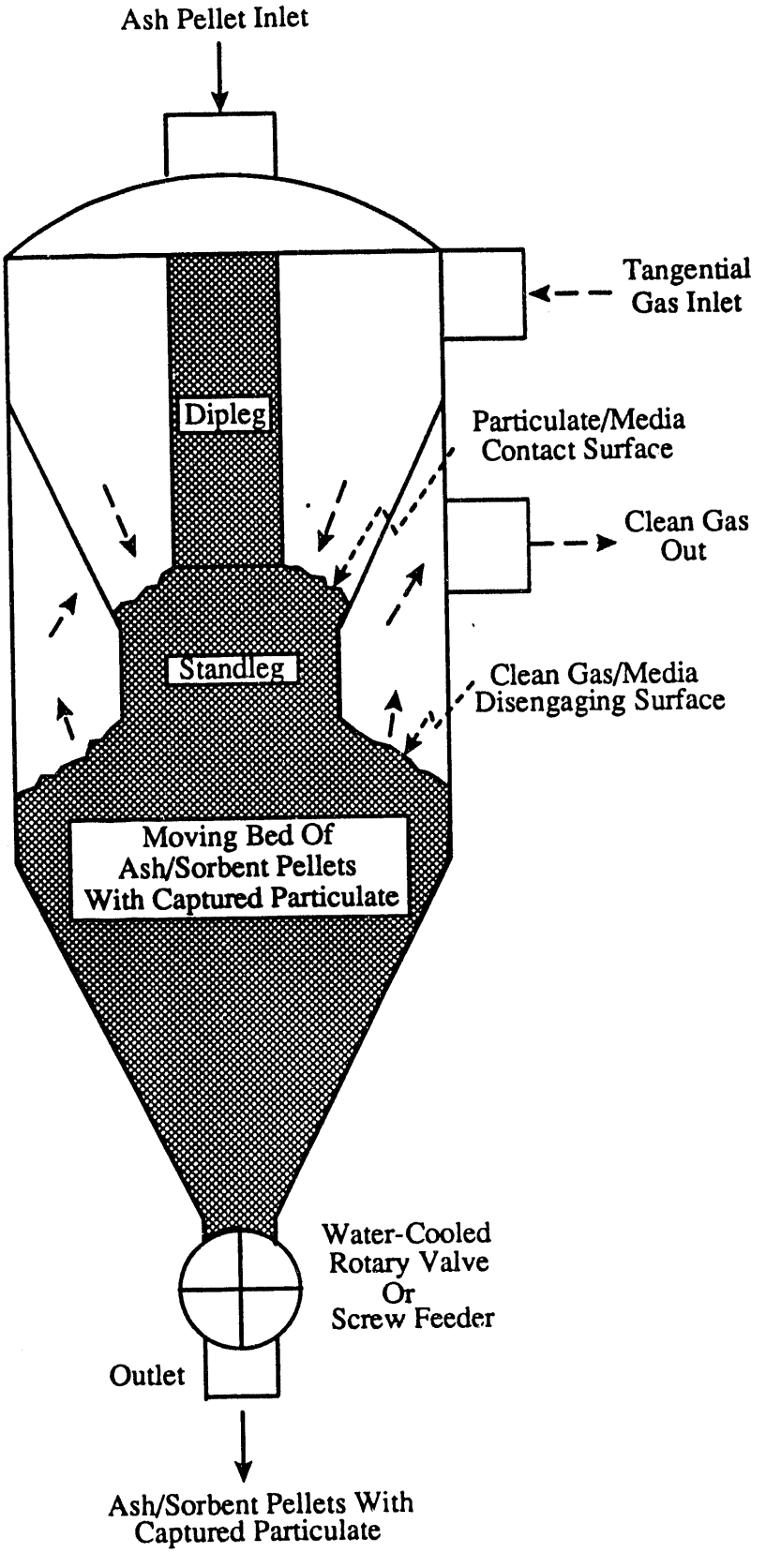


Figure 1.1 — SMGBF concept.

continuous flow technique. Experimental comparison is required to establish such an advantage.

Two approaches for handling the bed media can be applied to the SMGBF: "Once-Through" media operation, and "Recycle" media operation. Once-Through media operation applies pelletization technology to generate pellets from the power plant solid waste materials, and uses these pellets as a "once-through" filtering media to eliminate the need for costly, complex, and large filter media recycling equipment. This pelletizing step also generates a more environmentally acceptable solid waste product and provides the potential to incorporate gas-phase contaminant sorbents into the filtering media.

Recycle media operation recirculates granules from the SMGBF bottom withdrawal point to a top feed point, much as in the traditional moving granular bed filter approach. The SMGBF system performs this media circulation function by applying standleg, dense-phase flow and pneumatic transport that uses the dirty process gas to carry the granules. The granules are purchased bed media selected for its attrition resistance and it performance as a filtering media.

A general schematic diagram of the Once-Through SMGBF system in PFBC and IGCC applications is shown in Figure 1.2. The Once-Through SMGBF system is closely integrated with the power plant because of its need to utilize the power plant solid waste as the moving bed filter media while maintaining high power plant performance and economics. The major system components are:

- the S-MGBF modules and their connecting piping
- the plant solid waste handling system (solids cooling and heat recovery, depressurization, transport)
- the pelletization system (size reduction, pelletization)
- the pellet handling system (pressurization, transport, feeding and distribution)
- the pellet/dust cake handling system (cooling and heat recovery, depressurization, transport)

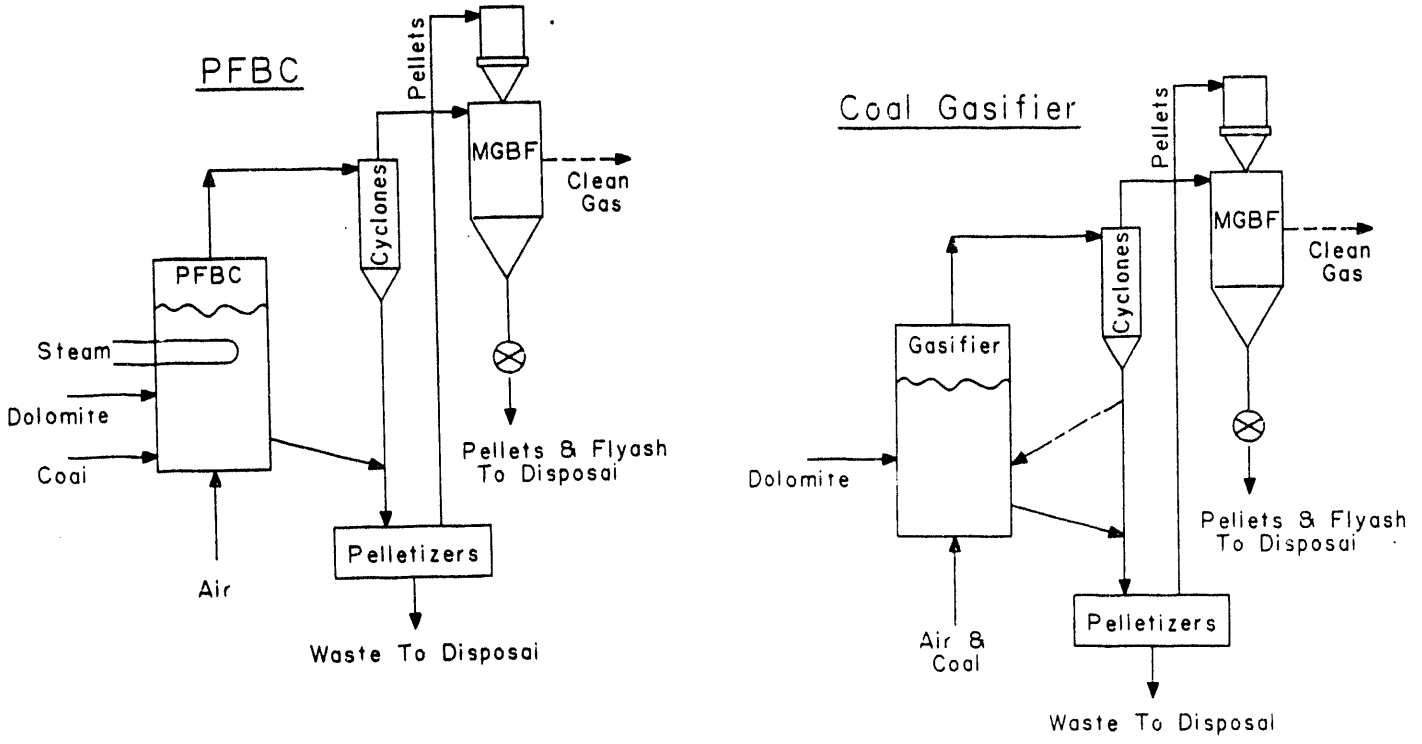


Figure 1.2 — Once-Through SMGBF system concept.

There are several equipment options for each of these system components, and some of them replace system components that would exist in the power plant when using ceramic barrier filters for particulate control. The solids handling systems and pelletization system are generally commercially available components, but their selection is highly dependent on the nature of the solid waste streams, and they may need to be adapted to environments (eg., high pressure) where they have not been previously demonstrated.

The pelletization system is a key system, and many pelletization techniques are available, applying principles of

- granulation
- pressure compaction
- extrusion compaction
- agglomeration (with or without binders)
- globulation (for slags, such as those in some entrained gasifiers and some DCFT)
- Heat bonding

The pelletization system must be integrated into the power plant to minimize complexity and to maximize energy efficiency, as well as being selected to produce sufficiently durable pellets for the SMGBF system.

The Recycle SMGBF system is conceptually illustrated in Figure 1.3. Granules and captured fly ash are drained from the SMGBF and ash-granule separation is performed to, at least, remove a portion of the captured fly ash. The granules are then aerated in a standleg pipe to increase their pressure so that they may be pneumatically transported back to the entrance of the SMGBF. The SMGBF configuration allows the transport to be accomplished by the dirty process gas, and fly ash not separated from the granules in the ash-granule separator are reintroduced to the SMGBF.

The SMGBF concept has apparent advantages over conventional granular bed filter technologies, as well as potential advantages over ceramic barrier filter technologies. Relative to conventional granular bed filter technology, the SMGBF is potentially

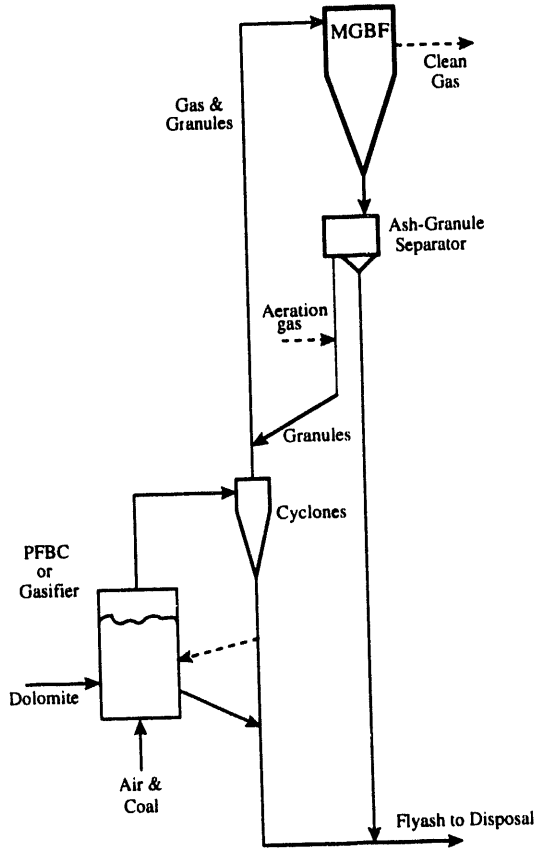


Figure 1.3 — Recycle SMGBF system concept.

- more compact, with fewer modules;
- simpler in design and layout, with no media recycle, or with simplified media recycle;
- lower in power consumption, with small media feed rate;
- more easily scaled up to commercial size;
- capable of dealing with plant solid waste issues;
- higher in performance.

These potential advantages can only be confirmed through experimental testing and conceptual design comparisons.

A meaningful comparison of the SMGBF system and ceramic barrier filters can be made in terms of their design features, cost factors, and technical issues and capabilities. The SMGBF has the following potential advantages over ceramic barrier filters:

- Simpler in design and scaleup;
- Comparable gas throughput;
- Easier operation and maintenance;
- Ability to handle difficult flyash particles (e. g., sticky particles) and gases (e. g., coking);
- Can operate at very high temperatures without water-cooled internals;
- Can operate with higher reliability, having no high-risk internals;
- More tolerant to process thermal and flow transients and upset conditions.

A SMGBF module is compared with a Westinghouse ceramic cross flow filter module in Figure 1.4, both having flow capacities of about 10,000 acfm. The SMGBF module is larger (about 13 ft vs about 10 ft) in diameter, and taller (about 45 ft vs about 35 ft). However, the internals design is much simpler in the SMGBF, requiring only one basic element for the SMGBF versus about 150 individual ceramic elements for the cross flow filter with associated gaskets, supports and blowback piping. Thus the internal structural design for the SMGBF should be simpler and cheaper.

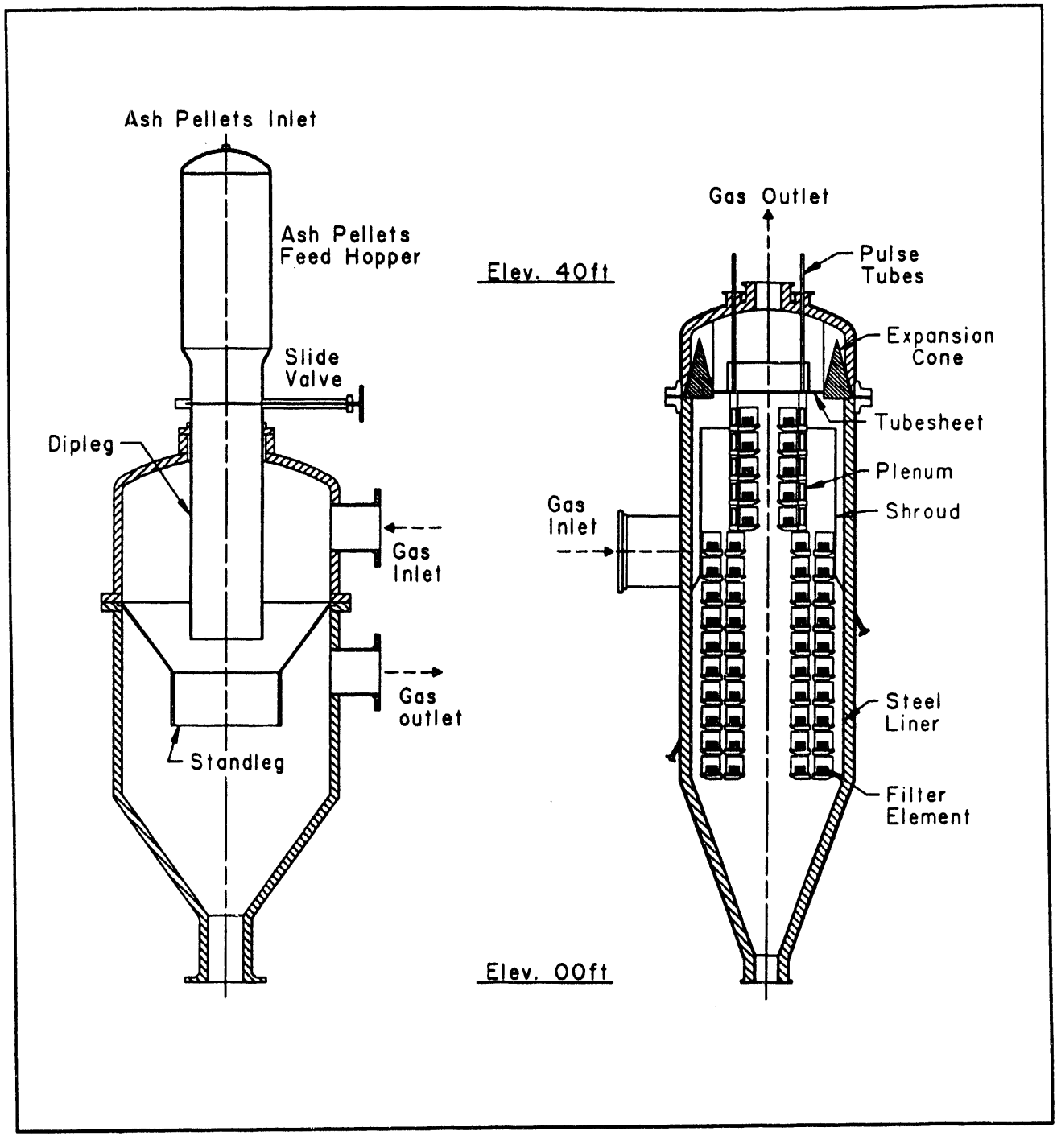


Figure 1.4 — SMGBF comparison with ceramic barrier filter.

The issues indicated for the two technologies reflect, to some extent, the state of development of these two gas cleaning systems. The nature of the uncertainties differ between the two technologies. The SMGBF system uncertainties are largely process oriented, as well as relating to the basic performance of the system. The ceramic barrier filter uncertainties are largely materials and mechanical design oriented, relating to both short-term and long-term component life. Overall, the key performance issues for the two technologies are the same: the reliability, operability, and availability of the particle removal system under conditions that meet all application performance requirements and constraints.

2. Summary

The SMGBF development program has completed the initial, Base Contract period of the four-phase program. The objective of the Base Contract period was to identify and resolve the barrier technical issues, demonstrating conceptual feasibility. The technical approach applied to achieve the Base Contract objective was to conduct commercial plant conceptual design evaluation, in combination with laboratory and bench-scale testing that focus directly on the barrier issues. These activities were performed in parallel to ensure that each had the appropriate perspective to provide significant results.

The SMGBF Base Contract program has addressed two barrier technical issues that were identified early in the program:

- the ability to achieve sufficient levels of fly ash removal with the SMGBF to meet environmental standards and turbine protection needs,
- the ability to generate sufficiently durable pellets by practical, economical pelletization methods that can be closely integrated into the advanced power plant.

While both of these issues are technical in nature, their degrees of freedom are greatly constrained by various economic and performance considerations.

Two major test efforts were undertaken to establish the conceptual feasibility of the SMGBF with respect to its ability to achieve sufficient fly ash removal, a cold flow model test program, and a high-temperature, high-pressure (HTHP) test program. The cold flow model test program was conducted first to investigate several design and operating features of the SMGBF in a facility where performance phenomena within the SMGBF unit could be visualized, where detailed probing could be easily performed, and where equipment changes could be

easily made. The HTHP testing was then conducted to show that the cold model trends were reproducible at HTHP conditions, and to demonstrate the SMGBF performance at small-scale, prototypic conditions. In parallel to the cold model test program, an effort to identify viable solid waste pelletization techniques, and to test pellet durability was conducted.

Section 4 of this report presents the details of the cold flow model test program. A new, cold flow model facility was designed and constructed. The model was constructed primarily of Plexiglas, with a vessel OD of 36", and a 36" long standleg having 12" OD. The test unit was designed to be highly sectionalized so that internal modifications could easily be performed, and was of a size that represented a reasonable scaling to commercial dimensions (factor of 4 to 10). Support facilities for the cold model test included a large bed media feed hopper located above the SMGBF vessel, a screw feeder and weight scale located below the SMGBF vessel to control and record the flow rate of bed media, a fly ash feed system (K-Tron, loss-in-weight screw feeder) to inject fly ash into the inlet gas, a fabric filter to capture the fly ash in the SMGBF outlet gas so that its particle removal performance could be monitored, and instrumentation to measure the pressure drop profile within the SMGBF unit.

The cold flow model testing was performed with crushed acrylic particles, having an average diameter of about 3800 μm, as the bed media. Acrylic was selected because it has a density low enough to provide proper scaling to the actual, high-pressure SMGBF environment. A series of cold flow model tests were performed to characterize the gas flow and bed pressure drop characteristics, and the bed media flow characteristics, without fly ash feed. No visible fluidization of the bed media could be detected at standleg velocities up to 6 ft/s, exceeding the bed media minimum fluidization velocity of 5 ft/s. The clean bed pressure drop was consistent with existing packed bed pressure drop correlations. Fly ash injection testing was performed with fly ash from a PFBC pilot plant (the Exxon Miniplant). Three SMGBF configurations were tested: the simple, constant diameter standleg

configuration, a flared skirt section added at the base of the standleg, and a secondary, or topping bed added to surround the standleg skirt. Operating with a standleg gas velocity of about 3 ft/s, a bed media to fly ash mass feed ratio of about 10, and an inlet fly ash loading of about 6400 ppmw, total unit pressure drop was acceptable at less than 40 in. H_2O, and the particle removal performance achieved was greater than:

- 97% removal with the simple standleg configuration,
- 99% removal with the added skirt section,
- 99.95% with the added topping bed.

Test durations were extended to relatively long periods of time to ensure that steady levels of performance were achieved. The cold flow model testing identified the key phenomena controlling the SMGBF performance, established the design features needed to achieve high levels of performance, and demonstrated the potential performance capabilities of the SMGBF. The cold flow model testing was representative of both the Once-Through and Recyle SMGBF performance capabilities.

The pelletization studies performed in the Base Contract are described in Section 5 of this report. Pelletization studies were performed by collecting representative solid waste samples from various advanced, coal-fired power plant units, and having commercial vendors prepare pellets from these wastes by several commercial techniques. Solid waste samples from both IGCC plants and PFBC plants were collected, as well as from some AFBC plants. All of these were successfully pelletized by several vendors. The generated pellets were then tested for durability by simple furnace heating tests, and by a standard rotary attrition test that was adapted by Westinghouse to high-temperature conditions. The attrition test subjected the pellets to much more severe attrition conditions than they would see in the SMGBF application. The results indicated that sufficiently durable pellets can be produced with advanced power plant solid wastes using conventional pelletization methods, but more evaluation is required to

develop optimum techniques for solid waste sizing, water and binder content, mixing, and curing.

The HTHP testing performed during the Base Contract is described in Section 6 of this report. An existing HTHP test facility previously used to test ceramic barrier filter elements was adapted to test the SMGBF. The pressure vessel used in the program had an OD of 40" and a total vessel height of about 10 feet. A new vessel head was constructed with a tangential gas inlet nozzle, and the natural gas-fired combustion system was moved to the head gas inlet location. The standleg internals inserted in the vessel had a 6" diameter, and were operated at a standleg velocity of about 3 ft/s in most of the testing. The standleg was constructed with a skirt section attached at its base, with its design based on the cold flow model results. A pressurized, water-cooled screw conveyor was added to the facility to control the flow of bed media through the unit. A batch feed hopper for bed media was located over the SMGBF vessel. The tests were performed under conditions simulating a PFBC application:

- temperature of 1500 to 1600°F,
- pressure of 100 psig,
- injected PFBC fly ash at inlet loadings of 1000 to 7000 ppmw.

A total of 18, high-temperature test runs were completed in the Base Contract test program. The tests were arranged in three major series:

1. On-off bed media flow with pelletized fly ash,
2. Continuous bed media flow with alumina beads,
3. Continuous bed media flow with pelletized fly ash.

The pelletized fly ash used in the tests was Aardelite, a commercial, pelletized, pulverized coal (PC) power plant fly ash product. The on-off bed media flow testing showed very high levels of particle removal performance, with outlet loadings of 2 to 20 ppmw, but operational problems would not permit representative, steady operation to be achieved. Subsequent, continuous bed media flow testing with alumina

beads, a mixture of 1/4" and 3/8" diameter beads, was performed without operational problems, but the higher density, more uniform sized and shaped; alumina beads resulted in poorer particle removal performance, with outlet loadings of 6 to 250 ppmw. The final series of tests, with continuous bed media flow of pelletized fly ash achieved good performance, with acceptable unit pressure drop and outlet loadings of 8 to 14 ppmw. The HTHP testing showed a clear trend for higher particle removal performance as the mass ratio of bed media to fly ash flow was increased, and demonstrated a particle removal performance acceptable for commercial applications. Mass ratios of bed media to fly ash were in the range of 10 to 20 for acceptable performance.

The overall goal of the SMGBF development program is to realize a moving granular bed filter system that meets all of the performance requirements and design constraints imposed by advanced power generation applications, and that is economically competitive with ceramic barrier filter systems. A conceptual, economic design evaluation was performed to assess this comparison, and this is described in Sections 7 and 8 of this report. Conceptual design evaluations were conducted for IGCC and Advanced-PFBC applications of the SMGBF technology, and comparisons were made with ceramic barrier filter technology by applying Reference Studies conducted previously for ceramic barrier filter applications. Process flow diagrams and material & energy balances were developed for the IGCC and Advanced-PFBC applications using SMGBF hot gas cleaning. Only the continuous bed media flow technique was considered in the evaluation. Both Once-Through and Recycle SMGBF were evaluated. The SMGBF system equipment was sized and specified to the extent needed to develop equipment delivered and installed cost estimates and to produce rough plant equipment layouts. The impact of the SMGBF system on the power plant thermal efficiency was estimated based on estimated heat losses, SMGBF system gas pressure drop, and auxiliary power consumption. Finally, total power plant capital requirements, annual operating costs and cost-of-electricity (COE) estimates were made, updating the Reference Studies to the current plant economic premises.

The evaluation results show that the SMGBF system is economically competitive with ceramic barrier filters for IGCC and Advanced-PFBC applications. The installed equipment costs of the SMGBF system are comparable to those of the ceramic barrier filter systems, although the pelletization system adds a significant equipment cost to the Once-Through SMGBF system:

- installed equipment cost for IGCC application
  - Once-Through SMGBF, 32 - 41 $/kW
  - Recycle SMGBF, 17 - 22 $/kW
  - ceramic barrier filter, 11 - 19 $/kW
- installed equipment cost for Advanced-PFBC application
  - Once-Through SMGBF, 31 $/kW
  - Recycle SMGBF, 18 $/kW
  - ceramic barrier filter, 17 $/kW

The Once-Through SMGBF system has a higher total power plant capital cost, annual operating cost, and COE than the ceramic barrier filter system for IGCC and Advanced-PFBC, but these cost increases are small, about 1% for IGCC, and about 3-5% for Advanced-PFBC. The waste material issued from the plants using Once-Through SMGBF potentially have a superior environmental character, or even byproduct possibilities. The Recycle SMGBF system total power plant capital cost, annual operating cost and COE is nearly identical with that of the ceramic barrier filter system.

While the economics of the SMGBF system are comparable with that of ceramic barrier filter systems, the key development aspects for commercial success for both of these technologies are reliability, availability, and operability. The specific development needs for the SMGBF system are:

- Scaleup to large SMGBF capacities (up to 18 ft standleg diameter for Advanced-PFBC), or arrangement and integration of large numbers of SMGBF modules.

- Once-Through SMGBF
  - effective process integration with the plant solid waste streams,
  - integrated process reliability and operability, including pellet durability and particle removal efficiency,
  - demonstration of pellet environmental performance advantages, or byproduct uses.

- Recycle SMGBF
  - operability and reliability of the granule circulation system,
  - development of an effective ash-granule separation system.

3. Conclusions and Recommendations

The Base Contract conclusions reached in the test program are:

- Design features have been identified in the cold flow model testing that improve the SMGBF particle removal performance — the standleg skirt and the secondary, topping bed are major examples.

- Cold flow model and HTHP testing trends are consistent.

- Particle penetration levels of 6 to 14 ppmw are representative performance levels based on the HTHP testing, with the cold flow model testing indicating that even higher performance levels can be achieved.

- Particle removal performance increases and the unit pressure drop decreases as the mass feed ratio of bed media to fly ash increases. Ratios of 10 to 20 are required for acceptable performance.

- Sufficiently durable pellets can be generated from advanced power plant solid waste using conventional pelletization techniques, but further evaluation of optimum solid waste sizing, water and binder content, mixing, and curing procedures is needed.

- The pelletized solid waste may provide particle removal performance superior to more regular shaped and uniformed sized purchased granules.

The conceptual design evaluation has resulted in the following conclusions:

- The Once-Through SMGBF system is more expensive than ceramic barrier filter systems for both IGCC and Advanced-PFBC applications, but total power plant capital requirements and COE are only marginally higher (1 to 5%).

- The Recycle SMGBF system is comparable in cost to the ceramic barrier filter system for both IGCC and Advanced-PFBC applications.

- The key development aspects for commercial success for both SMGBF and ceramic barrier filter technologies are reliability, availability, and operability.

- The specific development needs for the Once-Through SMGBF system are:
  - scaleup to large SMGBF capacities,
  - effective process integration with the plant solid waste streams,
  - integrated process reliability and operability, including pellet durability and particle removal efficiency,
  - demonstration of pellet environmental performance advantages, or byproduct uses.

- The specific development needs for the Recycle SMGBF system are:
  - scaleup to large SMGBF capacities,
  - operability and reliability of the granule circulation system,
  - development of an effective ash-granule separation system.

It is recommended that Option 1 of the SMGBF program be conducted and that it deal with these development issues through continued cold flow model and HTHP facility testing.

4. SMGBF Cold Model Testing

4.1 COLD MODEL TEST FACILITY

The cold model test facility depicted in Figure 4.1 is an integration of four separate subsystems — the air supply, the dust feeding, the SMGBF, and the air exhaust subsystems. The air was supplied by a Spencer Lobe-Aire positive displacement heavy duty blower (Model RB 110/V) rated at 1350 SCFM at a differential pressure of 12 psig. The air flow was controlled by adjusting the opening of the control valve located at the bypass line. The process air first passed through a heat exchanger to reduce the temperature and then through a turbine flowmeter for flow measurement. The outlet temperature of the air could be adjusted by varying the cooling water circulation rate in the heat exchanger. The simulated dirty gas was produced by injecting dust into the air stream employing the dust feeder. The amount of dust injected was measured by the loss in weight of dust in the feed hopper. The dust feeding system is capable of feeding dust up to 5 lb/min, or 4.9 ft^3/hr. The cleaned gas, after exiting the SMGBF, exhausted into a bag house with automatic pulse-back cleaning for final particulate removal. The amount of particulate retained in the baghouse could then be translated into collection efficiency for the SMGBF. Underneath the baghouse, there were two in-line valves with a particulate collection pot in between. This arrangement allowed continuous sampling of baghouse collection during operation.

The heart of the cold model test facility is the Standleg Moving Granular Bed Filter (SMGBF), shown in more detail in Figure 4.2 and pictured in Figure 4.3. The SMGBF subsystem consists of the pellet

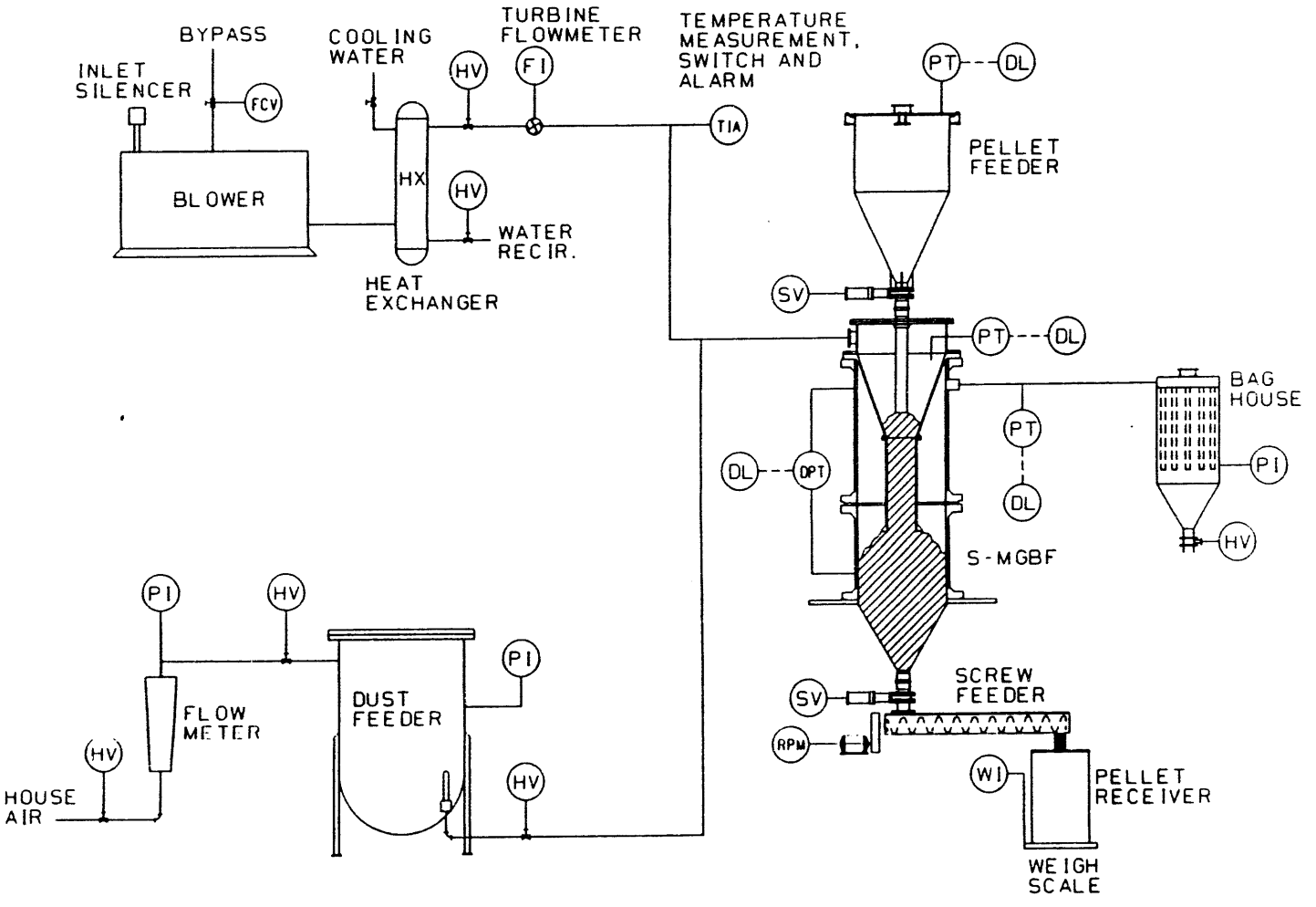


Figure 4.1 — Cold Model Test Facility.

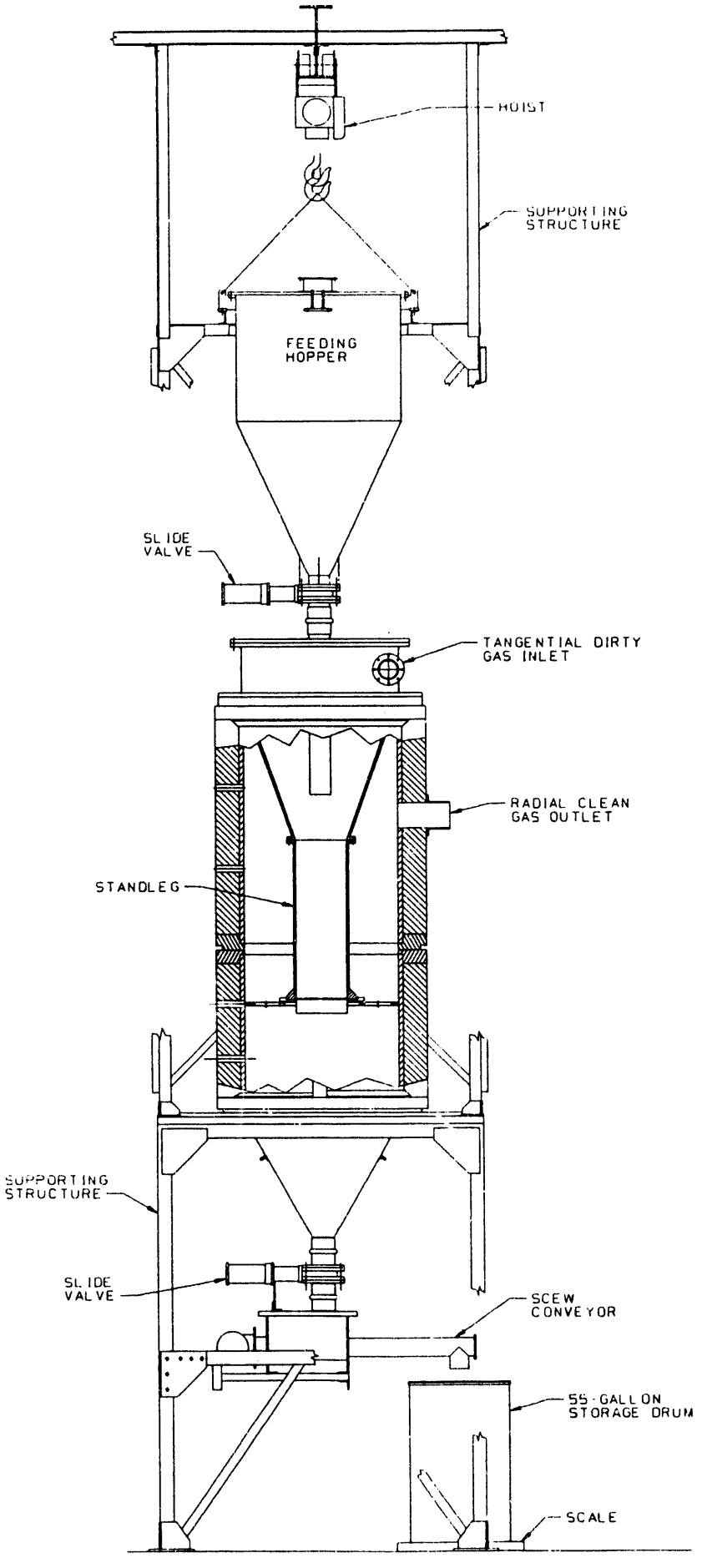


Figure 4.2 — The standleg moving granular bed filter, SMGBF.

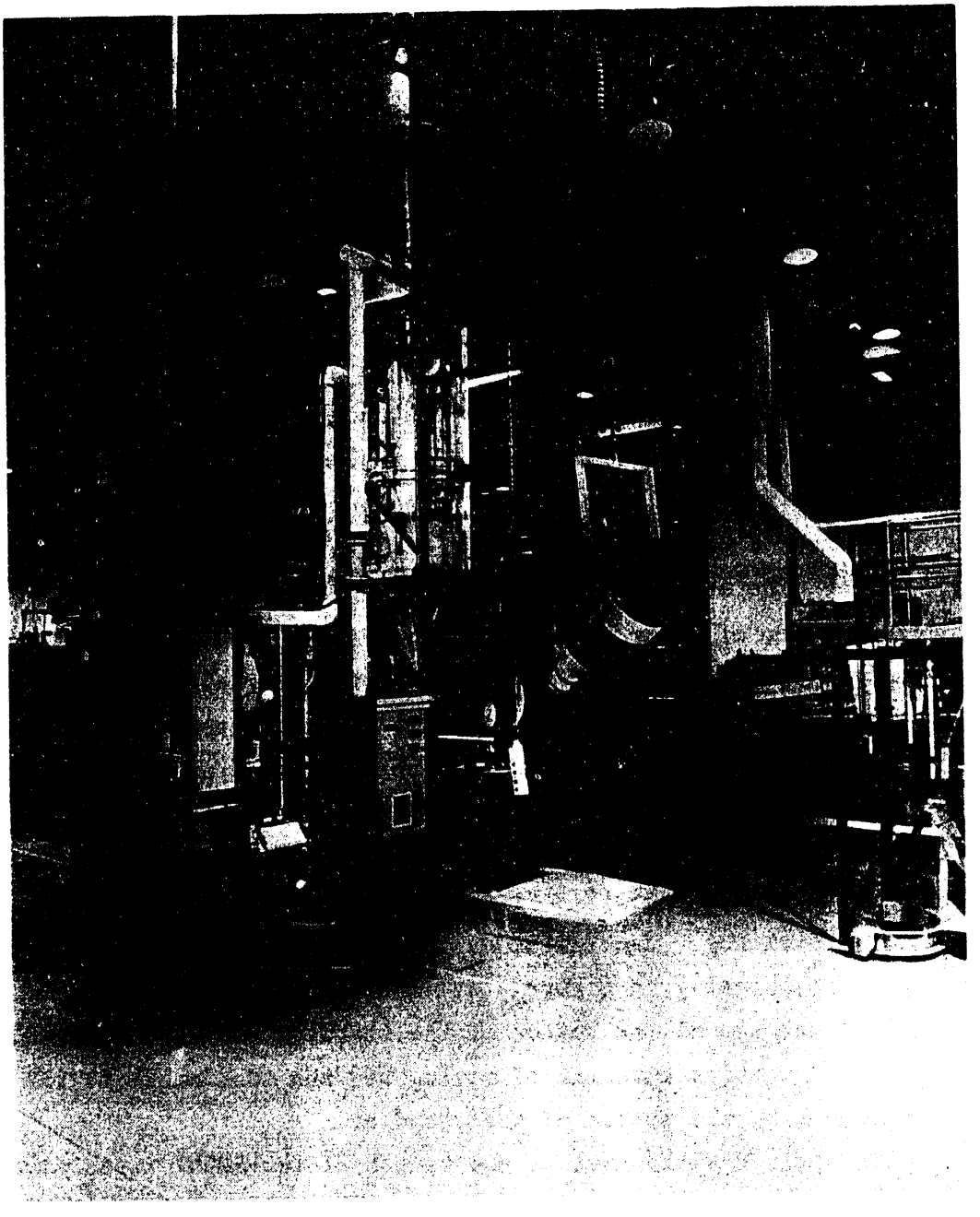


Figure 4.3 — Picture of standleg moving granular bed filter cold flow test facility.

feeder, the SMGBF, and the screw conveyor for pellet withdrawal into a pellet receiver, normally a 55-gallon storage drum. The pellet feeding hopper has a volumetric capacity of 24 ft^3. This provided a run duration of approximately 30 hours during normal test operation. A slide valve, operated pneumatically and located immediately below the feed hopper, could be used to shut off the pellet flow during maintenance. During normal operation, this slide valve was always fully open. The section for tangential dirty gas inlet was constructed of aluminum. The body of the SMGBF was contructed from transparent Plexiglas with an inside diameter of 34 inches and an outside diameter of 36 inches. Both the standleg and the cone immediately above it were also fabricated from transparent Plexiglas to facilitate visual observation. The standleg has an inside diameter of 11 inches, an outside diameter of 12 inches, and a length of 3 feet. The transparent cone has an included angle of 60 degree. The internal Plexiglas structure, the standleg and the cone section, is supported from below by a specially-designed steel and aluminum structure to prevent tensile failure during operation.

There were provisions at the bottom of the standleg to install different designs of "skirt" to evaluate their effectiveness on SMGBF operation efficiency. One skirt design evaluated during this period is shown photographically in Figure 4.4. The skirt allows the gas to gradually disengage at the bottom of the standleg and simultaneously minimize the relative movement of moving bed and thus minimize the dust re-entrainment at the bottom of the standleg.

The pellet withdrawal at the bottom of the SMGBF is an aluminum cone with an included angle of 60 degree. The pellets passed through a pneumatically-operated slide valve into a screw conveyor, then into a 55-gallon storage drum on a weigh scale. The rate of pellet withdrawal could be readily recorded during operation. The clean gas from the baghouse was exhausted into an existing laboratory exhaust duct. A 2-ton hoist and a drum handling system were also available to facilitate the handling of 55-gallon drums and the filling of the pellet feed hopper.

Figure 4.4 — The "skirt" design tested during cold flow tests.

The instrumentation of cold model test facility consists of primarily a turbine flowmeter for air flow measurement, a screw conveyor and a weigh scale for pellet flow rate, thermocouples for temperature measurement, manometers and transducers for absolute and differential pressure measurement, a load cell for loss-in-weight measurement of fines feed rate, and collection of fines at the baghouse for determination of fines collection efficiency.

4.2 PELLET AND FLY ASH MATERIALS

The bed material, the simulated pellet, for the cold flow tests is the crushed acrylic particles ordered from Atlantic Chemical Company, Atlanta, GA. Visual inspection revealed that the crushed acrylic particles were from crushed acrylic tubes, plates, and other forms of acrylic waste products and possessed widely different shapes. Thus three different samples of bed material were obtained for characterization of particle density and bulk density, and for determination of minimum fluidization velocity. The results are summarized in Table 4.1. The shape factors of the acrylic particles were determined from the packed bed pressure drops and the packed bed voidages obtained in a separate 2-3/4 inches diameter bed, and application of the Ergun equation.

Table 4.1 — Characterization of Acrylic Particles

Sample	Part Density lb/ft^3	Part Diameter μm	Voidage	Min. Fluid. Vel. ft/s	Shape
1	74.26	3893	.563	5.23	.20-.29
2	70.49	3707	.489	4.90	.27-.34
3	68.82	3474	.505	4.89	.29-.34

The angle of repose of the acrylic particles was also experimentally determined to be 34.5°. The minimum fluidization velocity of the acrylic particles, 4.9 to 5.2 ft/s, was determined separately in a 2 3/4 in. diameter fluidized bed (see Table 4.1). A typical fluidization curve is presented in Figure 4.5 for Sample No. 2. There is considerable hysteresis in the fluidization curve.

The dust employed in the cold model tests was Exxon PFBC flyash. The aerated bulk density of the dust is 47.14 lb/ft^3 (0.76 g/cm^3). The tapped bulk density can be more than 70% higher. Three samples of Exxon dust fed to the SMGBF and three samples of the dust collected at the baghouse were analyzed with a coulter counter. The particle size distribution results are shown in Figure 4.6. Because of the small sample size required for the Coulter Counter, the resulted size distribution scatters over quite a wide range. No conclusion can be drawn as yet regarding the preferential removal of size fraction by the SMGBF.

4.3 GAS FLOW TEST RESULTS

The baseline pressure profiles across the stationary and the moving granular beds were measured for superficial air velocities from 2.5 ft/s to 6.1 ft/s and superficial solids velocities from 0 ft/min to 0.08 ft/min. They are reported in Figure 4.7. The pressure profiles are predictable from the modified Ergun equation shown in Equation (1) with proper assumption of voidage in the bed. This comparison is also shown in Figure 4.7. An average particle size of 3707 μm and a particle density of 70.49 lb/ft^3, similar to that of sample No. 2 reported in Table 4.1, were used in the calculation. In addition, an average particle shape factor of 0.3 (see Table 4.1) was also used.

$$\Delta P = \frac{L}{g_c}\left[150\,\frac{(1-\epsilon)^2}{\epsilon^3}\,\frac{\mu(U_f + U_s)}{d_p^{\,2}\,\phi^2} + 1.75\,\frac{(1-\epsilon)}{\epsilon}\,\frac{\rho_f\,(U_f + U_s)^2}{d_p\,\phi}\right] \qquad (1)$$

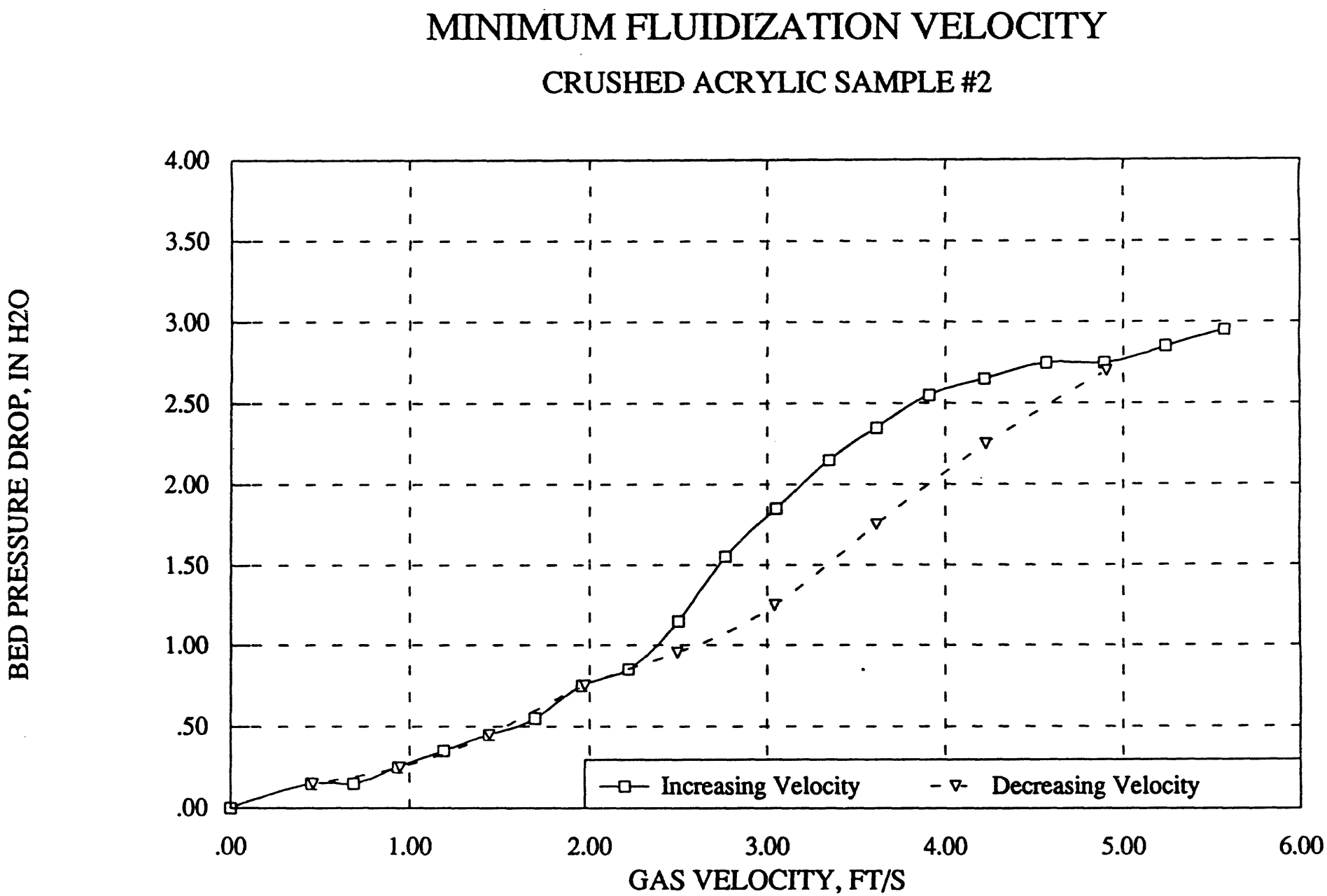


Figure 4.5 — Minimum fluidization velocity determination for crushed acrylic particles (Sample No. 2).

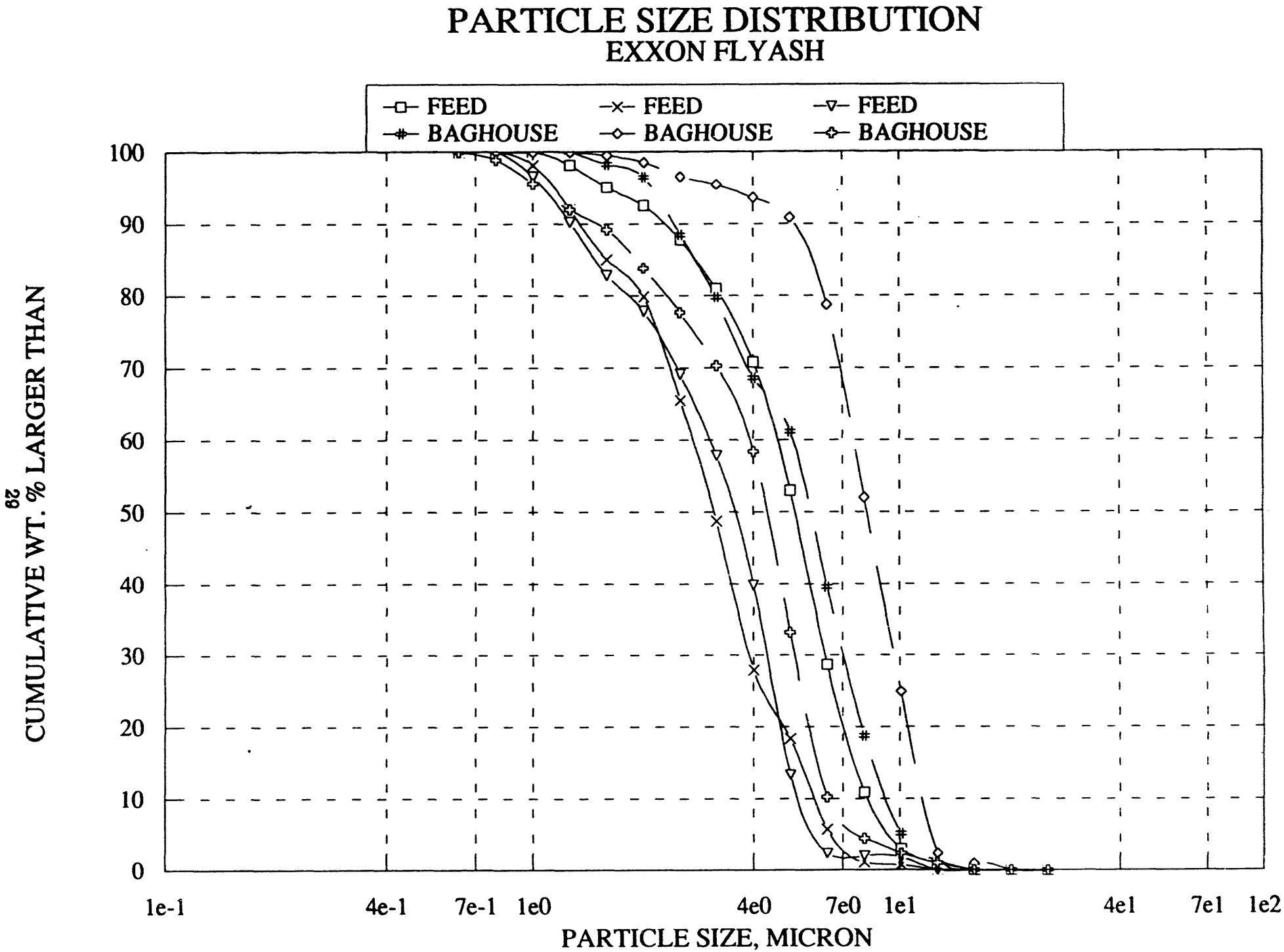


Figure 4.6 — Particle size distribution of Exxon feed dust and baghouse collection.

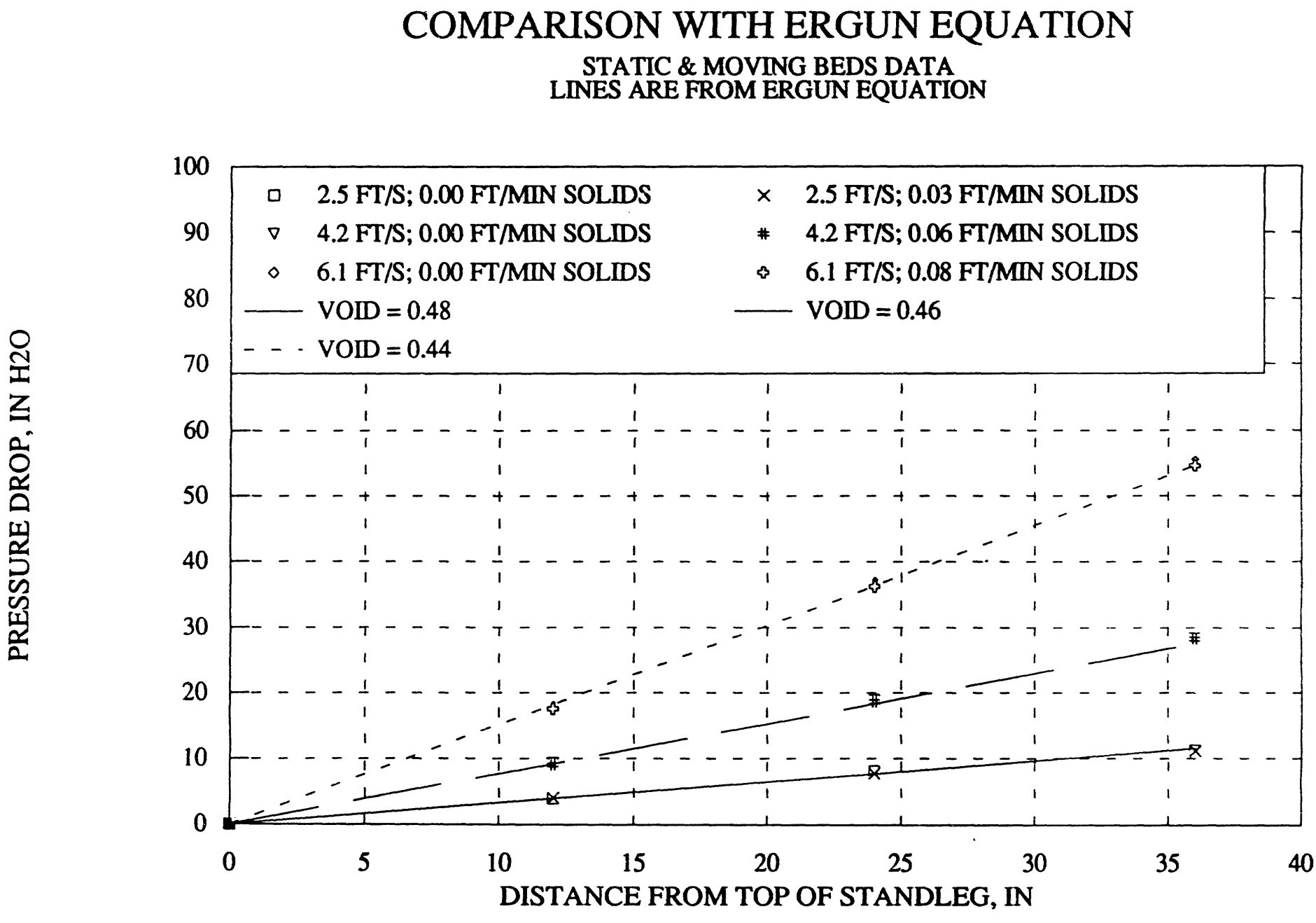


Figure 4.7 — Static and moving beds pressure drop data and comparison with Ergun equation.

where ΔP = pressure drop across the standleg

d_p = particle diameter

L = length of the standleg

U_f = interstitial gas velocity, positive upward; $U_f = U_o/\epsilon$

U_s = actual solid veloctity, positive downward

U_o = superficial gas velocity

ρ_f = fluid density

ϵ = voidage

μ = fluid viscosity

ϕ = particle shape factor

g_c = gravitational acceleration conversion factor

From Figure 4.7, it can be seen that the pressure drop across the standleg is hardly affected by movement of the bed under current operating conditions because the gas velocity was considerably higher than the solids velocity. It is also seen that a higher voidage assumption of 0.48 in the Ergun equation will fit both the stationary and moving bed data at a gas velocity of 2.5 ft/s. At a higher gas velocity of 6.1 ft/s, a smaller voidage assumption of 0.44 will fit the data. At the intermediate velocity of 4.2 ft/s, an intermediate voidage of 0.46 fits the data well. This is reasonable because the bed packing would be expected to be tighter at higher velocities. Also the voidage of 0.48 is very close to the loosely packed voidage of 0.489 obtained for sample No. 2 reported in Table 4.1.

4.4 FLYASH REMOVAL TEST RESULTS

Three test series were carried out during this base contract period. The detailed description of the tests follows.

4.4.1 Exploratory Tests With a Constant Diameter Standleg

The first dust injection test was an exploratory test where the moving bed velocity was varied from zero to approximately 0.04 ft/min and the dust injection rate was also varied to obtain calibration of the dust feeder. The gas flow rate was maintained at a superficial velocity

of 3 ft/s through the standleg. During the exploratory test, the behavior of dust re-entrainment at the bottom of the standleg was observed. The configuration employed for the exploratory test was a simple straight standleg of constant diameter.

4.4.2 Tests With a Flared Skirt

In the second dust injection test, a flared skirt (at an angle of 30° from vertical, see Figure 4.4) was attached to the bottom of standleg to reduce the exit gas velocity from the standleg by a factor of 3.64. A continuous steady state dust injection test was then carried out over a period of more than 12 hours at a superficial gas velocity in the standleg of 3 ft/s and a constant dust loading of 6400 ppm by weight. A dust collection efficiency over 99% was obtained over the entire test period. The test results are shown in Figures 4.8 and 4.9. During the test, a total of about 47 lb of dust was delivered and a total of approximately 470 lb of bed medium was withdrawn to maintain a bed medium vs dust weight ratio of about 10. The steady state operation over the entire test period is obvious from Figure 4.8.

Dust collection efficiency over the entire test period was calculated and presented in Figure 4.9. A collection efficiency over 99% was obtained over the entire test period. The collection efficiency was calculated based on the cumulative amount of dust collected from the baghouse and the cumulative amount of dust delivered. The pressure drop across the entire standleg is also reported in Figure 4.9. The pressure drop varies between 28 and 34 in. H_2O. The pressure drop variation is primary due to the packing variation of the moving bed during the run.

4.4.3 Tests With a Bed Outside of a Flared Skirt

During the previous two cold flow tests, the mechanism of dust collection in the moving bed and dust re-entrainment at the bottom of the standleg were observed and analyzed. The dust trapped in the interstices of the particles was re-entrained into the gas stream at the bottom of the standleg while the particles were tumbling down on the free surface of the bed material. The periodical puffs of dust

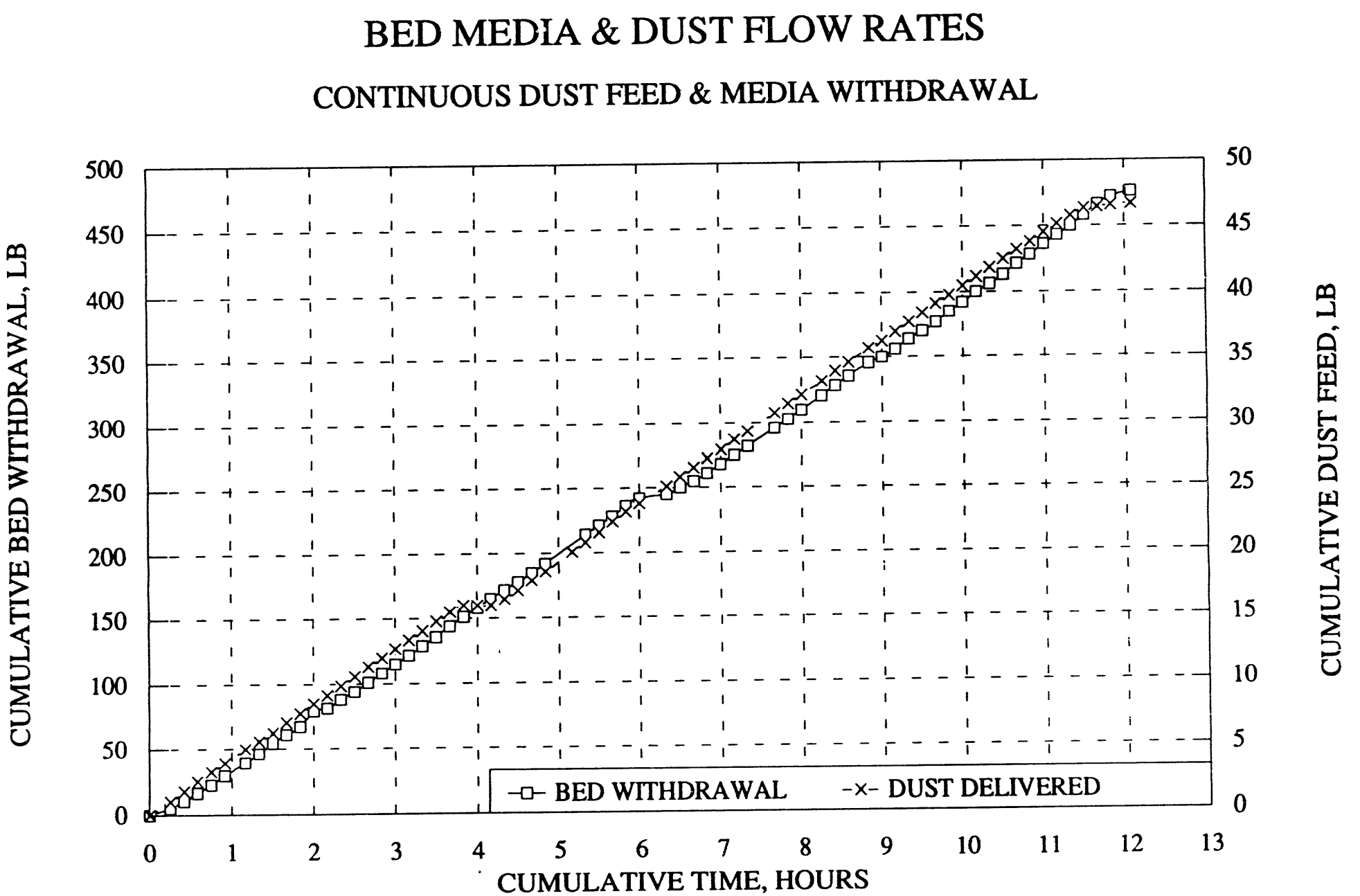


Figure 4.8 — Trend plot for bed media and dust flow rates — standleg with cone skirt at gas velocity = 3 ft/s and dust loading = 6400 ppmw.

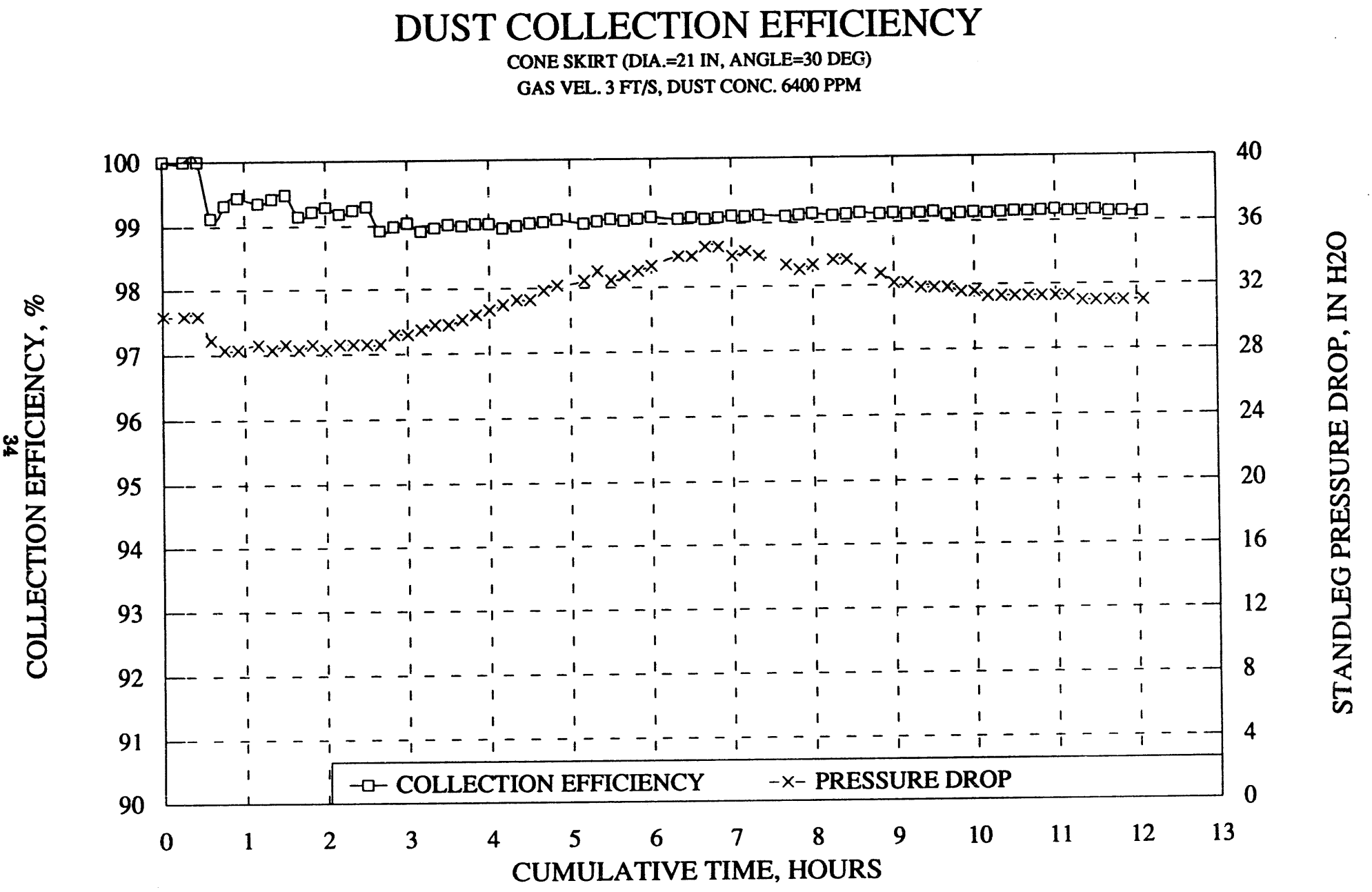


Figure 4.9 — Summary of dust collection efficiency and standleg pressure drop — standleg with cone skirt at gas velocity = 3 ft/s and dust loading = 6400 ppmw.

re-entrainment could be seen visually. The occurence of dust re-entrainment might be limited only to the bed layer close to the wall of the standleg, though it could not be certain.

In order to eliminate the dust re-entrainment, a separate bed was built at the outside of the standleg to a height about 25-in above the bottom of the skirt. The existence of the outside bed forced redistribution of the gas and prevented relative movement of the bed granules and release of dust trapped between the granules. This effectively minimized the dust re-entrainment mechanism described earlier. Under similar operating conditions of 3 ft/s gas face velocity in the standleg and 6400 ppmw dust loading, a dust collection efficiency higher than 99.9% with a dust penetration of less than 15 ppmw was recorded over a run period of more than 55 hours as shown in Figures 4.10 and 4.11, and pictured in Figure 4.12. After the first 11 hours of operation, all the clean bed material was used up. The dirty bed media were dry-sieved to separate out the dust and re-used. The experimental evidence indicated that the dirty bed media seemed to improve dust collection, probably because the surface morphology of dirty bed particles was no longer smooth as that of the clean plastic particles (see collection efficiency improvement after 11 hours of operation in Figure 4.11). This observation is consistent with that reported in the literature by other researchers.

Figure 4.10 shows the cumulative and Figure 4.11, the differential dust collection efficiency, over the test period. The differential dust collection efficiency was evaluated every 30 minutes on the basis of the total dust delivered and the total dust collected from the baghouse during the 30-minute time period. The unusually large amount of dust collected at the 4-hour mark was probably due to residue dust on the dust filters which was knocked off during pulse cleaning. The three dust filters in the baghouse were the dirty ones from earlier tests and they were purged sequentially every minute during the test. For convenience, the dust penetration in term of ppmw is also shown in Figures 4.10 and 4.11.

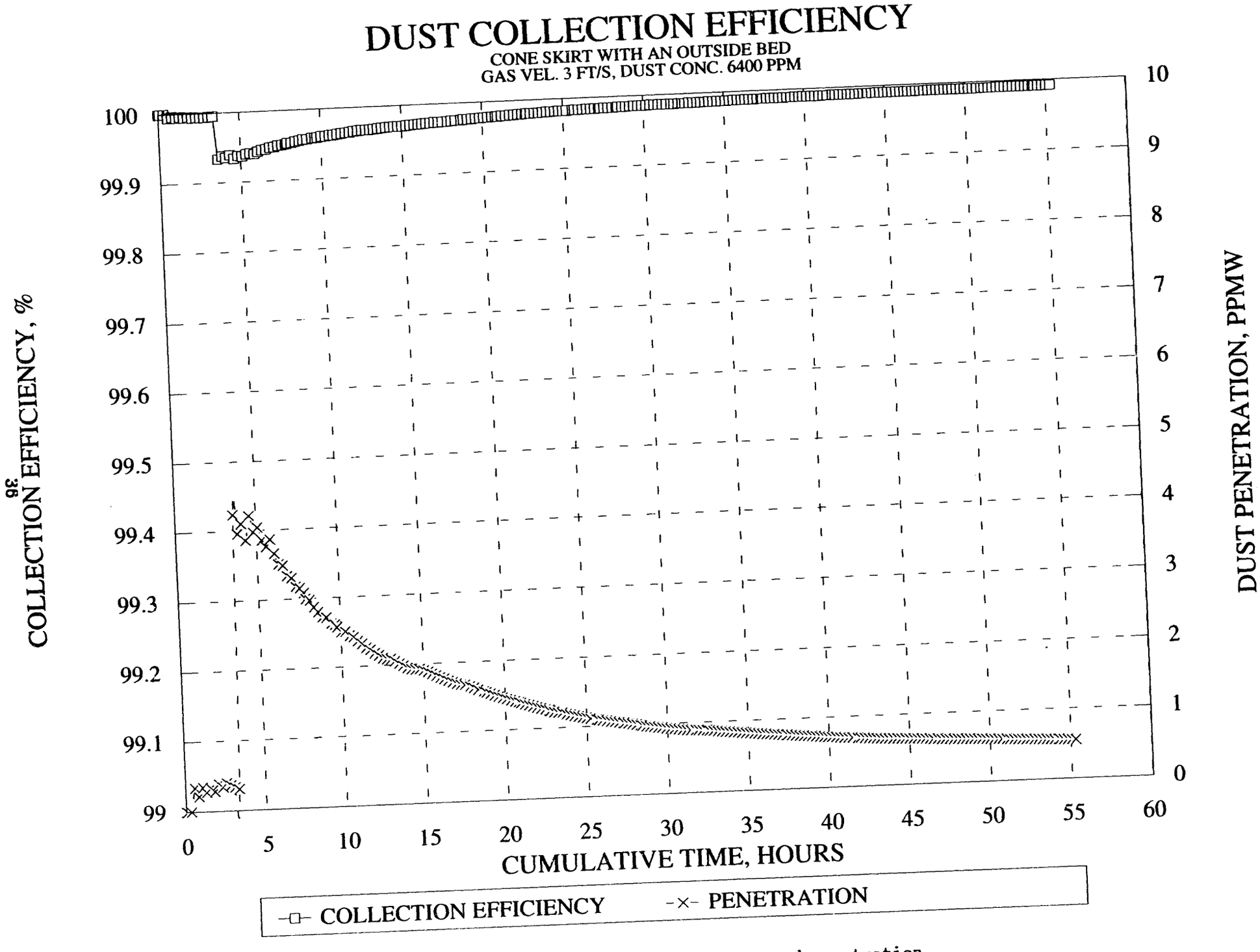


Figure 4.10 — Cumulative dust collection efficiency and penetration.

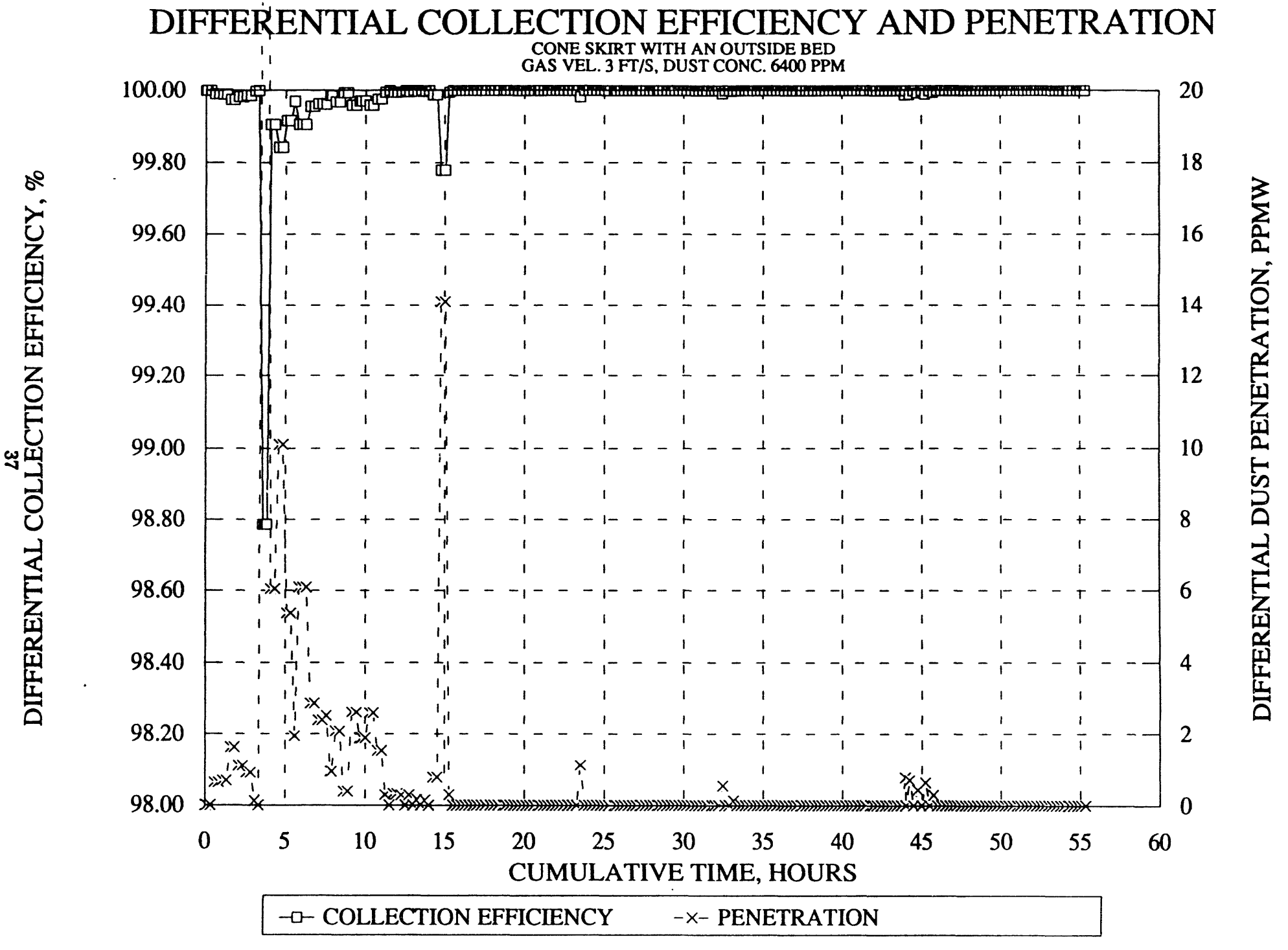


Figure 4.11 — Differential dust collection efficiency and penetration.

The new configuration allows two-stage dust removal, the first stage being the cocurrent downflow of gas and bed madia inside the standleg which trapped the majority of the dust in the gas stream. The second stage is the counter-current gas (upflow) and bed media (downflow) flow outside the standleg which cleanses the little dust that may escape from the first stage. The outside bed also serves as a barrier between the clean side and the dirty side. The bed outside the standleg does not have to be moving in actual application to be effective. The relative amount of bed movement for both the inside and outside beds can be designed based on the established principles governing the hopper flow.

The standleg pressure drop for the run is presented in Figure 4.13. The pressure drop penalty with an outside bed is very minimal, at most 2" H_2O column, because the gas velocity through the outside bed is only about 1/10 of the velocity in the standleg. The steady state operation for the run is evident from Figure 4.14 which presents the bed media and dust flow rates, a ratio of about 10, over the entire test period.

4.4.4 Development of a Core Sampling Technique

A core sampling device consists of two concentric tubes with a 3/4" slit cut along the length of both tubes was fabricated and a core sampling technique was developed. During core sample collection, the sampling device was traversed through the cross-section of the granular bed with the slit on the outer tube pointing upward and the slit in the inner tube mis-aligned such that no bed material would drop into the tubes. Once the sampling device was positioned at the desired location, the inner tube was rotated to align both slits to allow bed material to drop into the sampling device. Again, the inner tube was rotated to close off the slits and the sampling device was then withdrawn. The bed material was then taken out in sections of two-inch intervals and the concentration of the flyash in each section was determined by sieving through a 120 mesh screen.

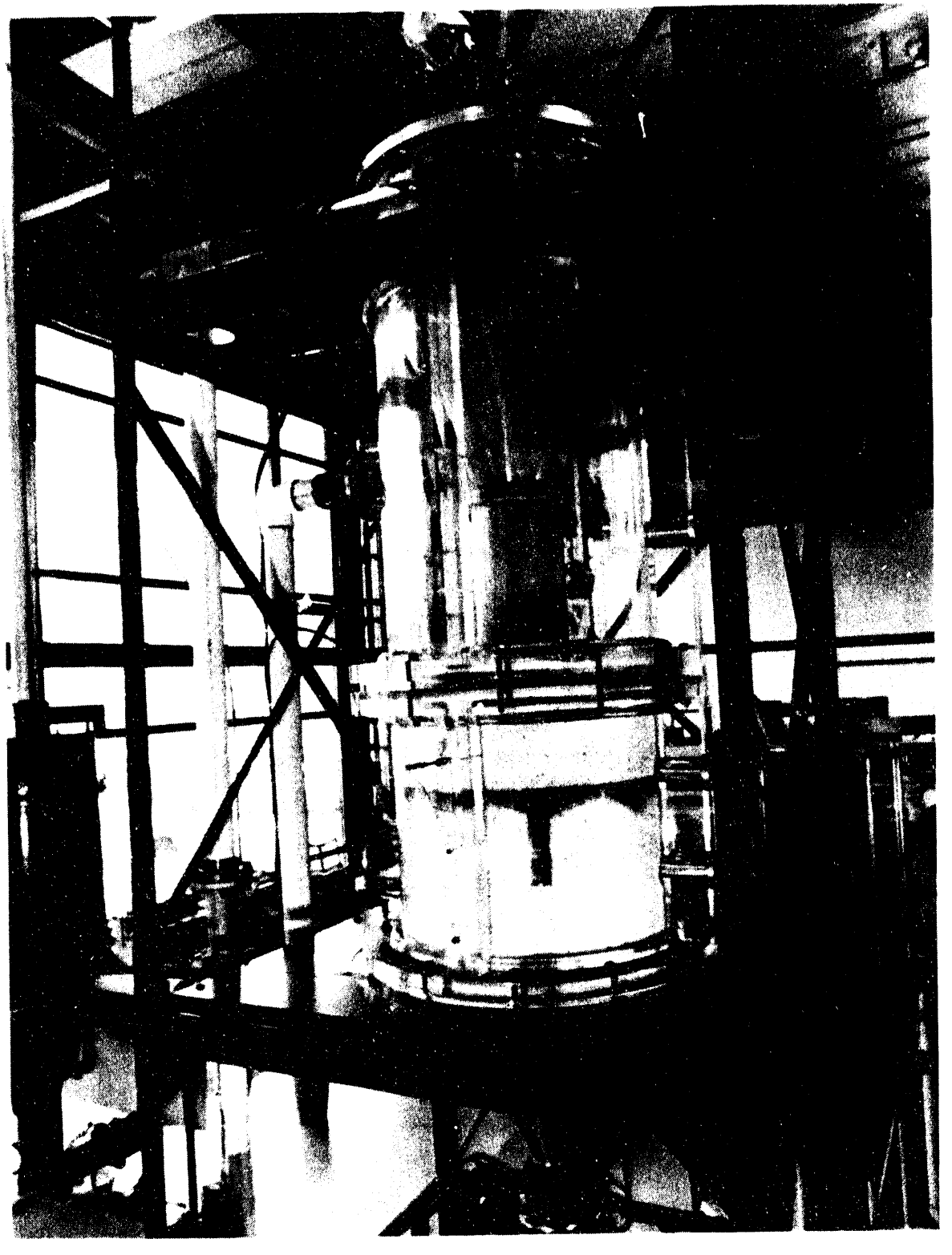


Figure 4.12 — Picture showing clean and dirty sides of the SMGBF.

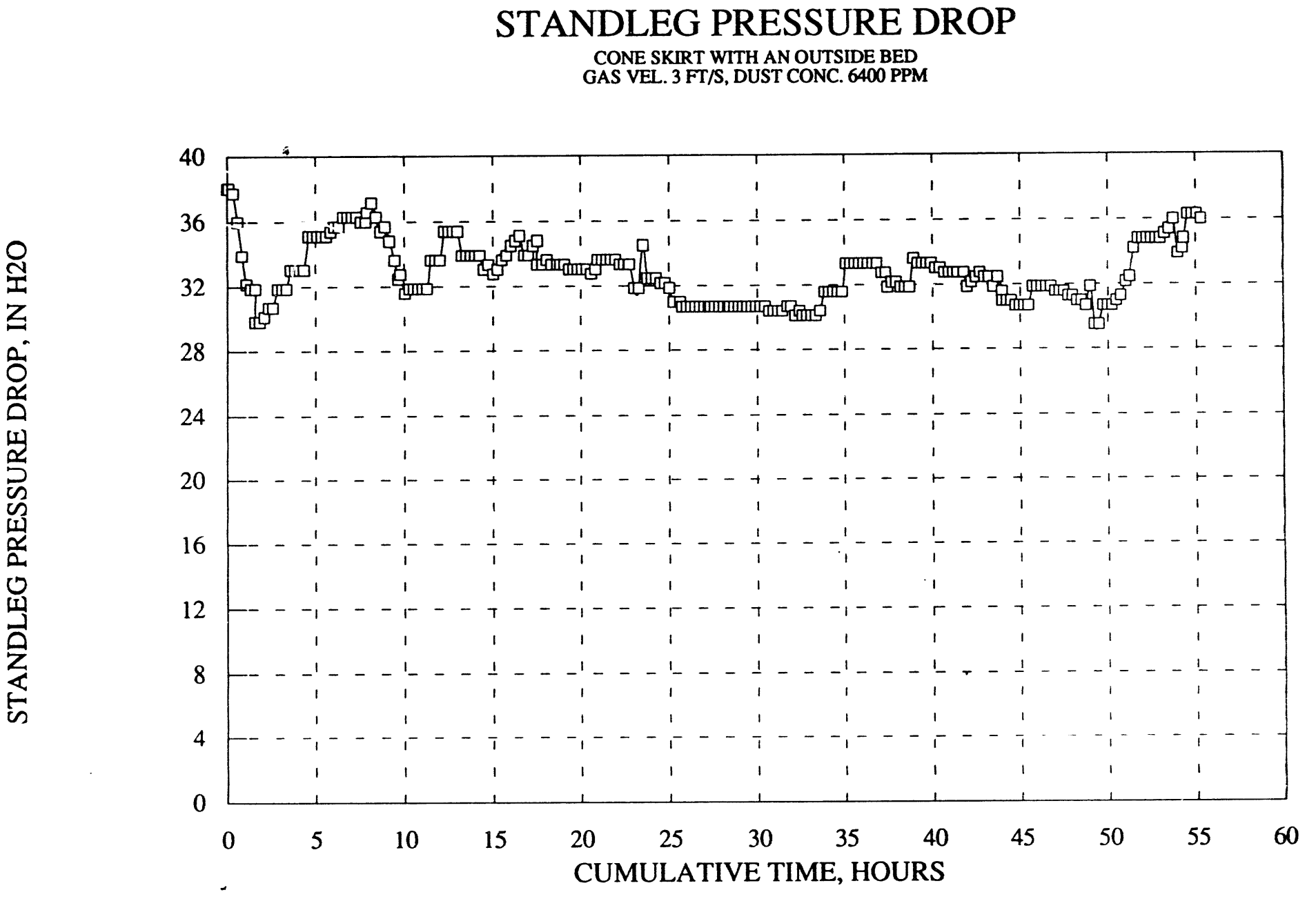


Figure 4.13 — Standleg pressure drop.

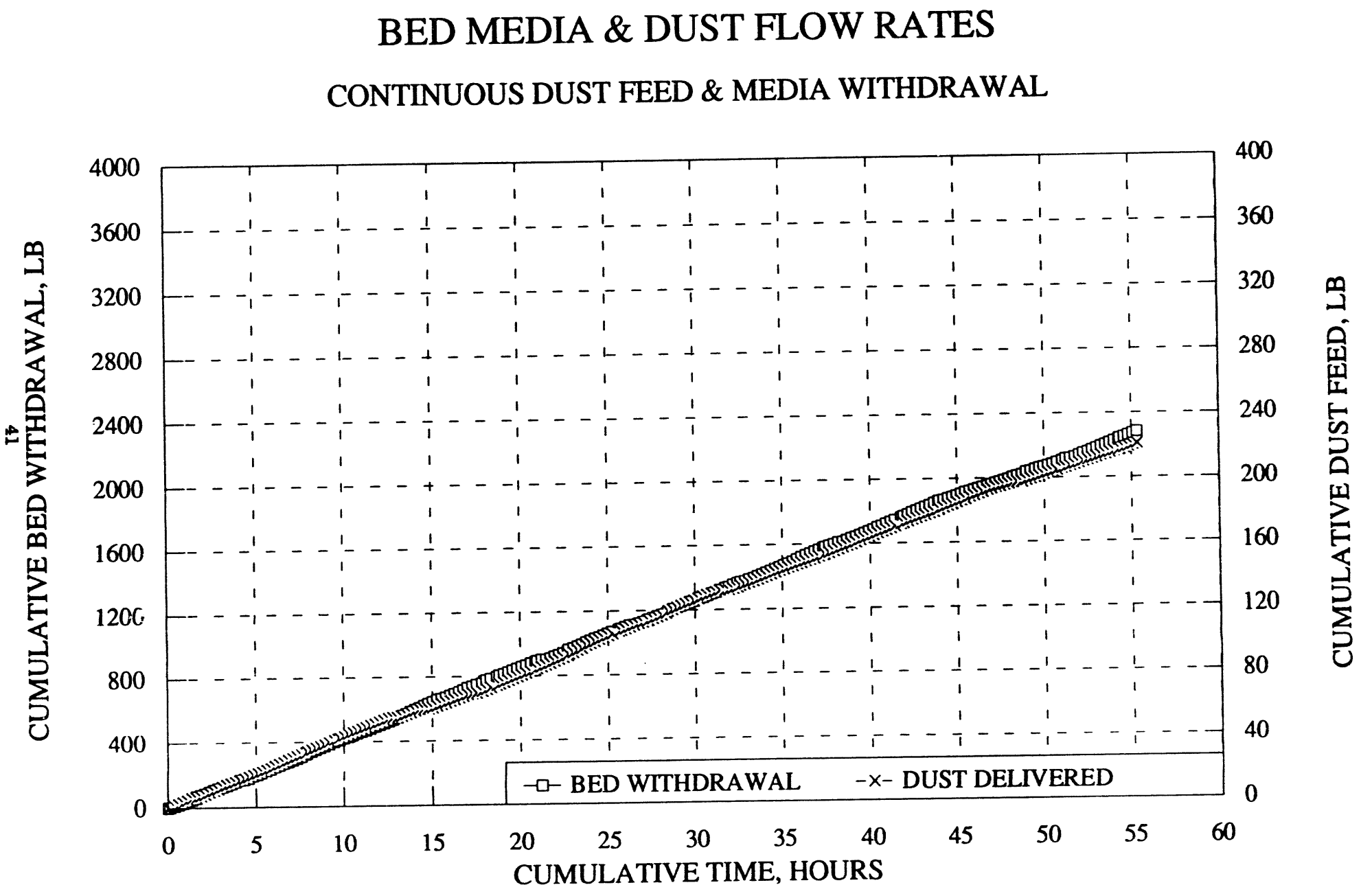


Figure 4.14 — Bed media and dust flow rates for a cone skirt with a outside bed.

At the end of the last continuous dust injection test, two core samples were taken using this device at two cross-sections, 2.25" and 3.25" from the bottom of the standleg cone. The two core samples were taken diagonally opposite to each other, i.e., 180° apart. The bed configuration at the time of sampling did not have a bed outside the standleg and the standleg bottom was a flared cone. The flyash distribution across the cross-section at two different locations is shown in Figure 4.15. The highest flyash concentration is closer to the outer boundary of the standleg as expected. However, there is substantial flyash concentration even at the centerline of the standleg, indicating a reasonable distribution of flyash across the standleg during opeation. At the bed cross-section closer to the standleg bottom, the flyash concentration in the centerline increases while that at the boundary decreases. Because of the locations of the vessel ports, samples even closer to the standleg bottom could not be obtained in this test.

The developed core sampling technique is quite simple to apply and the results are very useful and informative. With a separate bed outside of the standleg, it is expected that the flyash distribution will be even more uniform across the cross-section of the granular bed.

4.5 INTERPRETATION FOR HTHP CONDITIONS

During the cold flow tests, the pressure drop across the standleg was found to be predictable by the modified Ergun equation. The dust loading in the moving bed was found to be dilute enough such that the pressure drop was not appreciably affected. Similarly, solids in the moving bed move too slow to affect the overall pressure drop. A voidage similar to that of the loosely packed-bed can be used in the modified Ergun equation for pressure drop prediction with minor corrections for the moving bed and the dust loading. These observations are expected to be still applicable under HTHP conditions and the modified Ergun equation can still be applied to estimate the pressure drop. No difficulty is expected in the prediction of operating pressure drop in the SMGBF at HTHP conditions.

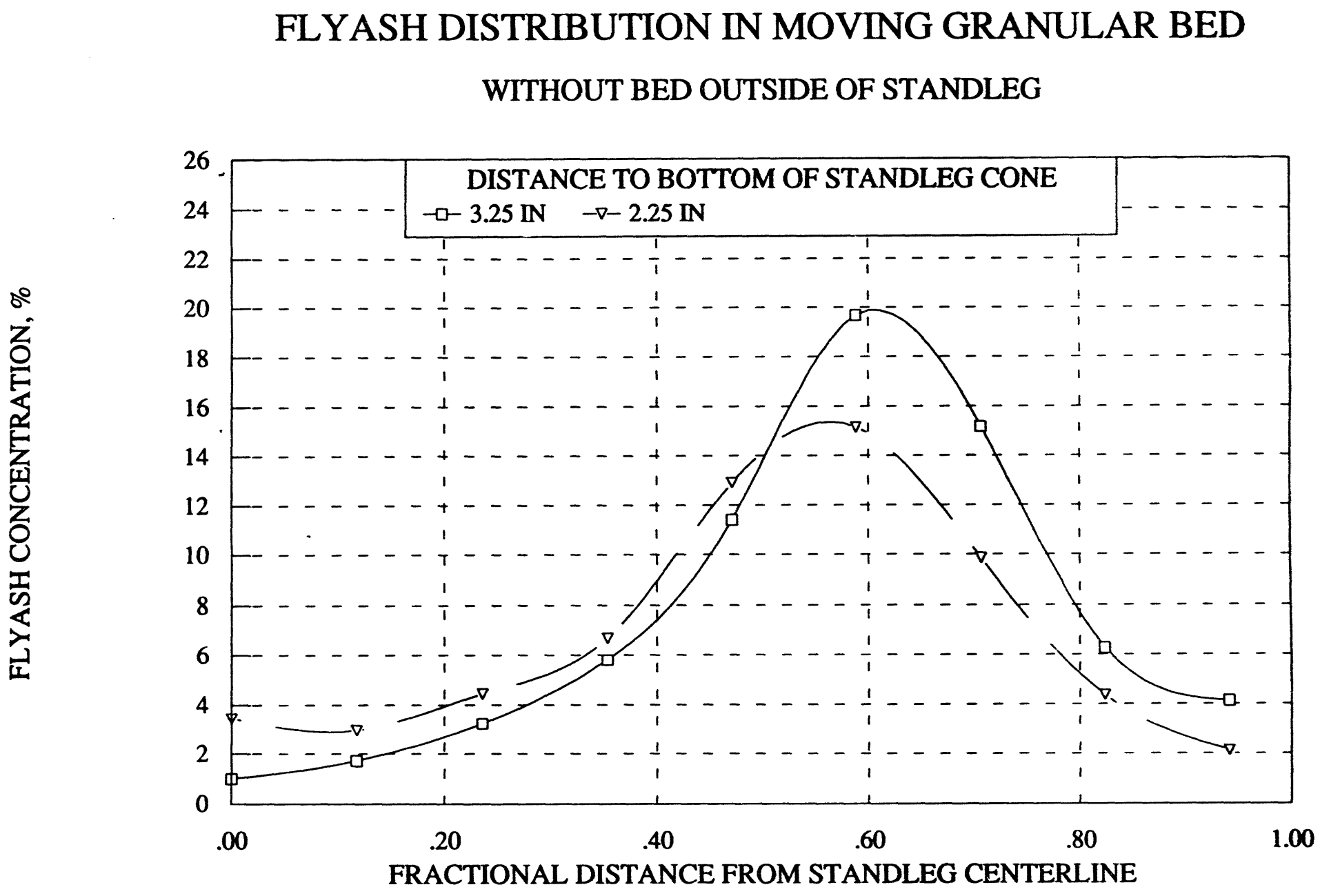


Figure 4.15 — Flyash distribution across the cross-sections of the granular bed filter.

The dust collection efficiency obtained during the cold flow tests is, however, harder to translate into that at HTHP conditions. The dust collection efficiency will depend very much on the stickyness of the dust at HTHP conditions and the particle morphology of the bed media, neither of them are predictable from the cold flow results. The exact dust collection mechanisms are also not completely understood. The effect of the difference of flow field and fluid dynamics at HTHP conditions on the final dust collection efficiency cannot be predicted. However, it is probably safe to say that under similar standleg configuration and design, the performance of the SMGBF at cold flow conditions is a more conservative case. The performance of the SMGBF at HTHP conditions should improve over that at the cold flow conditions simply because the bed media and/or the dust may be sticky. Of course, the static electricity may also play a role in dust collection efficiency at the cold flow conditions. Unfortunately, it cannot be quantified at the moment.

A completely separate issue which could not be realisticallly evaluated in the cold flow tests is the operability. Cold flow tests have successfully demonstrated the simplicity of the SMGBF startup, operation, and shutdown, and the controllability of the process. Under the HTHP conditions, the stickyness of dust and bed media may act as a glue to induce agglomeration and render the bed operation difficult. The bed media may also sinter due to combustion of residue carbon in the bed media or formation of low-melting eutectics. This operability issue can best be studied under the HTHP environment.

4.6 COLD MODEL TEST CONCLUSIONS

The results of dust injection tests with three different standleg configurations conducted during this contract period are summarized in Table 4.2. Under similar operating conditions of 3 ft/s superficial gas velocity and a dust loading of 6400 ppmw, the dust collection efficiency of SMGBF depends very much on the design configuration of the standleg. At the best, a dust collection efficiency higher than 99.9% was observed. This is considerably better

Table 4.2 — Summary of Test Conditions and Test Results of Cold Flow Tests

Test Configuration	Superficial Gas Velocity ft/s	Superficial Solids Velocity ft/min	Dust Loading ppmw	Bed Media/ Dust Radio	Data Collection Efficiency %	Standleg Pressure Drop, in. H_2O	Run Duration Hours
Constant-Diameter Standleg	3	0.02	0-6400	5-10	>97	25-34	13.5
Standleg with a Performated Skirt	3	0.03	6400	10	>99	28-34	12
An Outside Bed Over a Perforated Skirt	3	0.03	6400	10	>99.9	30-38	55

than the efficiency required for applications in advanced coal-fueled power plants, such as pressurized fluidized-bed combustion (PFBC), integrated coal-gasification combined cycles (IGCC), and direct coal-fueled turbines (DCFT). At the worst with a simple straight standleg design, a dust collection efficiency higher than 97% could still be realized.

The pressure drop across the filter, when scaled to the operating conditions of an actual commercial filter operated at high temperatures and pressures, is also well within the specified requirement (< 5 psig). The pressure drop is predictable through the modified Ergun equation. Other encouraging experimental results include:

- easy startup, operation, and shutdown;
- simple, reliable, and flexible process control; and
- improving dust collection efficiency through recycle of dirty bed media.

On the basis of the cold flow test results obtained under the base contract, it can be concluded that the SMGBF is a viable dust filtering system which meets and exceeds the specifications required for applications in the advanced power plants.

5. Pelletization Studies

The objectives of the pelletization studies were:

- to show feasibility of durable pellet production,
- to conduct tests at the Westinghouse Science and Technology Center and at vendor laboratories to evaluate techniques for generating pellets of sufficient strength for use in the SMGBF,
- to study interacting relationship between operating parameters (such as temperature and pressure of compression) and the type of pelletization equipment to serve as basis for equipment selection for commercial application,
- to evaluate comparative economics among competing pelletization technologies, and
- to explore advanced pelletization technologies for application at high temperature and high pressure conditions.

5.1 PELLETIZATION BACKGROUND

Pelletization is one of several technologies generally employed for particle size enlargement. The beneficiation of fine particulates by size enlargement has been practiced in the industry for many years. For example, synthetic solid fertilizer is now produced almost exclusively through a particle agglomeration step. In the ore beneficiation plants, balling and pelletizing ores are now common practices. In the pharmaceutical industry, high-speed rotary presses can produce large amounts of tablets from fine powder feed routinely and efficiently. Similar advancement can also be observed in the food industry and other process industries, especially those involving environmental applications and waste management.

The principal advantages of size enlargement are:

- to minimize dusting and handling hazards, and to reduce dusting losses,

- to reduce overall powder volume,
- to render powders free-flowing and to facilitate storage, transportation and handling,
- to produce useful structural forms and to improve product appearance, and
- to provide products suitable for metering, dispensing, and administering.

Pelletization is a general term applicable to several different size enlargement technologies. The most common ones are the technologies employing the pressure compaction such as tableting and roll-type presses, pellet mills, and screw extruders. Other technologies are tumbling and mixer agglomeration (such as disk pelletizers and rotary-drum agglomerators), thermal processes (such as rotary kiln and flakers), spray methods (such as spray dryers and fluidized- and spouted-bed agglomerators), and liquid systems (such as turbine mixers and pellet flocculators). These technologies and their applications are summarized in Table 5.1. [1-2]

5.2 POWER PLANT WASTE PELLETIZATION EXPERIENCE

Although pelletization technologies have been in existence for many years, their application in power plant waste is relatively new. Power plant waste, once a routine disposal practice, now represents a growing challenge for the utilities under new environmental regulations. Pelletization, as applied to power plant waste, has the following objectives

- to offer as an environmentally sound disposal alternative, e.g., in draining settling ponds,
- to reduce the power plant waste volume,
- to enhance handlability of the waste and minimize pollution concern, and
- to improve marketability of the waste product itself.

Table 5.1 — Summary of Pelletization Technologies

Pelletization Technology	Pelletization Equipment	Industrial Applications
Pressure Compaction	Piston/Molding Press	Plastic preforms, machine parts from metal powders
	Tableting Press	Pharmacenticals, catalysts, industrial chemicals, ceramic and metal powders
	Roll Press	Minerals, ores, chemicals, charcoal, lime, metal powders
	Pellet Mill	Pharmaceuticals, fertilizers, animal feeds, plastics, clays, carbon, charcoal, chemicals, bauxite, catalysts, clays, plastics
	Extruder	Bauxite, catalysts, clays, plastics
Tumbling/Mixer Agglomeration	Disc Pelletizer/ Rotary-Drum Agglomerator	Fertilizers, iron ores, minerals, clays, carbon black solid-waste products
	Blenders	"Instant" foods, detergents
Thermal Processes	Rotary Kiln/ Dryers/Flakers	Ores, minerals, cement clinker, chemicals, solid-waste products
Spray Methods	Spray Dryers/ Fluidized and Spouted Beds	"Instant" foods, detergents, dyestuffs, chemicals, fertilizers, clays, waste by-products
Liquid systems	Turbine Mixers/ Flocculation Drums/Stirred Vessels	Coal fines, waste sludge, clay slurries

Wisconsin Electric Power Co. is developing a technology by mixing fly ash with sewage sludge to produce a pelletized lightweight aggregate for concrete and masonry applications. The utility has applied to EPA for permits to construct the pelletization plant at its Oak Creek power plant. [3]

Researchers at the University of North Dakota's Energy and Environmental Research Center have recently demonstrated a process conceived by Community Energy Alternatives Inc. to recycle pelletized coal ash in FBC boilers. [4] In the technology being developed, solid waste from the FBC boilers with unreacted calcium was processed into pellet form. The pellets were then recycled for capturing more sulfur. The resulted increasing limestone utilization led to a 25% reduction in limestone requirement as well as a proportional reduction in waste product from fluid beds.

Briquetting and compacting of FGD-gypsum are being carried out at EVS Steam Power Station, Heilbronn, Germany. [5] The installed roller briquetting presses have a capacity of 17 tons/hr.

Experimental work was also successfully carried out to evaluate the feasibility of using the slag produced at the Cool Water Coal Gasification Plant to produce a synthetic lightweight aggregate. [6] The pellets were produced both by extrusion and drum pelletization. The concrete made from these Synthetic Lightweight Aggregates exceeds ASTM requirements for compressive strength.

According to Holley [7], essentially any fly ash can be agglomerated into non-dusting and non-leaching agglomerates using a disc pelletizer. Pelletization of bottom ash is, however, difficult because of variation in particle size and in moisture content. Pre-screening of bottom ash and mixing with fly ash are required.

Allied Concrete Company is operating a commercial-scale 100,000 ton per year Agglite facility at Virginia Power's Chesapeake Energy Center in Chesapeake, Virginia. [8] The manufacture of Agglite, a lightweight aggregate, starts with dry fly ash. The fly ash is then mixed with cement in a dry mixer before fed into a high-speed mixer (a turbulator mixer) along with water and other liquid chemicals. The

resultant mixture is then discharged onto a rotating disc pelletizer to produce pellets of controlled size. Curing normally takes about 3 to 5 days, however, the pellets are usually strong enough to handle within 24 to 48 hours. No process wastewater or solid waste are generated in the Agglite production.

The Progress Materials Inc. (PMI) owns and operates a pelletization facility at Crystal River, FL, for the production of Aardelite lightweight aggregate from non-saleable flyash. Since startup in 1988, this plant has produced more than 400,000 tons of high-quality aggregate, thereby providing the ash producer, Florida Power Corporation, with an ash utilization rate exceeding 90%, compared with a 25% average rate for U. S. coal-fired power plants. [9] The aggregate is used by customers in producing concrete masonry and structural concrete that meet or exceed all applicable standards. The Aardelite technology is owned by Aardelite Holding B. V. of Netherlands. PMI is under an exclusive licence of the technology for the state of Florida and a non-exclusive licence for the U. S..

The Aardelite process is based on the pozzolanic properties of the ash in combination with a binder, usually lime. Together with the silica and alumina in the ash, cementitious minerals are formed at atmospheric pressure. Hazardous constituents in the ash residue are encapsulated in the aggregates produced. The process generates no waste streams, neither solid nor liquid. The dry flyash from the power plant is first mixed with the recycled fines (< 1 mm in sizes) and the slaked lime in an intensive mixer before being fed into the pelletizer. The commercial quicklime is slaked into a slurry containing approximately 65% water. The amount of lime addition is about 4.5% to 5% of the dry ash material. The moisture content of the solids stream from the mixer is approximately 16% which is then fed through a rotary valve into the disk pelletizer. The heart of the plant is the 16-ft diameter disk pelletizer manufactured by Ferro-Tech. The pelletizer rotates at 18 rpm and is capable of processing 30 tons/hr. The original disk pelletizer has been modified to increase residence time of material in the pelletizer. The inclination of the disk, the location of feed material

and water spray, and the arrangement of baffles have all been found to be important operating parameters for production of pellets of desired specifications. Those parameters have been optimized at the PMI plant and are no longer changed during the commercial production run.

The green pellets with about 19% moisture is then transport via a conveyor belt to a bucket elevator and to four curing silos. The curing step takes 16 hours. The pellets after curing has a moisture content of 15% and they are conveyed through screw conveyors to a rotary screen (trommel) where the coarse pellets (> 3/4") are crushed and recycled, and the fine pellets (< 1 mm) are also recycled. The product is the pellets with sizes between 1 mm and 3/4".

Currently, the pellets (Aardelite lightweight aggregates) are sold to concrete manufacturers at $15/ton. Portland cement, instead of lime, was also tried as a binder. It was found that it required 10% cement addition, compared to 5% addition of lime, to generate pellets of comparable strength. The crushing strength for -4+6 mesh pellets was measured at the PMI to be 3-4 newtons/mm^2. At current cost of $75/ton for the lime and $45/ton for the cement, the economics favors the lime addition. From the process point of view, lime addition is also more compatible.

During operation, the flyash was found to be extremely abrasive. The primary maintenance items are the mixer, the rotary valve, and the baffles at the disk pelletizer. Because of the abrasive nature of the flyash, the extrusion pelletization is not recommended. The wear on the die will be excessive.

Samples of Aardelite lightweight aggregates were tested at Westinghouse Science and Technology Center and found to be extremely durable. If the moisture was driven out first, the pellets could be heated up to 1600°F with no degradation of pellet strength.

5.3 POWER PLANT WASTE MATERIALS TESTED

The power plant waste materials tested during the pelletization studies are three materials from the following sources:

Texaco Coal Gasification Process Slag

This coal gasification process slag is from the gasification process byproduct/waste stream of the Texaco pilot plant gasifier at Texaco Montebello Research Laboratory, California. The specific gravity of the material is 2.28 g/cm^3. The primary chemical constituents are similar to that of ordinary coal ash, i.e., silica, iron oxide, aluminum oxide, calcium oxide, magnesium oxide, and other minor metal oxides. The as-received particle size distribution is presented in Table 5.2.

Foster Wheeler AFBC Waste Ash

The Foster Wheeler AFBC waste ash was obtained from a Foster Wheeler commercial circulating AFBC. The as-received particle size distribution was analyzed and summarized in Table 5.2 as well.

Tidd PFBC Waste Ash

Two 55-gallon drums of bed ash and cyclone ash were obtained from the Tidd PFBC Demonstration Plant of Ohio Power Company. The major constituents of the ashes are amorphous silica, aluminum oxide, iron oxide, calcium oxide, magnesium oxide, and sulfur trioxide. The cyclone ash consists principally of minute, separate glassy particles with some crystalline matter and varying amount of unburned carbon. It ranges in color from light tan to light gray. The bed ash is a granular material with an angular shape. Its color ranges from medium brown to light tan. The particle size distributions of both the cyclone and the bed ashes were not determined. The specific gravity of the material ranges between 2 to 3 g/cm^3. This material yields a pH range of 9-12 in a 1% slurry.

5.4 PELLET VENDORS AND TECHNIQUES USED

A survey was conducted of the existing pelletization technologies and equipment vendors. A list of the equipment vendors and their relative capabilities is included as Appendix A. The pelletization technologies can be classified into the following three different categories based on application of pressure, binders, and the type of equipment.

Table 5.2 — Particle Size Distribution of Power Plant Waste Ashes Used in the Pelletization Studies

Size Range µm	AEP/Tidd Bottom Ash wt. %	PFBC Ash Baghouse Ash wt. %	Foster Wheeler Ash wt. %	AFBC Ash Baghouse Ash wt. %	Texaco IGCC Ash wt. %
+ 8000					0.24
-8000 + 4000			0.23		4.47
-4000 + 2000			0.23		26.44
-2000 + 1000			0.56		25.58
-1000 + 500	ND	ND	24.10		7.00
-500 + 250			40.48		13.62
-250 + 125			30.92	0.21	14.23
-125 + 75			3.39	3.19	1.59
-75 + 45			0.10	6.02	1.49
-45 + 30				28.77	--
-30 + 20				24.18	4.30
-20				37.63	1.05

ND: Not determined

Granulation:

The most common granulation devices are the rotating pan or drum granulators. The growth of granules relies primarily on binders and/or moisture. The same granulation process can also be performed in fluidized beds as well.

Pressure Agglomeration:

The equipment in this category accepts fine particle feedstocks to form a compacted strip, sticks, or a defined briquet for densification and sizing requirements. Counter-rotating rolls are usually employed with or without binders. Specific equipments include compactors, briquetters, and tabletizers.

Compactors require smooth or corrugated rolls to produce a sheet of densified material. This sheet may then be granulated or ground to a desired size and shape. Depending on powder properties, binders may be required and temperature may be applied.

Briquetters utilize the same principles but uses pocketed rolls to densify and form the material into a specific shape.

Tabletizers usually use specially-designed dies.

Extrusion:

Extrusion works according to the principle of extrusion moulding. The product to be pelletized is pressed through the perforations of a die by means of rotating rollers. It is thus formed into strands of uniform cross-section and they are subsequently cut with knives into the desired pellet lengths. The pellets from extrusion are usually in cylindrical shape with diameters varying from 1/8 in. to 1/2 in..

Most vendors contacted during the Base Contract program provide free feasibility tests in their laboratories employing equipments they supply. The tests may include variation in operating conditions during pelletization, different equipment types, the requirement and type of binders, and pellets characterization. The pellets characterization may involve hardness, crush strength, drop, and tumble tests. A small batch sample of about 5-gal size is usually requested with a turnaround time of one to four weeks. Special tests can also be contracted with a fee.

A large quantity of pellets can also be produced by the vendors under contract once the evaluation shows promises. The production cost for one ton of pellets ranges from $500 to $2000 depending on the vendor. The turnaround time is again about one to four weeks. Some of the vendors already have prior experience pelletizing power plant ash and fluidized bed combustion ash.

Thus, the approach in the test program was to send small solid waste samples to one to two selected vendors in each category of pelletization technology, i.e., granulation, pressure agglomeration, and extrusion, for feasibility evaluation. Some special tests were also requested during the course of evaluation depending on the pelletization results. The vendors selected to carry out the pelletization tests are summarized below:

Pelletization Technology	Vendor Selected
Granulation	Ferro-Tech
Pressure Agglomeration	Koppern Equipment, Inc.
	Prater Industrial Products, Inc.
	Bepex Corporation
Extrusion	California Pellet Mill Company

5.5 PELLET VENDOR RESULTS

The Texaco IGCC waste, the Foster Wheeler circulating AFBC waste, and the AEP/Tidd PFBC waste were sent to five different pelletization vendors identified in the last section. For both AFBC and PFBC ashes which contain different amounts of limestone or dolomite, no binder other than water is required. For the Texaco IGCC waste, 5 to 20% of cement was usually required. Addition of lime rather than cement probably will do as well. The pellets produced from both the disk pelletizers and the extrusion technique are quite strong and they have sustained the shipping and handling without breakage. The ashes sent to

different vendors and their pelletization treatment conducted by the vendors are summarized in Table 5.3. The individual reports submitted by the vendors after their pelletization evaluation are appended in Appendix B.

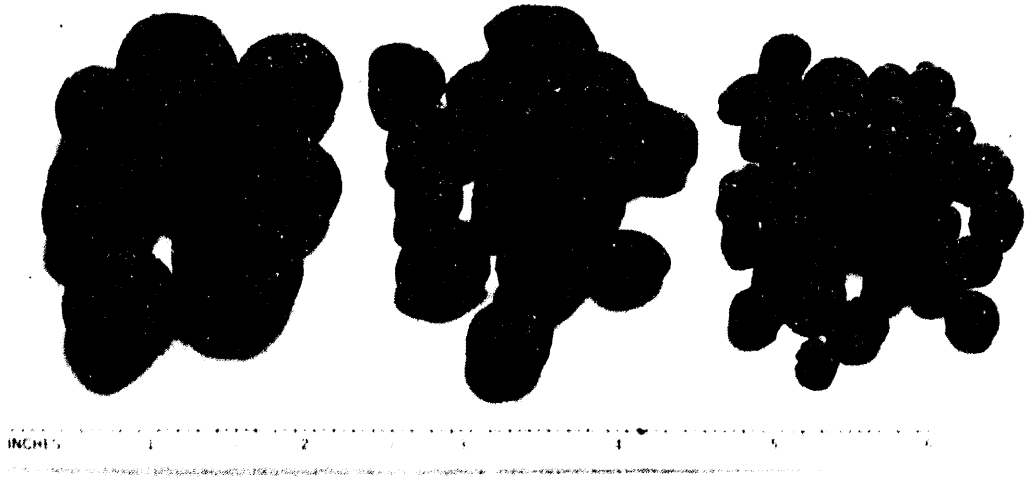
Pellets from the AEP/Tidd PFBC ash can be formed from all techniques employed by the vendors simply by adding up to 15% water depending on the technique used (see Table 5.3). For high temperature applications, sodium silicate was recommended as a binder. The Foster Wheeler AFBC ash behaved very similar to the AEP/Tidd PFBC ash with slightly more water required, up to 25% water. The Texaco IGCC ash could not be processed into pellets simply by addition of water. Up to 20% cement was required depending on the technology employed. The Texaco IGCC ash pellets also have the lowerest crushing strength, less than 32.2 pounds after 72-hour of curing. The crushing strength for pellets produced from the AEP/Tidd PFBC and the Foster Wheeler AFBC ashes is higher than 50 pounds after 72-hour of curing. Some of the pellets generated by extrusion and disk-pelletization techniques are shown photographically in Figures 5.1 through 5.6.

5.6 PELLET DURABILITY TESTING

All of the pellet samples received from vendors appeared to have ample cold strength, probably suitable for handling and transport by standard mechanical methods in the SMGBF system. Their durability at the high temperature conditions of the SMGBF was unknown. Some tests on the pellet samples were conducted to assess their durability while subjected to cold and hot conditions, with and without mechanical agitation. Since the samples were received over differing periods of time, not all of the pellet samples were subjected to the same tests, and the testing procedures used in the program evolved as more experience was gained. The tests conducted do not represent a comprehensive, exhaustive characterization of the pellet samples, but was sufficient to meet the needs of the Base Contract program.

Table 5.3 — Summary of Waste Pelletization By Vendors

Vendors	Pelletization Technology	Pelletization Equipment	Binder Requirement			Pellet Density and Crush Strength		
			Tidd PFBC	FWAFBC	Texaco IGCC	Tidd PFBC	FW AFBC	Texaco IGCC
Ferro-Tech	Granulation	Turbulator/ Disc Pelletizer	12.5% water	16% water	27.5% water/ 10% cement	Density: ND Crush strength: Green-2 lb 24 hr-27.8 48 hr-36.2 lb 72 hr->50 lb 96 hr-50 lb	1.65 g/cm^3 24 hr-39.6 lb 48 hr-54.2 lb 72 hr->65 lb 96 hr->65 lb	1.15 g/cm^3 24 hr-24 lb 48 hr-28.6 lb 72 hr-32.2 lb
California Pellet Mill	Extrusion	Pellet Mill	15% water 15% water/ 5% starch	25% water	15% water/ 5% starch 15% water/ 5% cement	Density: ND	ND	1.41-1.71 g/cm^3
Koppern Equipment	Pressure Agglomeration/ Granulation	Roll Compactor/ Crusher	5% water	5-9% water	20% cement	2.22 g/cm^3	1.91 g/cm^3	1.99 g/cm^3
Prater Industrial	Pressure Compaction	Press		5-13 water	10% cement 5% molasses/ 3% lime 6% sodium silicate			
Bepex Corporation	Pressure Compaction	Press	Sodium silicate	Sodium silicate	Sodium silicate			



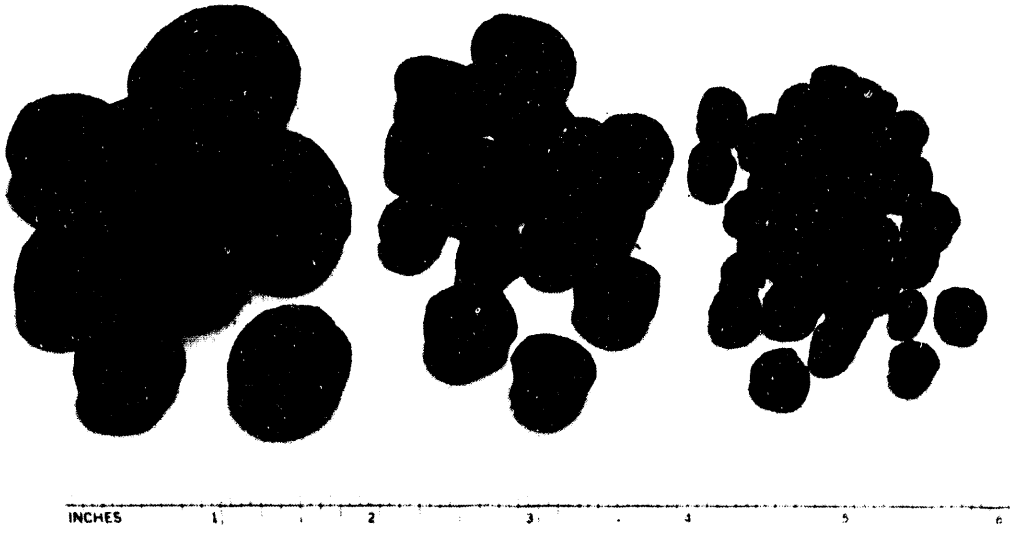
FOSTER-WHEELER ASH
FERRO-TECH
16% WATER, NO BINDER
(1) LARGER THAN 5/8 INCH
(2) 3/8 INCH - 5/8 INCH
(3) SMALLER THAN 3/8 INCH

Figure 5.1 — Foster Wheeler AFBC Ash - pelletized by Ferro-Tech.

FOSTER-WHEELER ASH
CALIFORNIA PELLET MILL
15% WATER, NO BINDER
1/4 INCH DIAMETER

Figure 5.2 — Foster Wheeler AFBC Ash extruded by California Pellet Mill.

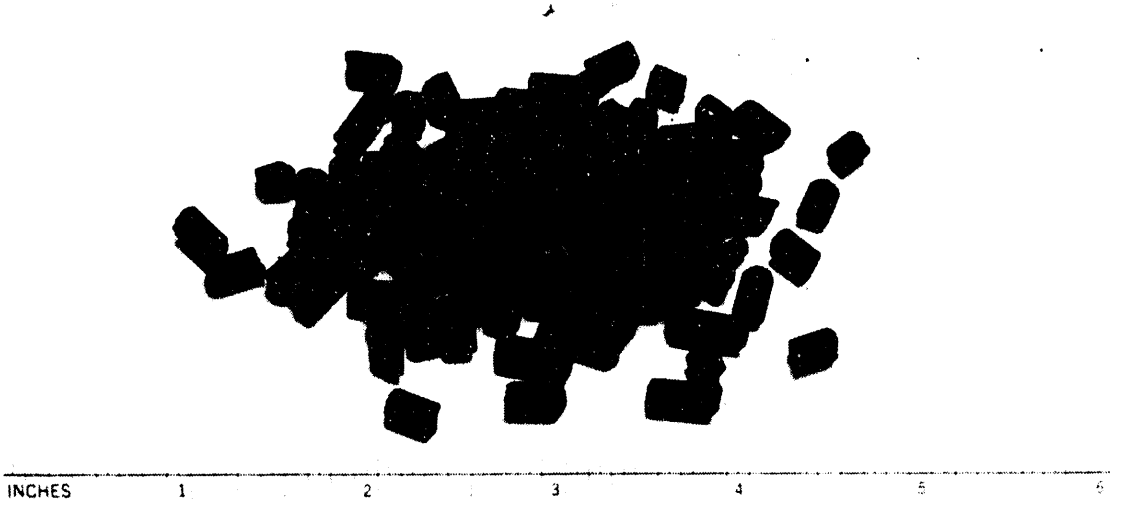
RM-28797



TEXACO ASH
FERRO-TECH
27.5% WATER, 10% CEMENT
(1) LARGER THAN 5/8 INCH
(2) 3/8 INCH - 5/8 INCH
(3) SMALLER THAN 3/8 INCH

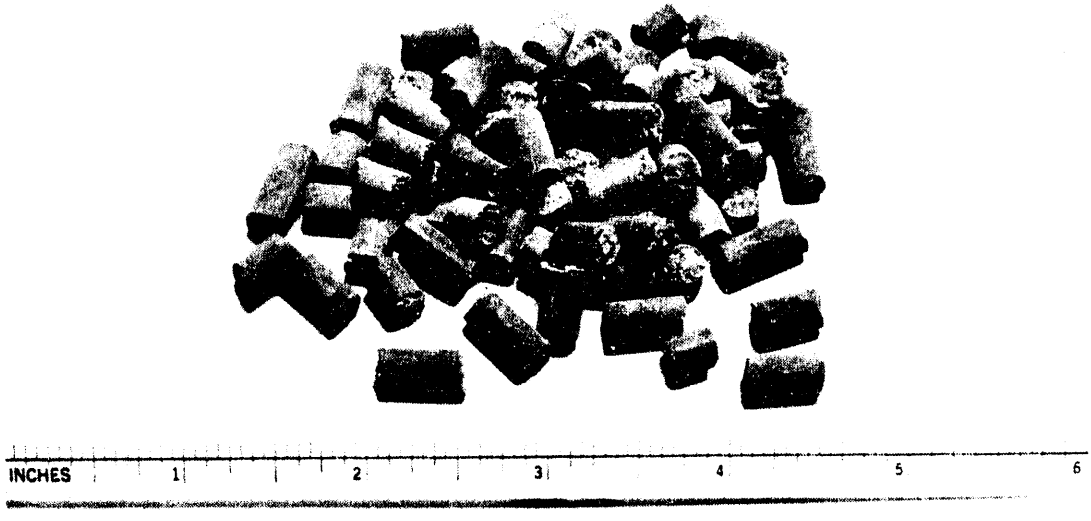
Figure 5.3 — Texaco gasifier ash disk-pelletized by Ferro-Tech.

RM-28798



TEXACO ASH
CALIFORNIA PELLET MILL
20% WATER, 5% CEMENT
3/16 INCH DIAMETER

Figure 5.4 — Texaco gasifier ash extruded by California Pellet Mill.



TIDD ASH
CALIFORNIA PELLET MILL
15% WATER, NO BINDER
1/4 INCH DIAMETER

Figure 5.5 — AEP/Tidd PFBC ash extruded by California Pellet Mill.

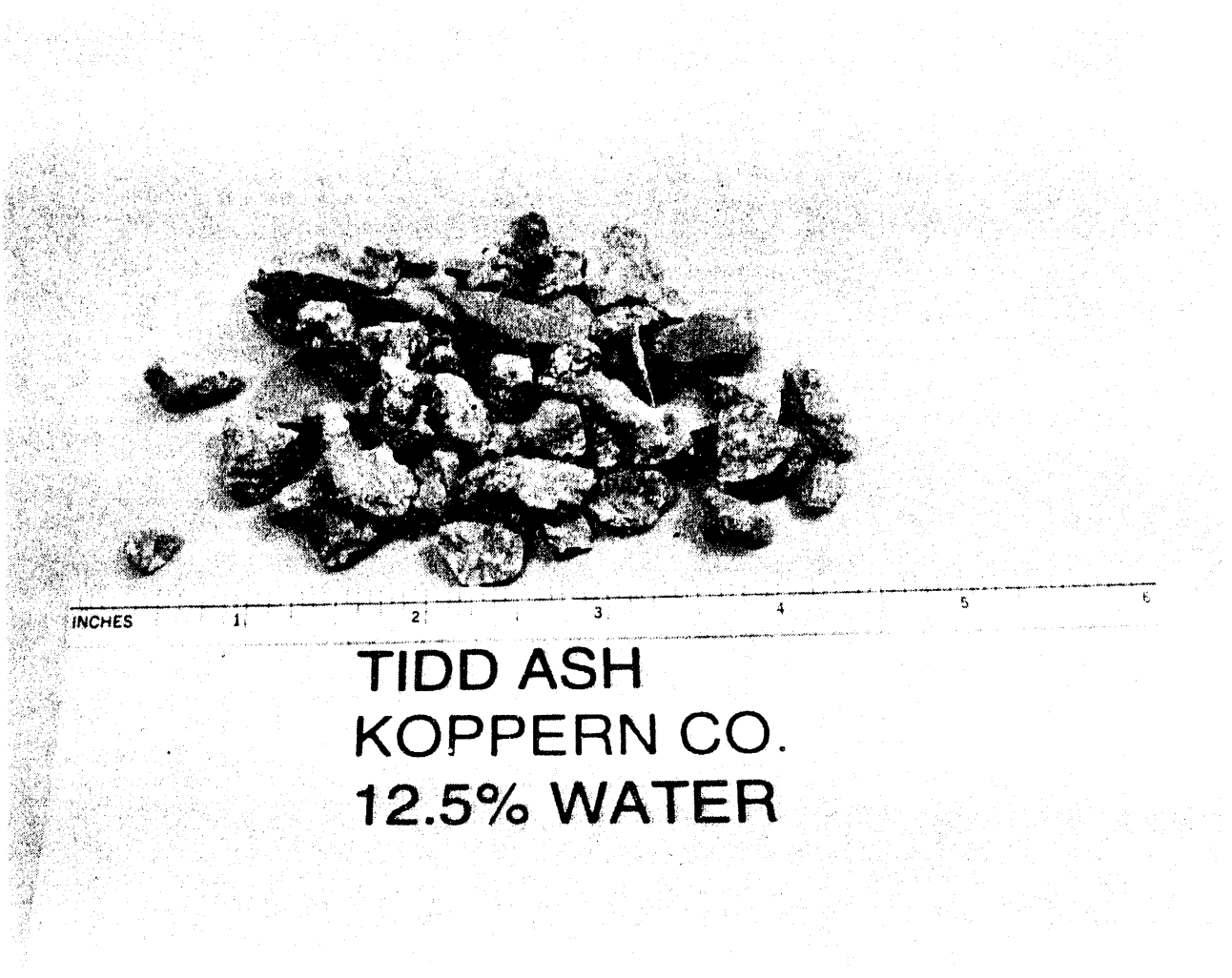


Figure 5.6 — AEP/Tidd PFBC ash - pressure compacted by Koppern equipment.

The types of tests conducted were

- sample drying to measure moisture content,
- furnace testing to characterize sample thermal degradation on heating to 1600°F, and environmental degradation after long time exposure to air,
- rotary attrition testing, by a standard ASTM method adapted to high temperatures, to characterize hot and cold sample attrition losses.

The pellet samples tested in the program, their sample number designation, their raw materials, binders, and vendor, were:

1. Large pellets (1/2" - 1") made from a circulating-AFBC plant fly ash, produced by Ferro-Tech and provided to Westinghouse early in the program as a preliminary sample.

2. Foster Wheeler circulating-AFBC plant solid waste pelletized by Ferro-Tech with 16 wt% water addition and no binder.

3. Texaco gasifier solid waste pelletized by Ferro-Tech with 27.5 wt% water addition and 10 wt% cement binder.

4. Texaco gasifier solid waste pelletized by California Pellet Mill with 25 wt% water addition and 5 wt% cement binder.

5. Texaco gasifier solid waste pelletized by California Pellet Mill with 20 wt% water addition and 5 wt% cement binder.

6. Texaco gasifier solid waste pelletized by California Pellet Mill with 20 wt% water addition and 5 wt% starch binder.

7. Texaco gasifier solid waste pelletized by California Pellet Mill with 15 wt% water addition and 5 wt% starch binder.

8. Foster Wheeler circulating-AFBC plant solid waste pelletized by California Pellet Mill with 15 wt% water addition and no binder.

9. Tidd PFBC plant solid waste pelletized by Ferro-Tech with 12.5 wt% water addition and no binder.

10. Tidd PFBC plant solid waste pelletized by California Pellet Mill with 15 wt% water addition and no binder.

11. Tidd PFBC plant solid waste pelletized by California Pellet Mill with 15 wt% water addition and 5 wt% starch binder.

12. Aardelite, commercial pellets produced from conventional, pulverized coal power plant fly ash by PMI, using water and lime binder.

The Aardelite pellets and the Ferro-Tech pellets were produced by similar disk pelletizer techniques and were roughly spherical in shape. The Ferro-Tech pellets were received with diameter less than 3/4" and mass-mean diameter about 1/2". The California Pellet Mill pellets were produced by extrusion and were cylindrical in shape, having a diameter of 3/16" and length less than 7/8", with a mean length of about 3/8". Only limited details of any size reduction performed on the plant solid wastes before pelletization, mixing and handling, and curing techniques were available from the vendors as reported in Appendix B. All of these aspects of the pelletization operation may have important impacts on the durability of the pellets.

Several pellet samples were dried by simple room exposure for 1 week after receipt, and then were vacuum dried at about 215°F to measure their moisture loss. The weight gain, by moisture and gases absorbed after re-exposure to the atmosphere for about 2 days, was also measured. The results are summarized in Table 5.4. These numbers reflect the relative surface activity of the pelletized samples, as well as the expected moisture weight losses and gains during processing in the SMGBF system.

Several of the pellet samples were heated to 1600°F in a furnace to observe the pellet appearance and degradation after high temperature exposure. Initial tests subjected the as-received pellets to fast heating, and this resulted in swelling, cracking and weakened condition in several of the pellet samples. In subsequent tests, pellet samples were seived to a representative size expected for use in the SMGBF system, and were heated more slowly. The initial appearance heating and cooling, and the long-time degradation of the cooled pellets on exposure to air for several days were noted. The slower heating was representative of a proper curing period, followed by a heatup in the SMGBF feed pipe. Most of the samples showed little change in strength following the heat exposure and cool down, but several of these also

Table 5.4 — Pellet Samples Moisture Content

Sample No.	Weight Lost (%) On Drying (215°F)	Weight Gain (%) On Room Exposure
2	12.92	4.02
3	16.13	4.44
4	12.63	1.70
5	5.14	1.65
6	3.12	1.19
7	2.60	1.20

degraded on long-time air exposure. These test results, since they include no mechanical forces on the pellets, represent the minimum loss conditions for the pellets in the SMGBF system.

Tests of the attrition resistance of the pellets were also performed based on ASTM method D 4058-87 (Standard Test Method for Attrition and Abrasion of Catalysts and Catalyst Carriers). The test equipment and procedures were modified to include high-temperature exposure. The severity of the attrition test used is orders-of-magnitude greater than the attrition conditions expected in the SMGBF system, so the test provides only relative information about the attrition resistance of the pellets.

The equipment, illustrated in Figure 5.7, is a rotary drum with an internal baffle to provide agitation of the pellet samples contained within a furnace. The drum is a nickel 200 cylinder, 8.375" in inside diameter and 6" long. A single, radial baffle plate, 2" high and 6" long, is attached to the inner wall. A tight-fitting nickel lid is attached to the drum with machine screws so that no material can escape. The drum is centered in a cylindrical furnace with an inside diameter of 10" and a length of 12". A shaft is attached to the center of each end of the drum, and passes through bronze bearings. A chain drive with variable speed motor rotates the unit.

Samples were weighed and loaded into the clean drum. The lid was attached with machine screws coated with anti-seize compound. The

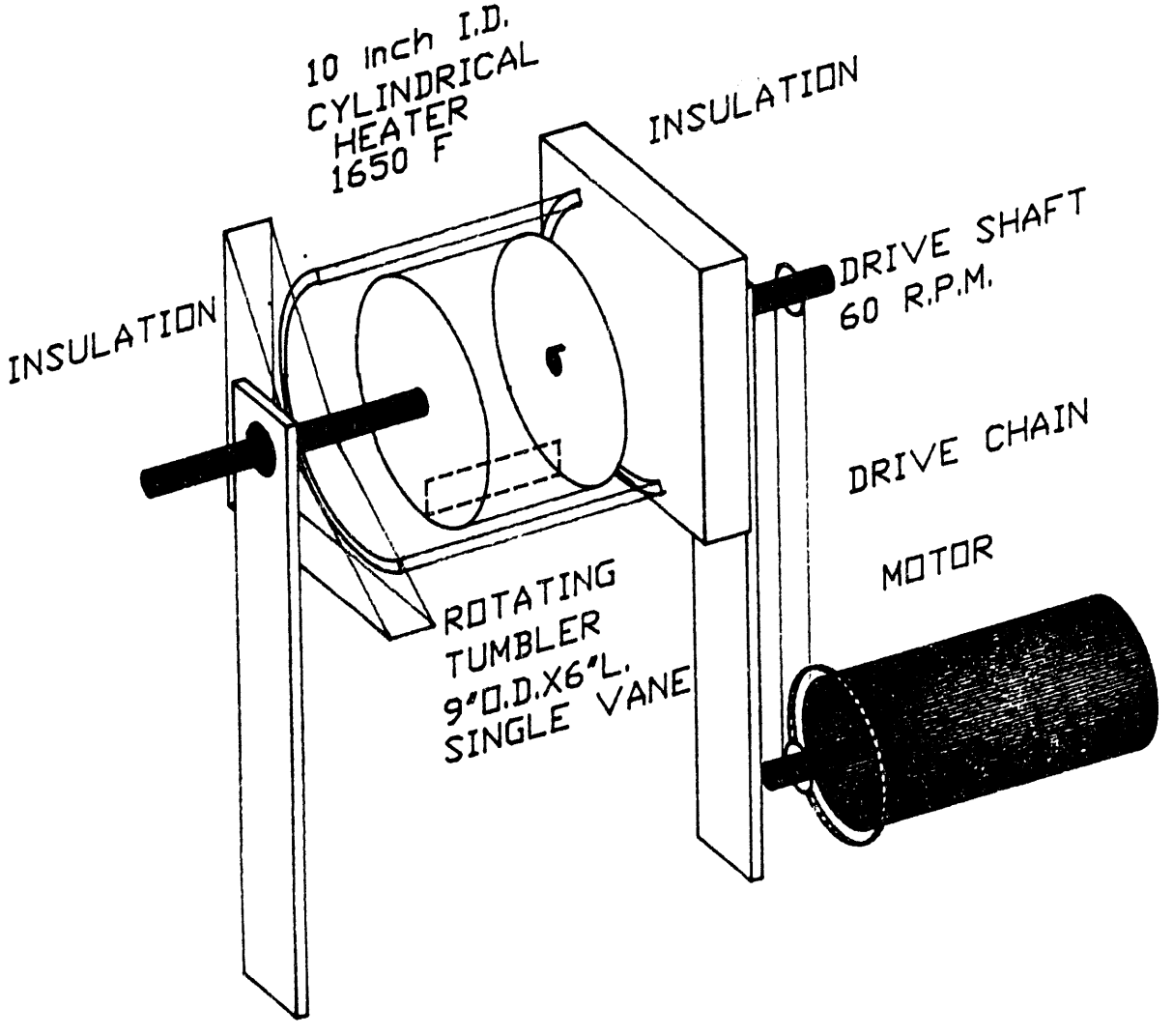


Figure 5.7 — Pellet attrition unit.

drum was then placed into the end mounts. Finally, the upper half of the furnace was set into place and the power leads connected. The tests were generally conducted by heating the furnace to temperature, starting the unit rotation at the prescribed rotational speed, and maintaining the conditions for the prescribed test duration, although some alternative procedures were also used. The heating and rotation was halted at the completion of the test, and the unit was allowed to cool. After cooling, the unit was dismantled, the sample was carefully poured into a set of sieves, and the drum and lid was brush cleaned into the sieve. The sieve was gently agitated to remove fines from the pellets, and the sample was weighed and sized.

The results of these tests are listed in Table 5.5. The first set of 11 tests in the table indicate that the samples pelletized by Ferro-Tech, using the disk pelletizer (samples 1, 2 and 3), had much less attrition loss than the extruded pellets produced by California Pellet Mill (samples 4-8). The sample 1 pellets were extremely durable, improving in attrition resistance when the temperature was increased. These pellets had apparently been properly cured, whereas the other pellets had not received a significant curing. The sample 2 pellets were very weak at 1600°F even without rotation of the unit. The extruded pellets attrited significantly at room temperature.

The remaining 18 tests listed in Table 5.5 considered the Aardelite pellets (sample 12), and their attrition behavior with respect to temperature, baffling, drum speed and test duration, and temperature history. The data indicates that the attrition of the Aardelite pellets, at 12 rpm and ambient temperature, levels off at about a 2.5 wt% attrition loss as the duration of the test increases. The attrition loss increases with increasing rotation speed, for the same total number of revolutions, and increases when the baffle is in place compared to when there is no baffle. More importantly, the extent of attrition decreases when the Aardelite pellets are first heated to 1600°F before rotation, getting stronger with heating. The last two tests listed in the table heated the sample from room temperature to 1600°F after rotation was initiated rather than the standard method of heating to full temperature before rotation.

Table 5.5 — Pellet Rotary Attrition Test Results

Sample No.	Sample Condition	Baffle	Temperature (°F)	Drum Speed (rpm)	Time (min)	Attrition Loss (%)
1	As received	yes	room	50	36	2.2
1	As received	yes	1500	50	36	0.9
2	3/16"-5/8"	yes	room	50	36	24.7
3	3/16"-5/8"	yes	room	50	36	5.2
4	As received	yes	room	50	36	99.9
5	As received	yes	room	50	36	100
6	As received	yes	room	50	36	99.4
7	As received	yes	room	50	36	92.9
8	As received	yes	room	50	36	95.5
2	3/16"-5/8"	yes	1600	50	36	100
2	3/16"-5/8"	yes	1600	0	36	weak
12	As received	yes	room	50	36	12.1
12	As received	yes	room	25	72	9.0
12	As received	yes	room	12	150	7.6
12	As received	yes	room	4	450	7.0
12	As received	no	room	50	36	8.2
12	As received	no	room	25	72	5.0
12	As received	no	room	4	450	1.0
12	As received	no	room	12	150	2.5
12	As received	no	room	12	75	2.5
12	As received	no	room	12	37.5	1.8
12	As received	no	room	12	18.75	1.7
12	As received	no	room	12	8.33	0.9
12	As received	no	room	12	4.17	0.6
12	As received	no	room	50	18	6.2
12	Preheat to 1600°F, store 1 week	yes	room	50	36	12.5
12	As received	no	1600 before rotation	12	75	0.2
12	As received	no	room to 1600°F	12	75	0.7
12	As received	yes	room to 1600°F	12	75	1.7

The major conclusions to be drawn from all the pellet testing is that proper curing, and preheating of the pellets will ensure that they will not degrade significantly when subjected to the SMGBF high-temperature conditions. The pellets will probably be sufficiently strong, in any case, for handling by mechanical systems. Even if properly cured, some types of advanced power plant solid wastes, especially those containing high calcium content, may degrade significantly after disposal and long contact with the atmosphere. The success of entrained gasifier plants in producing coarse aggregates that can be commercially marketed, and the acceptable characteristics of the commercial Aardelite pellets, adds strong evidence that sufficiently strong pellets can be produced from advanced power plant solid wastes using conventional pelletization techniques. The best procedures for solid waste sizing, binder and water content, mixing, and curing will differ somewhat between IGCC and PFBC applications, and needs additional evaluation.

5.7 PELLETIZATION CONCLUSIONS

On the basis of the pelletization evaluation conducted by five vendors employing three different pelletization technologies and using waste ashes from three different advanced power plant processes (PFBC, AFBC, and IGCC), it can be concluded that the advanced power plant waste ashes can be pelletized with the pelletization technologies available commercially. For waste ashes containing limestone or dolomite for sulfur control, pelletization can be accomplished simply by adding water as the binder. For IGCC waste ash, cement or lime needs to be added as a binder. The final selection of the available technologies for application will be based on economic considerations. For this evaluation, the turbulator/disc pelletizer technology employed by Ferro-Tech is the choice because of its simplicity, low maintenance, and experience in large commercial plants.

6. SMGBF HTHP Testing

6.1 HTHP FACILITY

The design of the SMGBF, HTHP test facility is described in this section. Figure 6.1 is the P&ID for the auxiliary systems of the HTHP test facility. The auxiliary systems are associated with the air supply, fuel supply and flyash feeding systems. The natural gas combustion leg and the vessel outlet leg are refractory lined pipe sections. A batch loaded, pressurized, screw feeder system is used to control the feed rate of power plant fly ash to the SMGBF vessel, injecting the fly ash downstream of the natural gas combustor. Provisions for measuring temperatures, pressures and differential pressures are utilized and located as shown in the drawing. A computer-based data logging system is used to collect and display the data during testing and to reduce the data after testing.

Figure 6.2 is a SMGBF vessel P&ID that also shows the arrangement of the major equipment in the HTHP test facility. A batch-loaded, pressurized bed media feed bin is located directly above the SMGBF vessel. Bed media flows by gravity, and without control valve or shutoff valve, from the feed bin into the SMGBF vessel. A high-temperature, water-cooled screw conveyor located below the SMGBF vessel controls the flow rate of bed media through the unit, and feeds the drained bed media and captured fly ash into a pressurized storage hopper. Temperatures at various locations within the SMGBF vessel are recorded. The pressure drop across the total vessel is recorded, as well as the pressure drop across various sections of the moving bed: between the gas inlet chamber and the gas outlet chamber, between a point near the top of the standleg (2-1/2" below the top) and the gas outlet chamber, between 2 intermediate points in the standleg (12-3/4" and 23" below the top of the standleg) and the gas outlet chamber, and

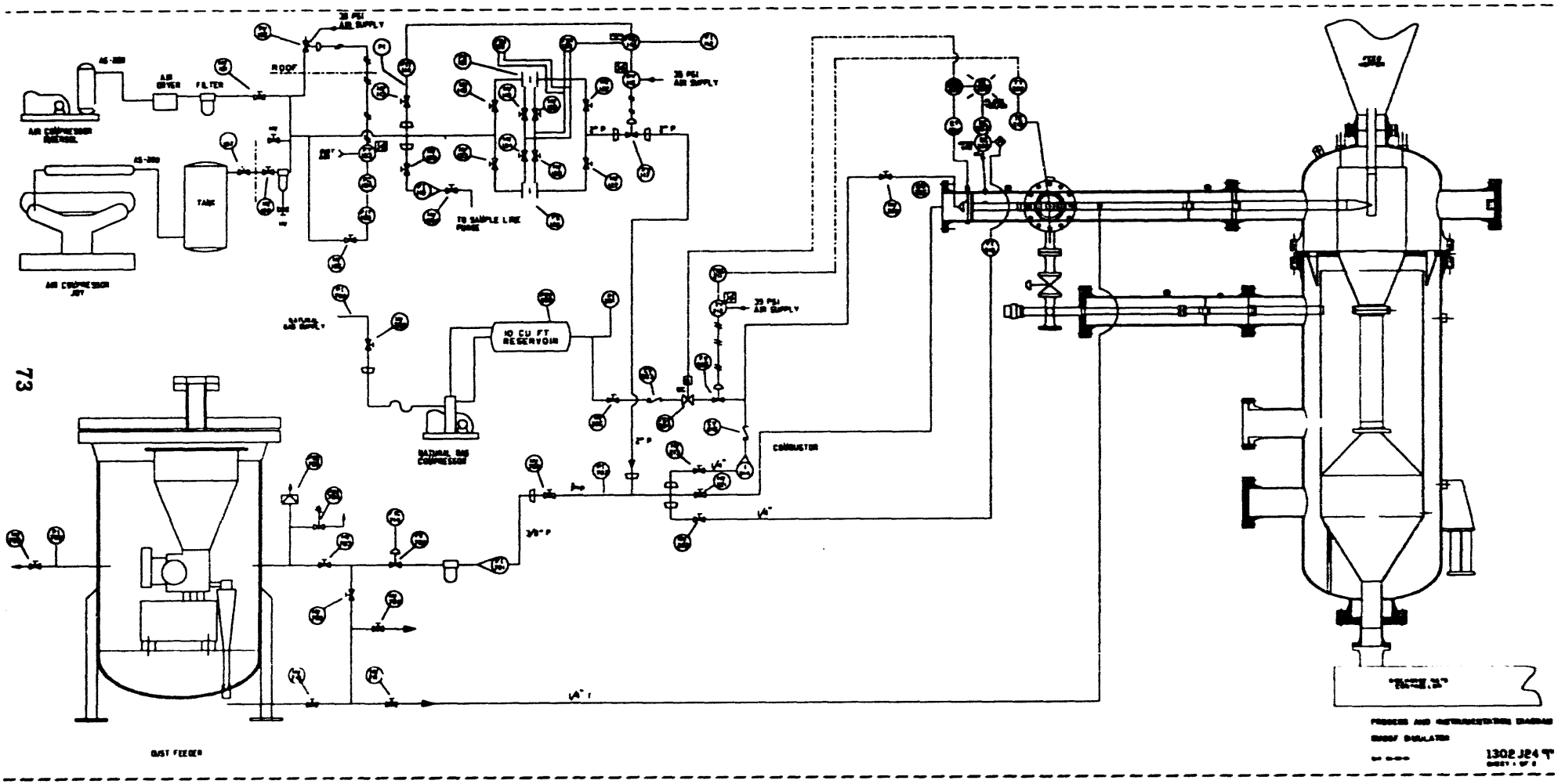


Figure 6.1 — HTHP facility arrangement and P&ID.

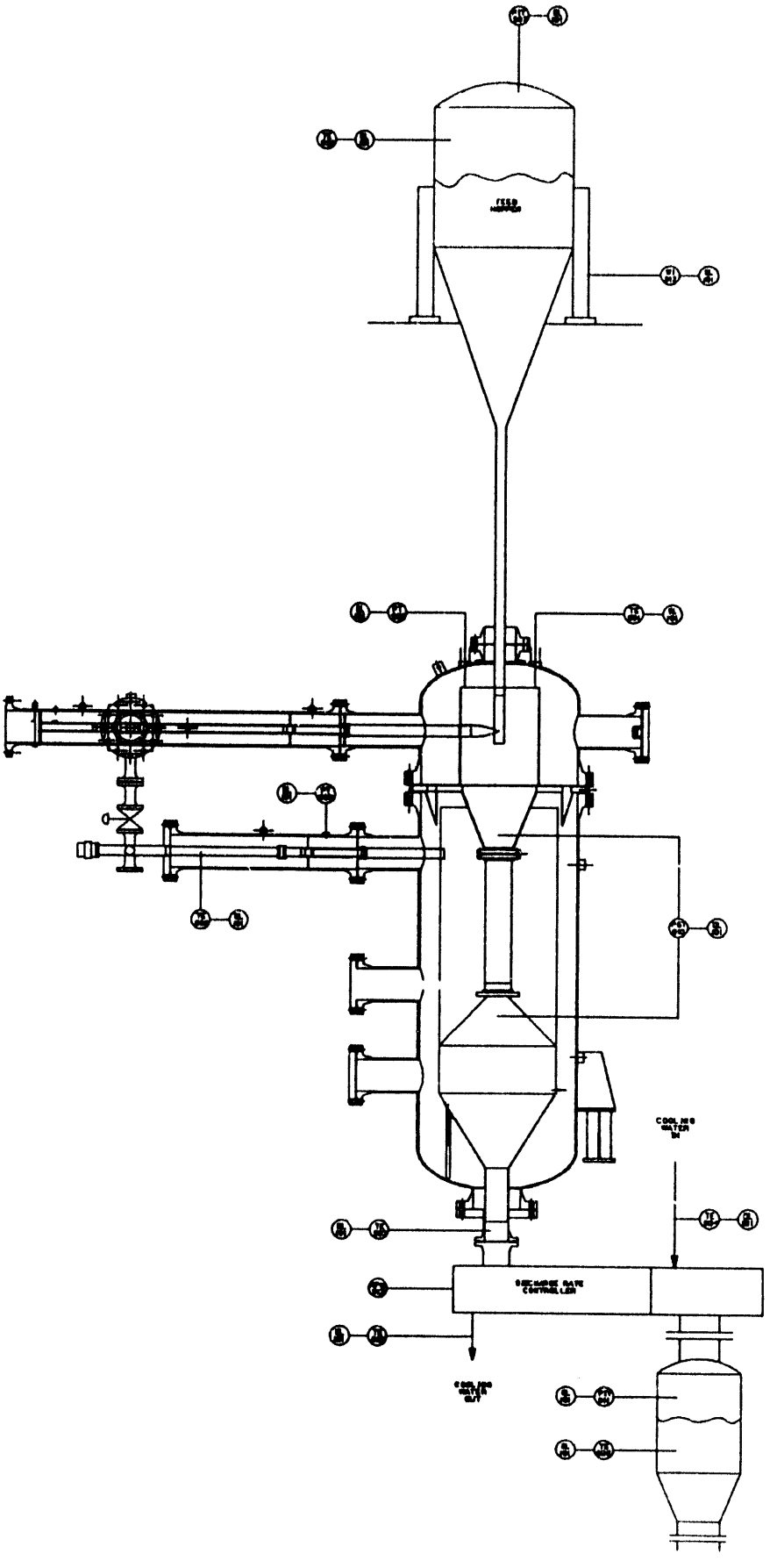


Figure 6.2 — HTHP unit conceptual layout and P&ID.

between a point near the base of the standleg (35-1/4" below the top of the standleg) and the outlet chamber.

The SMGBF pressure vessel is a refractory-lined vessel previously used for ceramic barrier filter testing. It has an outer diameter of about 40" and a total height of about 10 feet. The pressure vessel head is a new design to accommodate the tangential gas inlet and the support of the vessel internals, replacing the previous, ceramic barrier filter vessel head. The essential vessel features are similar with those shown in the cold flow model design drawings in Section 4, except that the vessel and internals are designed for operation at 1600°F and 350 psig pressure. Figure 6.3 shows the vessel head design. The elliptical head has been selected to minimize head space so that lifting of the head with the existing hoist could be accommodated. The dirty gas enters tangentially into the head. An alternative radial gas inlet has been included in the head. The bed media enters through the nozzle located in the top of the head.

Figure 6.4 shows the design of the internal components of the SMGBF unit. The bed media and gas pass cocurrently downward through the high-alloy cone and standleg pieces, and gas disengagement occurs at the base region of the standleg. The standleg is a 6" pipe section, about 3 feet in length. The internal support structure within the vessel for the cone and standleg pieces is similar in design to the tube sheet used in ceramic barrier filters. An expansion web accommodates the thermal expansion of the materials. The gas seals are located at the cold vessel flange.

The equipment designs were based on the following maximum flow rates of the major process streams:

- Gas flow: 70 acfm, or 820 lb/hr
- Fly ash flow: 4 lb/hr
- Bed media flow: about 80 lb/hr

The HTHP unit operating conditions were selected to simulate those of PFBC applications. The operating and design condition ranges are:

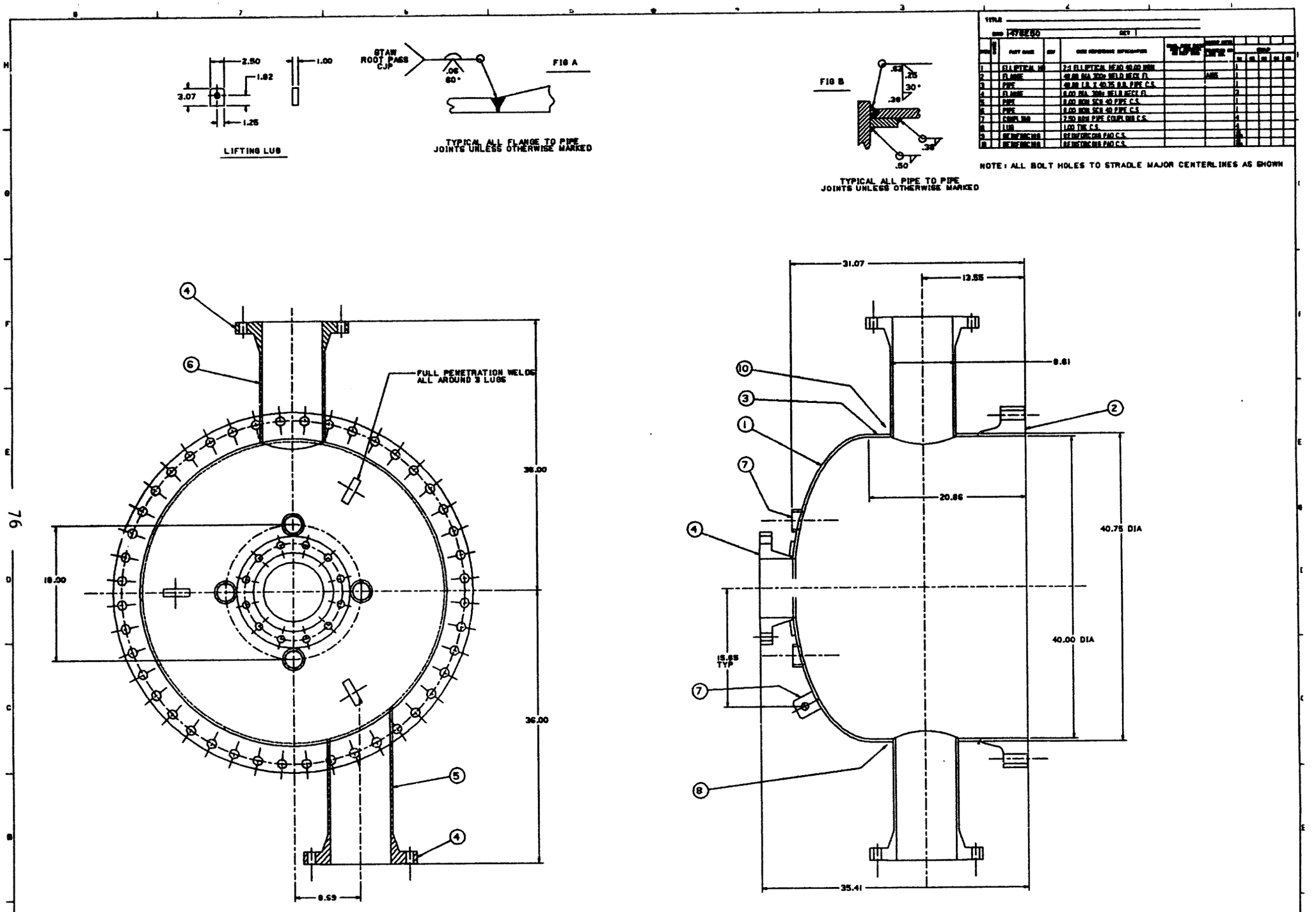


Figure 6.3 — HTHP unit vessel head design.

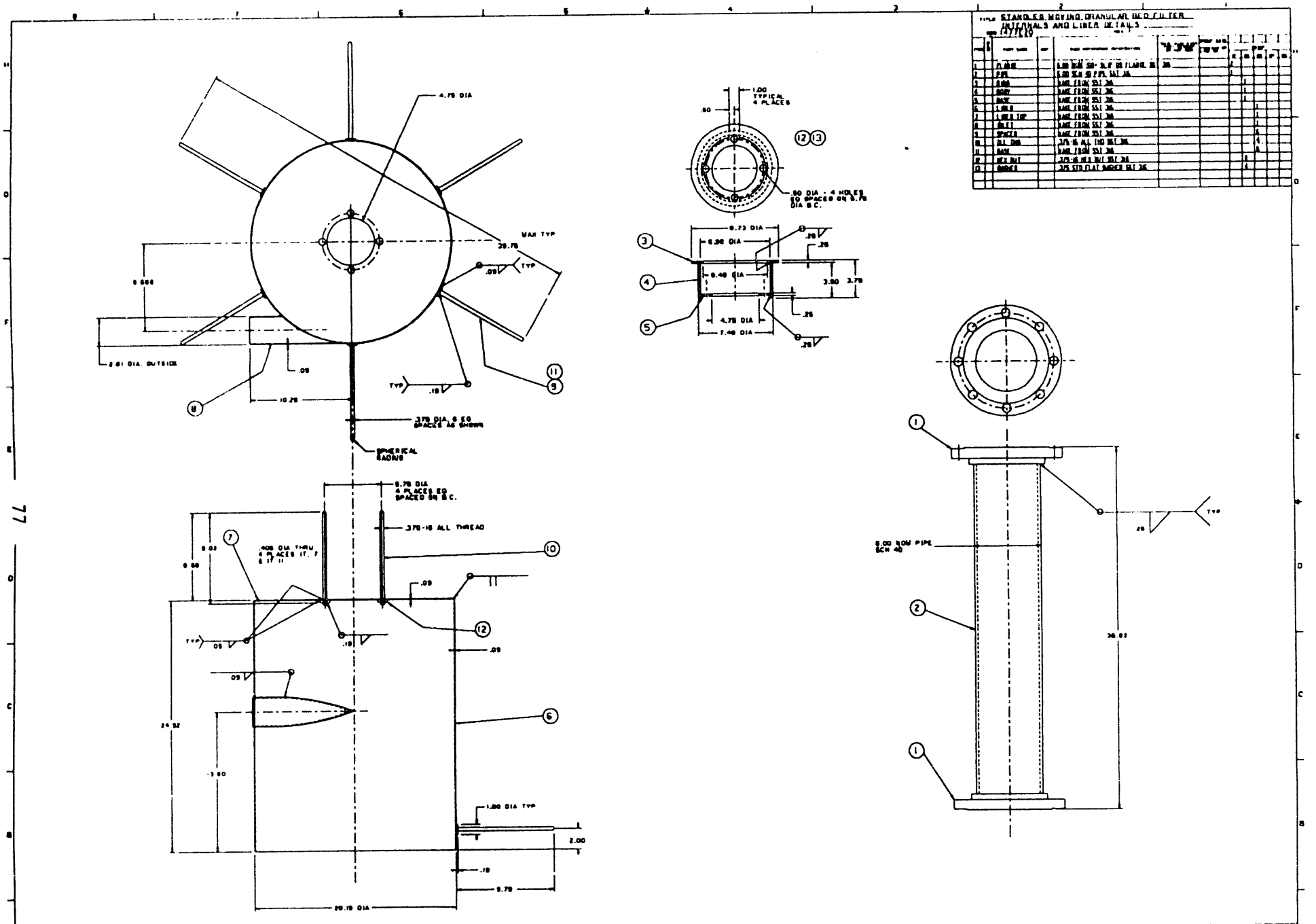


Figure 6.4 — HTHP unit internals design.

gas environment	- oxidizing
Temperature	- 1550°F
Pressure	- 10 atm
Gas face velocities	- 3 to 6 ft/s through the standleg
Moving bed velocities	- up to 0.02 ft/min
Bed media/ fly ash ratio	- 5 to 20
Dust loading	- nominally 5000 ppm by weight
Fly ash material	- PFBC fly ash
Operating modes	- continuous and on-off modes

6.2 TEST RESULTS

A total of 18, high-temperature test runs were completed in the Base Contract test program. The tests were arranged in three major series:

1. On-off bed media flow using pelletized fly ash (Aardelite),
2. Continuous bed media flow using alumina beads,
3. Continuous bed media flow using pelletized fly ash (Aardelite).

The on-off mode of bed media flow control was applied in the first series of tests because the water-cooled screw conveyor could not initially operate at sufficiently low enough feed rate to be used for the continuous flow mode. After the on-off bed media flow test series, the screw feeder equipment was modified so that lower bed media flow rates could be achieved, and continuous bed media flow tests were performed for the remainder of the test program.

The pelletized fly ash used in the testing was a commercial material, Aardelite pellets, made from conventional, pulverized coal power plant fly ash by Progress Materials Inc., Crystal River, FL. These pellets were used because they were readily available and of low cost compared to having pellets made from advanced power plant solid wastes. While these commercial pellets were representative of the physical characteristics of pellets that could be made from advanced

power plant solid wastes, they also contained periodic, high levels of carbon (as much as 10 wt%), in contrast to advanced power plant waste pellets that would be expected to contain less than 1 wt% carbon. The pellets had a bulk density of about 54 lb/ft^3, and a size range of about 1/8" to 1/2" diameter. The screw-conveyor, pelletized solid waste feed rate was calibrated with respect to the device rotational speed before test operation so that preselected feed rates could be used. Cold flow testing of the unit, without pellet flow and without fly ash injection was performed initially to assess the pellet permeability behavior and to ensure good gas flow distribution. The cold standleg pressure drop measured at a velocity of 5 ft/s was about 38 in H_2O.

The alumina beads used in the testing were a mixture of 3-parts 3/8" beads, and 2-parts 1/4" beads. The beads had a more spherical shape than the Aardelite pelletized fly ash. The alumina granules bulk density was about 99 lb/ft^3. Before the alumina bead testing, the screw conveyor was again calibrated, and cold flow testing of the unit was performed. At a standleg velocity of 5 ft/s, the cold standleg pressure drop was about 17 in-wg, much less than that of the Aardelite fly ash pellets because of the their larger size, and more regular, spherical shape.

Table 6.1 summarizes the HTHP tests performed in the Base Contract, showing their nominal operating conditions, and their general results. All of the tests were conducted at a nominal pressure of 100 psig. Each test represents a full day of testing, with 8 to 12 hours of hot operation. The nominal bed temperature ranged from 1100 to 1700°F, with most tests at 1500 to 1600°F. The results were not expected to be very sensitive to temperature variations within this range, and this appeared to be confirmed by the testing.

The first series of tests were characterized by excellent particle removal performance, but operating difficulties resulted from agglomerates and plugs formed in the SMGBF unit due to combustion of high carbon contents in some portions of the pellet feed. This was evident in the first test of the series where it was observed that the bed outlet gas temperature jumped suddenly, and exceeded the inlet temperature for a short period of time (see Appendix C, Figure C1).

Table 6.1 — SMGBF, HTHP Test Summary

SERIES 1 (9/28/93 - 11/1/93)

Bed media type: Aardelite, fly ash pellets
Bed media feed mode: On-Off
Fly ash type: Tidd PFBC fly ash (change to Grimethorpe PFBC fly ash during Test No. 7)

Test No.	Standleg Velocity (ft/s)	Bed Press. Drop (in. H_2O)	Inlet Dust Load (ppmw)	Media/Fly Ash Mass Ratio (---)	Outlet Dust Load (ppmw)	Observations
1	3.0	25-30	0	No media feed	17	Temperature excursions
2	3.3	20	0	No media feed	6, 4, 2	Good performance
3	3.3	15	0	101 lb fed in 1 hr period	2, 4	Standleg plug found
4	3.1	30-100	1500-3000	18 average	2-19, 10 average	Good performance
5	3.3	10-50	3000-4000	4.4 average	70-214	Lost pellet bed due to plug
6	3.1	30	4200	16.5 average	5-9, 7 average	Difficult dust feed Good performance
7	3.1	30-95	1900-4700	9.2 average	3-19, 11 average	Good performance Agglomerates found

Table 6.1 — (Continued)

SERIES 2 (1/19/94 - 1/28/94)

Bed media type: Alumina beads
Bed media feed mode: Continuous
Fly ash type: Grimethorpe PFBC fly ash

Test No.	Standleg Velocity (ft/s)	Bed Press. Drop (in. H_2O)	Inlet Dust Load (ppmw)	Media/Fly Ash Mass Ratio (---)	Outlet Dust Load (ppmw)	Observations
8	3.0	20	1500-3300	23.0 average	6-22, 12 average	Good performance
9	3.2	20-55	1200-5700	14.7 average	62-159, 88 average	High ash penetration
10	3.1	30-50	5000-5200	11.7 average	57-160, 100 average	High ash penetration
11	2.9	25-40	1000-5800	10.9 average	117-170, 137 average	High ash penetration
12	3.0	30-50	3500-5600	10.6 average	65-230, 108 average	High ash penetration
13	3.0	40-65	4700-6700	10.3 average	137-249, 183 average	High ash penetration
14	2.9	25-50	1900-5000	12.6 average	117-224, 161 average	High ash penetration

SERIES 3 (3/1/94 - 3/7/94)

Bed media type: Aardelite fly ash pellets
Bed media feed mode: Continuous
Fly ash type: Grimethorpe PFBC fly ash

Test No.	Standleg Velocity (ft/s)	Bed Press. Drop (in. H_2O)	Inlet Dust Load (ppmw)	Media/Fly Ash Mass Ratio (---)	Outlet Dust Load (ppmw)	Observations
15	3.0	40-45	0	No media feed	8-57	Decreasing background
16	3.0	40-45	0	No media feed	2-24	Decreasing background
17	3.5-5.0	65-110	0	No media feed	0.2-6.0	Decreasing background
18	2.5-2.9	40-50	2600	21.5 average	8-14, 11.7 average	Good performance

Using the on-off mode of pellet feeding, combined with the agglomerate formation difficulties, it was difficult to achieve steady SMGBF operation. During tests 3 and 5, agglomerates appeared to have disrupted operation, and in test 5 there was a sudden loss of standleg pressure drop when the standleg emptied without filling due to a large agglomerate blockage. In the on-off tests where pellets were fed, the on-off feed frequency was about once per hour, with pellets fed for 10 to 15 minute duration. Some response, such as a reduction in the bed pressure drop, was evident during the pellet feeding events.

There appeared to be a particle removal performance sensitivity to the mass feed ratio of pellet feed to fly ash feed, with higher values of this ratio resulting in better performance, and this is suggested by the results shown in the table. Tests 6 and 7 appear to have been the best tests in the series and resulted in particle outlet loadings of 7 to 11 ppmw on average, equivalent to particle removal efficiencies of 99.7 to 99.8%. Overall, the test results met or exceeded expectations and goals for the SMGBF performance, but the operational problems called for further testing to demonstrate the unit operability.

In the second test series, alumina beads were purchased to replace the Aardelite fly ash pellets so that the agglomeration problem could be eliminated, and so that a higher density, and more uniform particle shape could be assessed. The screw feeder was also modified so that the continuous feed mode of operation could be achieved. This second set of seven tests ran without any operating problems, although the screw feeder caused significant crushing of the alumina beads, in contrast to the relatively undamaged condition of the Aardelite fly ash pellets. It was concluded that the screw conveyor clearance was not large enough to accommodate the flow of the large, hard, uniformly sized beads. The alumina beads, because of their higher density, result in an equivalent mass ratio of bed media to fly ash almost half of the that of the Aardelite fly ash pellets. This is because the volumetric flow of the bed media is the actual controlling parameter for particle removal. The alumina bead tests showed lower unit pressure drops, but much higher particle penetrations than the fly ash pellet tests. Again, a sensitivity to the mass ratio of bed media flow to fly ash flow was

indicated by the results recorded in the table. Only in Test 8, when the bed media-to-fly ash feed ratio was about 23, was the particle penetration as low as it had been in the Aardelite fly ash pellet testing.

The final series of tests was conducted to test the performance of the Aardelite pelletized fly ash with the continuous feed mode of operation. Used fly ash pellets from the first series of tests, that had already been exposed to high temperature conditions and were, therefore, free of carbon, were seived to remove some of the fly ash that had been trapped with them. The SMGBF vessel was filled with the Aardelite fly ash pellets, and a secondary, topping bed of alumina beads was also placed around the outside portion of the standleg to assess its contribution to the particle removal performance. The first three tests of the series were conducted to entrain the fly ash particles contained in the previously used pellets from the unit, operating without fly ash feed or pellet feed. Not until the third test, after operating at higher velocities than usual, did the background outlet particle loading become relatively small. This difficulty in entraining fly ash from the bed is indicative of the high particle removal performance potential of the SMGBF.

The final test showed very good particle removal performance operating at steady conditions. It was found following the last test that most of the bed drainage had occurred from the secondary alumina pellet bed, and it is expected that the later performance of the unit was representative of operation without a secondary, topping bed. It is expected that, even though the background level of fly ash was low from the stagnant bed, once pellet flow was started the background level would have increased as dust trapped in bed pellet interstices was released by relative pellet motions. This may explain the single, high outlet dust loading of 43 ppmw measured after 2 hours of operation.

Plots of the test data for each of the 18 tests are shown in Appendix C. The plots include figures showing the temperature of the top of the SMGBF bed and of the outlet gas as a function of operating time. The standleg velocity and total bed pressure drop is shown in

separate plots. Sudden, period drops in the pressure drop curves that appear on these plots represent points in time when the pressure drop profile across the bed was sampled. For some of the tests, separate plots showing the bed pressure profile as a function of operating time are included. Finally, Appendix C includes plots of the inlet and outlet particle loading as a function of time for most of the tests. Note that the time axis in these plots represents the time of day, and not the hours of operation.

6.3 TEST CONCLUSIONS

The SMGBF cold flow model testing and the HTHP testing has demonstrated the small-scale performance feasibility of the SMGBF system with respect to the barrier technical issues. Operation with standleg velocities of about 3 ft/s and bed media to fly ash mass ratios of 10 to 20 will result in acceptable fly ash particle penetration (6-14 ppmw) with acceptable unit pressure drop (2-3 psi). Either a Once-Through or Recycle SMGBF system should achieve particle removal acceptable to IGCC or PFBC applications based on these test results. Pelletization of advanced power plant solid wastes, using commercial techniques, should generate sufficiently durable pellets for the Once-Through SMGBF system.

Comparison of the SMGBF test conditions and performance results with previous granular bed filter testing by the Combustion Power Corporation (CPC) unit at New York University (NYU) is made in Table 6.2. [10] The CPC granular bed filter operated with much higher bed media to fly ash feed ratios than the SMGBF. It achieved comparable outlet fly ash loadings with significantly lower inlet fly ash loadings.

Table 6.2 — Comparison of SMGBF Tests With CPC, NYU Tests [10]

	CPC-NYU	SMGBF Cold Flow	SMGBF HTHP
CONDITIONS			
Pressure (atm):	7-9	1	8
Temperature (°F):	1350-1550	80	1500-1600
Gas flow (acfm):	750	140	35
Inlet flyash loading (ppmw):	80-2800	5000	1000-5000
Media-to-flyash ratio:	200-2000	10	10-20
Test time (hr):	74	12	100
Gas residence time in bed (sec):	about 10	4	4
PERFORMANCE			
Outlet flyash loading (ppmw):	6 (average)	5-50	6-14
Removal efficiency (%):	96.8 (average) 99.0-99.8		99.0-99.9
Pressure drop (psi):	1	1	1.5-3.0

7. Evaluation For Integrated Gasification Combined-Cycle Applications

Integrated Gasification Combined-Cycle (IGCC) is an advanced, coal-fueled, power generation technology nearing commercialization through several U.S. Clean Coal Technology Projects, as well as in demonstration programs in Europe. Coal gasification technologies being demonstrated include all of the generic types: fixed bed, fluidized bed, and entrained. Both hot gas cleaning and cold gas cleaning are being incorporated into the various demonstration programs, and many of the IGCC demonstration plants will apply ceramic barrier filter systems for hot and cold fuel gas cleaning. The objective of this evaluation is to assess the conceptual feasibility of the Standleg Moving Granular Bed Filter (SMGBF) in IGCC applications and to compare its design, performance, and cost potential with that of ceramic barrier filters.

7.1 IGCC, SMGBF DESIGN AND EVALUATION BASIS

The basis for the process evaluation is a ceramic barrier filter feasibility study previously prepared under DOE/METC sponsorship: Ciliberti, D. F., et al., Westinghouse, "Performance Evaluation of a Ceramic Cross-Flow Filter on a Bench-Scale Coal Gasifier", Eighth Quarterly Report and Monthly Status Report for September 1, 1986 - September 30, 1986, Contract No. DE-AC21-86MC21338. In this Reference Study, Cross-Flow filter systems were conceptually designed, and equipment and power plant costs estimated for four IGCC plants:

- an air-blown, KRW fluidized bed gasifier,
- an oxygen-blown, KRW fluidized bed gasifier,
- an oxygen blown, Texaco entrained gasifier,
- an air-blown, Lurgi moving bed gasifier.

The hot gas cleaning, operating and design conditions extracted from the Reference Study for use as the SMGBF design basis are listed in Table 7.1. Selected performance targets applied to the SMGBF design, such as maximum pressure drop, maximum temperature drop, maximum fly ash emissions, and maximum turbine inlet dust loading, are also listed.

In the Reference Study, estimates of ceramic barrier filter design, performance, and cost were reported, as well as total power plant investment, annual operating cost, and cost-of-electric (COE) made by scaling of some 1981, EPRI plant cost information. While the gasification process designs, and the ceramic barrier filter designs applied in the Reference Study are not consistent with current practice, and the costs may not provide a valid picture of total IGCC power plant costs, the study provides a convenient means to compare the SMGBF system with ceramic barrier filters.

The evaluation conditions applied in the Reference Study were:

- Plant net generating capacity (MW_e): 100
- Plant heat rate (HHV, Btu/kWh): 9000
- Plant thermal efficiency (HHV, %): 37.9
- Coal type: Illinois #6
- Coal composition : 3.8 wt% sulfur, 9.6 wt% ash, 12,235 Btu/lb (HHV)
- Coal feed rate (lb/hr): 73,559
- Plant layout: single gasifier and gas cleanup train
- Cost year: mid-1981 dollars

The cost premises and procedures applied in this evaluation are as follows:

- Total plant capital investment, annual operating cost, and cost-of-electricity were compiled using an EPRI cost procedure and format adapted by DOE (Lotus Cost of Electricity (COE) - Users Manual, METC). Total capital requirement was estimated by replacing the ceramic filter system installed equipment costs from the Reference Study total power plant cost, with the respective, installed equipment costs for the SMGBF system.

- Power plant annual operating costs were estimated from the SMGBF raw materials and utility rates using standard materials costs:
  - Lime (delivered): 75 $/ton
  - Water: $0.6 per 1000 gal
  - Makeup granules: $500/ton

- These raw material costs were included in the total plant material consumptions in place of those representing the ceramic filter system. Ceramic filter elements were assumed to have an operating life of three years with a replacement cost of $1000 each (cross-flow elements including gaskets, nuts, and bolts).

- Operating costs also include labor to operate the SMGBF system, and these were taken to be the same as those used for the Reference Study. Maintenance costs were estimated from Electric Power Research Institute (EPRI) guidelines (EPRI, Vol. 1, EPRI-4463-SR, Dec. 1986) for maintenance representative of solid handling equipment, at about 4% of the cost of equipment.

- The COE is reported as 10th year levelized dollars (current basis), using the standard EPRI/DOE economic premises. Some of the economic assumptions applied to the IGCC, SMGBF plants were:
  - process contingency 30% for SMGBF system
  - process contingency 5% on balance of plant
  - project contingency 15%
  - plant construction period 3 years
  - coal delivered at $40/ton
  - ash disposal at $10/ton
  - plant capacity factor 65%
  - plant labor 28 Men/shift at $25/hr
  - no byproduct credits

Table 7.1 — IGCC, SMGBF Operating and Design Conditions

IGCC Process:	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
Operating Conditions				
Gas inlet temperature (°F):	1000	1600	1600	1600
Gas inlet pressure (psia):	300	500	385	385
Gas inlet rate (1000 lb/hr):	329.5	160.9	169.7	312.8
Gas inlet rate (acfm):	13030	5829	8027	12642
Fly ash rate (lb/hr):	755	1593	1690	2660
Bottom ash rate (lb/hr):	6307	5469	5372	4402
Design Conditions				
Temperature (°F):	1100	1700	1700	1700
Pressure (psia):	400	600	450	450
Max. gas flow (acfm)[a]:	13700	6120	8430	13275
Max. fly ash rate (lb/hr)[a]:	800	1675	1775	2800
Max. ΔP (psi)[b]:	4	4	4	4
Max. temperature drop (°F)[c]	15	15	15	15
Fly ash emission (lb/MBtu)[d]:	0.02	0.02	0.02	0.02
Turbine inlet load (ppmw)[e]:	15	15	15	15

a: System designed for 5% excess gas and fly ash flow.

b: Maximum pressure drop across the SMGBF vessel (inlet to outlet).

c: Maximum temperature drop across the SMGBF vessel due to vessel heat losses only (inlet to outlet). Does not include pellet mixing losses.

d: Assumed, future environmental emissions standard for particulate.

e: Assumed, acceptable total dust loading to turbine for erosion and deposition tolerance.

AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 3

7.2 IGCC, SMGBF PROCESS DESCRIPTION AND OPTIONS

Two process modes have been identified for the SMGBF system. The first mode utilizes the power plant solid waste as source material for pellet production, using the pellets essentially on a once-through basis. This mode of operation, "Once-Through SMGBF", does not, in concept, require recycle of granular bed filter media, or separation of captured fly ash from the media. The second process mode, "Recycle SMGBF", recycles granules much as the traditional granular bed filter system does, but with several recycle process simplifications. Both of these modes are evaluated here.

7.2.1 Once-Through SMGBF

A schematic process flow diagram of the Once-through SMGBF process is shown in Figure 7.1. The figure is generic to all four of the IGCC power plants being evaluated, and it defines the SMGBF system boundaries. Coal, oxidant (air or oxygen), and steam are fed to the gasifier, which may include heat recovery equipment or quenching to cool the fuel gas down to the cleanup temperature. Primary particle removal equipment, such as conventional cyclones, are also part of the gasification process. Primary particle removal ash and gasifier bottom drain material are combined to represent the bottom ash in the plant, and this waste material is fed to the pelletization system to generate the pellets fed to the SMGBF.

The pelletization process is a conventional process that is operated at atmospheric pressure and low temperature, so the bottom ash is cooled and depressurized before being transported to the pelletization system. Pellets produced are mechanically transported to the pressurization system (lock hoppers), then to the SMGBF feed hopper. The fuel gas fly ash is captured by the pellet stream in the SMGBF unit and is drained with the pellets, cooled and depressurized before disposal, or a portion of the pellets and fly ash maybe recycled to the pelletization system. The water-cooled screw conveyor under the SMGBF unit controls the pellet flow, cools the pellets, and transfer the pellet heat to boiler feed water (BFW) coolant. The cleaned fuel gas

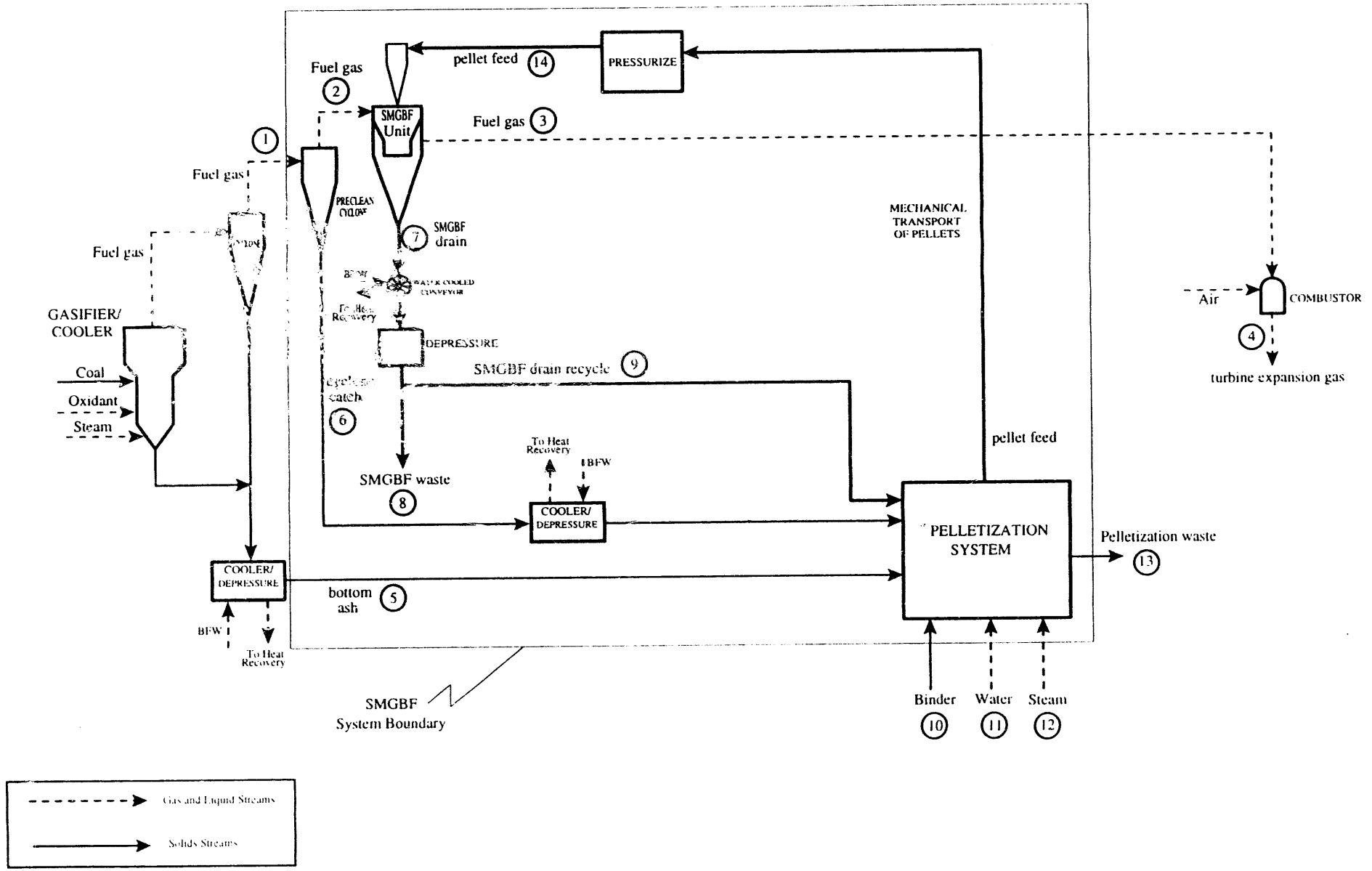


Figure 7.1 — IGCC, Once-through SMGBF Process.

passes on to other gas cleaning steps (eg., sulfur and alkali removal) and is then combusted before being expanded in the gas turbine.

The desired pellet-to-ash mass ratio in Once-Through SMGBF is about 10, or larger, and it is apparent from the tabulated information in Table 7.1 that this ratio cannot be achieved directly in the IGCC cases. Several process options exist that can be used alone, or in combination, to achieve the desired pellet-to-flyash ratio: 1) add a second-stage cyclone, the preclean cyclone, to increase the effective bottom ash rate, reducing the pellet feed rate needed for the SMGBF unit; 2) separate fly ash from the pellet-ash waste (Steam 8) and feed this to the pelletization process step; or 3) recycle some portion of the pellet waste stream back to the SMGBF unit (Stream 9). Since the particle removal performance of a second-stage cyclone will not be very high with the fine fly ash from the gasifiers, this step alone may not be sufficient. The IGCC plant material balances with respect to the pellet-to-flyash ratio, using these potential process configurations are summarized in Table 7.2. The selected Once-Through SMGBF process uses a preclean cyclone in all cases except for the Lurgi IGCC case, and recycles a portion of the SMGBF drain material (Stream 9) in all four cases.

A variety of pelletization processes can be used to generate sufficiently durable pellets for the Once-Through SMGBF system. The selected process for this evaluation is a simple, disk pelletizer system shown schematically in Figure 7.2. It is representative of commercial technology and of pelletization techniques tested in the pelletization test segment of this program. The pelletization process includes conventional size reduction equipment to control the size of the gasifier bottom ash to 80% less than 500 μm. Properly sized bottom ash from the gasifier is mixed with the preclean cyclone ash, with recycled under-sized pellets separated from the curing chamber outlet stream, and with slaked quicklime. The mixture requires a lime content of about 5 wt%, and a water content of about 15 wt%. This mixture is fed through a rotary valve to a commercial disk pelletizer. The green pellets from the pelletizer are mechanically transported to curing chamber, for about

Table 7.2 — Once-through SMGBF Pellet-to-Flyash Ratio Options

	Pellet-to-Flyash Mass Ratio			
	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
NO PRECLEAN CYCLONE:	8.35	3.43	3.18	1.65
with Separated Ash Recycle: (from Stream 8)	9.35	4.43	4.18	2.65
with Pellet and Ash Recycle: (Stream 9)	10	10	10	10
Recycle rate needed, %:	14	62	65	80
PRECLEAN CYCLONE ADDED:	16.83	7.46	6.45	3.37
with Separated Ash Recycle: (from Stream 8)	17.83	8.46	7.45	4.37
with Pellet and Ash Recycle: (Stream 9)	---	10	10	10
Recycle rate needed, %:	0	22	32	61

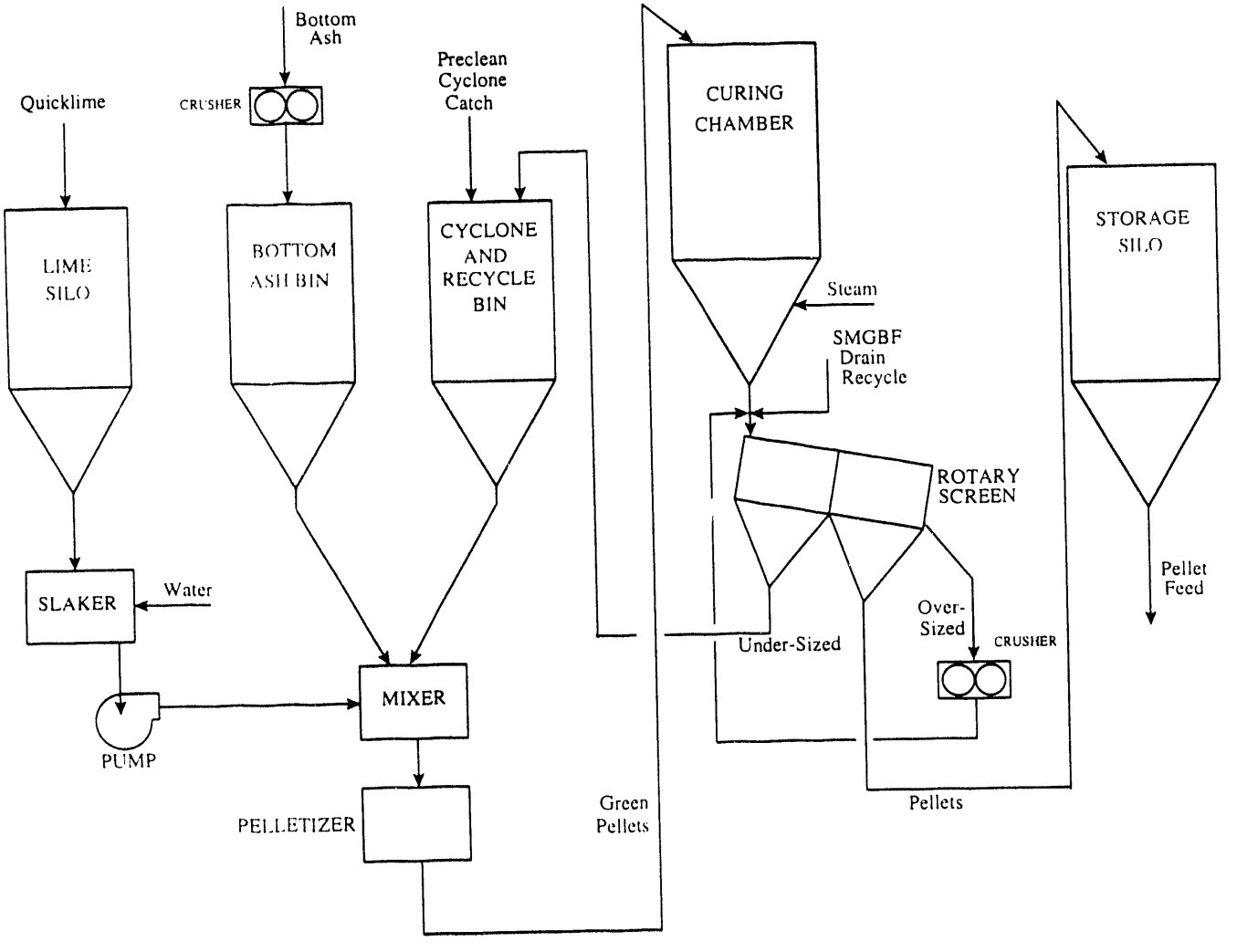


Figure 7.2 — Reference pelletization system.

20 hours curing under steam at about 180°F. The cured pellets and the recycled pellet stream from the SMGBF (Stream 9) are conveyed to a rotary, or vibrational screen where under-sized pellets and ash are separated and recycled, and over-sized pellets are crushed and recycled.

7.2.2 Recycle SMGBF

The Recycle SMGBF process is shown in the process flow diagram of Figure 7.3. Again, the diagram is representative of all four of the IGCC processes, and it defines the SMGBF system boundaries. Coal, oxidant, and steam are fed to the gasifier producing a dirty fuel gas stream and a bottom drain stream of solid waste. A primary cyclone may also be part of the IGCC process that removes some of the fly ash, and this is combined with the bottom drain to form the plant bottom ash. Heat recovery or fuel gas quench may be included with the gasifier to reduce the fuel gas temperature to the cleanup temperature. A preclean cyclone could be added as shown to remove an additional portion of the fly ash and reduce the granule recycle rate needed. No preclean cyclone is used with any of the IGCC processes considered here. The fuel gas passes through the SMGBF, followed by other gas cleaning stages, before being combusted and expanded in the gas turbine.

The circulating granules drained from the SMGBF contain the captured fly ash particles. This fly ash is separated from the granules in an ash-granule separator. Several devices might be used for separation, such as a mechanical seiving device, a fluid bed separator, or a pneumatic separator. All of these require certain development efforts to adapt them to high-temperature, high-pressure conditions, but the mechanical seiving separator is selected for this evaluation because it does not produce a significant gas purge stream requiring secondary cleaning. Only partial separation of the granule and ash mixture is required, because the product granule-ash mixture is recycled pneumatically to the SMGBF using the fuel gas stream as the transport gas. A makeup granule feed hopper is also situated above the SMGBF vessel.

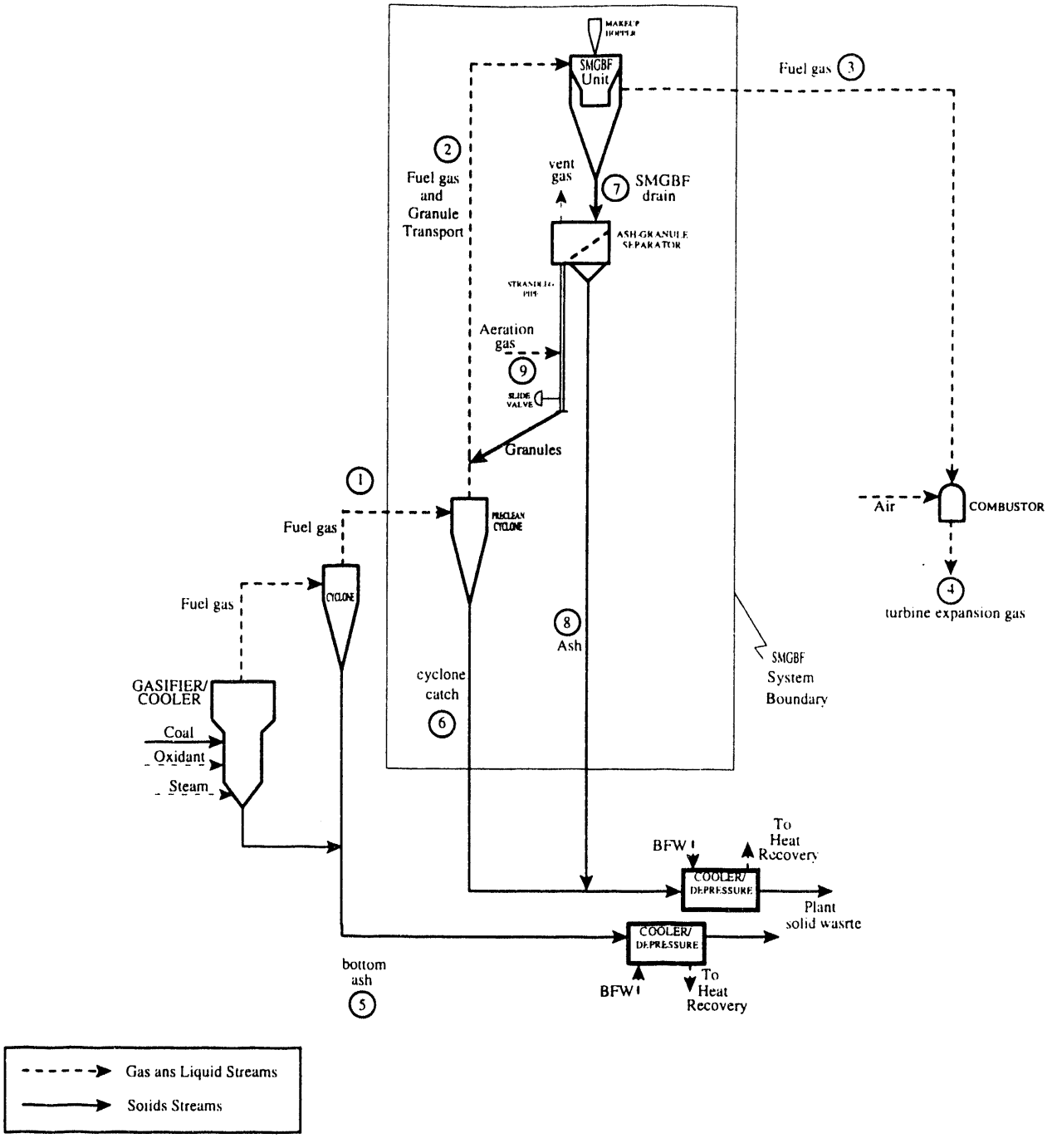


Figure 7.3 — IGCC - recycle SMGBF process.

An aerated standleg is used below the granule-ash separator to buildup the pressure in the standleg. Recycled fuel gas is used for aeration, although steam could also be used. A slide-valve is used in the standleg to set the granule flow rate, and this remains in a relatively fixed position over all plant operating conditions. Other types of high-temperature, solids flow control valves , such as are used in petroleum catalytic cracking applications could also be used. A small amount of vent gas is generated that is sent to the normal lock hopper vent gas treatment equipment in the IGCC plant. The hot gas piping line transporting granules to the SMGBF is designed to have sufficient velocity to effectively transport the granules at full-load conditions, as well as at part-load.

7.3 DESIGN, PERFORMANCE, AND COST OF ONCE-THROUGH SMGBF

This section presents the design, performance and cost of the Once-Through SMGBF process with all four IGCC plants. The basis for the designs, the performance projections, and the cost estimates are also described in this section.

7.3.1 Once-Through SMGBF Material and Energy Balances

Material and energy balance results are listed in Tables 7.3 - 7.6 for each of the IGCC cases. The stream numbers are those listed in Figure 7.1. Major assumptions are listed in each table. Many of the items tabulated are performance results obtained from Westinghouse design algorithms. In each case, the mass ratio of pellet feed to fly ash feed is about 10. Conservative estimates are made for the pellet material losses based on vendor information.

Table 7.3 — Lurgi (Air-Blown) IGCC, Once-Through SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	300	1000	329,500	755
2	Fuel gas	300	1000	329,500	755
3	Clean fuel gas	297	969	329,500	15.1
4	Expansion gas[a]	267	2000	2,550,000	15.1
5	Bottom ash	300	100	---	6307
6	Cyclone catch[b]	---	---	---	0
7	SMGBF drain	297	969	---	8279
8	SMGBF waste	15	250	---	7120
9	Drain recycle	15	250	---	1159
10	Binder feed[c]	15	80	---	377
11	Water feed[d]	15	65	---	1131
12	Steam[e]	50	480	3,890	---
13	Pelletizer waste[f]	15	100	---	203
14	Pellet feed	300	100	---	7539

a: 30 psi pressure drop over the fuel gas combustor

b: no preclean cyclone used

c: binder is commercial lime fed at 5% of pellet material rate

d: water for pelletization at 15% of pellet material rate

e: steam for curing pellets

f: pellet material losses about 1%

Table 7.4 — Texaco (Oxygen-blown) IGCC, Once-Through SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	500	1600	160,900	1593
2	Fuel gas	498	1600	160,900	835
3	Clean fuel gas	495	1521	160,900	16.7
4	Expansion gas[a]	465	2000	2,550,000	16.7
5	Bottom ash	500	1600	---	5469
6	Cyclone catch	498	1596	---	578
7	SMGBF drain	495	1516	---	9183
8	SMGBF waste	15	250	---	7163
9	Drain recycle	15	250	---	2020
10	Binder feed[b]	15	80	---	317
11	Water feed[c]	15	65	---	952
12	Steam[d]	50	480	3,815	---
13	Pelletizer waste[e]	15	100	---	211
14	Pellet feed	500	100	---	8365

a: 30 psi pressure drop over the fuel gas combustor

b: binder is commercial lime fed at 5% of pellet material rate

c: water for pelletization at 15% of pellet material rate

d: steam for curing pellets

e: pellet material losses about 1%

Table 7.5 — KRW (Oxygen-Blown) IGCC, Once-Through SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	385	1600	169,700	1690
2	Fuel gas	384	1596	169,700	948
3	Clean fuel gas	381	1514	169,700	19.0
4	Expansion gas[a]	351	2000	2,550,000	19.0
5	Bottom ash	385	1600	---	5372
6	Cyclone catch	384	1596	---	742
7	SMGBF drain	381	1514	---	10499
8	SMGBF waste	15	250	---	7139
9	Drain recycle	15	250	---	1159
10	Binder feed[b]	15	80	---	377
11	Water feed[c]	15	65	---	932
12	Steam[d]	50	480	3,905	---
13	Pelletizer waste[e]	15	100	---	223
14	Pellet feed	385	100	---	9570

a: 30 psi pressure drop over the fuel gas combustor

b: binder is commercial lime fed at 5% of pellet material rate

c: water for pelletization at 15% of pellet material rate

d: steam for curing pellets

e: pellet material losses about 1%

Table 7.6 — KRW (Air-Blown) IGCC, Once-Through SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	385	1600	312,800	2660
2	Fuel gas	384	1595	313,800	1617
3	Clean fuel gas	351	1504	313,800	16.2
4	Expansion gas[a]	351	2000	2,550,000	16.2
5	Bottom ash	385	1600	---	4402
6	Cyclone catch	384	1595	---	1043
7	SMGBF drain	381	1504	---	17800
8	SMGBF waste	15	250	---	6995
9	Drain recycle	15	250	---	10804
10	Binder feed[b]	15	80	---	270
11	Water feed[c]	15	65	---	809
12	Steam[d]	50	480	3,820	---
13	Pelletizer waste[e]	15	100	---	291
14	Pellet feed	385	100	---	16199

a: 30 psi pressure drop over the fuel gas combustor

b: binder is commercial lime fed at 5% of pellet material rate

c: water for pelletization at 15% of pellet material rate

d: steam for curing pellets

e: pellet material losses about 1%

7.3.2 Once-Through SMGBF Equipment Sizing and Arrangement

The Once-Through SMGBF system equipment has been conceptually sized and specified to the extent needed to develop rough layouts and equipment costs. The SMGBF vessels and other major equipment sizing is summarized in Tables 7.7 - 7.10. A general arrangement drawing of the SMGBF vessel, representative of all of the IGCC cases, is shown in Figure 7.4. The vessel consists of upper and lower sections connected by the standleg fixture. Gas enters tangentially into the upper section. Pellets are fed by gravity through a dipleg pipe, forming a natural angle of repose within the standleg. The standleg and skirt internals hang into the lower vessel section, and form a second angle of repose for gas-pellet disengaging. The vessel hopper is not designed as a mass flow hopper, the distribution of pellet flow that results leading to potentially better particle removal performance. In addition to the vessel gas inlet and outlet nozzles, and the pellet inlet and outlet nozzles, nozzles for instrumentation and for vessel inspection and maintenance are located on the vessel.

In the IGCC cases, single modules of pelletization system, mechanical conveyor, pressurization system (lock hoppers), feed hopper, SMGBF vessel, preclean cyclone, and pellet flow control/cooler (water-cooled screw conveyor) are used. A general layout drawing of the Once-Through SMGBF system, representative of all of the IGCC cases, is shown in Figure 7.5. The SMGBF vessels were sized using granular bed filter algorithms developed specifically for the SMGBF configuration, as well as applying applicable refractory-lined, pressure vessel codes. The cyclones were sized using standard design criteria for high-efficiency cyclones, and pressure vessel codes. Other hoppers, conveyors and size reduction equipment specifications were selected from general equipment design references. The pelletizer system design was scaled from design information provided to Westinghouse by vendors.

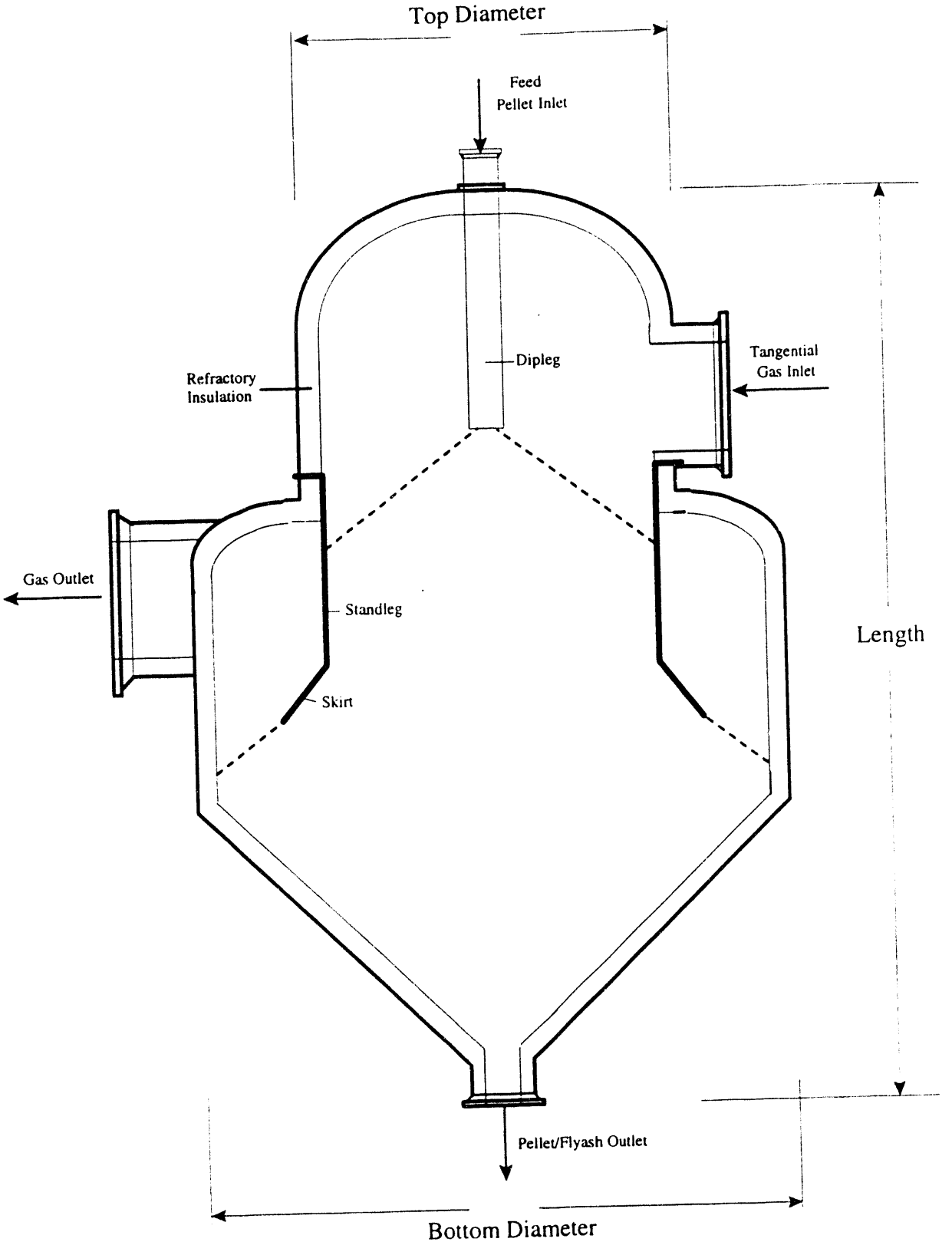


Figure 7.4 — SMGBF vessel arrangement.

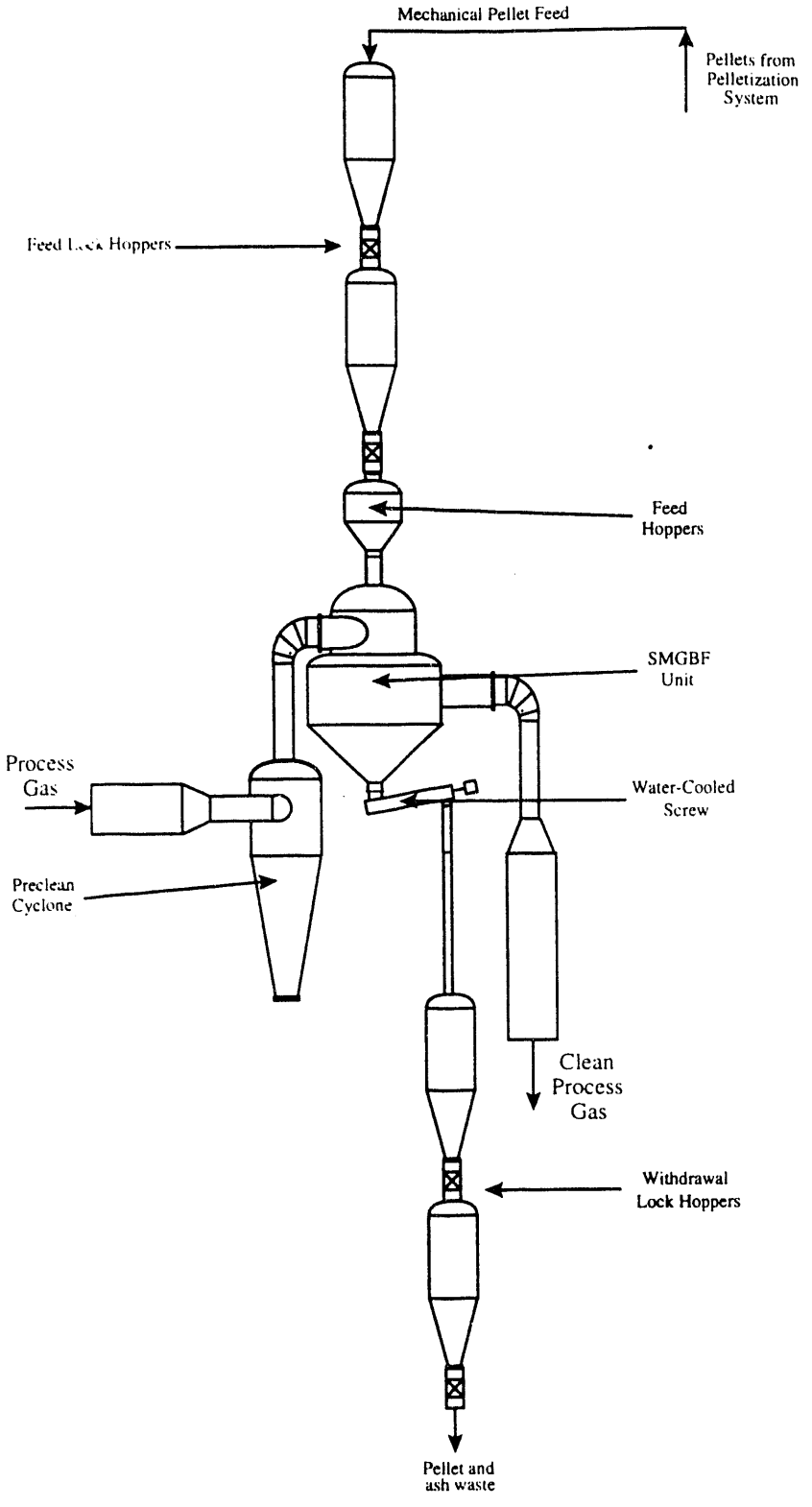


Figure 7.5 — IGCC, Once-through SMGBF equipment arrangement.

Table 7.7 — Lurgi (Air-blown) IGCC, Once-Through SMGBF Equipment

Equipment	Number	Description	Specifications
SMGBF	1	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 12.3 Bottom OD (ft): 18.0 Standleg ID (ft): 11.0 Total height (ft): 27.4 Shell thickness (in): 2.4 Refractory thickness (in): 5 Weight (tons): 149
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 4.5 Height (ft): 18.0 Pellet capacity (hr): 1
Pellet Flow Control/cooler	1	Water-cooled screw conveyor with BFW coolant	Pellet rate (ft^3/hr): 171 Outlet temperature (F): 200
Pellet Pressurization	1	Lock hopper system	Pellet capacity (hr): 0.5 Hopper OD (ft): 5 Hopper height (ft): 20
Pellet Conveying	1	Belt conveyors Bucket elevators	Length (ft): 100 Height (ft): 85
Pellet Depressurize	1	Lock hopper system	Pellet capacity (hr):0.5 Hopper OD (ft): 5 Hopper length (ft): 20
Size Reduction (bottom ash)	1	Conventional size reduction equipment	Crush rate (lb/hr): 6300 Crush size: 80% <500μm
Pelletizer System	1	Disk pelletizer system	Pellet rate (lb/hr): 6400 Curing time (hr): 20

Table 7.8 — Texaco (Oxygen-blown) IGCC, Once-Through SMGBF Equipment

Equipment	Number	Description	Specifications
Preclean Cyclone	1	High-efficiency cyclone; refractory lined	OD (ft): 5.1 Height (ft): 20.6 Inlet velocity (ft/s): 70
SMGBF	1	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 9.1 Bottom OD (ft): 13.5 Standleg ID (ft): 7.4 Total height (ft): 21.9 Shell thickness (in): 2.5 Refractory thickness (in): 8 Weight (tons): 98
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 4.7 Height (ft): 18.7 Pellet capacity (hr): 1
Pellet Flow Control/cooler	1	Water-cooled screw conveyor with BFW coolant	Pellet rate (ft^3/hr): 190 Outlet temperature(F): 200
Pellet Pressurization	1	Lock hopper system	Pellet capacity (hr): 0.5 Hopper OD (ft): 5 Hopper height (ft): 20
Pellet Conveying	1	Belt conveyors Bucket elevators	Length (ft): 1 Height (ft)85
Pellet Depressure	1	Lock hopper system	Pellet capacity (hr):0.5 Hopper OD (ft): 5 Hopper length (ft): 20
Size Reduction (bottom ash)	1	Conventional size reduction equipment	Crush rate (lb/hr): 5500 Crush size: 80% <500μm
Pelletizer System	1	Disk pelletizer system	Pellet rate (lb/hr): 6400 Curing time (hr): 20

Table 7.9 — KRW (Oxygen-blown) IGCC, Once-Through SMGBF Equipment

Equipment	Number	Description	Specifications
Preclean Cyclone	1	High-efficiency cyclone; refractory lined	OD (ft): 5.8 Height (ft): 23.2 Inlet velocity (ft/s): 70
SMGBF	1	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 9.7 Bottom OD (ft): 14.7 Standleg ID (ft): 8.0 Total height (ft): 23.8 Shell thickness (in): 2.1 Refractory thickness (in): 8 Weight (tons): 99
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 4.9 Height (ft): 19.5 Pellet capacity (hr): 1
Pellet Flow Control/cooler	1	Water-cooled screw conveyor with BFW coolant	Pellet rate (ft^3/hr): 218 Outlet temperature(F): 200
Pellet Pressurization	1	Lock hopper system	Pellet capacity (hr): 0.5 Hopper OD (ft): 5.2 Hopper height (ft): 21
Pellet Conveying	1 Bucket	Belt conveyors elevators	Length (ft): 100 Height (ft): 85
Pellet Depressurize	1	Lock hopper system	Pellet capacity (hr):0.5 Hopper OD (ft): 5.2 Hopper length (ft): 21
Size Reduction (bottom ash)	1	Conventional size reduction equipment	Crush rate (lb/hr): 5400 Crush size: 80% <500 μm
Pelletizer System	1	Disk pelletizer system	Pellet rate (lb/hr): 6300 Curing time (hr): 20

Table 7.10 — KRW (Air-blown) IGCC, Once-Through SMGBF Equipment

Equipment	Number	Description	Specifications
Preclean Cyclone	1	High-efficiency cyclone; refractory lined	OD (ft): 6.9 Height (ft): 27.6 Inlet velocity (ft/s): 70
SMGBF	1	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 12.6 Bottom OD (ft): 18.2 Standleg ID (ft): 10.8 Total height (ft): 28.0 Shell thickness (in): 2.6 Refractory thickness (in): 8 Weight (tons): 176
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 5.4 Height (ft): 21.6 Pellet capacity (hr): 1
Pellet Flow Control/cooler	1	Water-cooled screw conveyor with BFW coolant	Pellet rate (ft^3/hr): 295 Outlet temperature(F): 200
Pellet Pressurization	1	Lock hopper system	Pellet capacity (hr): 0.5 Hopper OD (ft): 5.6 Hopper height (ft): 22.5
Pellet Conveying	1	Belt conveyors Bucket elevators	Length (ft): 100 Height (ft): 85
Pellet Depressurize	1	Lock hopper system	Pellet capacity (hr):0.5 Hopper OD (ft): 5.6 Hopper length (ft): 22.5
Size Reduction (bottom ash)	1	Conventional size reduction equipment	Crush rate (lb/hr): 4400 Crush size: 80% <500 μm
Pelletizer System	1	Disk pelletizer system	Pellet rate (lb/hr): 5400 Curing time (hr): 20

7.3.3 IGCC, Once-Through SMGBF System Performance

The Once-Through SMGBF system performance is summarized in Table 7.11. The pellet mean diameter was selected to be a feasible value for commercial pelletization equipment, to provide acceptable particle removal capability, and reasonable pressure drop characteristics. The standleg velocity was selected to achieve the desired maximum vessel pressure drop of about 3 psi when operating with a pellet-to-fly ash mass ratio of about 10. The preclean cyclone adds a significant pressure drop as well. The mixing of the cold pellets with the fuel gas in the SMGBF results in an acceptable temperature loss, yielding only a slight reduction in the power plant thermal efficiency. The major contributor to steam consumption is for curing of the pellets in the pelletization system, and this is done with low-grade steam generated in the pellet cooling steps. In any case, the steam consumption is very low. Auxiliary power is consumed for pressurization, depressurization, and conveying of pellets, as well as for bottom ash size reduction.

The power plant thermal efficiency reduction from the Reference Study using ceramic barrier filters is listed in the table. In the Reference Study, it is assumed that the barrier filter operates with a 3 psi pressure drop, and 10°F temperature drop. The barrier filter pulse gas supply, power consumption was estimated at 5.4 kW for the Lurgi gasifier case, 4.9 kW for the Texaco gasifier, 4.8 for the oxygen-blown KRW gasifier, and 6.0 for the air-blown KRW gasifier case. Most of the loss in power plant efficiency, relative to the Reference Study, is due to the SMGBF system pressure drop and temperature drop. Since no credit was given for the additional steam cycle power generated by cooling the pellets drained from the SMGBF unit, these efficiency numbers should be considered the worst case values. It is known from recent testing that ceramic barrier filters operating in a gasifier environment may require pressure drops as high as 6 to 8 psi, face velocities as low as 1 ft/min, and very high pulse gas rates with significant power consumption, so it can be concluded that the Once-Through SMGBF system may provide plant performance advantages over ceramic barrier filters in such cases.

Table 7.11 — IGCC, Once-Through SMGBF System Performance

	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
Pellet mean diameter (in):	7/16	7/16	7/16	7/16
Standleg velocity (ft/s):	2.3	2.3	2.7	2.3
Total pressure drop (psi):	3.1	4.6	4.2	4.4
- preclean cyclone (psi):	---	1.6	1.2	1.4
- SMGBF (psi):	3.1	3.0	3.0	3.0
Total temperature drop:	31	80	86	96
- preclean cyclone (F):	0	4	4	5
- SMGBF heat losses (F):	10	12	13	17
- SMGBF pellet mixing (F):	21	64	69	74
Utility requirements				
- Power (kW):	19.2	20.5	19.3	16.7
Plant efficiency (%, HHV):	37.78	37.54	37.60	37.41
Reduction from Reference (%):	0.15	0.38	0.32	0.51
- Due to pressure loss(%):	8.2	55.8	49.9	37.4
- Due to temperature loss(%):	81.0	39.6	44.4	57.7
- Due to auxiliary power(%):	10.8	4.6	5.7	4.9
Raw material requirements:				
- Lime (lb/hr):	319	317	311	270
- Water (lb/hr):	957	952	932	809
Flyash removal				
- cyclone inlet load (ppmw):	---	9901	9959	8504
- cyclone removal (%):	---	47.6	43.9	39.2
- cyclone outlet load (ppmw):	---	5190	5585	5170
- SMGBF inlet load (ppmw):	2291	5190	5585	5170
- SMGBF removal (%):	98.0	98.0	98.5	99.0
- SMGBF outlet load (ppmw):	45.8	103.8	83.8	51.7
- turbine inlet load (ppmw):	5.9	6.5	7.4	6.4
- emission (lb/MBtu):	0.017	0.019	0.017	0.018

A summary of the fly ash removal performance of the Once-Through SMGBF systems is shown in the table. The SMGBF unit removal efficiency was selected to yield acceptable plant emissions, less than 0.02 lb/MBtu. This results in turbine inlet loadings that are less than the turbine protection limit of about 15 ppmw total loading. The SMGBF outlet loadings (46-104 ppmw) and the removal efficiencies (98-99%) are well within the capabilities of the SMGBF unit measured in the Base Contract testing.

The nature of the power plant solid waste is greatly influenced by the Once-Through SMGBF process, with the solid waste being issued as a pelletized materials having much lower fugitive dust emissions, easier handling, and more environmentally stable behavior, as well as potential by-product uses. No economic credit was taken for these potential advantages.

The reliability and controllability of the plant with the Once-Through SMGBF is also a key performance factor. Reliability should be high, with no critical components in the system having high risk. Control is centered on the water-cooled screw conveyors that regulate pellet flow as a function of the unit pressure drop. The large capacity of the SMGBF unit, and its long response time, makes it tolerant to IGCC process upset conditions.

7.3.4 Once-Through SMGBF System Cost

The Once-Through SMGBF system costing was developed from major equipment, delivered-cost algorithms reported in standard costing references and from vendor quotes for equipment, some adapted by Westinghouse for high-temperature, high-pressure duty. Costs are reported in December-1991 dollars. The Marshall & Swift Equipment Cost Index ("Chemical Engineering", McGraw-Hill) was used to escalate costs to the December-1991 basis. Standard installation factors were applied to the delivered equipment costs to estimate installed equipment costs.

Delivered equipment costs and installed equipment costs are reported in Table 7.12, in units of thousands of dollars. The most expensive components are the SMGBF vessel and the pelletization system.

Table 7.12 — IGCC, Once-Through SMGBF System Equipment Costs

	1000$ (Dec-1991)			
	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
Preclean Cyclone				
Delivered:	---	89.9	110.8	151.3
Installed:	---	184.3	227.2	310.2
SMGBF Vessel				
Delivered:	621.7	392.6	454.5	638.6
Installed:	1274.5	804.8	931.7	1309.1
Feed Hopper				
Delivered:	51.1	73.1	79.0	94.0
Installed:	104.8	149.8	161.9	192.8
Pressurization System				
Delivered:	133.8	182.3	192.2	217.2
Installed:	274.3	373.8	394.0	445.2
Depressurize System				
Delivered:	133.8	182.3	192.2	217.2
Installed:	274.3	373.8	394.0	445.2
Pellet Flow Control/Cooler				
Delivered:	165.3	175.9	190.7	228.7
Installed:	338.8	360.6	390.9	468.9
Pellet Conveying				
Delivered:	98.6	98.6	98.6	98.6
Installed:	138.0	138.0	138.0	138.0
Size Reduction				
Delivered:	12.0	10.7	10.6	9.0
Installed:	15.6	14.0	13.8	11.8
Pelletization System				
Delivered:	402.1	400.7	395.6	363.6
Installed:	824.3	821.5	811.1	745.3
Total Delivered (1000$):	1618.4	1606.1	1724.2	2018.2
Total Installed (1000$):	3244.6	3220.6	3462.6	4066.5

The relatively low fly ash content of the fuel gas in the Lurgi gasifier case, and the resulting low pellet rate, makes this air-blown gasifier, SMGBF system of comparable or lower cost than the oxygen-blown gasifier cases, even though the gas volumetric flow rate is much larger in the Lurgi case. The installed costs range from 30 to 40 $/kW in magnitude.

The total IGCC, Once-Through SMGBF plant capital requirement, annual operating cost, and COE are summarized in Table 7.13. The installed equipment costs from the Reference Study were escalated by a factor of 1.29, and the SMGBF system installed costs added to this to estimate the total plant installed costs. The total capital requirement was estimated using these installed costs. Power plant consumable material rates were extracted from the Reference Study (water and catalysts & Chemicals) as inputs to estimate the power plant annual operating cost.

7.4 DESIGN, PERFORMANCE, AND COST OF RECYCLE SMGBF

This section considers the Recycle SMGBF system, with recycle of purchased granules in place of the once-through, pelletized ash. The major differences in the Recycle and the Once-Through SMGBF plants are the degree of overall power plant integration required, and the nature of the power plant solid waste product.

7.4.1 Recycle SMGBF Material and Energy Balances

Material and energy balance results are listed in Tables 7.14 - 7.17 for each of the gasifier cases. The stream numbers are those listed in Figure 7.3. In each case, the mass ratio of the granule recycle rate to the fly ash rate is maintained at about 20. This ratio has been selected to provide greater potential for efficient particle removal with low pressure drop. No preclean cyclone is used in the Recycle SMGBF cases, although there may be advantages that would result by using a preclean cyclone in some cases.

7.4.2 Recycle SMGBF Equipment Sizing and Arrangement

The Recycle SMGBF system equipment has been conceptually sized and specified to the extent needed to develop rough layouts and

Table 7.13 — IGCC, Once-Through SMGBF Power Plant Costs

	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
Capital Requirement (1000$):	316,467	321,029	316,164	298,112
($/kW):	3165	3210	3162	2981
Annual Operating Cost (1000$):	36,585	36,890	36,460	35,383
COE - Current $ (mills/kWh):	175.2	177.3	174.9	167.1

Table 7.14 — Lurgi (Air-Blown) IGCC, Recycle SMGBF M&E Balances

1	Fuel gas	300	1000	329,500	755
2	Fuel gas	300	1000	329,500	15948
3	Clean fuel gas	297	986	329,500	15.1
4	Expansion gas	267	2100	2,550,000	15.1
5	Bottom ash	300	100	---	6307
6	Cyclone catch	---	---	---	0
7	SMGBF drain	297	986	---	15933
8	SMGBF ash	297	986	---	740
9	Aeration gas	320	120	8,900	0

Table 7.15 — Texaco (Oxygen-blown) IGCC, Recycle SMGBF M&E Balance

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	500	1600	160,900	1593
2	Fuel gas	500	1600	160,900	33743
3	Clean fuel gas	596	1581	160,900	15.9
4	Expansion gas	566	2100	2,550,000	15.9
5	Bottom ash	500	100	---	5469
6	Cyclone catch	---	---	---	0
7	SMGBF drain	596	1581	---	33727
8	SMGBF ash	596	1581	---	1577
9	Aeration gas	520	120	14,782	0

Table 7.16 — KRW (Oxygen-Blown) IGCC, Recycle SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	385	1600	169,700	1690
2	Fuel gas	385	1600	169,700	36323
3	Clean fuel gas	381	1579	169,700	16.9
4	Expansion gas	351	2100	2,550,000	16.9
5	Bottom ash	385	100	---	5372
6	Cyclone catch	---	---	---	0
7	SMGBF drain	381	1579	---	36300
8	SMGBF ash	381	1579	---	1683
9	Aeration gas	405	120	12,379	0

Table 7.17 — KRW (Air-Blown) IGCC, Recycle SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	385	1600	312,800	2660
2	Fuel gas	385	1600	312,800	56273
3	Clean fuel gas	381	1576	312,800	16.0
4	Expansion gas	385	2100	2,550,000	16.0
5	Bottom ash	385	100	---	4402
6	Cyclone catch	---	---	---	0
7	SMGBF drain	381	1576	---	56257
8	SMGBF ash	381	1576	---	2644
9	Aeration gas	405	120	11,671	0

equipment costs. The SMGBF vessels and other major equipment sizing is summarized in Tables 7.18 - 7.21. A general arrangement drawing of the Recycle SMGBF vessels, representative of all of the IGCC cases, is the same as that shown for the Once-Through SMGBF in Figure 7.4. The differences between the Once-Through and the Recycle SMGBF vessels are that the Recycle vessel diplet feeds only a relatively small feed of makeup granules to the unit, and the tangentially flowing inlet gas carries and distributes the recirculating granules within the upper region of the vessel.

The components of the system are a single SMGBF vessel and makeup feed hopper, a single granule-ash separator, and a single granule standleg pipe. A general layout drawing of the Recycle SMGBF system, representative of all of the IGCC cases, is shown in Figure 7.6.

7.4.3 Recycle SMGBF System Performance

The Recycle SMGBF system performance is summarized in Table 7.22. The granule mean diameter was selected to be a feasible value to provide acceptable particle removal capability, and reasonable pressure drop characteristics. It may be more effective, based on the Base Contract test results, to pelletize some plant waste material to be used a bed granules rather than purchasing relatively expensive, durable beads (e.g., alumina spheres) as is typically down for granular bed filters. The pelletized waste, in addition to being cheaper, has lower density, and has better distribution of particle size and shape, conducive to better particle removal.

The standleg velocity was selected to achieve the desired maximum vessel pressure drop of about 3 psi when operating with a granule-to-fly ash mass ratio of about 20. The higher granule-to-ash ratio allows the SMGBF standleg velocity to be higher than was used with Once-Through SMGBF. The mixing of the hot, recycled granules with the fuel gas in the SMGBF results in a very low temperature loss. There is no auxiliary fuel consumption. Auxiliary power is consumed primarily for recycled fuel gas compression for use as aeration gas.

Table 7.18 — Lurgi (Air-blown) IGCC, Recycle SMGBF Equipment

Equipment	Number	Description	Dimensions
SMGBF	1	Refractory-lined pressure vessel	Top OD (ft): 10.9 Bottom OD (ft): 16.9 Standleg ID (ft): 9.7 Total height (ft): 26.5 Shell thickness (in): 2.2 Refractory thickness (in): 5 Weight (tons): 126
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 2.7 Height (ft): 10.7 Pellet capacity (hr): 0.1
Granule Conveyor	1	Belt conveyors Bucket elevators	Length (ft): 100 Height (ft): 85
Ash-Granule Separator	1	Mechanical seive adapted to high-pressure, high-temperature	Diameter (ft): 4.0 Length (ft): 16.0
Hot Gas Piping	1	Refractory-lined pipe	Length (ft): 80 OD (ft): 2.8
Aeration Gas Compressor	1	Recycle fuel gas compressor	Capacity (hp): 59

Table 7.19 — Texaco (Oxygen-blown) IGCC, Recycle SMGBF Equipment

Equipment	Number	Description	Dimensions
SMGBF	1	Refractory-lined pressure vessel	Top OD (ft): 8.2 Bottom OD (ft): 12.8 Standleg ID (ft): 6.5 Total height (ft): 21.3 Shell thickness (in): 2.4 Refractory thickness (in): 8 Weight (tons): 85
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 3.0 Height (ft): 12.0 Pellet capacity (hr): 0.1
Granule Conveyor	1	Belt conveyors Bucket elevators	Length (ft): 100 Height (ft): 85
Ash-Granule Separator	1	Mechanical seive adapted to high-pressure, high-temperature	Diameter (ft): 4.8 Length (ft): 19.0
Hot Gas Piping	1	Refractory-lined pipe	Length (ft): 80 OD (ft): 2.7
Aeration Gas Compressor	1	Recycle fuel gas compressor	Capacity (hp): 100

Table 7.20 — KRW (Oxygen-blown) IGCC, Recycle SMGBF Equipment

Equipment	Number	Description	Dimensions
SMGBF	1	Refractory-lined pressure vessel	Top OD (ft): 8.7 Bottom OD (ft): 13.9 Standleg ID (ft): 7.0 Total height (ft): 23.2 Shell thickness (in): 2.0 Refractory thickness (in): 8 Weight (tons): 87
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 2.9 Height (ft): 11.6 Pellet capacity (hr): 0.1
Granule Conveyor	1	Belt conveyors Bucket elevators	Length (ft): 100 Height (ft): 85
Ash-Granule Separator	1	Mechanical seive adapted to high-pressure, high-temperature	Diameter (ft): 4.6 Length (ft): 18.4
Hot Gas Piping	1	Refractory-lined pipe	Length (ft): 80 OD (ft): 2.9
Aeration Gas Compressor	1	Recycle fuel gas compressor	Capacity (hp): 93

Table 7.21 — KRW (Air-blown) IGCC, Recycle SMGBF Equipment

Equipment	Number	Description	Dimensions
SMGBF	1	Refractory-lined pressure vessel	Top OD (ft): 11.2 Bottom OD (ft): 17.1 Standleg ID (ft): 9.5 Total height (ft): 27.1 Shell thickness (in): 2.5 Refractory thickness (in): 8 Weight (tons): 151
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 3.0 Height (ft): 12.0 Pellet capacity (hr): 0.1
Granule Conveyor	1	Belt conveyors Bucket elevators	Length (ft): 100 Height (ft): 85
Ash-Granule Separator	1	Mechanical seive adapted to high-pressure, high-temperature	Diameter (ft): 5.1 Length (ft): 20.4
Hot Gas Piping	1	Refractory-lined pipe	Length (ft): 80 OD (ft): 3.3
Aeration Gas Compressor	1	Recycle fuel gas compressor	Capacity (hp): 88

Table 7.22 — IGCC, Recycle SMGBF System Performance

	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
Granule mean diameter (in):	3/8	3/8	3/8	3/8
Standleg velocity (ft/s):	3.0	3.0	3.4	3.0
Total pressure drop (psi):	3.1	3.6	3.5	3.5
- granule transport (psi):	0.1	0.6	0.5	0.5
- SMGBF (psi):	3.0	3.0	3.0	3.0
Total temperature drop:	14	19	21	24
- SMGBF heat losses (F):	10	10	12	16
- SMGBF pellet mixing (F):	4	9	9	8
Utility requirements				
- Power (kW):	43.8	74.2	69.5	65.2
Plant efficiency (%, HHV):	37.84	37.78	37.79	37.76
Reduction (%):	0.08	0.14	0.13	0.16
- Due to pressure loss(%):	16.4	56.4	53.3	40.8
- Due to temperature loss(%):	64.3	24.4	26.8	44.3
- Due to auxiliary power(%):	19.3	19.2	19.9	14.9
Raw material requirements:				
- Granule makeup (lb/hr)[a]:	152	322	346	536
Flyash removal				
- SMGBF inlet load (ppmw):	2291	9901	9959	8504
- SMGBF removal (%):	98.0	99.0	99.0	99.4
- SMGBF outlet load (ppmw):	45.8	99.0	99.6	51.0
- turbine inlet load (ppmw):	5.9	6.2	6.6	6.3
- emission (lb/MBtu):	0.017	0.018	0.019	0.018

a: granule loss assumed to be 1% of the granule recycle rate

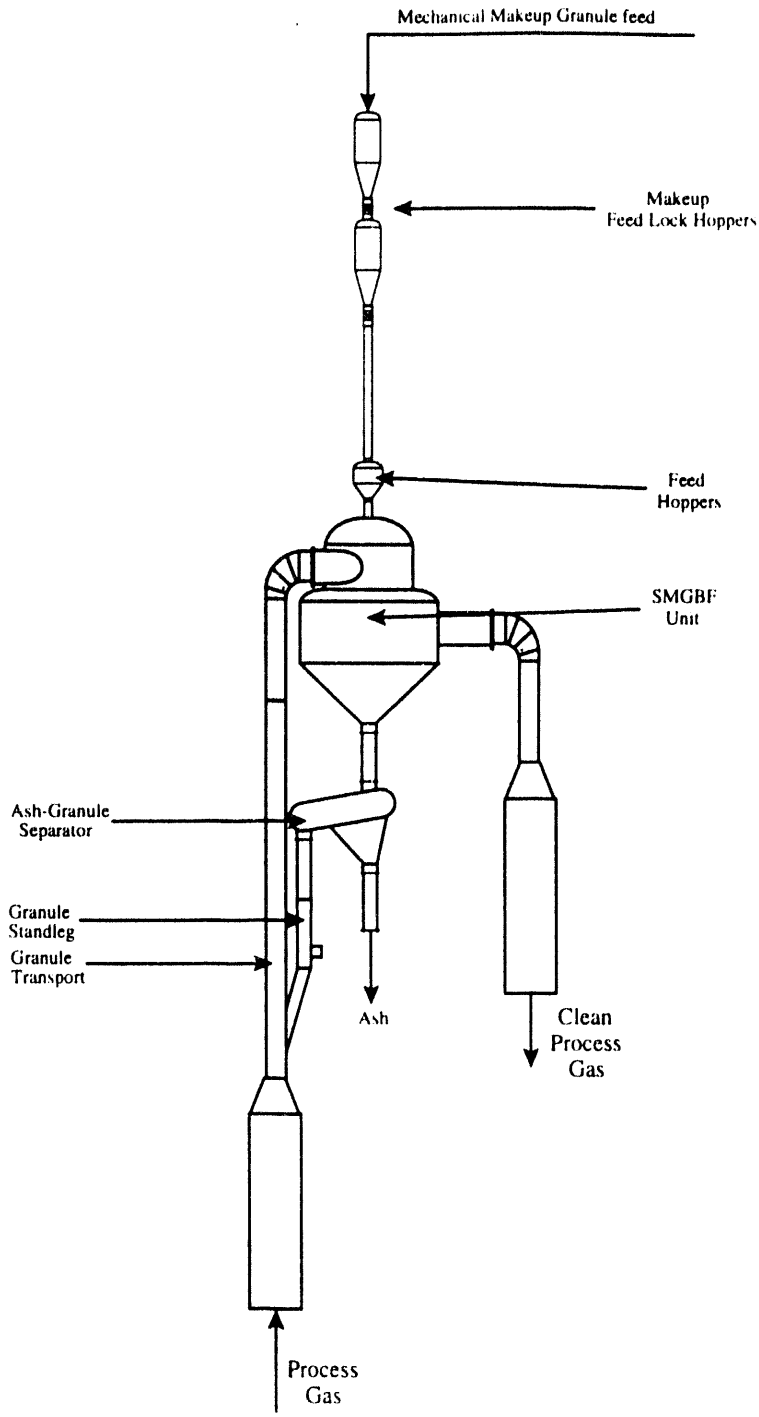


Figure 7.6 — IGCC, recycle SMGBF equipment arrangement.

The power plant efficiency reduction from the Reference Study using ceramic barrier filters is listed in the tables. Most of the loss in power plant efficiency, relative to the Reference Study is due to the SMGBF system pressure drop and temperature drop. It is now known that gasifier operation of ceramic barrier filters may require pressure drops on the order of 6 to 8 psi, and very high pulse gas rates with significant power consumption, so it can be concluded that the Recycle SMGBF system is comparable in plant performance to ceramic barrier filters, and may have advantages in some cases.

A summary of the fly ash removal performance of the Recycle SMGBF systems is shown in Table 7.22. The Recycle SMGBF unit removal efficiency was selected to yield acceptable plant emissions, less than 0.02 lb/MBtu. This results in turbine inlet loadings that are less than the turbine protection limit of 15 ppmw total loading. The SMGBF outlet loadings and the removal efficiencies are well within the capabilities of the SMGBF unit measured in the Base Contract testing. The nature of the power plant solid waste is not greatly influenced by the Recycle SMGBF process.

The reliability and controllability of the plant with the Recycle SMGBF is similar to that of the Once-Through SMGBF system.

7.4.4 Recycle SMGBF System Cost

The cost basis for the Recycle SMGBF system costing are major equipment, delivered cost algorithms reported in standard costing references and adapted from quotes for high-temperature, high-pressure duty. Costs are reported in December-1991 dollars. Standard installation factors were applied to the delivered equipment costs to estimate installed equipment costs. Delivered equipment costs and installed equipment costs are reported in Table 7.23. Installed costs range from 17 to 22 $/kW, about 55% of the installed equipment costs for Once-Through SMGBF.

The total IGCC, Recycle SMGBF plant capital requirement, annual operating cost, and COE are summarized in Table 7.24, and are slightly lower than the comparable costs for Once-Through SMGBF. The uncertainty

Table 7.23 — IGCC, Recycle SMGBF System Equipment Costs

	1000$			
	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
SMGBF vessel				
Delivered:	567.6	364.2	422.6	586.2
Installed:	1163.6	746.6	866.3	1201.7
Makeup feed hopper				
Delivered:	20.5	34.5	31.7	33.5
Installed:	42.0	70.6	64.9	68.7
Pressurization/Conveying				
Delivered:	139.6	167.6	162.0	165.6
Installed:	220.0	279.1	267.8	265.4
Ash-Granule separator				
Delivered:	43.7	78.3	73.7	88.4
Installed:	89.7	160.6	151.0	181.2
Hot Gas piping				
Delivered:	110.2	139.1	149.4	169.9
Installed:	226.0	285.2	306.2	348.2
Aeration gas compressor				
Delivered:	98.6	150.2	142.5	135.4
Installed:	128.2	195.3	185.2	176.0
Total Delivered (1000$):	980.2	933.9	981.9	1179.0
Total Installed (1000$):	1869.5	1737.4	1841.4	2241.2

in the absolute numbers in Table 7.24 is much greater than the differences between the Once-Through (Table 7.13) and Recycle SMGBF costs. Certainly, Once-Through SMGBF should be more expensive than Recycle SMGBF, but the performance should be comparable, and other key factors such as reliability and availability could favor either of these two operating modes.

Table 7.24 — IGCC, Recycle SMGBF Power Plant Costs

	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
Capital Requirement (1000$):	313,671	318,255	313,223	294,795
($/kW):	3137	3183	3132	2948
Annual Operating Cost (1000$):	36,500	37,103	36,715	35,907
COE - Current $ (mills/kWh):	174.4	176.9	174.5	167.2

7.5 SMGBF COMPARISON WITH CERAMIC BARRIER FILTER SYSTEM

Ceramic barrier filter (cross-flow type) system installed equipment costs were extracted from the Reference Study and were escalated to December-1991 costs. Table 7.25 compares the Once-through SMGBF, Recycle SMGBF, and ceramic barrier filter major equipment design features, and installed equipment costs. The Total Capital Requirement, and COE for these systems are also compared in Table 7.25. The ceramic barrier filter designs are based on an optimistic assumption that a 10 ft/min face velocity can be used. Actual face velocities for IGCC ceramic barrier filters may range from 1 to 5 ft/min, with significantly higher equipment costs and pulse gas power consumption resulting. In general, it is expected that ceramic barrier filter cost and IGCC plant thermal performance will be comparable to Recycle SMGBF. Once-Through SMGBF costs will be slightly higher than ceramic barrier filter costs, and IGCC plant performance may be comparable. It is expected that ceramic barrier filters will have higher particle removal performance potential than SMGBF, but the SMGBF may have better reliability and availability. The relative attributes of the close plant integration required by Once-Through SMGBF, versus the improved nature of the plant solid waste are uncertain.

Major development issues for the SMGBF as it applies to IGCC are:

- complexity of close plant integration with Once-Through SMGBF
- reliability of the SMGBF system
- operability of the granule circulation technique (Recycle SMGBF)
- development of an ash-granule separator (Recycle SMGBF)
- granule attrition performance (Recycle SMGBF)

These are the issues that should be the focus of future development efforts. Particle removal efficiency and scaleup of equipment are not major issues for SMGBF for IGCC because the particle removal requirements are relatively moderate, and the equipment is relatively compact.

Table 7.25 — IGCC, SMGBF and Ceramic Barrier Filter Comparison

	Lurgi Air-blown	Texaco O_2-blown	KRW O_2-blown	KRW Air-blown
Equipment Features				
Once-Through SMGBF				
OD/length (ft):	18/27	14/22	15/24	18/28
Standleg velocity (ft/s):	2.3	2.3	2.7	2.3
Pellet rate (lb/hr):	7539	8365	9570	16,199
Recycle SMGBF				
OD/length (ft):	17/27	13/21	14/23	17/27
Standleg velocity (ft/s):	3.0	3.0	3.4	3.0
Pellet rate (lb/hr):	15,193	32,150	34,617	53,613
Ceramic Filter				
OD/length (ft):	7/24	7/20	7/18.5	7/24
Face velocity (ft/min):	10	10	10	10
Number elements:	162	100	73	158
Installed Equipment ($k)				
Once-Through SMGBF:	3,244.6	3,220.6	3,462.6	4,066.5
Recycle SMGBF:	1,869.5	1,737.4	1,841.4	2,241.2
Ceramic Filter:	1,191.0	1,561.0	1,580.0	1,945.0
Total Plant Capital ($k)				
Once-Through SMGBF:	316,467	321,029	316,164	298,112
Recycle SMGBF:	313,671	318,255	313,223	294,795
Ceramic Filter:	312,267	317,854	312,555	294,044
COE - Current $ (mills/kWh)				
Once-Through SMGBF:	175.2	177.3	174.9	167.1
Recycle SMGBF:	174.4	176.9	174.5	167.2
Ceramic Filter:	173.4	175.8	173.2	165.3

8. Evaluation For Advanced-PFBC Application

Advanced, Pressurized Fluidized Bed Combustion (APFBC) is an advanced, coal-fueled, power generation technology nearing commercialization through a Clean Coal Technology Project, and its development is supported by major DOE/METC development programs. APFBC applies ceramic barrier filter systems for hot gas cleaning. The objective of this evaluation is to assess the conceptual feasibility of the Standleg Moving Granular Bed Filter (SMGBF) in APFBC applications and to compare its design, performance, and cost potential with that of ceramic barrier filters.

8.1 APFBC PROCESS BASIS AND DESCRIPTION

The process evaluation is based on a previously completed Reference Study: Foster Wheeler Development Corporation, Second-Generation PFBC Plant Conceptual Design and Optimization of a Second Generation PFB Combustion Plant, Phase 1, Task 1, Volume 1, DOE/MC/2023-2825, September 1989. The study used ceramic barrier filters, cross-flow type, for hot gas particulate removal. The Reference Study presents power plant material & energy balances, equipment designs, plant layouts, and equipment and total plant costs. The evaluation conditions applied in the Reference Study were:

- Plant net generating capacity (MW_e): 452.8
- Plant heat rate (HHV, Btu/kWh): 7820
- Plant thermal efficiency (HHV, %): 43.63
- Coal type: Pittsburgh #8
- Coal composition : 3.0 wt% sulfur, 10.3 wt% ash, 12,916 Btu/lb (HHV)
- Coal feed rate (lb/hr): 274,200
- Plant layout: two parallel gas turbines, each with coal processing and gas cleanup trains
- Cost year: Dec-1987 dollars

The cost premises and procedures applied in this evaluation are the same as those described for the IGCC evaluation.

The hot gas cleaning operating and design conditions extracted from the Reference Study for the SMGBF design basis are listed in Table 8.1. Assumed levels of performance applied to the design are also listed. The power plant contains two parallel, identical coal processing and gas cleaning trains, each fueling a single combustion turbine, and each being made up of a single coal carbonizer and a single circulating-PFBC unit (CPFB). High-temperature particle removal is needed both on the carbonizer and on the CPFB. The flow rates provided in Table 8.1, and in subsequent tables, are for a single combustion turbine train.

8.2 APFBC SMGBF PROCESS DESCRIPTION AND OPTIONS

Two SMGBF operating modes are considered for APFBC, as was done for the IGCC evaluation: "Once-Through" SMGBF and "Recycle" SMGBF.

8.2.1 APFBC, Once-Through SMGBF

A schematic process flow diagram of the Once-Through SMGBF process is shown in Figure 8.1. Coal, air, steam and sulfur sorbent (limestone) are fed to the carbonizer, producing a low-Btu fuel gas at the cleanup temperature. Primary particle removal equipment, a conventional cyclone, is also part of the carbonization process. Primary particle removal ash (char and sorbent) and carbonizer bottom drain material (char and sorbent) are combined and fed to the CPFBC unit, representing both the fuel and the sorbent for that unit. Once-Through SMGBF cleanup systems are used on both the carbonizer and the CPFBC gas streams to meet the process particle control needs, and their boundaries are designated in the figure. The pelletization process is a conventional process that is operated at atmospheric pressure and low temperature, so the plant bottom ash is cooled and depressurized before being transported to the pelletization system.

Pellets produced are mechanically transported, and pressurized, to the carbonizer- and CPFBC-SMGBF feed hoppers. The gas fly ash is

Table 8.1 — APFBC Hot Gas Cleaning System Operating and Design Conditions

Vessel:	Carbonizer	CPFBC
Operating Conditions		
Gas inlet temperature (°F):	1500	1600
Gas inlet pressure (psia):	208	188
Gas inlet rate (1000 lb/hr):	244.7	2,644.2
Gas inlet rate (acfm):	15,886	179,138
Fly ash rate (lb/hr):	2459	10,567
Plant bottom ash rate (lb/hr):	35,006	
Design Conditions		
Temperature (°F):	1600	1650
Pressure (psia):	270	270
Max. gas flow (acfm)[a]:	16,680	188,095
Max. fly ash rate (lb/hr)[a]:	2582	11,095
Max. ΔP (psi):	4	4
Max. temperature drop (°F)[c]	15	15
Plant fly ash emission (lb/MBtu)[d]:	0.02	
Turbine inlet load (ppmw)[e]:	15	

a: System designed for 5% excess gas and fly ash flow.

b: Maximum pressure drop across the SMGBF vessel (inlet to outlet).

c: Maximum temperature drop across the SMGBF vessel due to vessel heat losses (inlet to outlet).

d: Assumed, future environmental emissions standard for particulate.

e: Assumed, acceptable total dust loading to turbine for erosion and deposition damage.

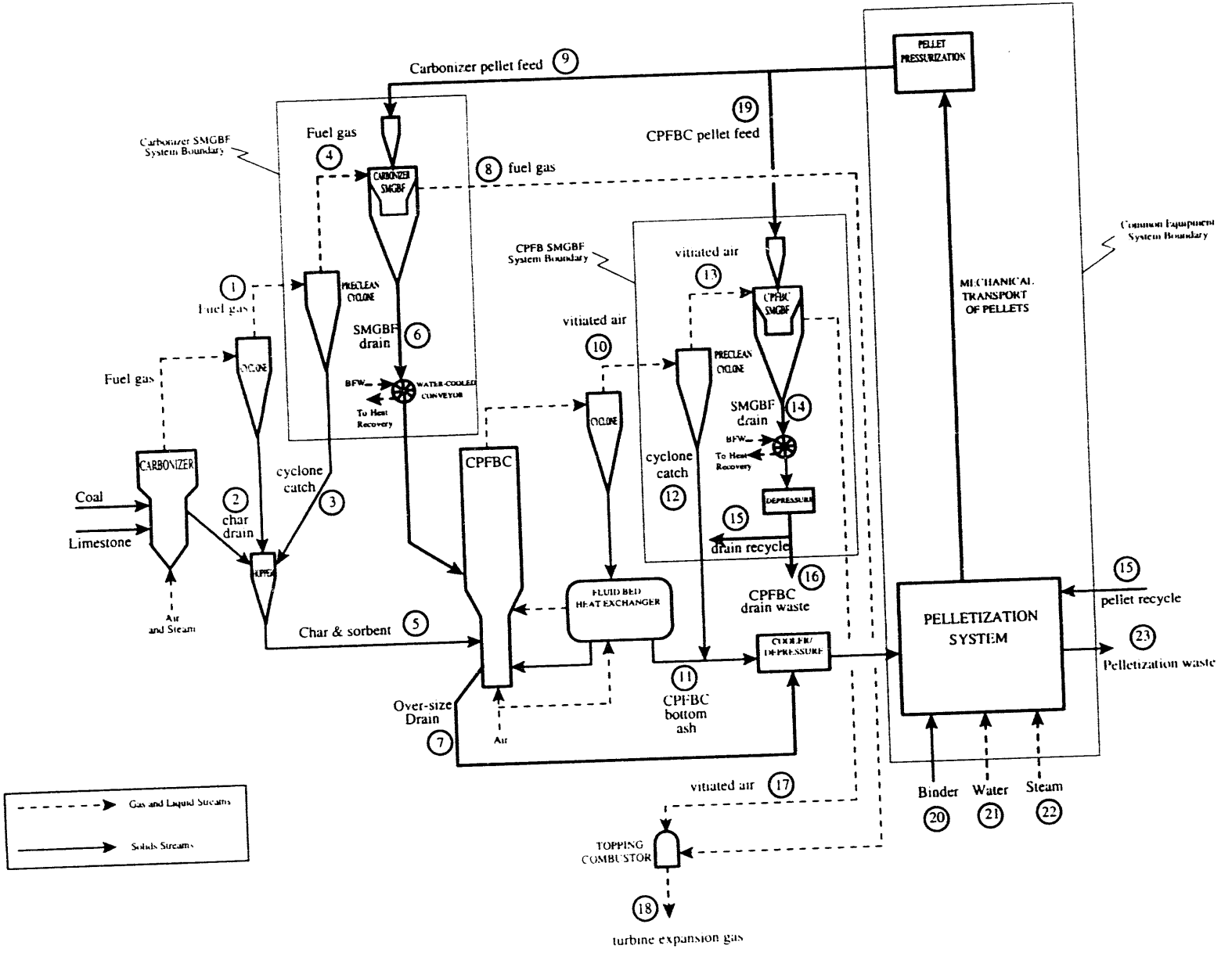


Figure 8.1 — APFBC - Once-Through SMGBF process.

captured by the pellet stream in the carbonizer- and CPFBC-SMGBF units, and is drained, cooled and depressurized before disposal or recycle to the pelletization system. Because the carbonizer fly ash contains a significant content of carbon that must be consumed in the CPFBC unit, the pellet-ash mixture from the carbonizer-SMGBF is fed directly to the CPFB. The pellets are withdrawn from CPFB bottom drain and are circulated to the pelletization system. Water-cooled screw conveyors under the SMGBF units control the pellet flow, cool the pellets, and transfer the pellet heat to boiler feed water (BFW) coolant. Only partial cooling of the carbonizer-SMGBF drain stream is accomplished, down to about 1000°F. The cleaned fuel gas and the vitiated air from the CPFBC are combined after cleaning to combust the fuel gas at the desired turbine inlet temperature.

A second stage of cyclone particle removal, the preclean cyclone, may be included in the Once-Through SMGBF process to increase the effective bottom ash rate, reducing the pellet feed rate needed for the SMGBF units. The desired pellet-to-ash ratio in Once-Through SMGBF is about 10, or larger, and it is apparent from the tabulated information in Table 8.1 that this ratio cannot be achieved directly with the total plant bottom ash to total fly ash mass ratio being only 2.7. Several process options exist that can be used alone, or in combination, to achieve the desired pellet-to-flyash ratio: 1) add a second-stage cyclone to the carbonizer-SMGBF and/or the CPFB-SMGBF, 2) separate fly ash from the CPFBC-SMGBF pellet-ash waste and feed this to the pelletization process step, 3) circulate the carbonizer SMGBF pellets to the CPFB-SMGBF unit, or 4) recycle some portion of the pellet waste streams back to the SMGBF units. Since the particle removal performance of a preclean cyclone will not be very high with the fine fly ash from the carbonizer and CPFB, this step alone may not be sufficient. The selected Once-Through SMGBF process uses a preclean cyclone before both the carbonizer- and CPFB-SMGBF units, and recycles a portion of the CPFB-SMGBF drain material (Stream 15).

A variety of pelletization processes can be used to generate sufficiently durable pellets for the Once-Through SMGBF system. The

selected process for this evaluation is the same as that used for the IGCC, SMGBF pelletization process, a simple, disk pelletizer system shown schematically in Figure 7.2. It is representative of commercial technology and of pelletization techniques tested in the pelletization segment of this program. The pelletization process includes conventional size reduction equipment to control the size of the gasifier bottom ash to 80% less than 500 μm.

Properly sized bottom ash from the plant is mixed with the preclean cyclone ash, with recycled ash and pellets, and with slaked quicklime. The mixture requires a lime content of about 5 wt%, and a water content of about 15 wt%, although the lime addition might be significantly reduced, or even eliminated, because of the high calcium content of the plant waste. This mixture is fed through a rotary valve to a commercial disk pelletizer. The green pellets from the pelletizer are mechanically transported to curing chambers, for about 20 hours curing under steam at about 180°F. The cured pellets and the recycled pellet streams from the SMGBF units are conveyed to a rotary, or vibrational screen where under- sized pellets and ash are separated and recycled, and over-sized pellets are crushed and recycled.

8.2.2 APFBC, Recycle SMGBF

The Recycle SMGBF process is shown in the process flow diagram of Figure 8.2. The process differs from the Once-Through SMGBF process in that the carbonizer- and CPFBC-SMGBF units operate entirely independent of each other. A preclean cyclone could be added as shown to remove an additional portion of the fly ash and reduce the granule recycle rate needed. No preclean cyclone is used with the APFBC process considered here. The circulating granules drained from the SMGBF units contain the captured fly ash particles. This fly ash is separated from the granules in ash-granule separators. Several devices might be used for separation, such as a mechanical seiving device, a fluid bed separator, or a pneumatic separator. All of these require certain development efforts to adapt them to high-temperature, high-pressure conditions, but the mechanical seiving separator is selected because it

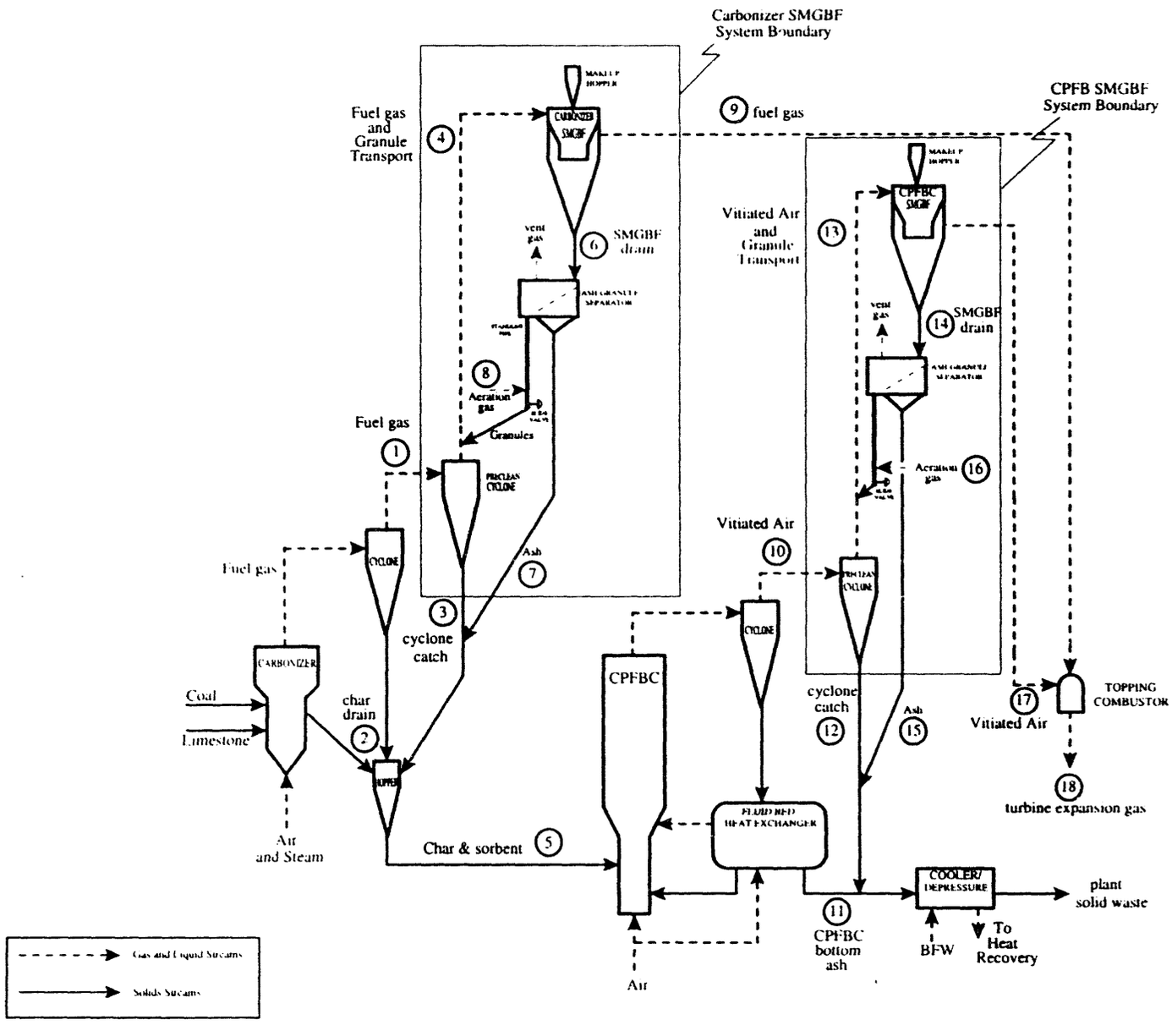


Figure 8.2 — APFBC - Recycle SMGBF process.

does not produce a significant gas stream requiring secondary cleaning. Only partial separation of the granule and ash mixture is required, because the product granule-ash mixing is recycled pneumatically to the SMGBF using the process gas stream as the transport gas.

An aerated standleg is used below the granule-ash separator to buildup the pressure in the standleg. Recycled fuel gas, or steam, is used for aeration in the carbonizer-SMGBF, and air is used in the CPFB-SMGBF. A slide-valve is used in each standleg to set the granule flow rate, and this remains in a relatively fixed position over all plant operating conditions. A small amount of vent gas is generated that is sent to the normal lock hopper vent gas treatment equipment for the APFBC process. The hot gas piping lines transporting granules to the SMGBF are designed to have sufficient velocity to effectively transport the granules at full-load conditions as well as at part-load.

8.3 DESIGN, PERFORMANCE, AND COST OF SMGBF

This section presents the design, performance, and cost information for both the Once-Through and the Recycle SMGBF cases.

8.3.1 SMGBF Material and Energy Balances

Once-Through SMGBF material and energy balance results are listed in Table 8.2. The stream numbers are those listed in Figure 8.1. Major assumptions are listed in the table. The mass ratio of pellet feed to fly ash feed is about 10 for both the carbonizer- and the CPFBC-SMGBF units.

Recycle SMGBF material and energy balance results are listed in Table 8.3. The stream numbers are those listed in Figure 8.3. Major assumptions are listed in the table. The mass ratio of pellet feed to fly ash feed is about 20 for both the carbonizer- and the CPFBC-SMGBF units. Many of the items tabulated in Tables 8.2 and 8.3 are performance results obtained from Westinghouse design algorithms applied.

Table 8.2 — APFBC, Once-through SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	208	1500	244,649	2,459
2	Char drain	208	1500	---	115,165
3	Cyclone catch	207	1495	---	1,138
4	Fuel gas	207	1495	244,649	1,321
5	Char & sorbent	208	1500	---	116,303
6	SMGBF drain	204	1405	---	14,542
7	Over-sized drain	188	1600	---	12,000
8	Clean fuel gas	204	1405	244,649	5.3
9	Pellet feed	208	100	---	13,226
10	Vitiated air	188	1600	2,644,236	10,567
10	Bottom ash	188	1050	---	35,006
12	Cyclone catch	187	1598	---	5,474
13	Vitiated air	187	1598	2,644,236	5,092
14	SMGBF drain	184	1557	---	57,982
15	Drain recycle	15	200	---	2,899
16	Drain waste	15	200	---	55,082
17	Clean vitiated air	184	1557	2,644,236	15.3
18	Expansion gas[a]	158	2100	2,888,886	20.6
19	Pellet feed	188	100	---	52,905
20	Binder feed[b]	15	80	---	3,307
21	Water feed[c]	15	65	---	9,920
22	Steam[d]	50	480	39,679	---
23	Pellet waste[e]	15	100	---	1,979

a: 26 psi pressure drop over the fuel gas topping combustor
b: binder is commercial lime fed at 5% of pellet material rate
c: water for pelletization at 15% of pellet material rate
d: steam for curing pellets
e: pellet material losses about 1%

Table 8.3 — APFBC, Recycle SMGBF M&E Balances

Stream No.	Description	Pressure (psia)	Temperature (°F)	Gas Flow (lb/hr)	Solid Flow (lb/hr)
1	Fuel gas	208	1500	244,649	2,459
2	Char drain	208	1500	---	115,165
3	Cyclone catch	---	---	---	---
4	Fuel gas	208	1500	244,649	2,459
5	Char & sorbent	208	1500	---	118,491
6	SMGBF drain	204	1467	---	51,896
7	Separated ash	204	1467	---	3,326
8	Aeration gas	220	100	10,144	11,136
9	Clean fuel gas	204	1405	244,649	4.9
10	Vitiated air	188	1600	2,644,236	10,567
11	Bottom ash	188	1050	---	35,006
12	Cyclone catch	---	---	---	---
13	Vitiated air	188	1600	2,644,236	10,567
14	SMGBF drain	185	1581	---	223,047
15	Separated ash	185	1581	---	13,263
16	Aeration gas	200	100	36,816	44,402
17	Clean vitiated air	184	1557	2,644,236	21.1
18	Expansion gas[a]	158	2100	2,888,886	26.0

a: 26 psi pressure drop over the fuel gas topping combustor

8.3.2 SMGBF Equipment Sizing and Arrangement

The SMGBF system equipment has been conceptually sized and specified to the extent needed to develope rough layouts and equipment costs. The Once-Through SMGBF vessels and other major equipment sizing is summarized in Table 8.4. The Recycle SMGBF vessels and other major equipment sizing is summarized in Table 8.5. A general arrangement drawing of the SMGBF vessels, representative of both the Once-through and the Recycle cases, is the same as shown in Figure 7.4 for IGCC. The carbonizer-SMGBF equipment layout is similar to that of the IGCC, SMGBF equipment layouts shown in Figures 7.5 and 7.6. A general layout drawing of the Once-Through, CPFB-SMGBF system is shown in Figure 8.3, and for the Recycle, CPFB-SMGBF system in Figure 8.4. Multiple (4) SMGBF vessels are arranged around a single process gas/granule transport pipe for the CPFB unit. The SMGBF vessels were sized using granular bed filter algorithms developed specifically for the SMGBF configuration, as well as applying applicable refractory-lined pressure vessel codes. The cyclones were sized using standard design criteria for high-efficiency cyclones, and pressure vessel codes. Other hoppers, conveyors and size reduction equipment specifications were selected from general equipment design references. The pelletizer system design was scaled from design information provided by vendors.

8.3.3 SMGBF System Performance

The Once-Through SMGBF system performance is summarized in Table 8.6. The pellet mean diameter was selected to be a feasible value for commercial pelletization equipment, to provide acceptable particle removal capability, and reasonable pressure drop characteristics. The standleg velocity was selected to achieve the desired maximum vessel pressure drop of about 3 psi when operating with a pellet-to-fly ash mass ratio of about 10. The preclean cyclone adds a significant pressure drop as well. The mixing of the cold pellets with the fuel gas in the SMGBF results in an acceptable temperature loss, yielding only a slight reduction in the power plant thermal efficiency. The major contributor to steam consumption is for curing of the pellets in the

pelletization system, done with low-grade steam. Auxiliary power is consumed for pressurization, depressurization, and conveying of pellets, as well as for bottom ash size reduction.

Table 8.4 — APFBC, Once-through SMGBF Equipment

Equipment	Number	Description	Specifications
CARBONIZER SYSTEM			
Preclean Cyclone	1	High-efficiency cyclone; refractory lined	OD (ft): 7.6 Height (ft): 30.3 Inlet velocity (ft/s): 70
SMGBF Unit	1	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 11.8 Bottom OD (ft): 17.4 Standleg ID (ft): 10.4 Total height (ft): 27.8 Shell thickness (in): 1.6 Refractory thickness (in): 7 Weight (tons): 106
Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 5.0 Height (ft): 20.2 Pellet capacity (hr): 1
Pellet Flow Control/cooler	1	Water-cooled screw conveyor with BFW coolant	Pellet rate (ft^3/hr): 239 Outlet temperature (F): 200
CPFBC SYSTEM			
Preclean Cyclone	4	High-efficiency cyclone; refractory lined	OD (ft): 11.7 Height (ft): 47.0 Inlet velocity (ft/s): 70
SMGBF Unit	4	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 20.1 Bottom OD (ft): 27.9 Standleg ID (ft): 18.4 Total height (ft): 41.4 Shell thickness (in): 2.5 Refractory thickness (in): 7.5 Weight (tons): 387

Table 8.4 — (Continued)

Equipment	Number	Description	Specifications
Feed Hopper	4	Carbon steel pressure vessel	OD (ft): 5.0 Height (ft): 20.2 Pellet capacity (hr): 1
Pellet Flow Control/cooler	4	Water-cooled screw conveyor with BFW coolant	Pellet rate (ft^3/hr): 239 Outlet temperature (F): 200
Hot Gas Piping	4	Refractory-lined piping	Length (ft): 30 OD (ft): 6
COMMON EQUIPMENT			
Pelletizer System	1	Disk pelletizer system	Pellet rate (lb/hr): 6400 Curing time (hr): 20
Pellet Pressurization	2	Lock hopper system	Pellet capacity (hr): 0.5 Hopper OD (ft): 8.1 Hopper height (ft): 32.6
Pellet Conveying	1	Belt conveyors Bucket elevators	Length (ft): 300 Height (ft): 85
Pellet Depressurize	2	Lock hopper system	Pellet capacity (hr):0.5 Hopper OD (ft): 8.1 Hopper length (ft): 32.6
Size Reduction (bottom ash)	1	Conventional size reduction equipment	Crush rate (lb/hr): 7460 Crush size: 80% <500μm

Table 8.5 — APFBC, Recycle SMGBF Equipment

Equipment	Number	Description	Specifications
CARBONIZER SYSTEM			
SMGBF Unit	1	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 10.6 Bottom OD (ft): 16.4 Standleg ID (ft): 9.2 Total height (ft): 27.0 Refractory thickness (in): 7 Weight (tons): 92
Makeup Feed Hopper	1	Carbon steel pressure vessel	OD (ft): 2.9 Height (ft): 11.7 Pellet capacity (hr): 0.05
Ash-Granule Separator	1	Mechanical seive adapted to high-high-temperature	Diameter (ft): 5.0 Length (ft): 20.0
Hot Gas Piping	1	Refractory-lined piping	Length (ft): 20 OD (ft): 4
CPFBC SYSTEM			
SMGBF Unit	4	Refractory-lined pressure vessel (see Figure 7.4)	Top OD (ft): 17.8 Bottom OD (ft): 26.2 Standleg ID (ft): 16.2 Total height (ft): 39.7 Refractory thickness (in): 7.5 Weight (tons): 327
Feed Hopper	4	Carbon steel pressure vessel	OD (ft): 3.0 Height (ft): 12.0 Pellet capacity (hr): 0.05
Ash-Granule Separator	4	Mechanical seive adapted to high-high-temperature	Diameter (ft): 5.0 Length (ft): 20.0
Hot Gas Piping	4	Refractory-lined piping	Length (ft): 30 OD (ft): 6
COMMON EQUIPMENT			
Makeup Granule Pressurization	2	Lock hopper system	Pellet capacity (hr): 0.05 Hopper OD (ft): 6.4 Hopper height (ft): 25.4
Granule Conveying	1	Belt conveyors Bucket elevators	Length (ft): 500 Height (ft): 85

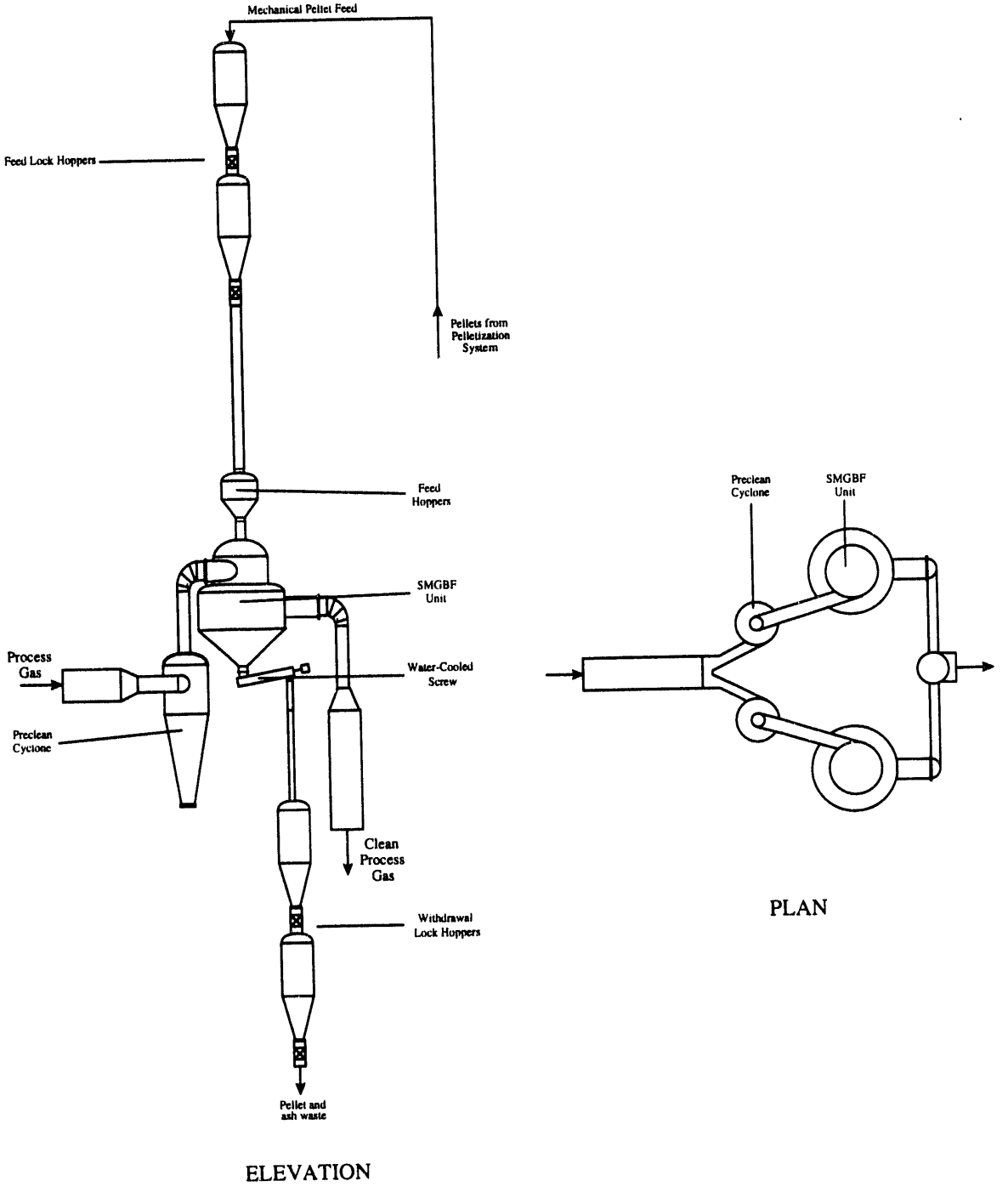


Figure 8.3 — APFBC, Once-Through SMGBF equipment arrangement.

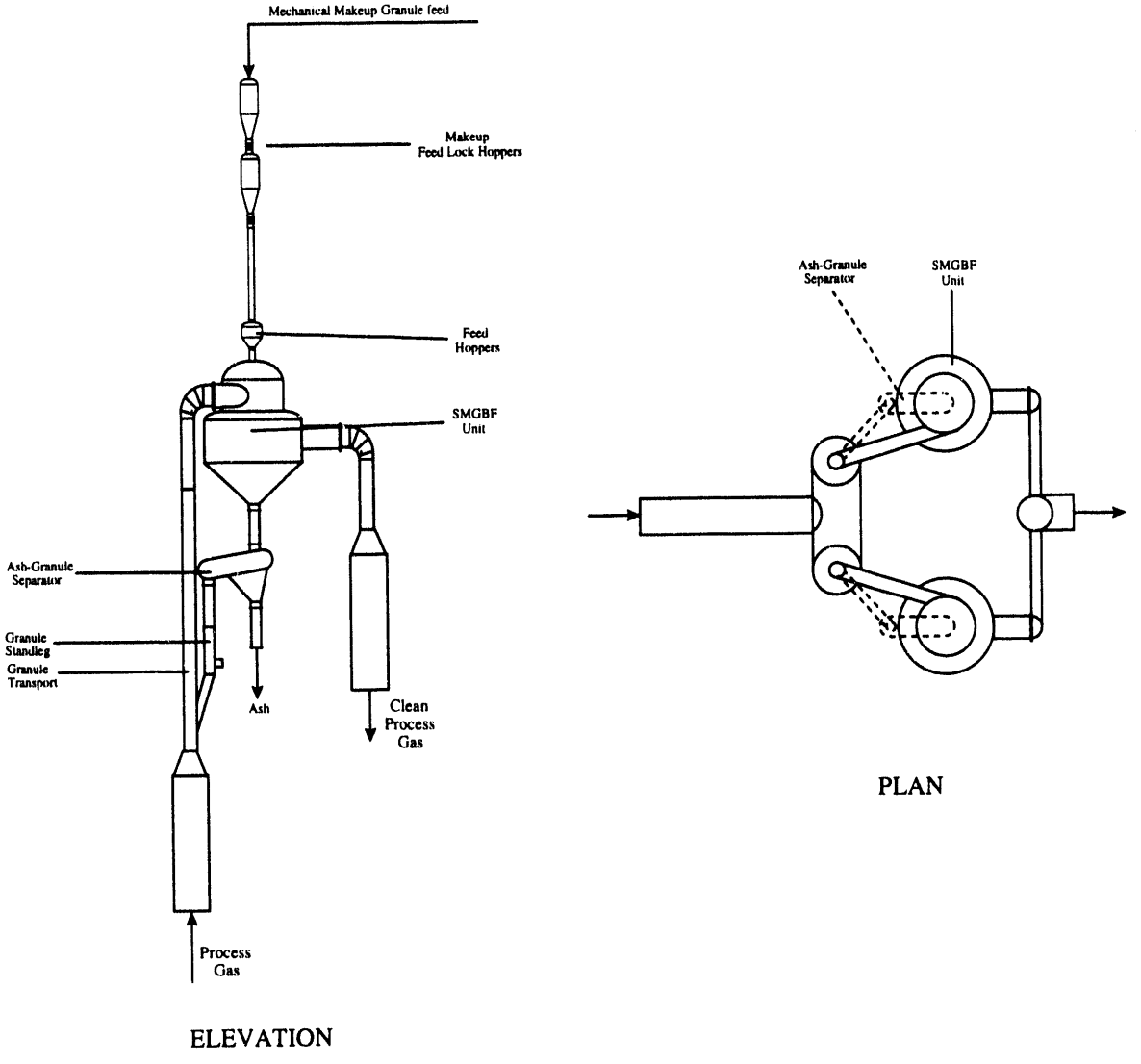


Figure 8.4 — APFBC, recycle SMGBF equipment arrangement.

Table 8.6 — APFBC, Once-through SMGBF System Performance

	Carbonizer	CPFBC	Overall
Pellet mean diameter (in):	7/16	7/16	
Standleg velocity (ft/s):	2.8	3.1	
Total pressure drop (psi):	3.1	3.8	
- preclean cyclone (psi):	0.9	0.8	
- SMGBF (psi):	3.0	3.0	
Total temperature drop:	96	44	
- preclean cyclone (F):	6	3	
- SMGBF heat losses (F):	19	12	
- SMGBF pellet mixing (F):	71	29	
Utility requirements			
- Power (kW):			407
Plant efficiency (%, HHV):			42.88
Reduction (%):			0.75
- Due to pressure loss(%):			20.6
- Due to temperature loss(%):			74.1
- Due to auxiliary power(%):			5.3
Raw material requirements:			
- Lime (lb/hr):			3307
- Water (lb/hr):			9920
Flyash removal			
- cyclone inlet load (ppmw):	10,049	4000	
- cyclone removal (%):	46.3	51.9	
- cyclone outlet load (ppmw):	5398	1926	
- SMGBF inlet load (ppmw):	5398	1926	
- SMGBF removal (%):	99.6	99.7	
- SMGBF outlet load (ppmw):	21.6	5.8	
- turbine inlet load (ppmw):			7.1
- emission (lb/MBtu):			0.012

The Recycle SMGBF system performance is summarized in Table 8.7. The granule mean diameter was selected to be a feasible value, to provide acceptable particle removal capability, and reasonable pressure drop characteristics. The standleg velocity was selected to achieve the desired maximum vessel pressure drop of about 3 psi when operating with a granule-to-fly ash mass ratio of about 20. The mixing of the recycled granules with the fuel gas in the SMGBF results in a very low temperature loss. There is no auxiliary fuel consumption. Auxiliary power is consumed primarily for gas compression for use as aeration gas.

The power plant efficiency reduction from the Reference Study using ceramic barrier filters is listed in the tables. In the Reference Study it is assumed that the barrier filters operate with a 3 psi pressure drop, and 10°F temperature drop. The total pulse gas supply power consumption for the ceramic barrier filters is estimated to be 55.2 kW. Most of the loss in power plant efficiency, relative to the Reference Study is due to the SMGBF system pressure drop and temperature drop. Since no credit was given for the additional steam cycle power generated by cooling the solids drained from the SMGBF unit, these efficiency number should be considered the worst case values. It can be concluded that the SMGBF system may provide plant performance comparable to ceramic barrier filters.

A summary of the fly ash removal performance of the SMGBF systems is shown in the tables. The SMGBF unit removal efficiency was selected to yield acceptable plant emissions, less than 0.02 lb/MBtu. This results in turbine inlet loadings that are less than the turbine protection limit of 15 ppmw total loading. The SMGBF outlet loadings (6-22 ppmw) and the removal efficiencies (99.6 - 99.8 %) are within the capabilities of the SMGBF unit measured in the Base Contract testing.

The nature of the power plant solid waste is greatly influenced by the Once-through SMGBF process, with the solid waste being issued as a pelletized materials having much lower fugitive dust emissions, easier handling, more environmentally stable behavior, as well as potential by-product uses. The plant waste is not greatly influenced by the Recycle SMGBF system.

Table 8.7 — APFBC, Recycle SMGBF System Performance

	Carbonizer	CPFBC	Overall
Pellet mean diameter (in):	3/8	3/8	
Standleg velocity (ft/s):	4.0	3.7	
Total pressure drop (psi):	3.4	3.2	
- SMGBF (psi):	3.0	3.0	
- Granule transport (psi):	0.4	0.2	
Total temperature drop:	34	19	
- SMGBF heat losses (F):	17	12	
- SMGBF granule mixing (F):	17	7	
Utility requirements			
- Power (kW):			238
Plant efficiency (%, HHV):			43.33
Reduction (%):			0.30
- Due to pressure loss(%):			43.0
- Due to temperature loss(%):			49.4
- Due to auxiliary power(%):			7.6
Raw material requirements:			
- Granule makeup (lb/hr):			2605
Flyash removal			
- SMGBF inlet load (ppmw):	10,000	4000	
- SMGBF removal (%):	99.8	99.8	
- SMGBF outlet load (ppmw):	20.1	8.0	
- turbine inlet load (ppmw):			9.0
- emission (lb/MBtu):			0.015

The reliability and controllability of the plant with the SMGBF is also a key performance factor. Reliability should be high, with no critical components having high risk. Control is centered on the water-cooled screw conveyors that regulate pellet flow as a function of the unit pressure drop. The large capacity of the SMGBF unit, and its long response time, makes it tolerant of IGCC process upset conditions.

8.3.4 SMGBF System Cost and Impact on Plant Cost

The SMGBF system costing was developed from major equipment, delivered-cost algorithms reported in standard costing references and from vendor quotes for equipment adapted for high-temperature, high-pressure duty. Costs are reported in December-1991 dollars. The Marshall & Swift Equipment Cost Index (Chemical Engineering, McGraw-Hill) was used to escalate costs to the December-1991 basis. Standard installation factors were applied to the delivered equipment costs to estimate installed equipment costs.

Delivered equipment costs and installed equipment costs for Once-Through and Recycle SMGBF are reported in Table 8.8, in units of thousands of dollars. The costs are for a single combustion turbine train. The most expensive components are the SMGBF vessel and the pelletization system. The Recycle SMGBF equipment is cheaper than the Once-Through SMGBF equipment.

The total APFBC plant capital requirement, annual operating cost, and COE are summarized in Table 8.9. Again, the total APFBC power plant costs are lower using the Recycle SMGBF than using Once-Through SMGBF. The relative virtues of pelletized plant waste, and differences in plant integration, and cost need to be assessed to complete a rational comparison of the two modes of operation.

8.4 SMGBF COMPARISON WITH CERAMIC BARRIER FILTER SYSTEM

Table 8.10 provides a comparison between SMGBF and ceramic barrier filters as applied to APFBC. Included in the comparisons are features of the major filtering vessels, installed filtering equipment costs, and total power plant costs. The major filtering vessels are

Table 8.8 — APFBC, SMGBF System Equipment Costs
(Basis: single gas turbine train)

	1000$ (Dec-1991)			
	Once-Through		Recycle	
	Carbonizer	CPFBC	Carbonizer	CPFBC
Preclean Cyclone				
Delivered:	105.0	916.2	---	---
Installed:	215.2	1,878.2	---	---
SMGBF Vessel				
Delivered:	375.8	3,304.7	346.4	3,008.9
Installed:	770.4	6,774.6	710.1	6,168.2
Feed Hopper				
Delivered:	47.6	190.6	18.2	76.0
Installed:	97.7	390.7	37.4	155.8
Pellet Flow Control/Cooler				
Delivered:	201.8	201.8	---	---
Installed:	413.7	413.7	---	---
Ash-Granule Separators				
Delivered:	---	---	50.1	206.6
Installed:	---	---	102.7	423.6
Hot Gas Piping				
Delivered:	41.8	344.8	41.8	344.8
Installed:	85.7	706.8	85.7	706.8
SUBTOTAL				
Delivered:	771.2	4,958.1	614.1	3,636.3
Installed:	1,582.7	10,164.0	1,259.1	7,454.4
	COMMON		COMMON	
Pressurization System				
Delivered:	235.7		157.6	
Installed:	483.3		323.2	
Depressurize System				
Delivered:	235.7			
Installed:	483.3			

Table 8.8 — (Continued)

	COMMON	COMMON
Pellet Conveying		
Delivered:	129.7	153.9
Installed:	181.6	215.5
Size Reduction		
Delivered:	7.5	
Installed:	9.7	
Pelletization System		
Delivered:	1,368.7	
Installed:	2,805.9	
TOTAL DELIVERED (1000$):	7,707.4	4,404.3
TOTAL INSTALLED (1000$):	15,710.5	8,929.0

Table 8.9 — APFBC, SMGBF Power Plant Costs

	Once-Through SMGBF	Recycle SMGBF
Capital Requirement (k$):	654,372	628,775
($/kW):	1445	1389
Annual Operating Cost (k$):	83,905	85,405
COE - Current $ (mills/kWh):	84.1	83.1

Table 8.10 — APFBC, SMGBF and Ceramic Barrier Filter Comparison

Major Equipment Features	
Once-through SMGBF	
Carbonizer vessels (2)	
OD/length (ft):	17/28
standleg velocity (ft/s):	2.8
pellet feed rate (lb/hr):	13,147
CPFBC vessels (8)	
OD/length (ft):	28/41
standleg velocity (ft/s):	3.1
pellet feed rate (lb/hr):	52,588
Recycle SMGBF	
Carbonizer vessels (2)	
OD/length (ft):	16/27
standleg velocity (ft/s):	4.0
granule circulation rate (lb/hr):	48,570
CPFBC vessels (8)	
OD/length (ft):	26/40
standleg velocity (ft/s):	3.7
granule circulation rate (lb/hr):	212,784
Ceramic Filter	
Carbonizer vessels (2)	
OD/length (ft):	15/54
number elements:	720
face velocity (ft/min):	5
CPFBC vessels (4)	
OD/length (ft):	20/54
number elements:	3840
face velocity (ft/min):	10
Installed Equipment ($k)	
Once-through SMGBF:	31,421
Recycle SMGBF:	17,858
Ceramic Filter:	16,789
Total Plant Capital ($k)	
Once-through SMGBF:	654,372
Recycle SMGBF:	628,775
Ceramic Filter:	625,660
COE - Current $ (mills/kWh)	
Once-through SMGBF:	84.1
Recycle SMGBF:	83.1
Ceramic Filter:	81.8

comparable in overall size, although their shapes differ significantly. Recycle SMGBF is comparable to the ceramic barrier filter, APFBC installed equipment costs and total power plant costs. Once-Through SMGBF is slightly more expensive than the ceramic barrier filter APFBC. A complete comparison can not be performed until the differences in reliability and availability, and the benefits of pelletized plant solid waste are better understood.

Major development issues for the SMGBF as it applies to APFBC are similar to those for IGCC, but also relate to the large scale of the APFBC power plant gas cleaning equipment:

- complexity of close plant integration with Once-Through SMGBF
- scaleup of the SMGBF unit to the CPFB size (18 ft standleg ID)
- reliability of the SMGBF system
- particle removal performance at the stringent CPFB requirements (6 to 8 ppmw in outlet gas)
- operability of the granule circulation technique (Recycle SMGBF)
- development of an ash-granule separator (Recycle SMGBF)
- granule attrition performance (Recycle SMGBF)

These are the issues that should be the focus of future development efforts.

9. References

1. Perry's Chemical Engineers' Handbook, Sixth Edition, p. 8-61, McGraw-Hill Book Company, 1984.

2. Browning, J. E., "Agglomeration: Growing Larger in Applications and Technology," Chem. Eng., 147 (December 4, 1967).

3. Coal & Synfuels Technology, February 8, 1993.

4. Power Engineering, p. 12, February 1944.

5. Pietsch, W., and R. Zisselmar, "Pressure Agglomeration with Roller Presses for Waste Processing and Recycling," p. 117, 5th International Symposium on Agglomeration.

6. Choudhry, V., and S. Hadley, "Production of Synthetic Lightweight Aggregate using Cool Water Slag," p. 21-1, Eighth Annual EPRI Conference on Coal Gasification, 1989.

7. Holley, C. A., "Ash Utilization and Disposal," p. 1761, Vol. 36, No. 4, Preprints of papers presneted at the 202nd ACS National Meeting, New York, August 1991.

8. Courts, G. D., "The Aggregate of the Future is Here Today," Proceedings: Ninth International Ash Use Symposium, p. 21-1, American Coal Ash Association, Washington, D.C., 1991.

9. P. Hay, "Plant Visit and Private Communication," Progress Materials Inc., Crystal River, FL, 1992.

10. Wilson, K. B., Performance Evaluation of a Screenless Granular Bed Filter on a Subpilot-Scale PFBC, Proc. of the Sixth Annual Coal-Fueled Heat Engines and Gas Stream Cleanup Systems Contractors Review Meeting, March 1989, DOE/METC-89/6101.

Appendix A

A List of Pelletization Equipment Vendors and Their Capability

Prater Industries, Inc.
Martin A. Barone, Manager
Material Processing Division
1515 South 55th Court
Chicago, Il 60650
708-656-8500
FAX 708-656-8576

- Equipment available - compactor, briquetter, flake and cake breaker, continuous mixer.
- Chicago plant has an application test center for feasibility studies, equipment trials and a toll factility.

Local Rep.
WRC Industrial Sales, Inc.
P. O. Box 429
McKeesport, PA 15134
412-673-0042

Ferro-Tech
Jamieson B. Rumley
Sales Engineer
467 Eureka Road
Wyandotte, Michigan 48192
313-282-7300
FAX 313-282-7305

- Ferro-Tech maintains a complete testing and research laboratory. Contract agglomeration services have produced quantities from 10 to one million pounds. Has an invertory of equipment for rent.
- Equipment supplied - disc pelletizer, tubulator, extruder, hot melt granulator, compactor, and briquetter.
- Compactors are normally used in conjunction with granulators, screens and recycling equipment to produce granules. The size and density of the granules can be controlled closely.
- Also supply other supporting equipment, screw feeders, bin dischargers, bucket elevators, table feeders, metering pumps.

Luwa Corporation Wayne A. West Manager, Business Development Suite 204, 220 Cont. Dr. Newark, DE 19713-4304 302-733-7481	• Wet granulation of fine powders.
The Fitzpatrick Company J. E. Frawley Vice President of Sales Norb Dubros, Sales Engineer 832 Industrial Drive Elmhurst, IL 60126 312-530-3333	• A manufacturer of stainless steel, sanitary process equipment, used by the food, chemical, and pharmaceutical industries. A supplier of Chilsonator and FitzMill granulator. System capability.
Koppern Equipment, Inc. Wolfgang Pietsch, President 5215 Chinley Court Charlotte, NC 28226 704-541-1978 FAX 704-541-8624	• Roller presses for briquetting and compacting. System capability. Primary in industries handling coal, ores and minerals, potash and mixed fertilizers, refractory materials, and sponge iron.
Sandvik Process Systems Per A. Linden Marketing Services Manager 409 Minnisink Road Totowa, NJ 07512 201-812-1066 FAX 201-812-0733	• In the field of solidification and forming of molten materials, pressing of laminates, and drying and freezing of food products.

California Pellet Mill Company Paul J. Tucker Engineering Specialist 1114 E. Wabash Avenue Crawfordsville, Indiana 47933 317-362-2600	• Quote on pellet mills.
Bepex Corporation Frank Palcher Product Manager 333 N. E. Taft St. Minneapolis, MN 55413 612-331-4370	• Offers total capability in equipment and systems in agglomeration, briquetting, compacting, extruding, drying, mixing, and granulation.
K. R. Komarek Inc. Barney Dalton 1825 Estes Avenue Elk Grove Village, IL 60007 312-956-0060	• Specializes in the design and manufacture of roll type briquetting and compacting machines. • K. R. Komarek Briquetting Research, located in Anniston, Alabama, is equipped with bench scale, pilot plant, and production size briquetters and compactors which are available for testing and development work. • Supply machines for briquetting ores and steel mill waste products heated to 1000°C.

Eirich Machines Inc. 521 Fifth Avenue New York, N. Y. 10175 416-832-2241 Eirich Machines Ltd. P. O. Box 550 Maple, Ont. L0J 1E0 Canada 416-832-2241	• Eirich pelletizer for fly ash agglomeration.
Sahut-Conreur & C° (France) U. S. Rep. Teledyne Readco 901 South Richland Avenue P. O. Box M-552 York, PA 17405 717-848-2801 FAX 717-848-2811 Local Rep. Jerry Raupp Nelson Engineering Sales 1725 Washington Road Suite 601 Pittsburgh, PA 15241 412-854-1314	• Kahl pelleting presses (Amandus Kahl Nachf, Hamburg, Germany) work according to the principle of extrusion moulding. The product to be pelleted is pressed through the perforations of a die by means of rotating pan grinder rollers. It is thus formed into strands of uniform section and subsequently cut with knives into the desired pellet lengths.

Appendix B

Vendors' Reports on Pelletization Results

FERRO-TECH®

467 eureka road, wyandotte, michigan 48192
telephone: (313) 282-7300
fax no. 313-282-7305

DATE: August 26, 1992

SHIPPING TRANSMITTAL

SHIP TO: Westinghouse Electric Corporation

Science & Technology Center

1310 Beulah Rd., Pittsburgh, PA 15235-5098

ATTENTION: Wen-Ching Yang

NAME OF MATERIAL: Fly Ash

LABORATORY NUMBER: 9207-076

MACHINE AGGLOMERATED ON:

DISC PELLETIZER	[x]
BRIQUETTER	[ ]
COMPACTOR/GRANULATOR	[ ]
TURBULATOR™	[x]

SHIPPED VIA:

UNITED PARCEL SERVICE	[x]
NEXT DAY AIR	[ ]
SECOND DAY AIR	[ ]
GROUND	[x]
AIR MAIL	[ ]
TRUCK	[ ]
CARRIER NAME	

WEIGHT OF ITEM SHIPPED: 30 lbs.

LOOK-SEE® x CONTRACT TEST ___

MAILING ADDRESS: _____

ATTENTION: _____

FERRO-TECH®

467 eureka road, wyandotte, michigan 48192
telephone: (313) 282-7300
fax no. 313-282-7305

CONFIDENTIAL

LABORATORY REPORT

LABORATORY NO.: 9207-076-1 DATE: August 28, 1992

TEST DATE: August 24, 1992

COMPANY: Westinghouse Electric Corp.
Science & Technology Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235-5098

CONTACT: Wen-Ching Yang
(412) 256-2207

PURPOSE OF TEST: To produce a pellet for use in a dry scrubber.

MATERIAL: AFBC Fly Ash
Bulk Density: 52.7 lbs./cu.ft.
Moisture: 0%

EQUIPMENT: Ferro-Tech Model 12TB34 Batch Turbulator™
Ferro-Tech Model 036 3'0" Disc Pelletizer

TEST: Look-See®

PELLETIZING MOISTURE: 16.0%

PROCEDURE: Mixed 4 lbs. of AFBC fly ash with 100 ml water in the Model 12TB34 Batch Turbulator™ for 18 seconds. Hand fed the Model 036 3'0" Disc Pelletizer. Water was sprayed onto the disc at a 4:30/6:30 position. Removed pellets by hand and placed in a sealed plastic container to cure. Screened cured pellets at plus 6 mesh.

COMMENTS:

AFBC fly ash agglomerated easily and with no problem.

Temperature of pellets, when removed from disc, rose to 160°F. No pellet breakage was noticed.

A small amount of 1/2" x 1/4" pellets were placed in a sealed plastic container in oven at 150°F to speed curing process so crush strengths could be taken.

Average Crush Strength

24 hrs.	48 hrs.	72 hrs.	96 hrs.
39.6 lbs.	54.2 lbs.	Plus 65 lbs.	Plus 65 lbs.

If you have any questions or require additional information, please feel free to call Jamie Rumley or myself.

Richard C. Lysogorski
Agglomeration Specialist

FERRO-TECH®

467 eureka road, wyandotte, michigan 48192
telephone: (313) 282-7300
fax no. 313-282-7305

CONFIDENTIAL

LABORATORY REPORT

LABORATORY NO.: 9207-076 DATE: August 28, 1992

TEST DATE: August 24, 1992

COMPANY: Westinghouse Electric Corp.
Science & Technology Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235-5098

CONTACT: Wen-Ching Yang
(412) 256-2207

PURPOSE OF TEST: To produce a pellet for use in a dry scrubber.

MATERIAL: Texaco IGCC Fly Ash
Bulk Density: 54.5 lbs./cu.ft.
Moisture: 7.0%

EQUIPMENT: Ferro-Tech Model 12TB34 Batch Turbulator™
Ferro-Tech Model 036 3'0" Disc Pelletizer

TEST: Look-See®

PELLETIZING MOISTURE: 27.5%

PROCEDURE: Mixed 4 lbs. of Texaco IGCC fly ash with 10% portland cement in the Model 12TB34 Batch Turbulator™ for 18 seconds. Hand fed the Model 036 3'0" Disc Pelletizer. Water was sprayed onto the disc at a 4:30/6:30 position. Removed pellets by hand and placed in a sealed plastic container. Screened cured pellets at plus 6 mesh.

COMMENTS:

In full production equipment, "as received" material will have to be milled to minus 250 mesh or finer. IGCC fly ash used was minus 30 mesh.

Test was performed using water only as a binder. After curing process pellets fell apart.

If cement is not a satisfactory binder another type can be used.

Pellets shipped to customer were not cured in oven.

A small amount of 1/2" x 1/4" pellets were placed in a sealed plastic container in oven at 150°F to speed curing process so crush strengths could be taken.

Average Crush Strength

24 hrs.	48 hrs.	72 hrs.
24.0 lbs.	28.6 lbs.	32.2 lbs.

If further test work is to be performed, more material will be needed.

If you have any questions or require additional information, please feel free to call Jamie Rumley or myself.

Richard C. Lysogorski
Agglomeration Specialist

FERRO-TECH®

467 eureka road, wyandotte, michigan 48192
telephone: (313) 282-7300
fax no. 313-282-7305

CONFIDENTIAL

LABORATORY REPORT

LABORATORY NO.: 9207-076-2 DATE: October 13, 1992

TEST DATE: October 5, 1992

COMPANY: Westinghouse Electric Corp.
Science & Technology Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235-5098

CONTACT: Wen-Ching Yang
(412) 256-2207

PURPOSE OF TEST: To produce a pellet for use in a dry scrubber.

MATERIAL: TIDD Fly Ash
Bulk Density: 81.7 lbs./cu.ft.
Moisture: 0%

EQUIPMENT: Ferro-Tech Model 12TB34 Batch Turbulator™
Ferro-Tech Model 036 3'0" Disc Pelletizer

TEST: Look-See®

PRODUCT BULK DENSITY: 87.0 lbs./cu.ft.

PELLETIZING MOISTURE: 12.5%

PROCEDURE: Mixed 5 lbs. of TIDD fly ash with 100 ml water in the Model 12TB34 Batch Turbulator™ for 18 seconds. Hand fed the Model 036 3'0" Disc Pelletizer. Water was sprayed onto the disc at a 4:30/6:30 position. Removed pellets by hand and placed in a sealed plastic container to cure. Screened cured pellets at plus 6 mesh.

COMMENTS:

TIDD fly ash agglomerated easily and with no problem.

A small amount of 1/2" x 1/4" pellets were placed in a sealed plastic bag so crush strengths could be taken.

Average Crush Strength

Green	24 hrs.	48 hrs.	72 hrs.	96 hrs.
2.0 lbs.	27.8 lbs.	36.2 lbs.	Plus 50 lbs.	Plus 50 lbs.

If you have any questions or require additional information, please feel free to call Jamie Rumley or myself.

Richard C. Lysogorski
Agglomeration Specialist

FERRO-TECH®

467 eureka road, wyandotte, michigan 48192
telephone: (313) 282-7300
fax no. 313-282-7305

FERRO-TECH LABORATORY PROCEDURES TESTING OUTLINE

SCREEN ANALYSIS

A group of eight (8) inch laboratory sieves are stacked with the largest opening size on top and the smallest opening on the bottom. A 100 gram representative sample of material to be analyzed is weighed and placed on the top sieve. The stack of sieves with a cover and a pan is placed in a "Ro-Tap" which is then set to operate for three minutes. The material retained on each sieve is added to the previous material weighed in grams. When the material in the pan is added, it should total to the original 100 grams.

MOISTURE ANALYSIS

Microwave Drying Method:

A 100 gram sample of material is placed on a plate and after weighing, is dried in a microwave for a period of one (1) or two (2) minutes. The plate with the sample is again weighed and again placed in the microwave for one (1) or two (2) minutes. This procedure is continued until the weight is constant. The difference between the starting weight (100 grams) and the final weight is the percent moisture on a wet basis.

Oven Drying Method:

Some materials are incompatible being dried in a microwave and are therefore dried in a conventional oven at 200°F. For this procedure, a 100 gram sample is placed on a plate in the oven for one (1) hour and then it is again weighed and the weight noted. The sample is again placed in the oven for one-half (1/2) hour and the weight is again checked. This continues until there is no weight loss. The difference between the starting weight (100 grams) and the final weight is the percent moisture on a wet basis.

BULK DENSITY

Poured:

Bulk density is the weight of a unit volume of material, normally expressed in pounds per cubic foot. Ferro-Tech's method of determining a bulk density is to pour material into a pint container from approximately six (6) inches above the top until the material overflows. The top of the container is leveled off utilizing a spatula, being careful not to force the material into the container. The material in the pint container is weighed in grams. The weight in

granule, you would produce a representative sample of 10 x 20 mesh granules. Fifty (50) grams of these granules would be placed on a 60 mesh sieve which has been stacked with a pan and cover. This stack is placed in a "Ro-Tap" for five minutes. The material in the pan is weighed so the quantity can be compared to that from other samples.

AEP Fly Ash

Test No.: 3341 B

Code: Rank:

Page: 1 Of: 4

Date: 92/9/30

CPM

Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: ASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): 72 Moisture Content:

Description: Quantity:

Flow: GOOD Sample No.: 2

********** TEST RUN NO.: 1 **********

Equipment Used For Test: CL-3 Die Specification: 3/16 X 1

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 15% WATER (4):

(2): (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs/Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N/A Steam Pressure: N/A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance: GOOD

Comments:

Test Conducted By: PAUL TUCKER AND CHAD WILSON

Personnel Present:

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: ASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): 72 Moisture Content:

Description: Quantity:

Flow: GOOD Sample No.: 2

********** TEST RUN NO.: 2 **********

Equipment Used For Test: CL-3 Die Specification: 1/4 X 1

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 15% WATER (4):

(2): 5% STARCH (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs/Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N/A Steam Pressure: N/A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance: GOOD

Comments:

Test Conducted By: PAUL TUCKER AND CHAD WILSON

Personnel Present:

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: ASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): 72 Moisture Content:

Description: Quantity:

Flow: GOOD Sample No.: 2

********** TEST RUN NO.: 3 **********

Equipment Used For Test: CL-3 Die Specification: 1/4 X 1

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 17% WATER (4):

(2): (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs/Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N/A Steam Pressure: N/A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance:

Comments: MATERIAL TOO WET.

Test Conducted By: PAUL TUCKER AND CHAD WILSON

Personnel Present:

Test No.: 3341 B

Code: Rank:

Date: 92/9/30

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: ASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): 72 Moisture Content:

Description: Quantity:

Flow: GOOD Sample No.: 2

********** TEST RUN NO.: 4 **********

Equipment Used For Test: CL-3 Die Specification: 1/4 X 1

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 15% WATER (4):

(2): (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs/Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N/A Steam Pressure: N/A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance:

Comments: MATERIAL TOO DRY.

Test Conducted By: PAUL TUCKER AND CHAD WILSON

Personnel Present:

Foster Wheeler AFBC Waste

Test No.: 3341 A

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

Code: Rank:

Date: 92/9/24

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: FLYASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): 61 Moisture Content:

Description: FINE Quantity:

Flow: GOOD Sample No.:

********** TEST RUN NO.: 1 **********

Equipment Used For Test: CL-3 Die Specification: 1/4 X 1 1/4

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 15% WATER (4):

(2): (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs/Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N/A Steam Pressure: N/A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance:

Comments: TOO DRY.

Test Conducted By: CHAD WILSON

Personnel Present:

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: FLYASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): 61 Moisture Content:

Description: FINE Quantity:

Flow: GOOD Sample No.:

********** TEST RUN NO.: 2 **********

Equipment Used For Test: CL-3 Die Specification: 1/4 X 1 1/4

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 20% WATER (4):

(2): (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs/Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N/A Steam Pressure: N/A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance:

Comments: TOO DRY.

Test Conducted By: CHAD WILSON

Personnel Present:

Test No.: 3341 A

Code: Rank:

Date: 92/9/24

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: FLYASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): 61 Moisture Content:

Description: FINE Quantity:

Flow: GOOD Sample No.:

********** TEST RUN NO.: 3 **********

Equipment Used For Test: CL-3 Die Specification: 1/4 X 1 1/4

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 25% WATER (4):

(2): (5):

(3): (6):

Motor Load Amps: 6 Motor H.P. Used: 2.0

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F): 140

Pellet Rate, Gross (Lbs/Hr): 116 % Pellets: % Fines:

Conditioner Temperature (Deg F): N/A Steam Pressure: N/A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance: GOOD

Comments:

Test Conducted By: CHAD WILSON

Personnel Present:

Texaco IGCC

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

Test No.: 3341

Code: Rank:

Date: 92/8 31

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: FLYASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): Moisture Content:

Description: COARSE Quantity:

Flow: GOOD Sample No.:

********** TEST RUN NO.: 1 **********

Equipment Used For Test: CL-3 Die Specification: 3/16 X 1 1/4

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 15% WATER (4):

(2): (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N A Steam Pressure: N A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance: POOR

Comments: PLUGGED DIE

Test Conducted By: CHAD WILSON

Personnel Present:

Test No.: 3341

Code: Rank:

Page: 2 Of: 4

Date: 92/8 31

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: FLYASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): Moisture Content:

Description: COARSE Quantity:

Flow: GOOD Sample No.:

********** TEST RUN NO.: 2 **********

Equipment Used For Test: CL-3 Die Specification: 3/16 X 1

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 20% WATER (4):

(2): 5% STARCH (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N A Steam Pressure: N A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance: POOR

Comments: TOO WET.

Test Conducted By: CHAD WILSON

Personnel Present:

Test No.: 3341

Code: Rank:

Page: 3 Of: 4

Date: 92/8 31

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: FLYASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): Moisture Content:

Description: COARSE Quantity:

Flow: GOOD Sample No.:

********** TEST RUN NO.: 3 **********

Equipment Used For Test: CL-3 Die Specification: 3/16 X 1

Die S/N: R.P.M.: 251 Entrance: STD

Formulation: 15% WATER (4):

(2): 5% STARCH (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N A Steam Pressure: N A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance: FAIR

Comments:

Test Conducted by: CHAS [illegible]

Test Pool [illegible]

Test No.: 3341

Code: Rank:

Page: 4 Of: 4

Date: 92 8 31

CPM
Part of worldwide Ingersoll-Rand

California Pellet Mill Company
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933
(317) 362-2600

For : MR. WEN-CHING YANG

Company: WESTINGHOUSE STC

: SCIENCE AND TECHNICAL CENTER

: 1310 BEULSH RD.

: PITTSBURGH, PA 15235

Telephone No.: (412)256-2202

Material: FLYASH

********** PHYSICAL CONDITION OF MATERIAL AS RECEIVED **********

Bulk Density (lbs/cuft): Moisture Content:

Description: COARSE Quantity:

Flow: GOOD Sample No.:

********** TEST RUN NO.: 4 **********

Equipment Used For Test: CL-3 Die Specification: 3/16 X 1

Die S N: R.P.M.: 251 Entrance: STD

Formulation: 15% WATER (4):

(2): 5% CEMENT (5):

(3): (6):

Motor Load Amps: Motor H.P. Used:

Pellet Bulk Density (lbs/cuft): Pellet Temperature (Deg F):

Pellet Rate, Gross (Lbs/Hr): % Pellets: % Fines:

Conditioner Temperature (Deg F): N A Steam Pressure: N A

Pellet Moisture: Durability Index: Pellet Sample No.:

Pellet Quality & Appearance: FAIR

Comments:

Test Conducted By: CHAD WILSON

Personnel Present:

KOPPERN EQUIPMENT, INC.
One Oxford Centre, #4260
301 Grant Street
Pittsburgh, PA 15219
Tel: (412) 765-1060
Fax: (412) 765-1062
Tlx: 802028 KOPCOMPACT PIT

Köppern

FAXNO 1.1803/122
Pittsburgh, PA, December 5, 1992

Total number of pages: 2 (two)
Page 1/2

TO: WESTINGHOUSE CO.
Science and Technology Center, Pittsburgh, PA

COPY

Attn.: Dr. W.C. Yang

Subject: Compacting of Ash from Fluid Bed Combustors
Ref. : Testing of 3 (three) samples
Message left on your TAD dated Wednesday, December 2, 1992

Dear Dr. Yang,

you did send three (3) samples of ash to KOPPERN, Germany, for testing. Each sample was packed in two (2) 5 gallon pails. The undersigned just returned from Germany, where he was informed about the tests. 2 (two) kg of compacted product + 2 mm from each sample is being sent to us. We expect to receive it next week and will then bring these product samples to you for your evaluation. Some material is still left at KOPPERN for additional tests should you have specific processing ideas.

In short the following describes how the product samples were produced:

Quote:
SAMPLE 1: Texaco Ash
This ash looked like slag and featured high surface moisture (approx. 18%); it was not compactible as received. After addition of 20% cement (to absorb the water) it was compactible and hardened with time to achieve good strength.

SAMPLE 2: Commercial Ash
This ash contains CaO. After wetting and immediate compaction good sheet was obtained which fell apart during hydratisation of CaO to Hydroxide which is accompanied by a volume increase. If this chemical process was let take place prior to compaction the sheet held together and increased slightly in strength with time. This material may also be compactible

KOPPERN EQUIPMENT, INC.
One Oxford Centre, #4260
301 Grant Street
Pittsburgh, PA 15219
Tel: (412) 765-1060
Fax: (412) 765-1062
Tlx: 802028 KOPCOMPACT PIT

Köppern

FAXNO 1.1803/122
Pittsburgh, PA, December 5, 1992

without binder (water). However, humidity in air may cause hydratisation and disintegration of the granular product.

SAMPLE 3: TIDD Ash (received later)
This ash features good compactibility dry and, after addition of 5% water, can be compacted to yield an excellent product which hardens with time.

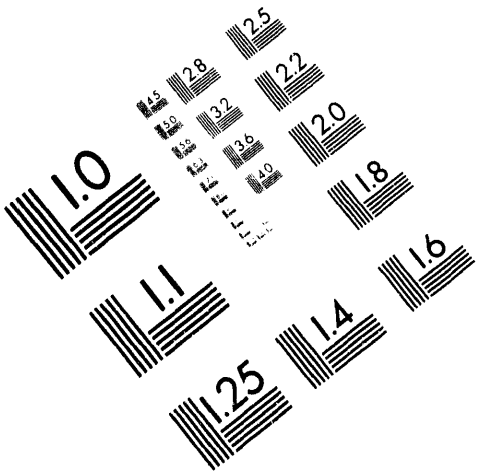
All compacted material was crushed in a double roll disc crusher with approx. 9 mm disc tip distance. Fines - 2 mm were screened out. 2 kg of each product, approx. + 2 - 14 mm, are being made available to the customer for evaluation.
Unquote.

We will contact you as soon as the product samples have arrived to arrange for the transfer.

Kindest regards, ~~yours sincerely~~
KOPPERN Equipment, Inc.
Dr.-Ing. Wolfgang Pietsch, President

Wolfgang Pietsch

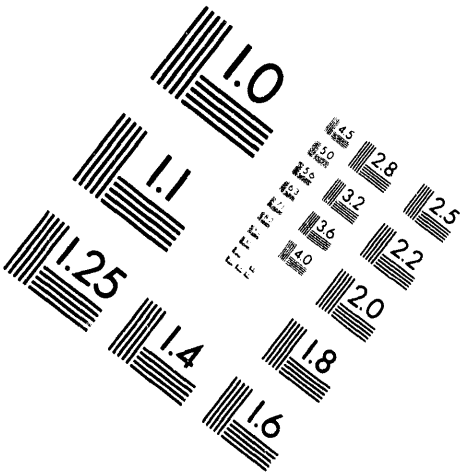
Compacting (Since 1898) and Complete Plants



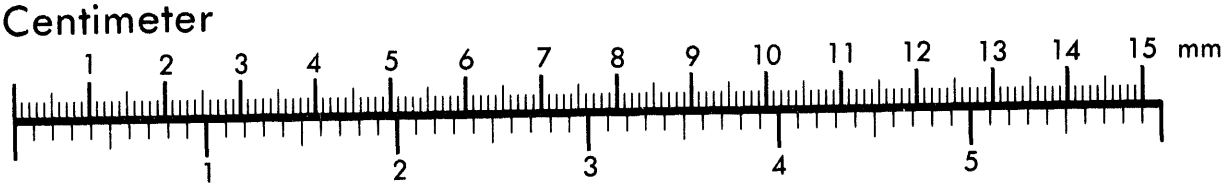
Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

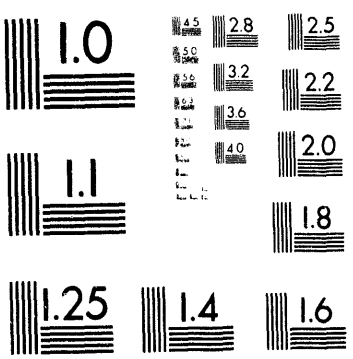
301/587-8202

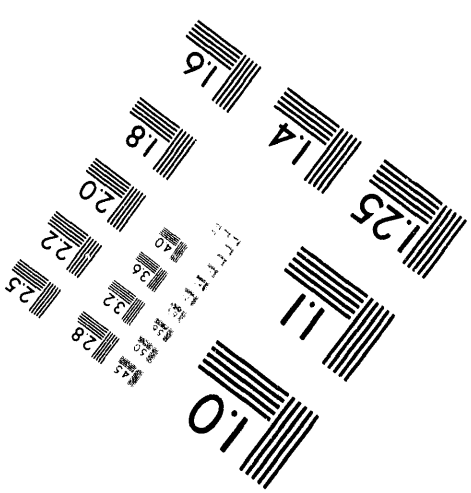


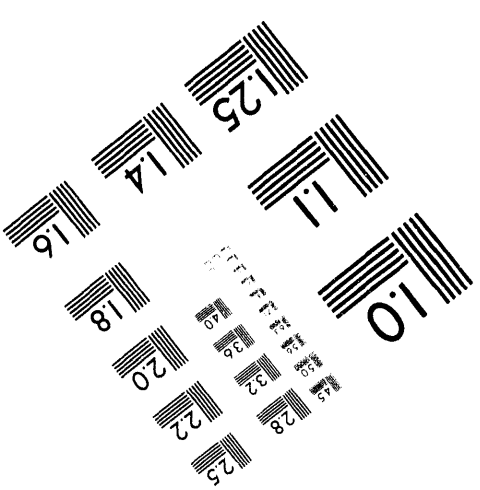
Centimeter



Inches







MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

3 of 3

Datenblatt zur Auswertung von Versuch: 18428/01		Köppern	
Versuchsmaterial: Asche	Firma: Westinghouse	Gesamtseiten: 6	Seite: 1
Materialkenndaten As-Received		Datum: 26./27.11. und 1.12.1992	

Probe:	Commercial	Tidd
Schüttdichte/kg/dm ^ 3: bulk	0,93	1,28
Rütteldichte/kg/dm ^ 3: Tap	1,11	1,51
Rutschwinkel Metall/ : angle of repose on metal	31 - 42	33 - 45
Rutschwink. CH 1000/ : " " " CH1000 plast.	25 - 40	30 - 39
Böschungswinkel/ : angle of repose	43	- 50
Wassergehalt in % : moisture content	0,4	0,2
(bei 105 C)		

slidi-fangle

Aufgabekörnung in mm:	Gew. in g	Ant. in %	R(x) in %	D(x) in %	Gew. in g	Ant. in %	R(x) in %	D(x) in %
> 16	lut.		Rtei ~	passing				
16 - 10								
10 - 8								
8 - 6,3								
6,3 - 5								
5,00 - 4		0	0	100		0	0	100
4,00 - 3,15	0,04	0,22	0,22	99,78	0,32	0,40	0,40	99,60
3,15 - 2	0,03	0,17	0,39	99,61	5,75	7,15	7,55	92,45
2,00 - 1	0,13	0,73	1,12	98,88	16,47	20,48	28,03	71,97
1,00 - 0,5	2,88	16,17	17,29	82,71	15,89	19,76	47,79	52,21
0,5 - 0,25	3,74	21,00	38,29	61,71	3,98	4,95	52,74	47,26
0,25 - 0,125	2,56	14,37	52,67	47,33	3,33	4,14	56,88	43,12
0,125 - 0,09	0,36	2,02	54,69	45,31	2,88	3,58	60,46	39,54
0,09 - 0,063	0,49	2,75	57,44	42,56	2,83	3,52	63,98	36,02
0,063 - 0,04	1,30	7,30	64,74	35,26	6,40	7,96	71,93	28,07
0,04 - 0,0	6,28	35,26	100	0	22,57	28,07	100	0
SUMME:	17,81	100			80,42	100		
d 50 in mm								
d 95 in mm								

Bemerkungen:

Commercial: enthält offensichtlich Branntkalk (vergl. Versuch auf Walzenpresse).
Tidd: Asche mit hydraulischen Eigenschaften, härtet nach.

Anwesend:	Köppern:	H. Schumacher
	Kunde:	-

18.12.92 fr

Datenblatt zur Auswertung von Versuch: 18428/01		Köppern	
Versuchsmaterial: Asche	Firma: Westinghouse	Gesamtseiten: 6	Seite: 2
Materialkenndaten		Datum: 26./27.11. und 1.12.1992	

Probe:	Texaco Ash	
Schüttdichte/kg/dm ^ 3:	0,97	
Rütteldichte/kg/dm ^ 3:	1,04	
Rutschwinkel Metall/ :	26 - 40	
Rutschwink. CH 1000/ :	26 - 38	
Böschungswinkel/ :	45	
Wassergehalt in % :	16,9	

Aufgabekörnung in mm:	Gew. in g	Ant. in %	R(x) in %	D(x) in %	Gew. in g	Ant. in %	R(x) in %	D(x) in %
> 16								
16 - 10								
10 - 8								
8 - 6,3		0	0	100				
6,3 - 5	0,23	1,15	1,15	98,85				
5,00 - 4	0,88	4,38	5,53	94,47				
4,00 - 3,15	1,66	8,27	13,80	86,20				
3,15 - 2	4,95	24,66	38,47	61,53				
2,00 - 1	4,77	23,77	62,23	37,77				
1,00 - 0,5	1,39	6,93	69,16	30,84				
0,5 - 0,25	2,62	13,05	82,21	17,79				
0,25 - 0,125	2,12	10,56	92,78	7,22				
0,125 - 0,09	0,54	2,69	95,47	4,53				
0,09 - 0,063	0,37	1,84	97,31	2,69				
0,063 - 0,04	0,31	1,54	98,85	1,15				
0,04 - 0,0	0,23	1,15	100	0				
SUMME:	20,07	100						
d 50 in mm								
d 95 in mm								

Bemerkungen:
Probe sieht aus wie Schlacke, vor dem Sieben getrocknet.

Anwesend:	Köppern:	H. Schumacher
	Kunde:	-

Datenblatt zur Auswertung von Versuch: 18428/01		Köppern	
Versuchsmaterial: Asche	Firma: Westinghouse	Gesamtseiten: 6	Seite: 3

VERSUCHE AUF DER VIERSÄULEN - STEMPELPRESSE	Datum: 26./27.11. und 1.12.1992

Teilversuch Nr.:	1	2	3	4	5	6
Mischkomponenten in %:						
Probe:	Commercial Asche					
Zugabe von H2O in %:					5	5
Mischertype :						
Mischzeit in min. :						
Brikettierparameter						
Schüttdichte kg/dm^3						
Schüttd.theor. kg/dm^3						
Aufgabetemp. C:	20	20	20	20	20	20
Wassergehalt %:	0,4	0,4	0,4	0,4	4,3	4,3
Pressdruck bar:	50	100	150	200	100	200
Pressdruck N/mm^2	124	248	372	496	248	496
Tablettengew. g:	25,93	28,12	26,81	*1	18,57	*2
Tablettenhöhe height mm:	20,5	21,3	19,6		12,8	
Tab.-Durchm. dia mm:	31,0	31,0	31,0		31,0	
Tablettenvol. volume cm^3:	15,47	16,08	14,79		9,66	
Dichte density g/cm^3:	1,68	1,75	1,81		1,92	
Verdichtung 1:	-	-	-	-	-	-
Punktdruckfestigkeit auf Erichsen-Prüfmaschine in N:						
sofort	98	151	227 kg		238	
nach 24 Std.	Compression strength tests					
nach 48 Std.						
nach 72 Std.						

Bemerkungen:

=1 mm dia tablet

*1: Überpreßt, Tabletten halbiert, nicht fester.

*2: wie *1

Bei den geringen Mengen war chem. Reaktion nicht nachweisbar. Tabletten trocken und feucht allerdings von unbefriedigender Festigkeit.

Anwesend:	Köppern:	H. Schumacher
	Kunde:	-

Datenblatt zur Auswertung von Versuch: 18428/01		Köppern	
Versuchsmaterial: Asche	Firma: Westinghouse	Gesamtseiten: 6	Seite: 4

VERSUCHE AUF DER VIERSÄULEN - STEMPELPRESSE	Datum: 26./27.11. und 1.12.1992

Teilversuch Nr.:	7	8	9	10	11	12
Mischkomponenten in %:						
Probe:	TIDD - Asche					
Zugabe von H2O in %:					5	5
Mischertype :						
Mischzeit in min. :						
Brikettierparameter						
Schüttdichte kg/dm^3						
Schüttd.theor. kg/dm^3						
Aufgabetemp. C:	20	20	20	20	20	20
Wassergehalt %:					4,1	4.1
Pressdruck bar:	50	100	150	200	100	200
Pressdruck N/mm^2	124	248	372	496	248	496
Tablettengew. g:	36,67	37,98	38,35	38,48	27,84	29.23
Tablettenhöhe mm:	26,0	25,8	25,2	25,0	17,2	16,8
Tab.-Durchm. mm:	30,5	30,6	30,6	30,5	30,7	30,8
Tablettenvol. cm^3:	19,00	18,97	18,53	18,27	12,73	12,52
Dichte g/cm^3:	1,93	2,00	2,07	2,11	2,19	2,34
Verdichtung 1:	-	-	-	-	-	-
Punktdruckfestigkeit auf Erichsen-Prüfmaschine in N:						
sofort Intermediate	223	453	1130	1271	1222	2112
nach 24 Std. after 1 hours					2751	4151
nach 48 Std.						
nach 72 Std.						

Bemerkungen: Probe sehr gut brikettierbar, insbesondere nach Anfeuchtung.

Anwesend:	Köppern:	H. Schumacher
	Kunde:	-

Datenblatt zur Auswertung von Versuch: 18428/01		Köppern	
Versuchsmaterial: Asche	Firma: Westinghouse	Gesamtseiten: 6	Seite: 5
VERSUCHE AUF DER VIERSÄULEN - STEMPELPRESSE		Datum: 26./27.11. und 1.12.1992	

Teilversuch Nr.:		13	14				
Mischkomponenten in %:							
Probe:		Texaco					
Zugabe von H2O	in %:						
Mischertype	:						
Mischzeit in min.	:						
Brikettierparameter							
Schüttdichte	kg/dm ^ 3						
Schüttd.theor.	kg/dm ^ 3						
Aufgabetemp.	C:						
Wassergehalt	%:						
Pressdruck	bar:	50	100				
Pressdruck	N/mm ^ 2	124	248				
Tablettengew.	g:	24,80	-				
Tablettenhöhe	mm:	17,0	-				
Tab.-Durchm.	mm:	31,4	-				
Tablettenvol.	cm ^ 3:	13,16	-				
Dichte	g/cm ^ 3:	1,88	-				
Verdichtung	1:	-	-				
Punktdruckfestigkeit auf Erichsen-Prüfmaschine in N:							
sofort		46					
nach 24 Std.							
nach 48 Std.							
nach 72 Std.							

Bemerkungen:
V 13: Beim Pressen Wasseraustritt, Tabletten plastisch.
V 14: Beim Pressen Wasseraustritt, Tabl. überpreßt und zerfällt beim Rausdrücken.

Probe bindemittellos nicht brikettierbar.

Anwesend:	Köppern:	H. Schumacher
	Kunde:	-

Datenblatt zur Auswertung von Versuch: 18428/01		Köppern	
Versuchsmaterial: Asche	Firma: Westinghouse	Gesamtseiten: 6	Seite: 6
Pressentype:	60/10	Datum:	26./27.11. und 1.12.1992
Walzendurchmesser: Roller dia.	1000 mm		

Teilversuch Nr.:		1	2.1	2.2	3
Mischertyp:					
Misch- bzw. Bindekomponenten in %	Asche	TIDD Commercial Texaco			
	Zement P235F	-	-	-	20
	Wasser (ad 100%)	5	5	9	-
				in zerfallene Schülpen von V 2.1	
			fall apart		
Mischzeit mixing time min:		2	2		
Mischungstemperatur feed temp. C:		~20	~20	~20	~20
Rückgut-Anteil Recycle material %:		-	-	100	-
Mischzeit mixing time min:		-	-	2 (+30) reaction time	-
Aufgabetemperatur C:		~20	~20	~30	~20
Schüttdichte-Mischung bulk kg/dm^3		1,18	0,73	1,09	1,05
Wassergeh. der Mischung mixture water content %:		4,5	4,0	7,5	14,8
Schneckendrehzahl min^-1:		-	-	-	-
Schneckenarbeitsdruck bar:			2* aufgeg.		2* aufgeg.
Walzendrehzahl roller speed min^-1:		2 rpm	2	2	2
Umfangsgeschwindigkeit circumferential speed m/s:		0,10	0,10	0,10	0,10
Stickstoffspeicher bar:		125	125	125	35
Hydraulik-Vordruck bar:		130	130	130	40
Hydraulik-Arbeitsdruck bar:		170	160 - 170	150 - 160	< 40
spez. Presskraft specific force kN/cm:		93	87 - 93	82 - 87	< 22
Naht-/Stegdicke gap mm:		8 - 8,5	< 8	5,5 - 6,5	3
Schülpendicke sheet thickness mm:		12 - 12,5	< 12	9,5 - 10,5	7
Brikettformat :		Waffel type of roller	Waffel	Waffel	Waffel
Brikettgewicht g:					
Volumen cm^3:					
Dichte apparent density g/cm^3:		2,22		1,91	1,99
Verdichtung densification ratio 1:		1,88		1,75	1,90
Mengenmessung kg;sek:					
Durchsatz der Presse t/h:					

Körnung Pressenaustrag:	kg	%	kg	%	kg	%	kg	%
> 20 mm								
20 - 5 mm								
< 5 mm								

Bemerkung: V 2: Schülpen zerfallen bei starker Wärmetönung
V 3: * Zwischenlagerung für chem. Reaktion zu Hydrat.
Schülpen aller Proben härten nach.

Anwesend:	Köppern:	H. Severins, H. Schumacher, H. Zech
	Kunde:	-

bepex corporation
A Member of the Hosokawa Micron Group
333 N.E. Taft Street – Minneapolis, MN 55413 – (612) 331-4370
FAX: (612) 627-1444

K-G
Rietz
Strong-Scott
Schugi

September 15, 1992

Mr. Wen-Ching Yang
Westinghouse Electric Corp.
1310 Beulah Road
Pittsburgh, PA 15235-5098

Reference: Bepex Project #M-92-S-6855

Dear Mr. Yang:

Thank you for your interest in Bepex. We have examined your flyash material and we have reached the conclusion that it will be rather difficult to meet the requirements of your process.

We tried to compact your material using pressure alone. Even when subjected to 40,000 psi, the material showed no tendency to stay together. It is our opinion that a binder will be necessary.

There are several binders which can be used, although the requirement for resistance to high temperatuer precludes many. One possibility is sodium silicate. I must point out that sodium silicate is not cheap. In fact, we can summarize the processing costs for granulation as follows:

Power:	$ 0.60/ton
Binder:	15.00/ton
Wear Parts:	1.00/ton
General Maintenance:	1.00/ton
Labor:	5.00/ton

Thus, the cost of processing your material, less the cost of equipment, is about $22.60/ ton. This is based on a system doing four tons/hour. Of course, higher rates would slightly lower the cost while lower rates could drive up the costs significantly.

Based on four tons/hour, a granulation system with mixer would be priced at approximately $800,000.

Bepex can undertake a binder study, if the above numbers sound attractive. Our price for a binder study is $400.

We look forward to working with you on this project. If you should have any questions, please contact me.

Sincerely,

BEPEX CORPORATION

Michael D. White

Michael D. White
Application Engineer

cc: D. Perrin

Appendix C

SMGBF HTHP Test Data Plots

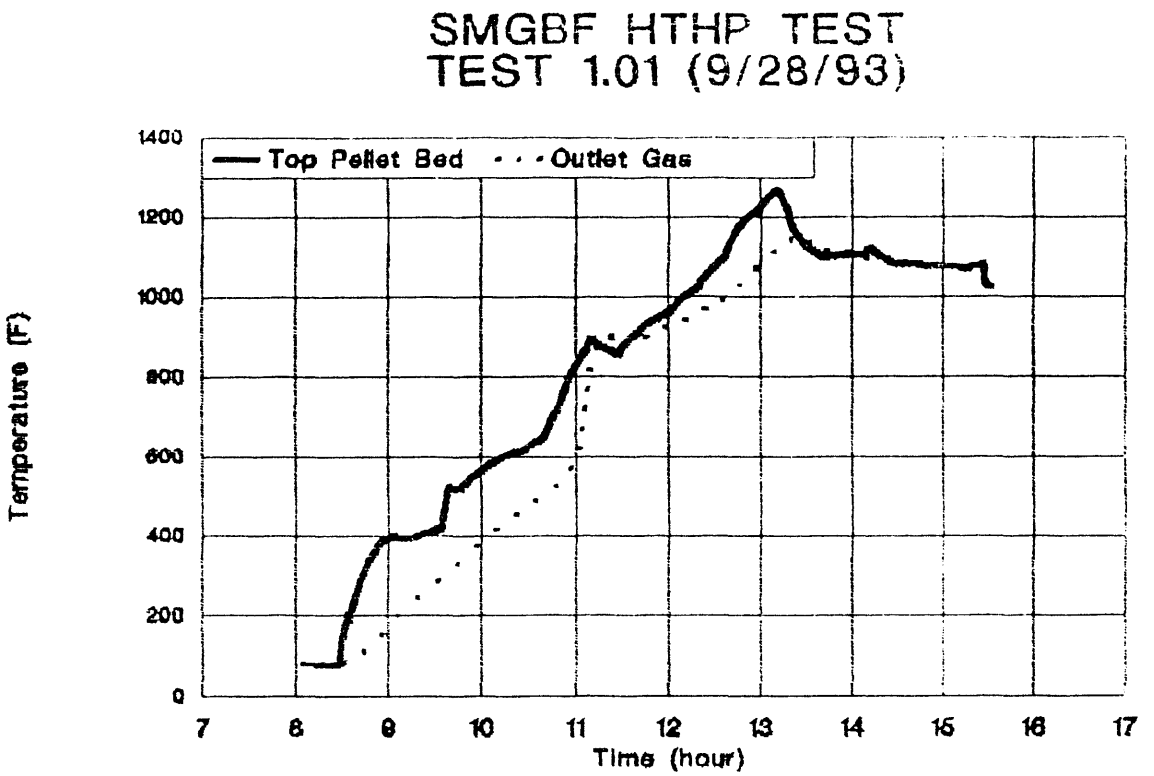


Figure C1 — Test 1.01 (9/28/93) temperatures.

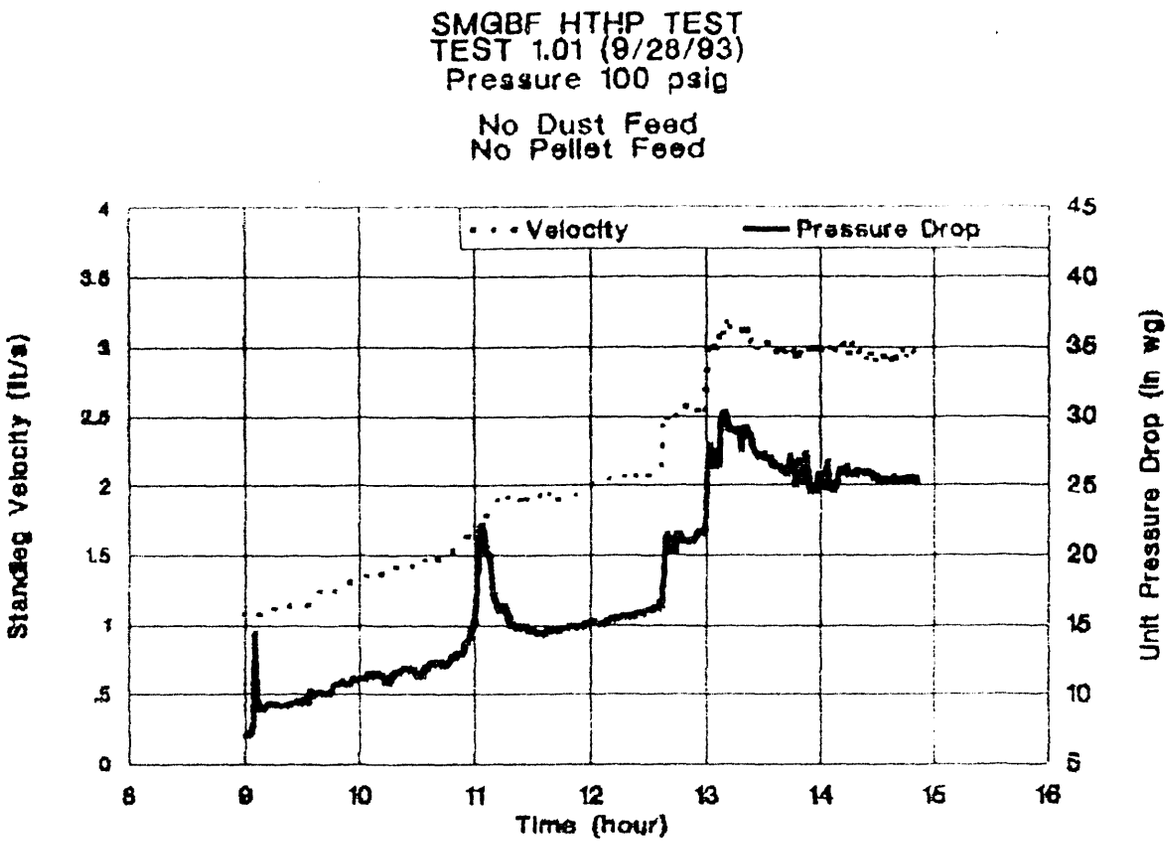


Figure C2 — Test 1.01 (9/28/93) velocity and pressure drop.

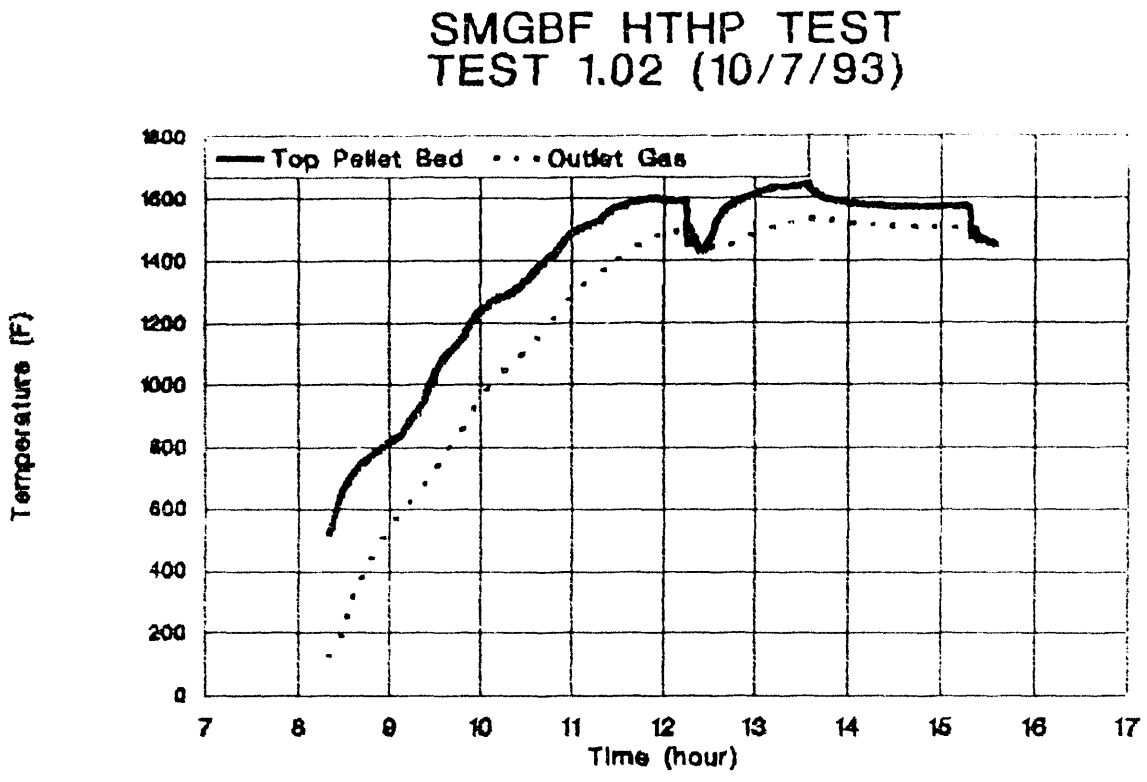


Figure C3 — Test 1.02 (10/7/93) temperatures.

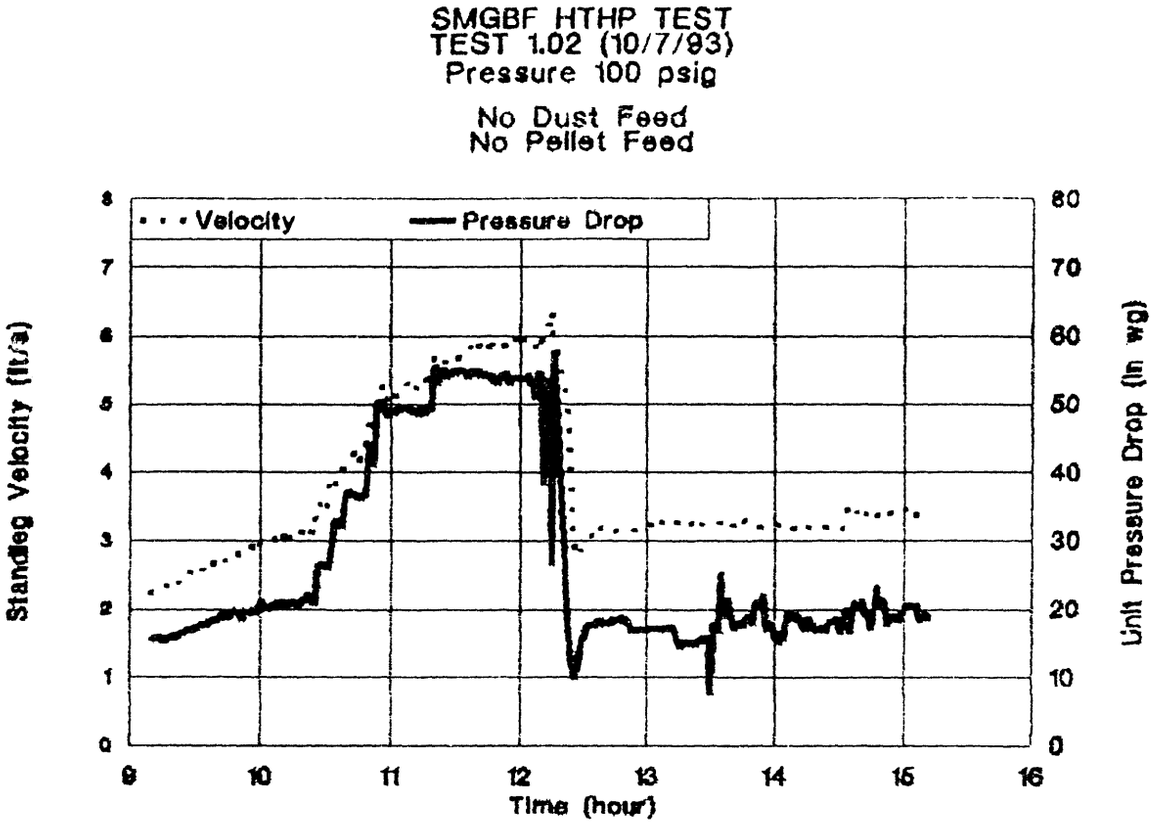


Figure C4 — Test 1.02 (10/7/93) velocity and pressure drop.

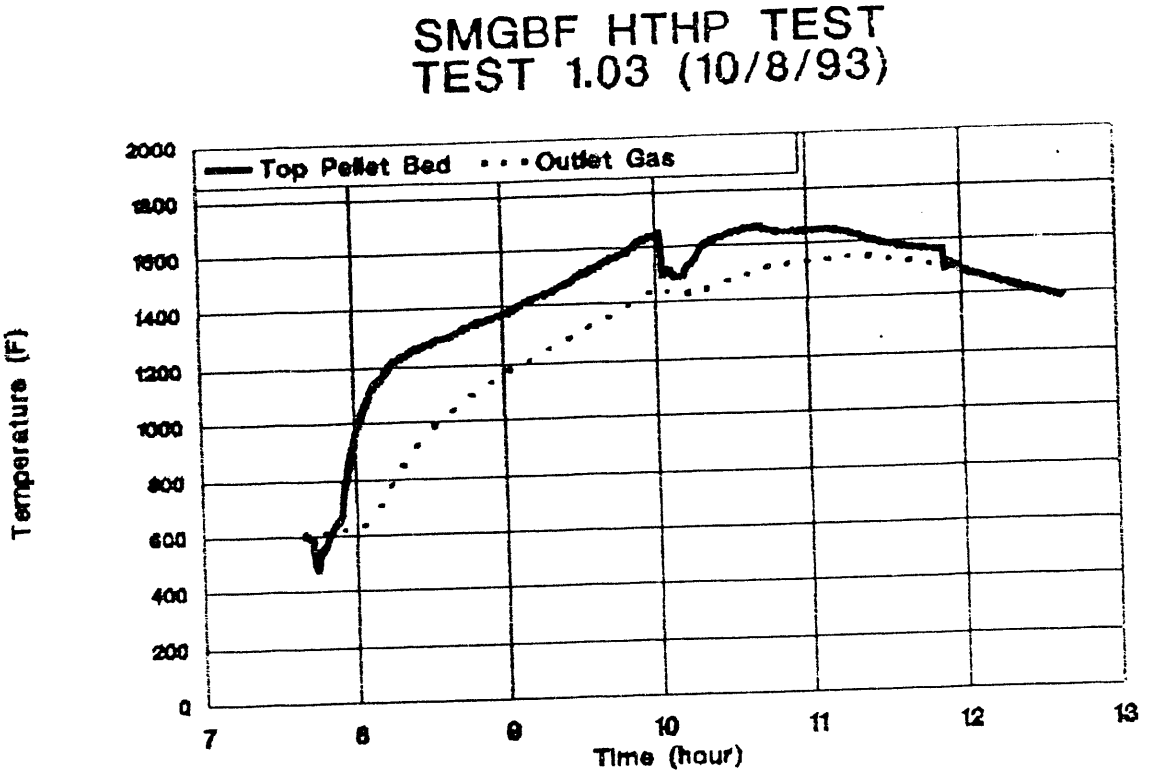


Figure C5 — Test 1.03 (10/8/93) temperatures.

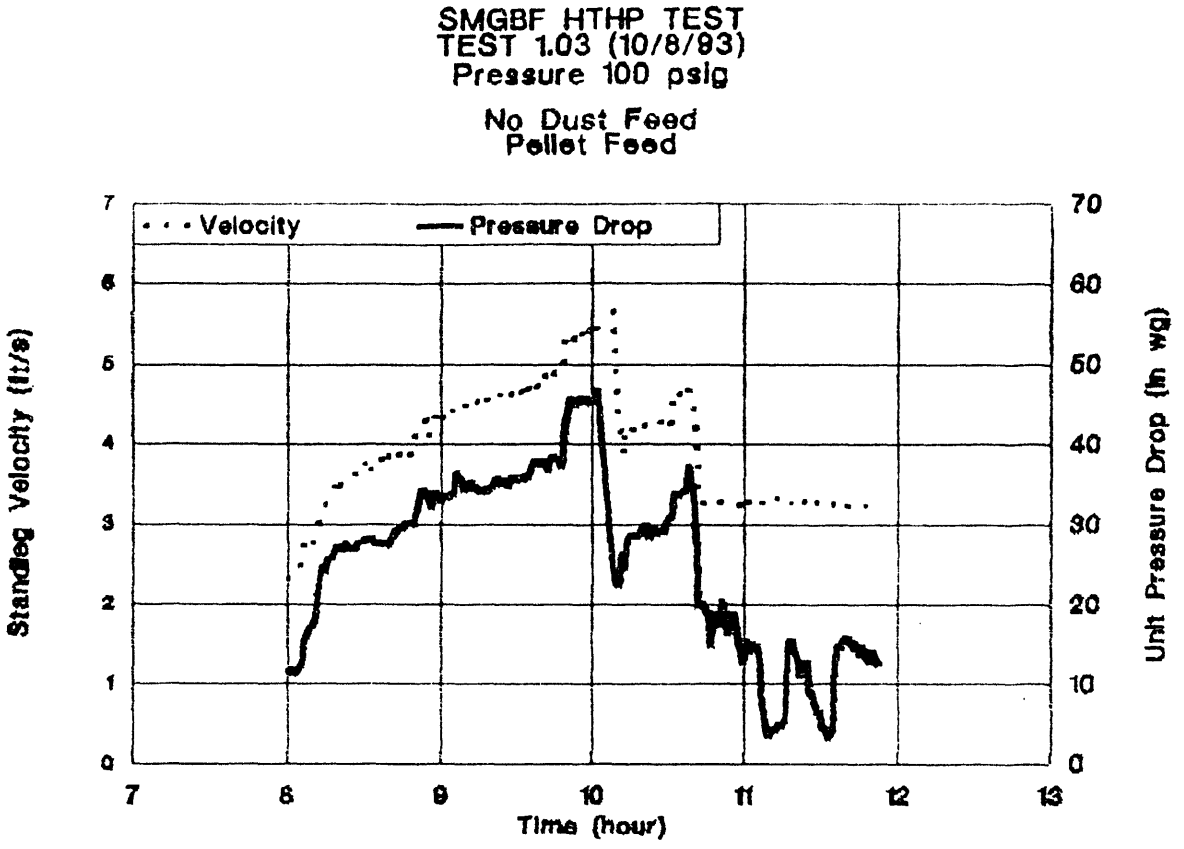


Figure C6 — Test 1.03 (10/8/93) velocity and pressure drop.

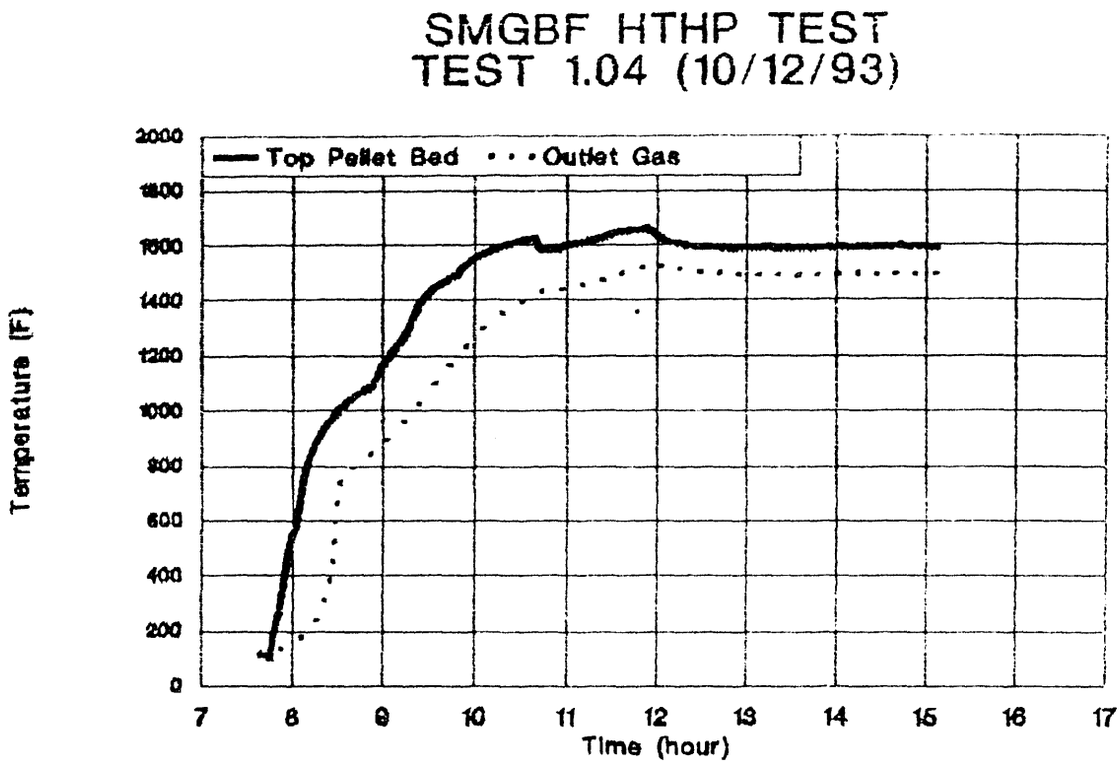


Figure C7 — Test 1.04 (10/12/93) temperatures.

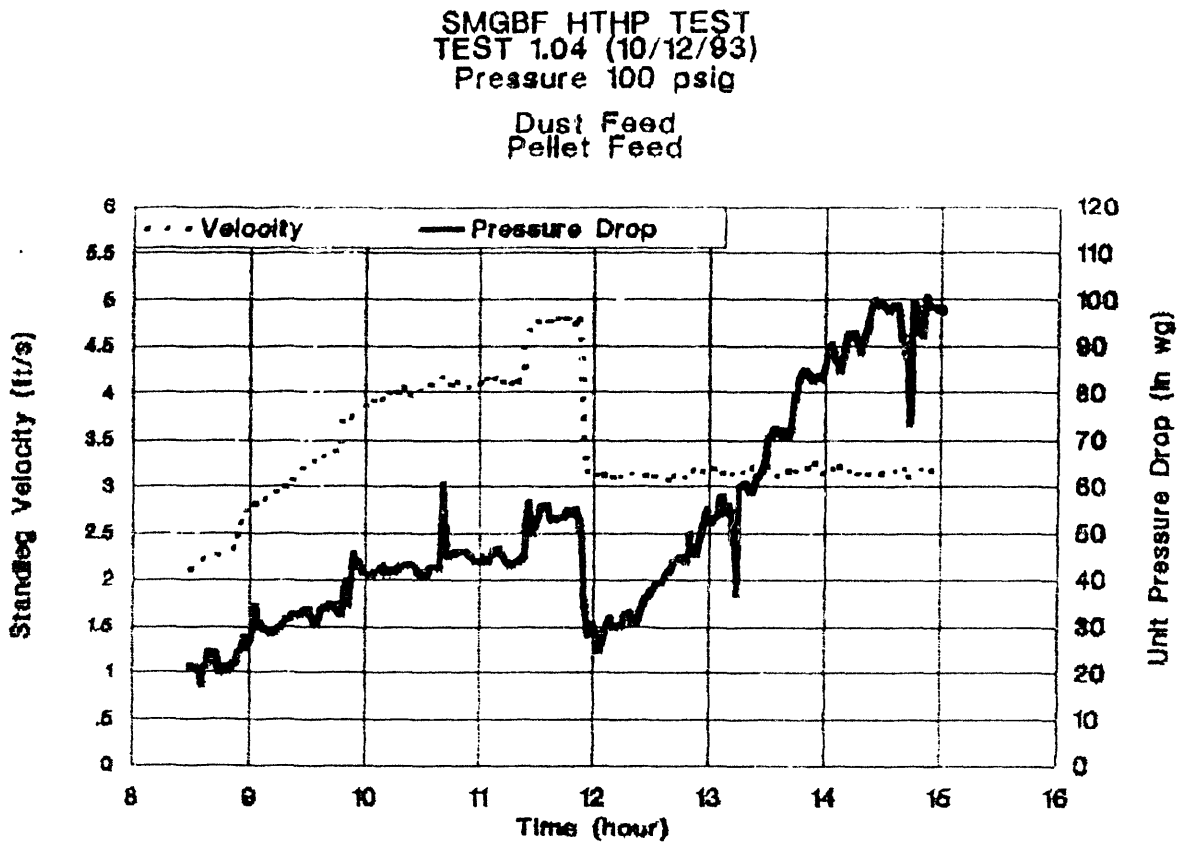


Figure C8 — Test 1.04 (10/12/93) velocity and pressure drop.

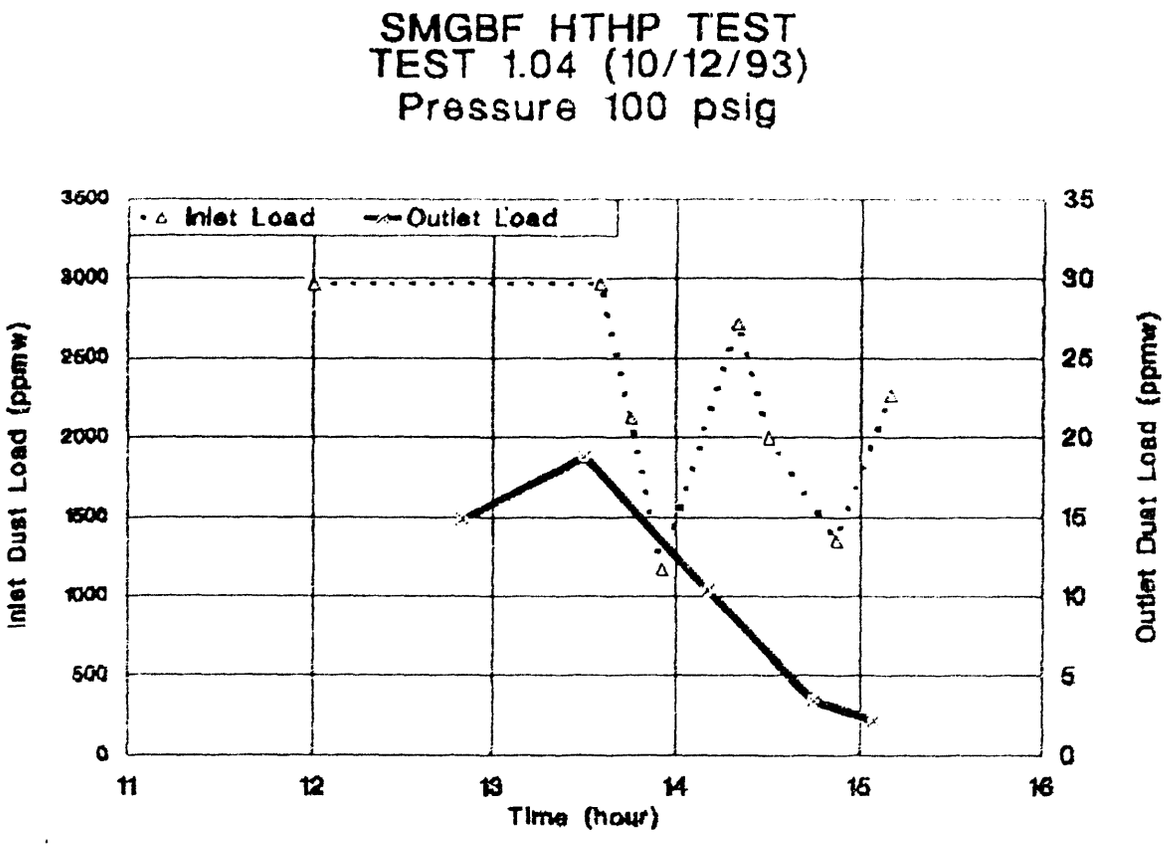


Figure C9 — Test 1.04 (10/12/93) dust loadings.

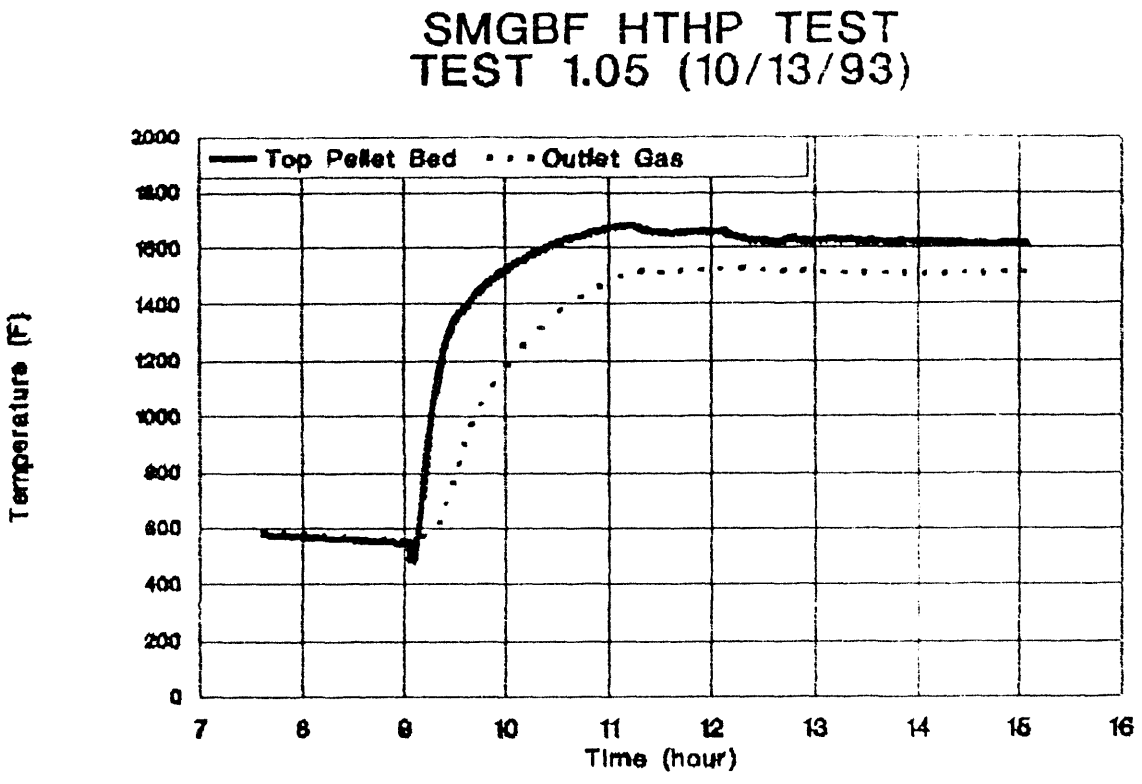


Figure C10 — Test 1.05 (10/13/93) temperatures.

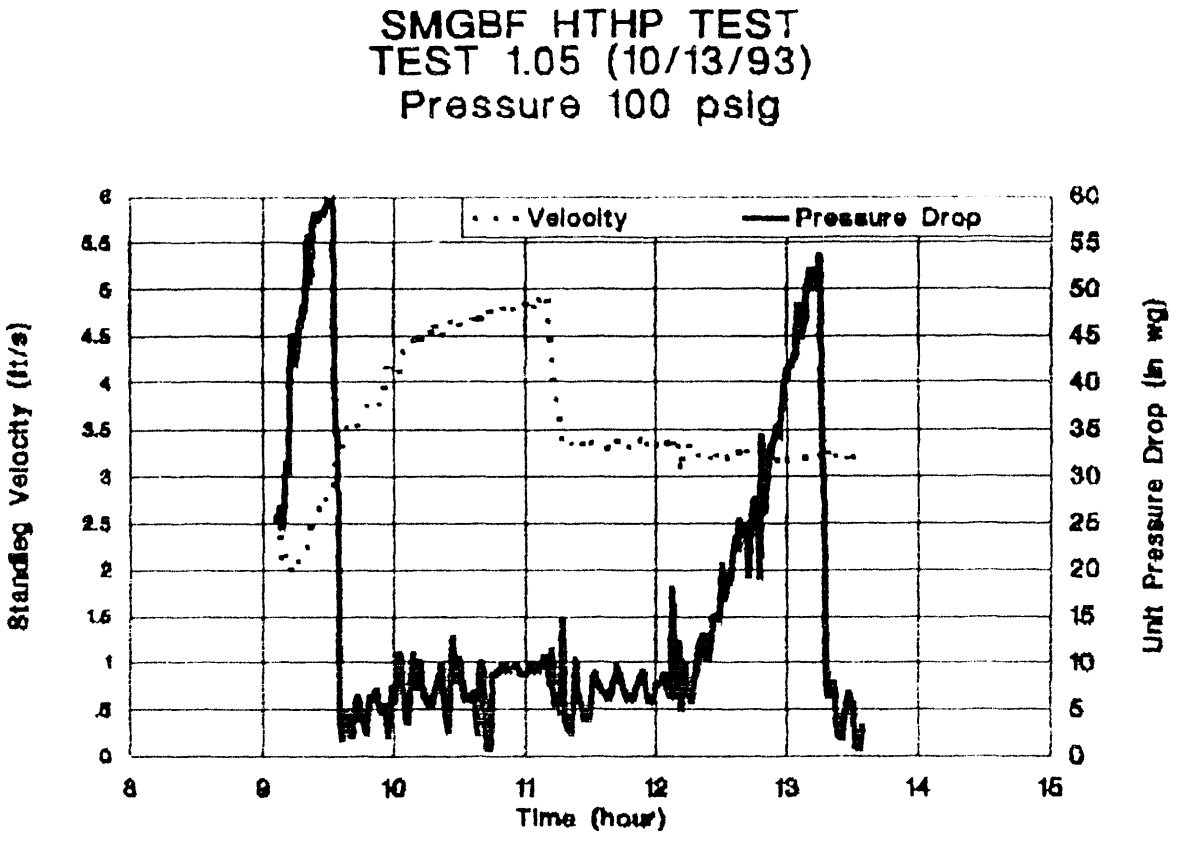


Figure C11 — Test 1.05 (10/13/93) velocity and pressure drop.

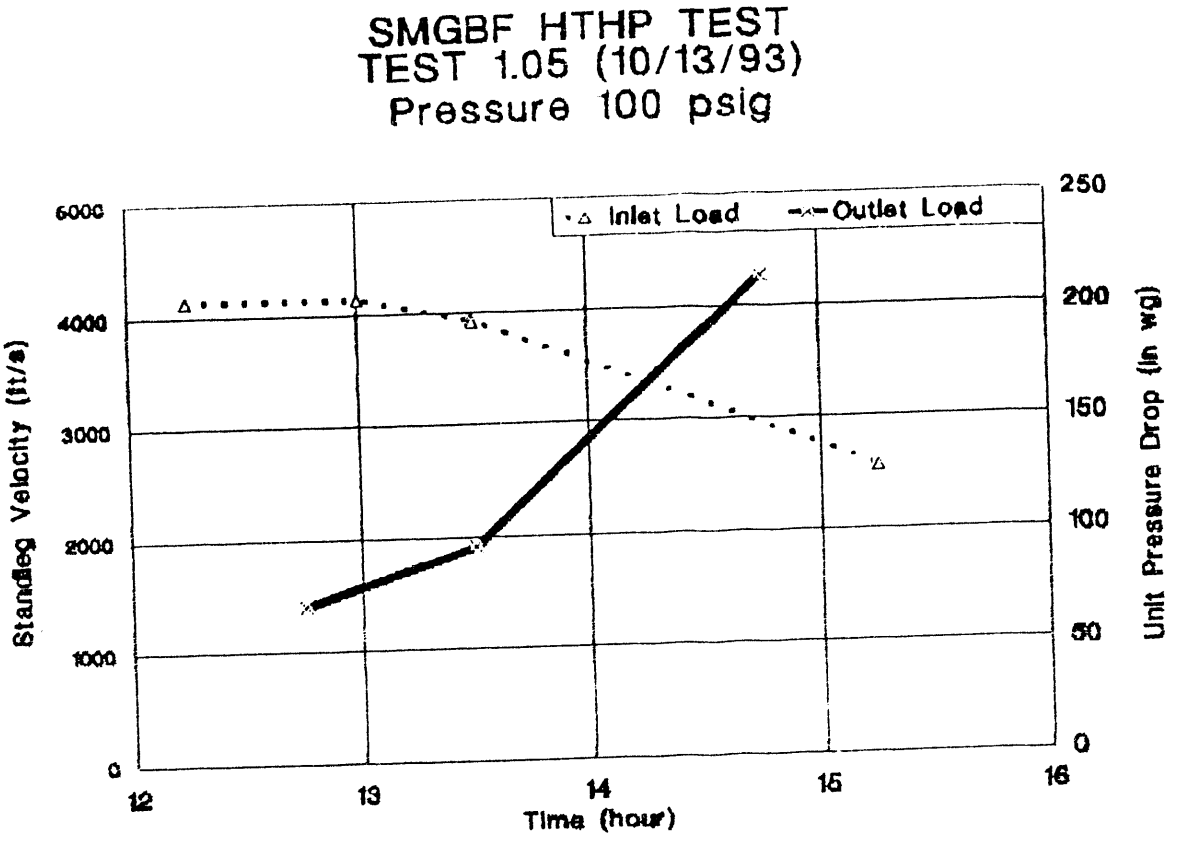


Figure C12 — Test 1.05 (10/13/93) velocity and pressure drop.

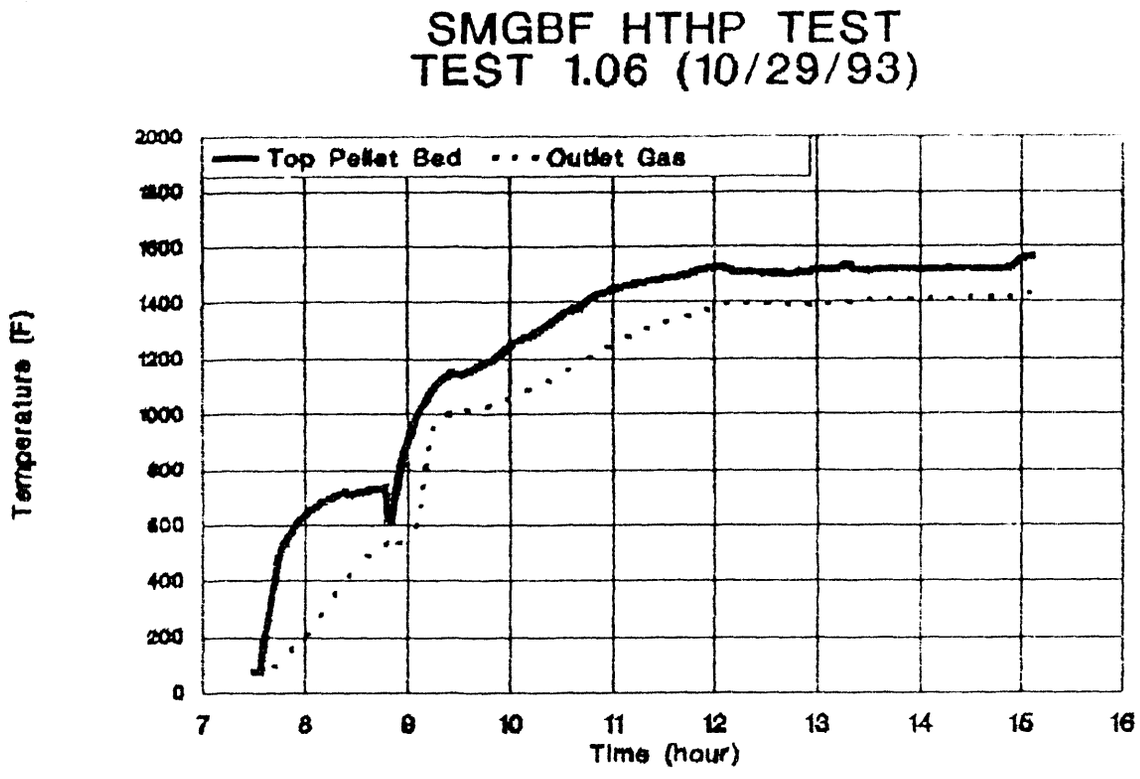


Figure C13 — Test 1.06 (10/29/93) temperatures.

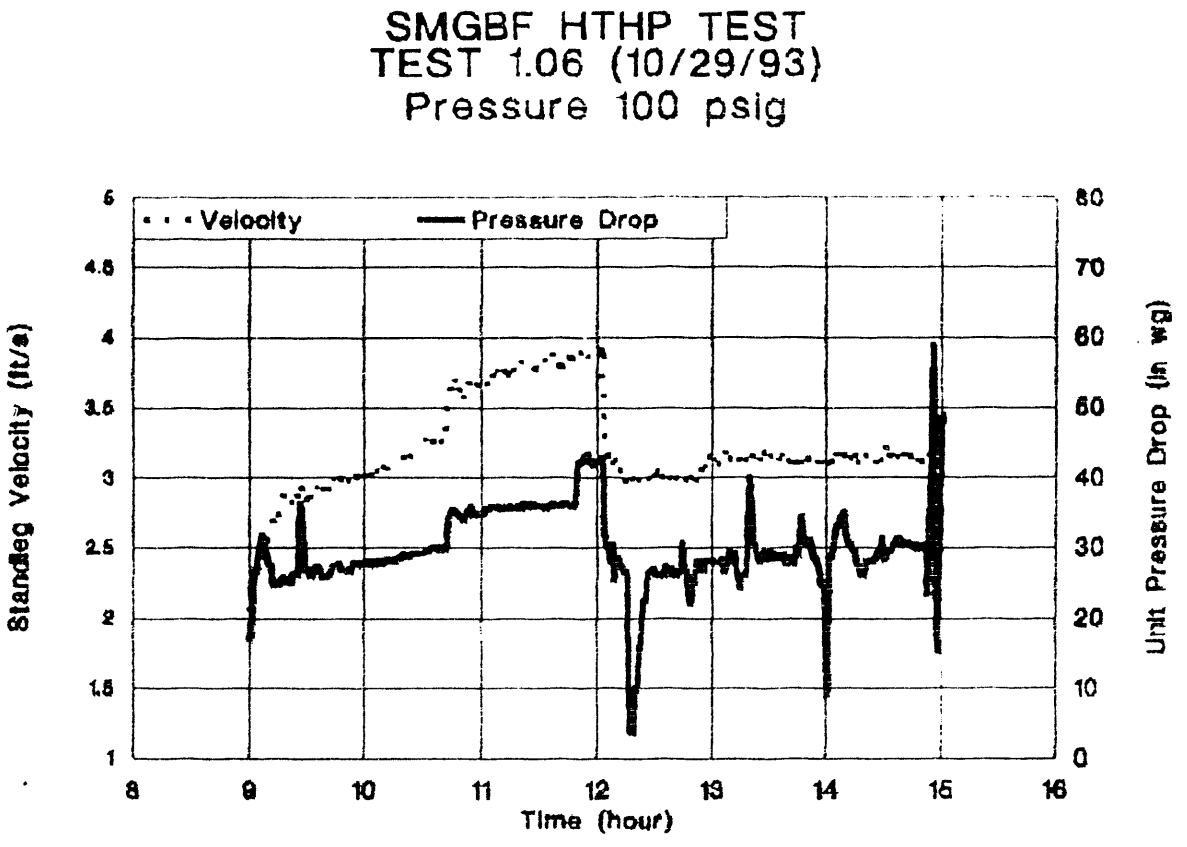


Figure C14 — Test 1.06 (10/29/93) velocity and pressure drop.

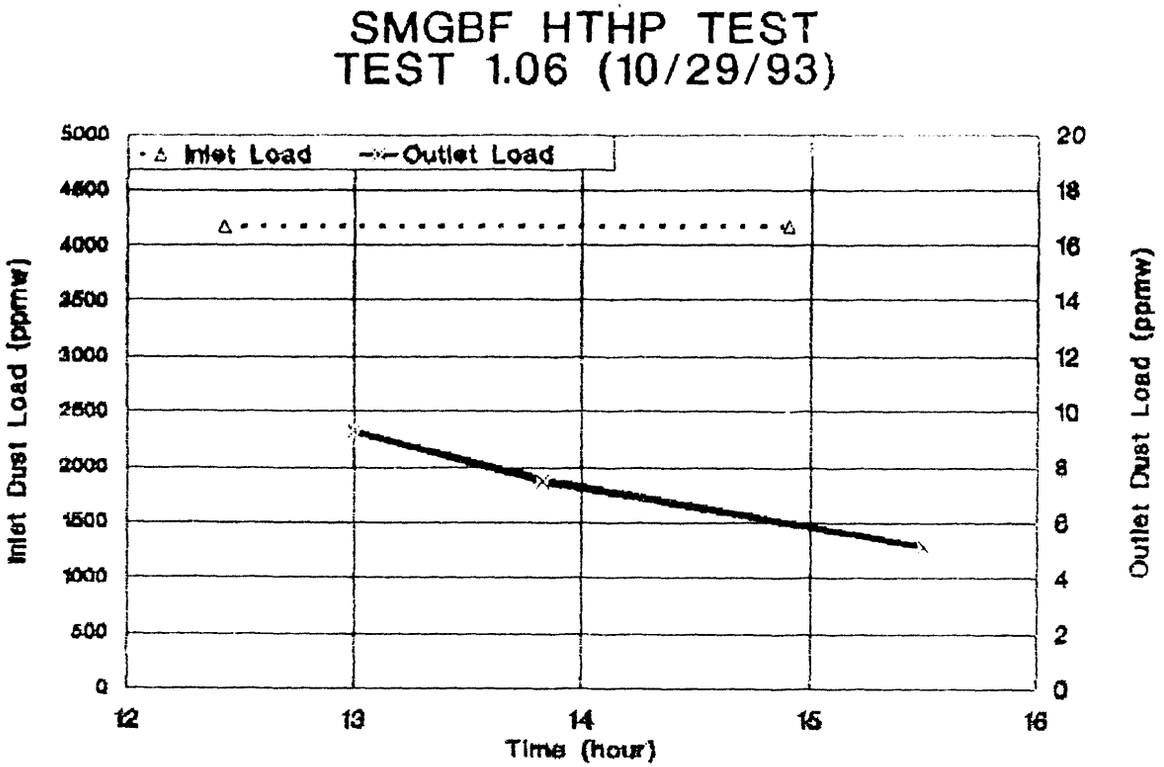


Figure C15 — Test 1.06 (10/29/93) dust loads.

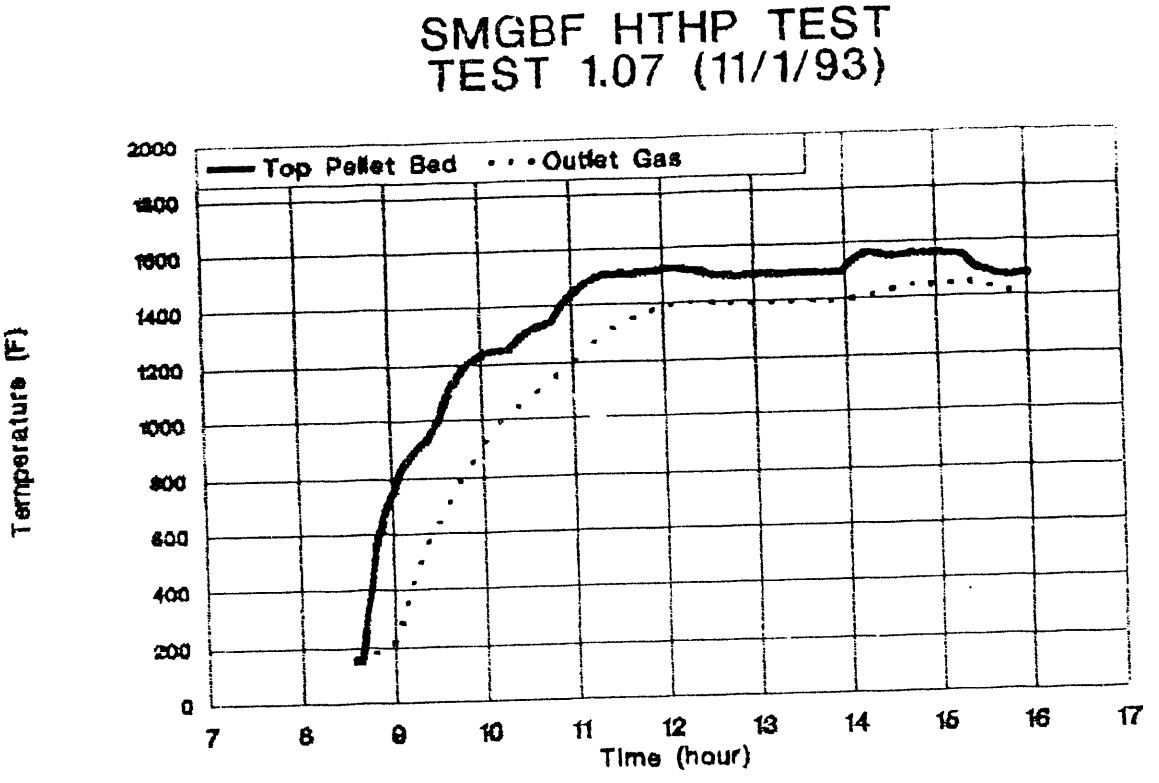


Figure C16 — Test 1.07 (11/1/93) temperatures.

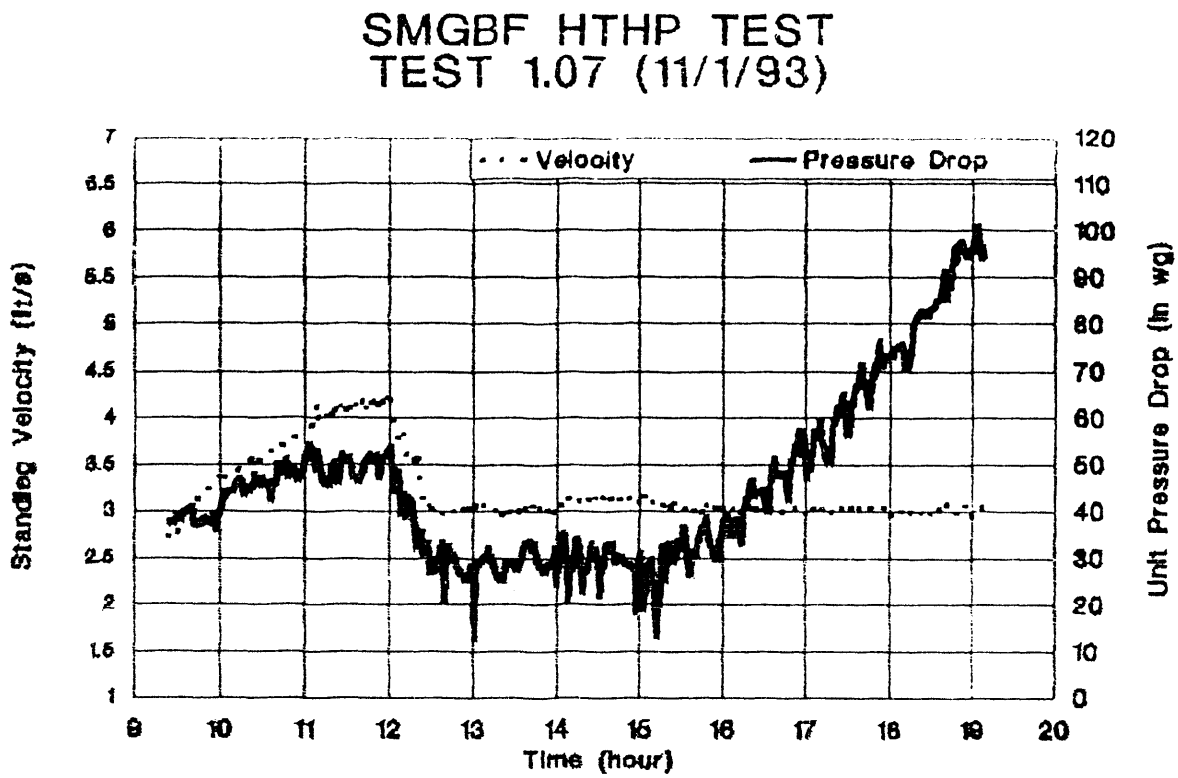


Figure C17 — Test 1.07 (11/1/93) velocity and pressure drop.

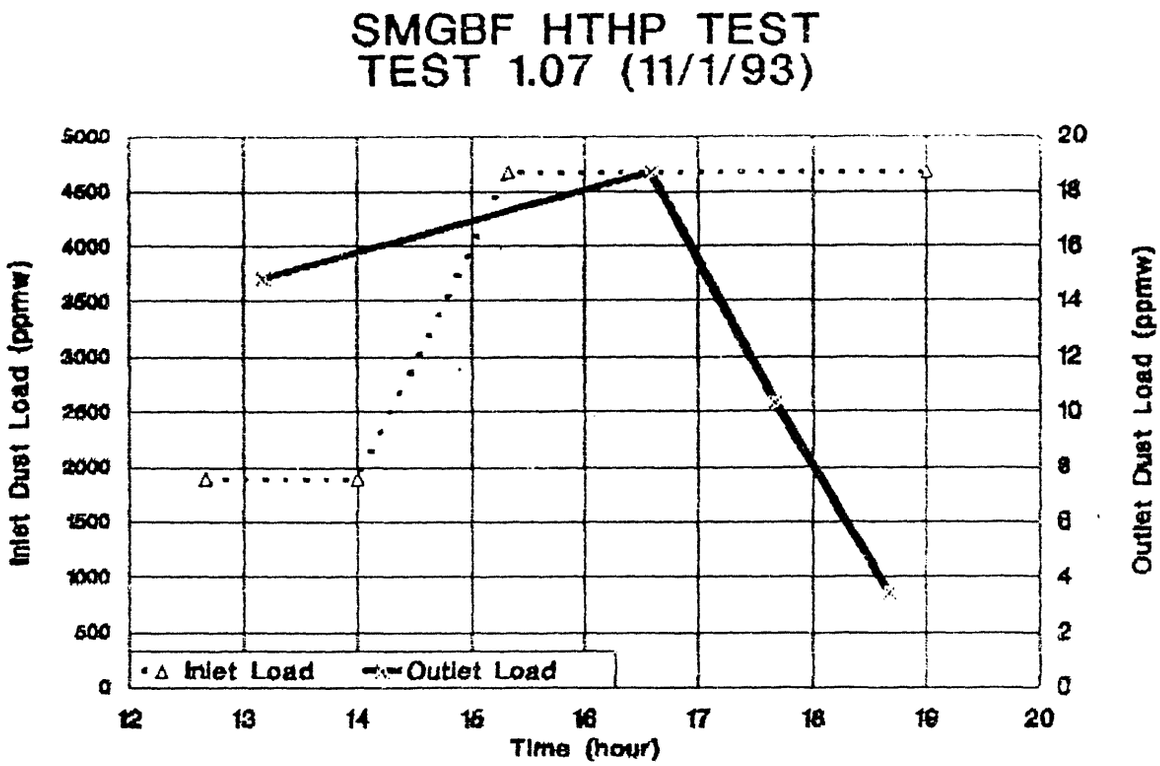


Figure C18 — Test 1.07 (11/1/93) dust loads.

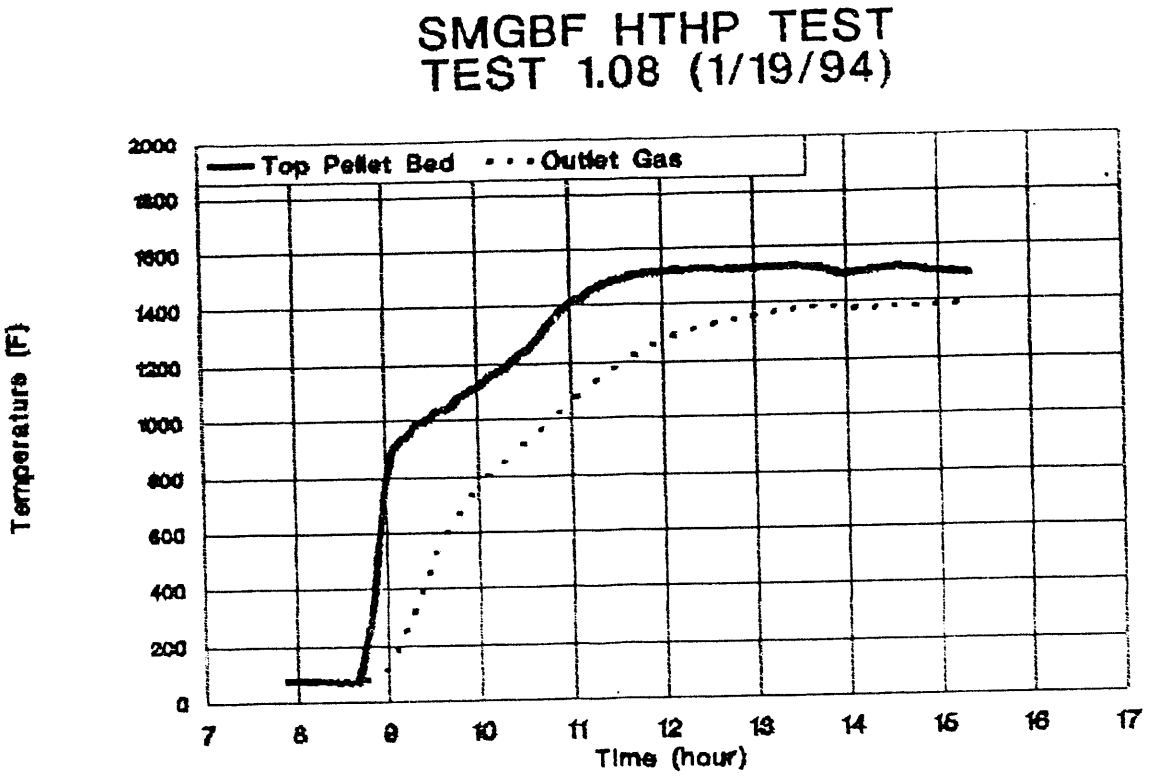


Figure C19 — Test 1.08 (1/19/94) temperatures.

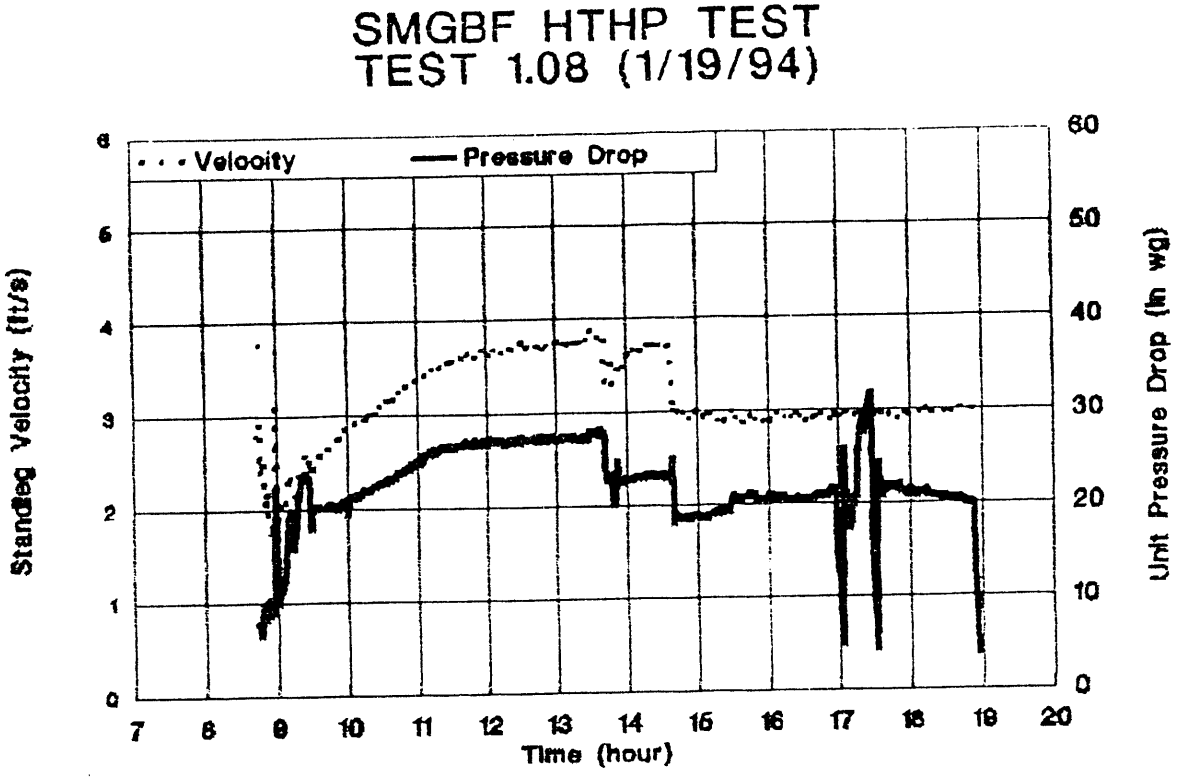


Figure C20 — Test 1.08 (1/19/94) velocity and pressure drop.

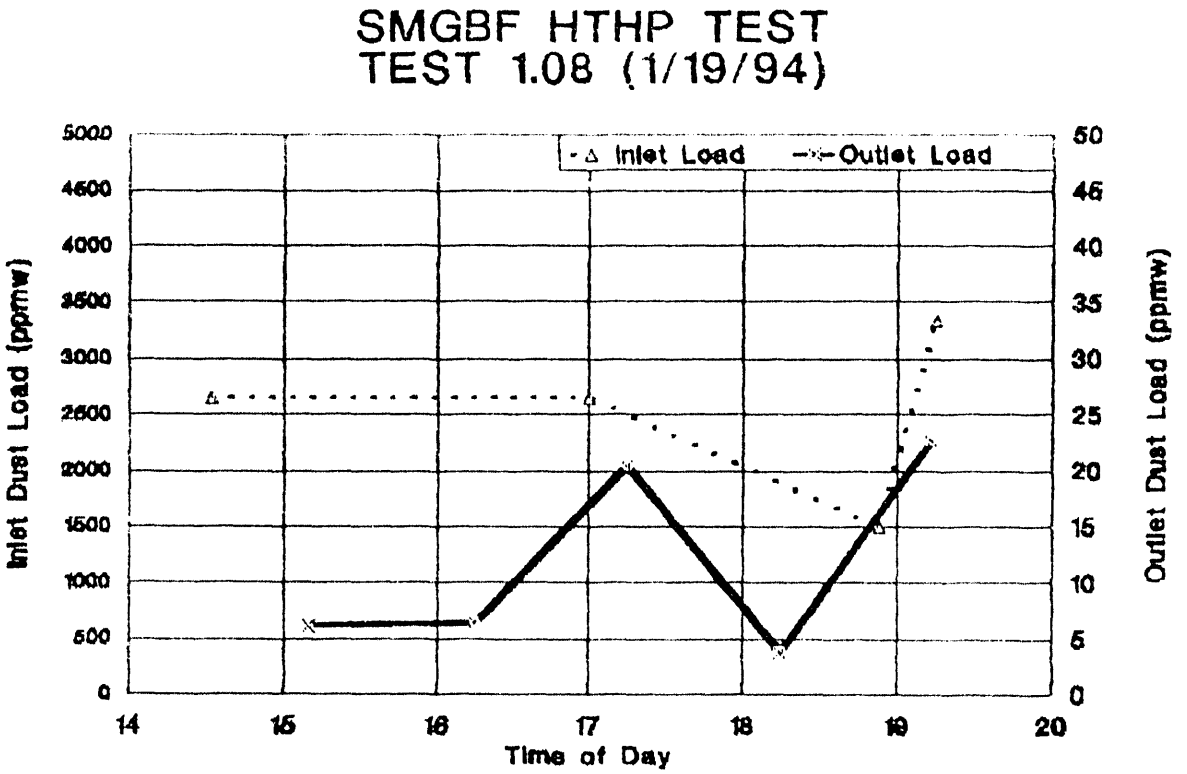


Figure C21 — Test 1.08 (1/19/94) dust loads.

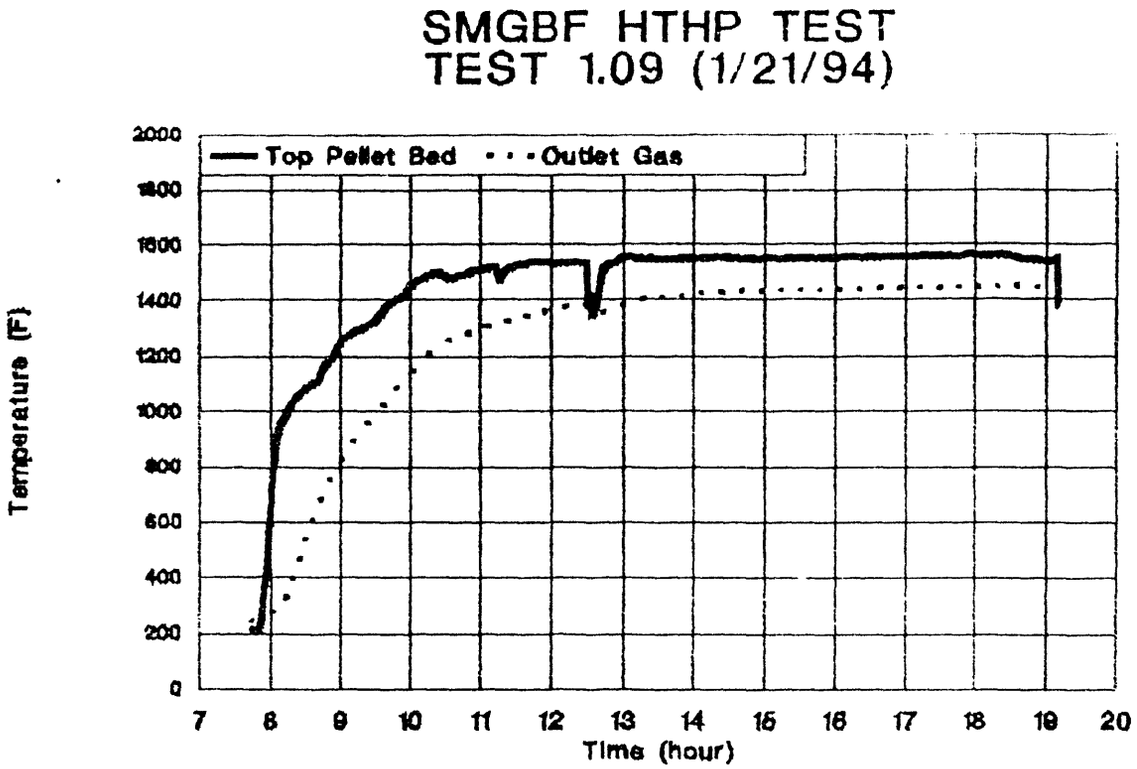


Figure C22 — Test 1.09 (1/21/94) temperatures.

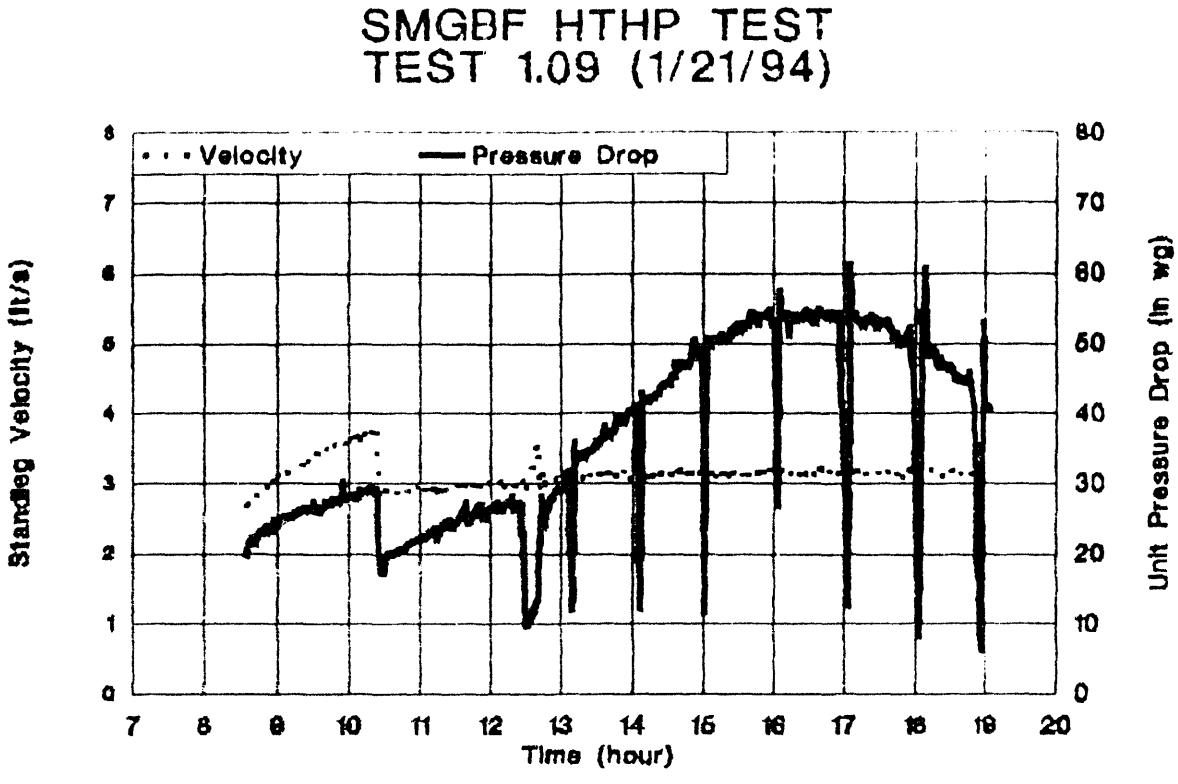


Figure C23 — Test 1.09 (1/21/94) velocity and pressure drop.

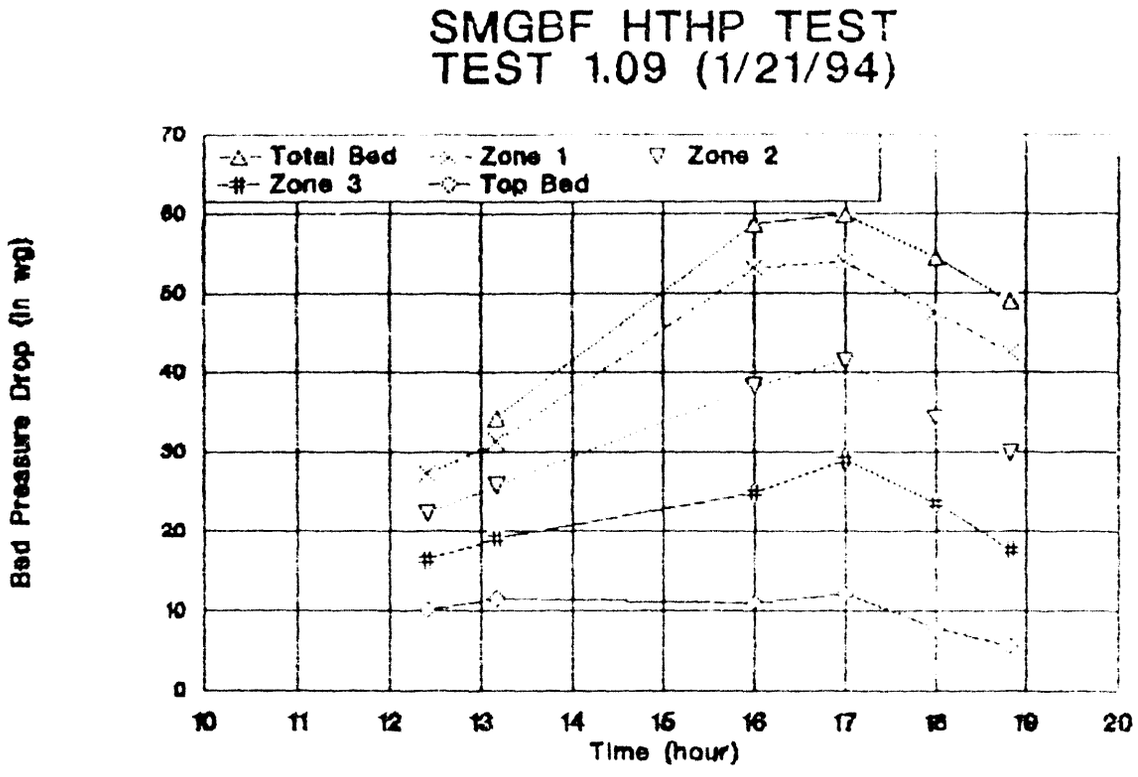


Figure C24 — Test 1.09 (1/21/94) pressure drop profiles.

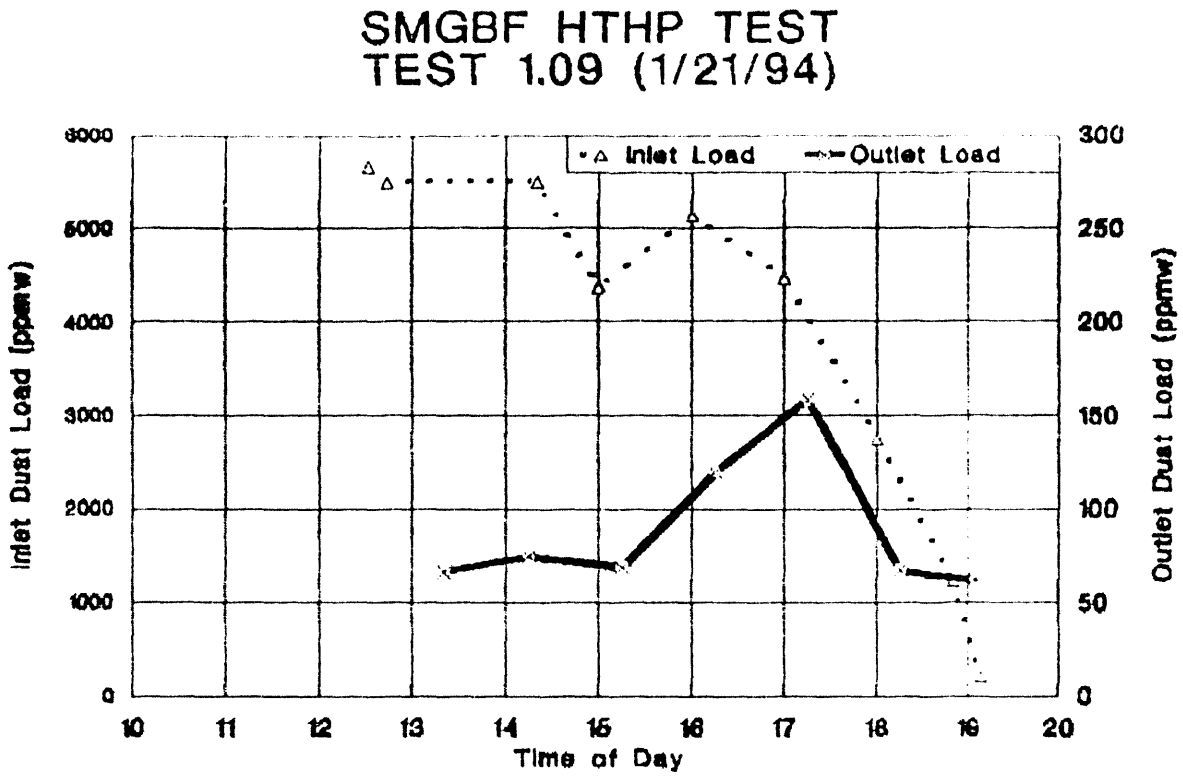


Figure C25 — Test 1.09 (1/21/94) dust loads.

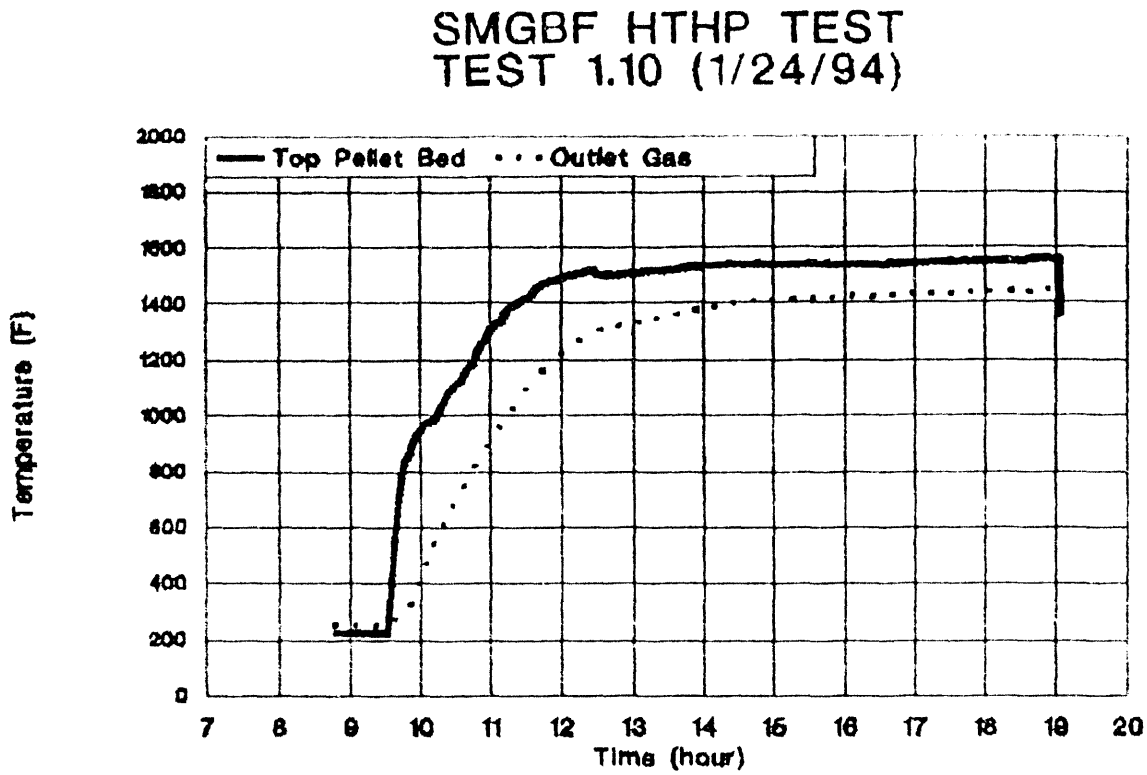


Figure C26 — Test 1.10 (1/24/94) temperatures.

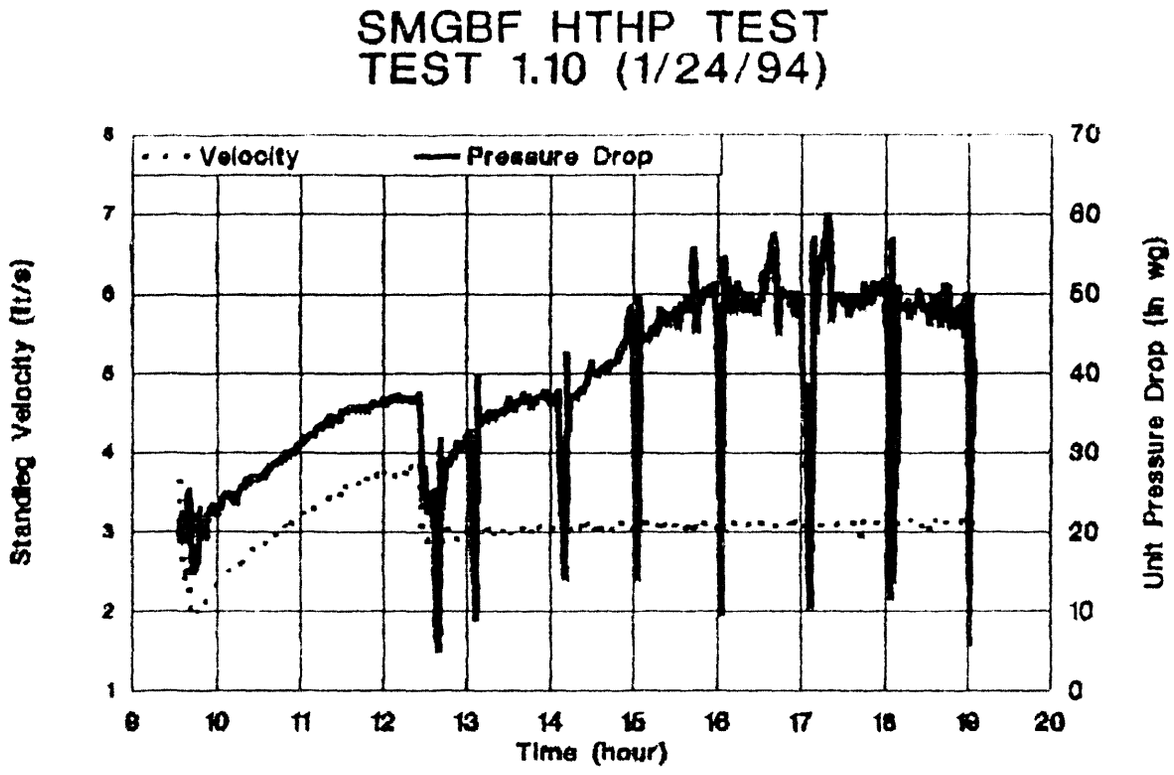


Figure C27 — Test 1.10 (1/24/94) velocity and pressure drop.

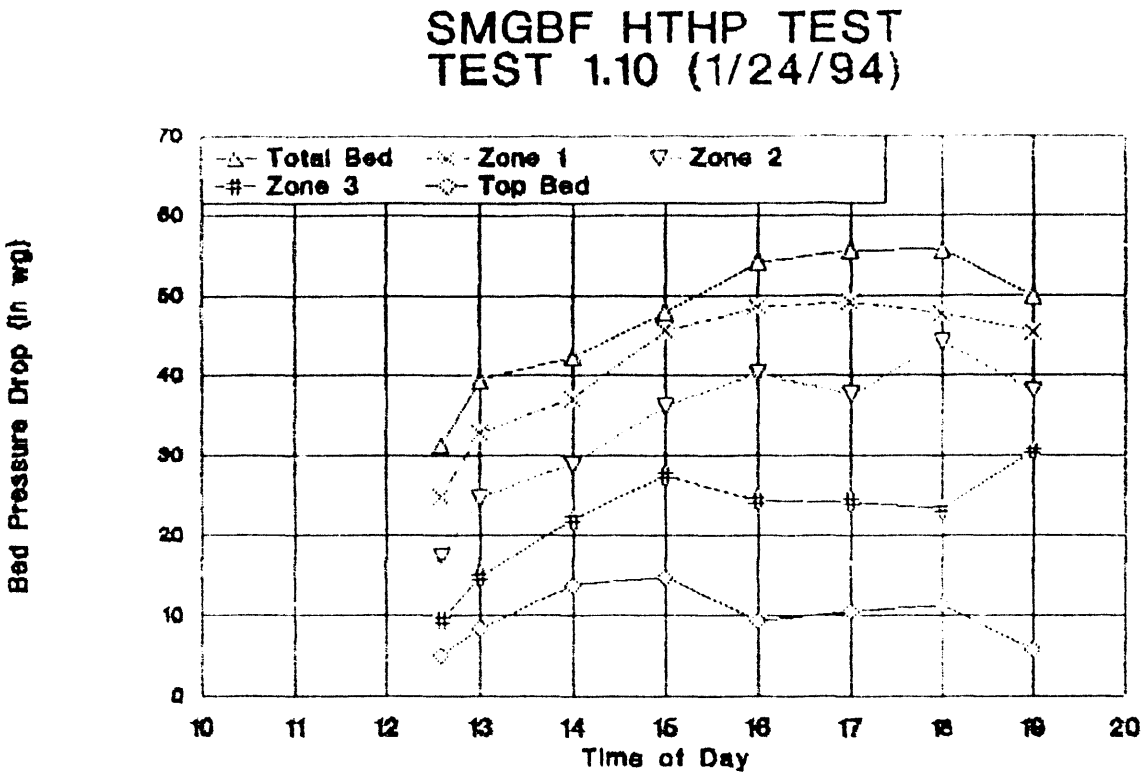


Figure C28 — Test 1.10 (1/24/94) pressure drop profiles.

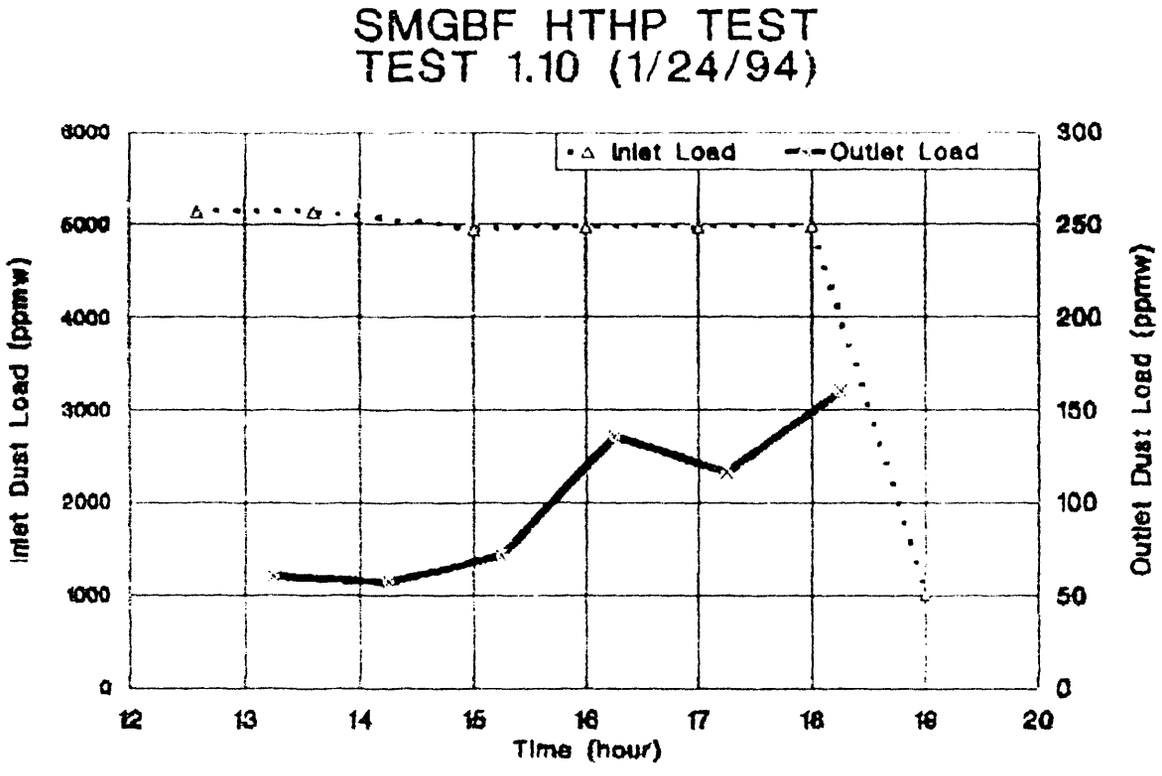


Figure C29 — Test 1.10 (1/24/94) dust loads.

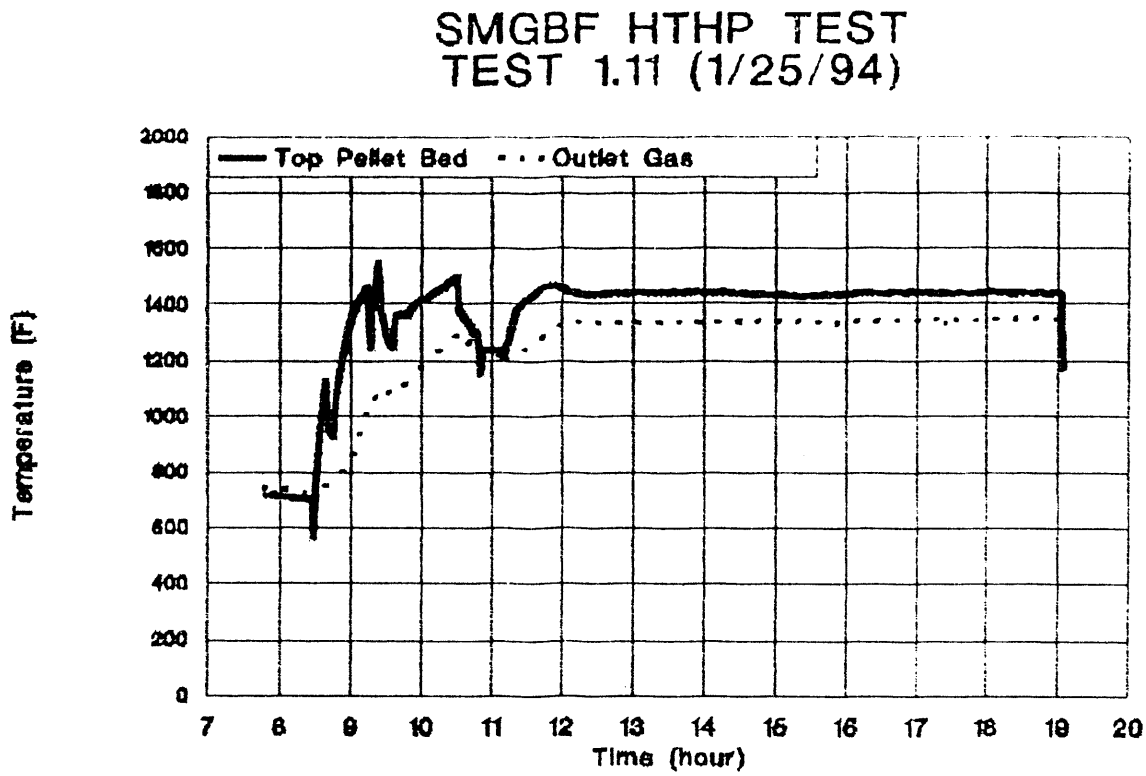


Figure C30 — Test 1.11 (1/25/94) temperatures.

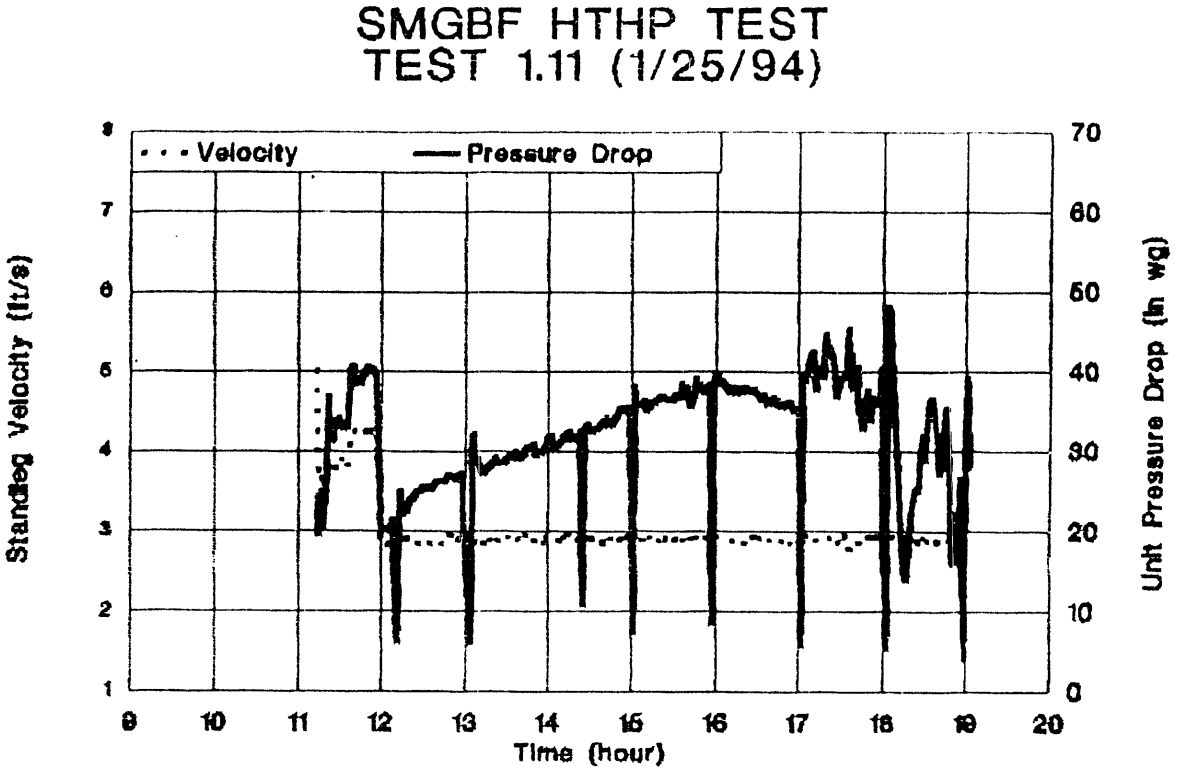


Figure C31 — Test 1.11 (1/25/94) velocity and pressure drop.

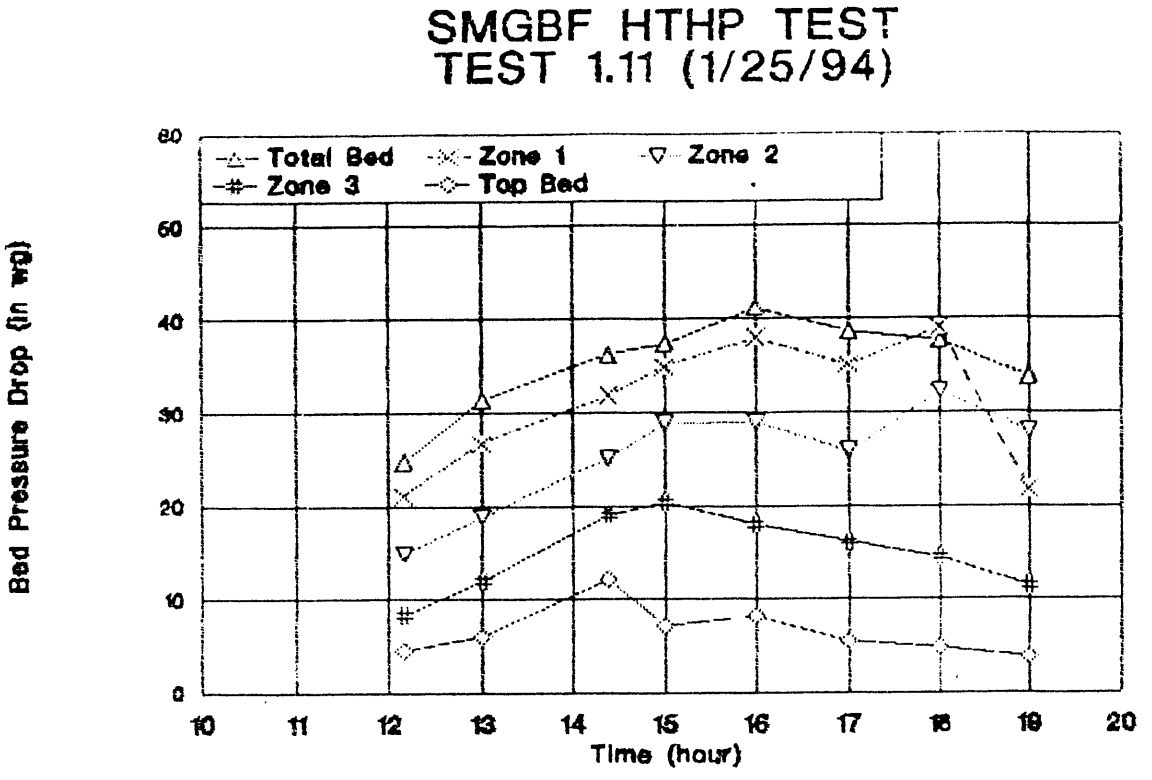


Figure C32 — Test 1.11 (1/25/94) pressure drop profiles.

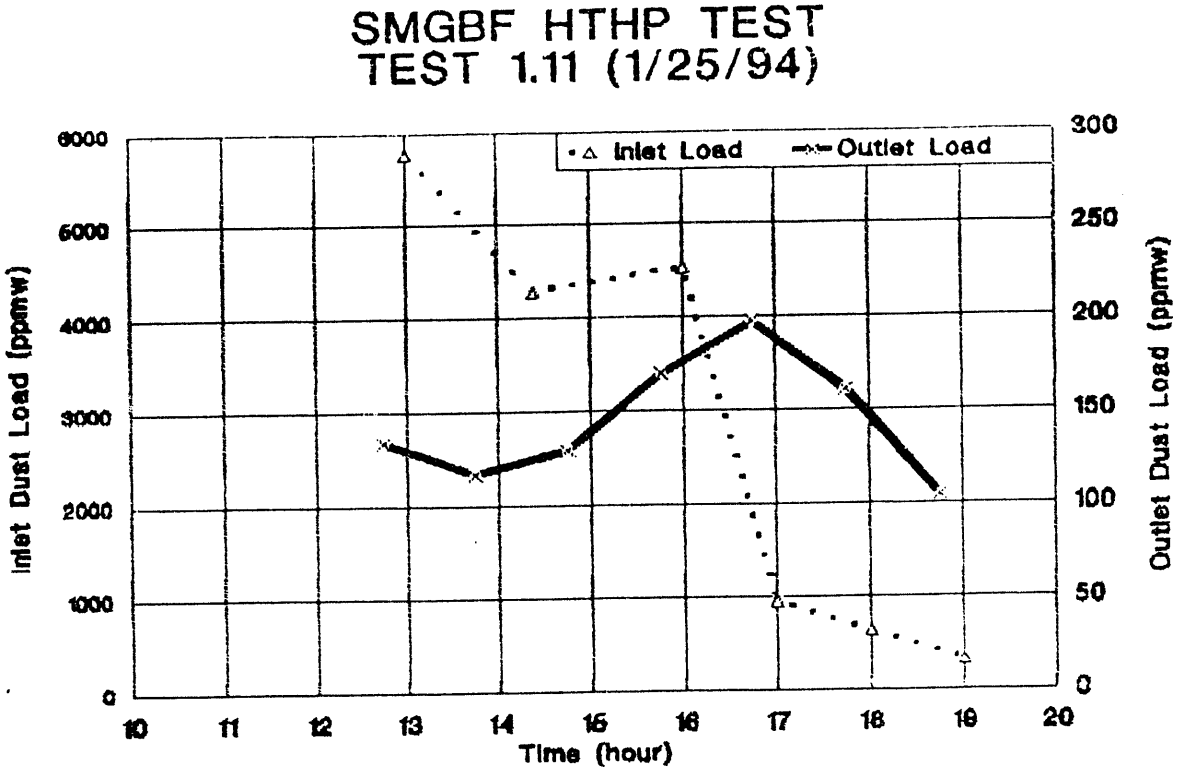


Figure 33 — Test 1.11 (1/25/94) dust loads.

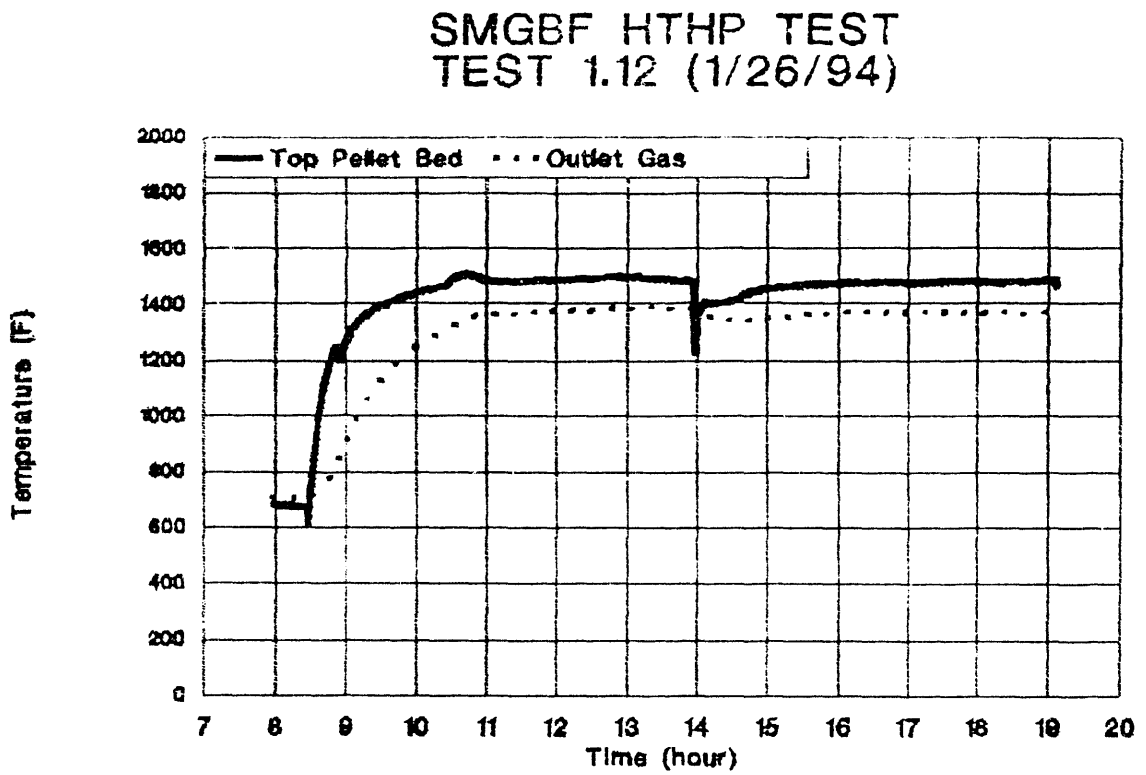


Figure C34 — Test 1.12 (1/26/94) temperatures.

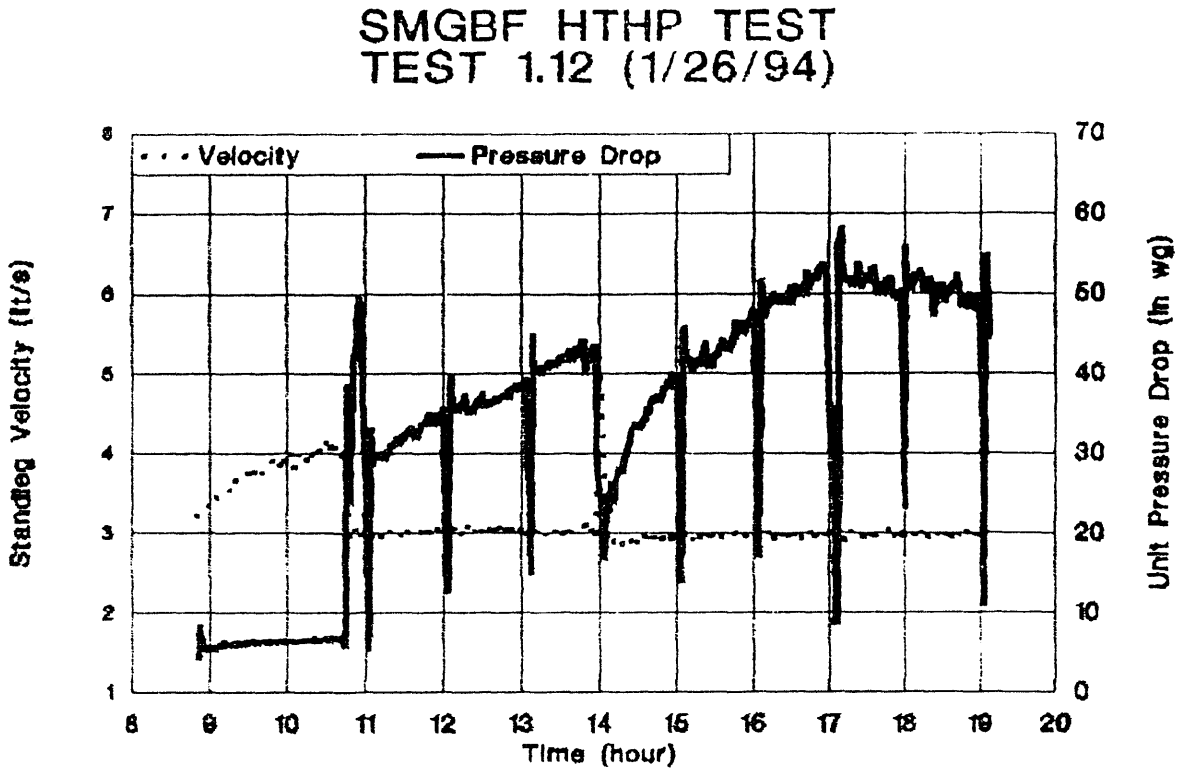


Figure C35 — Test 1.12 (1/26/94) velocity and pressure drop.

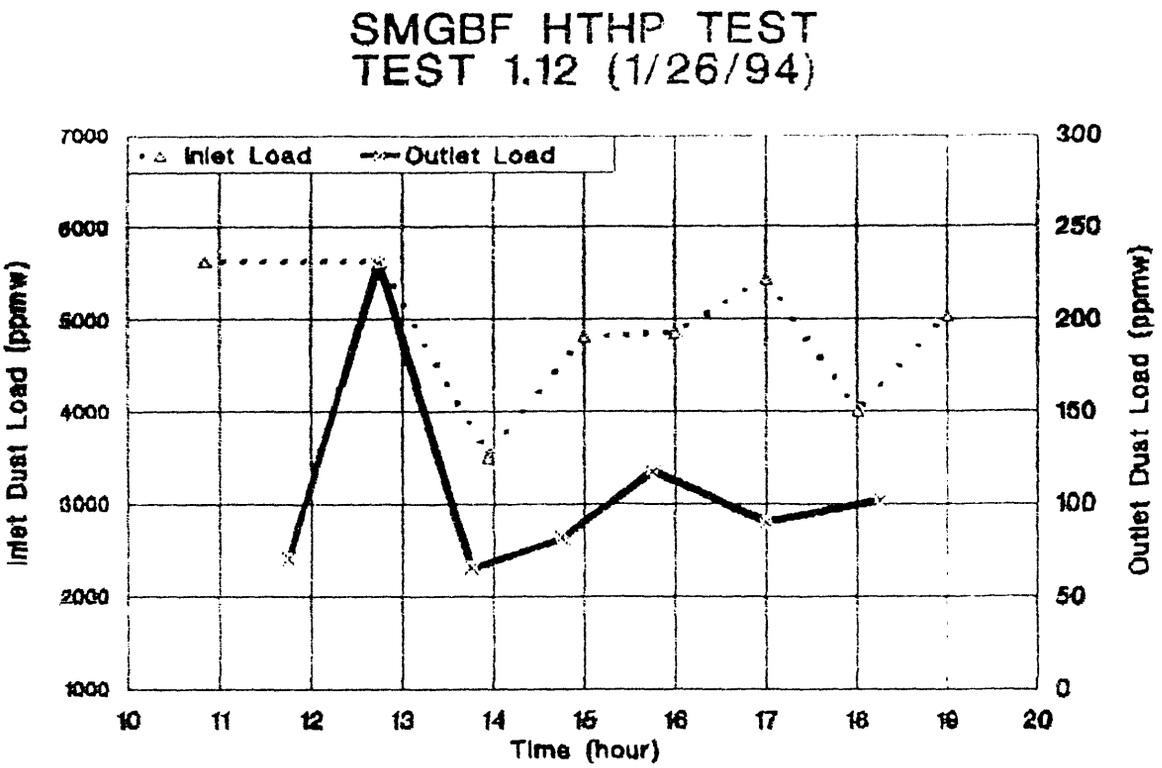


Figure C36 — Test 1.12 (1/26/94) dust loads.

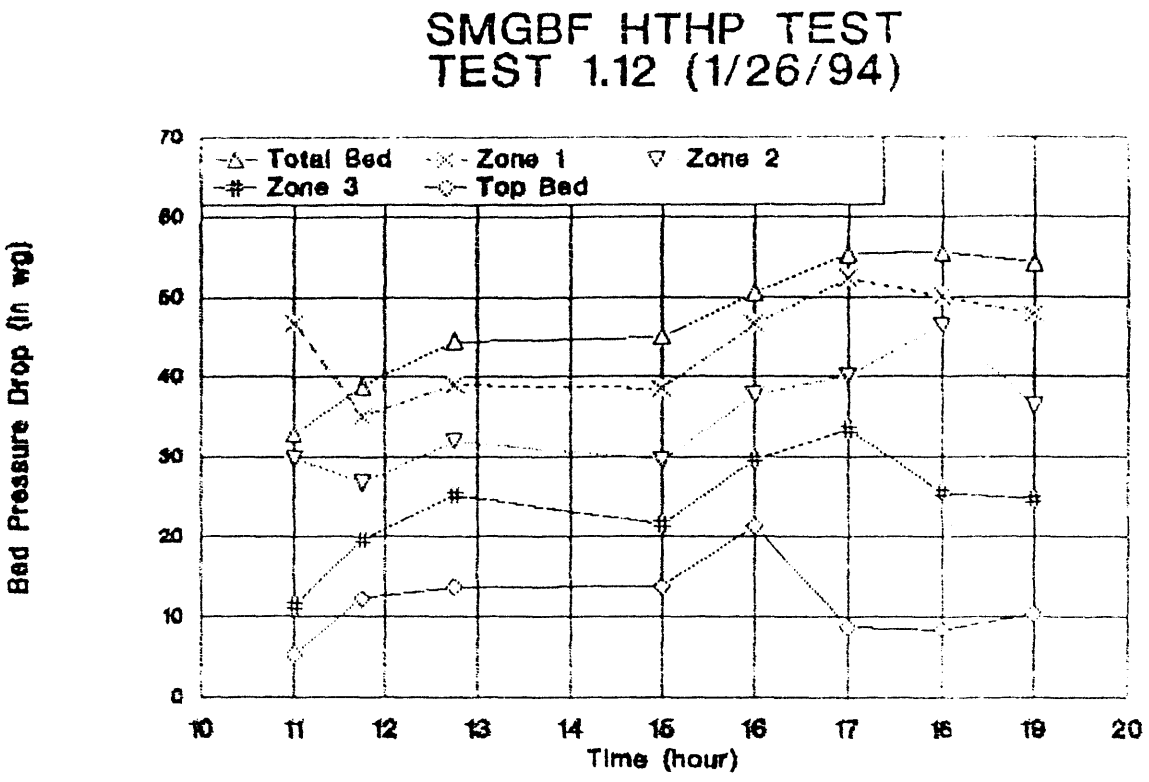


Figure C37 — Test 1.12 (1/26/94) pressure drop profiles.

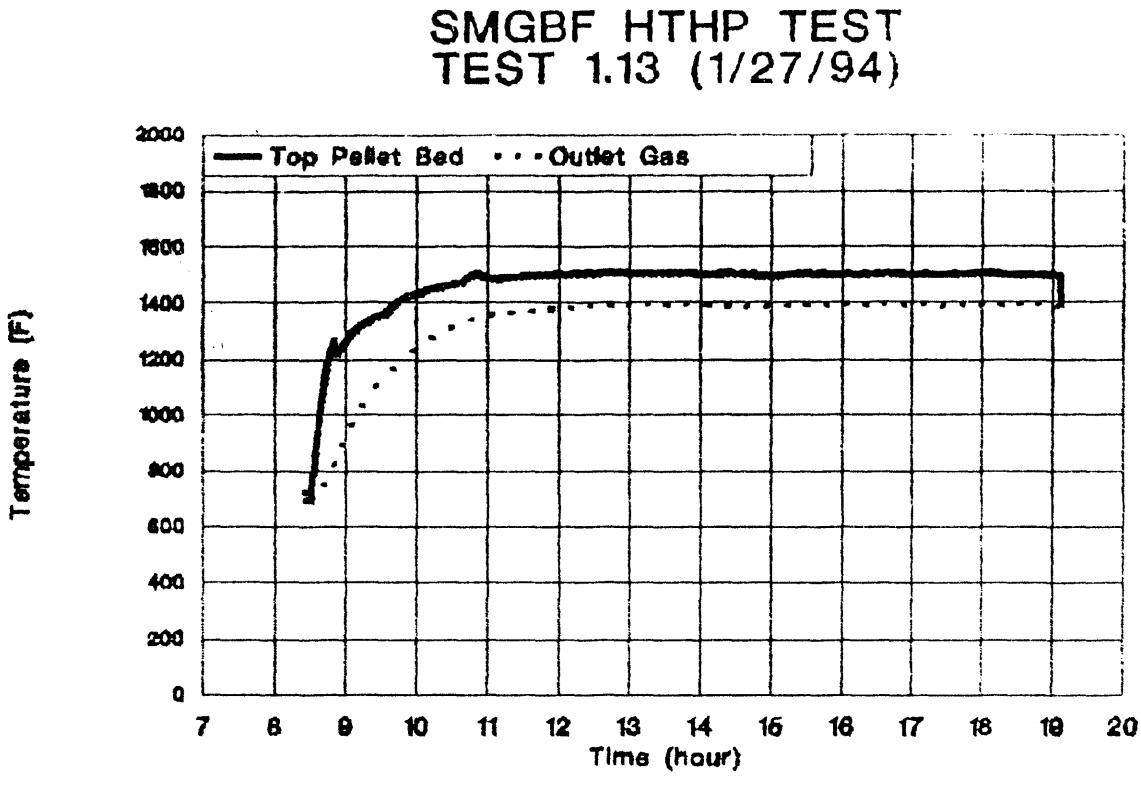


Figure C38 — Test 1.13 (1/27/94) temperatures.

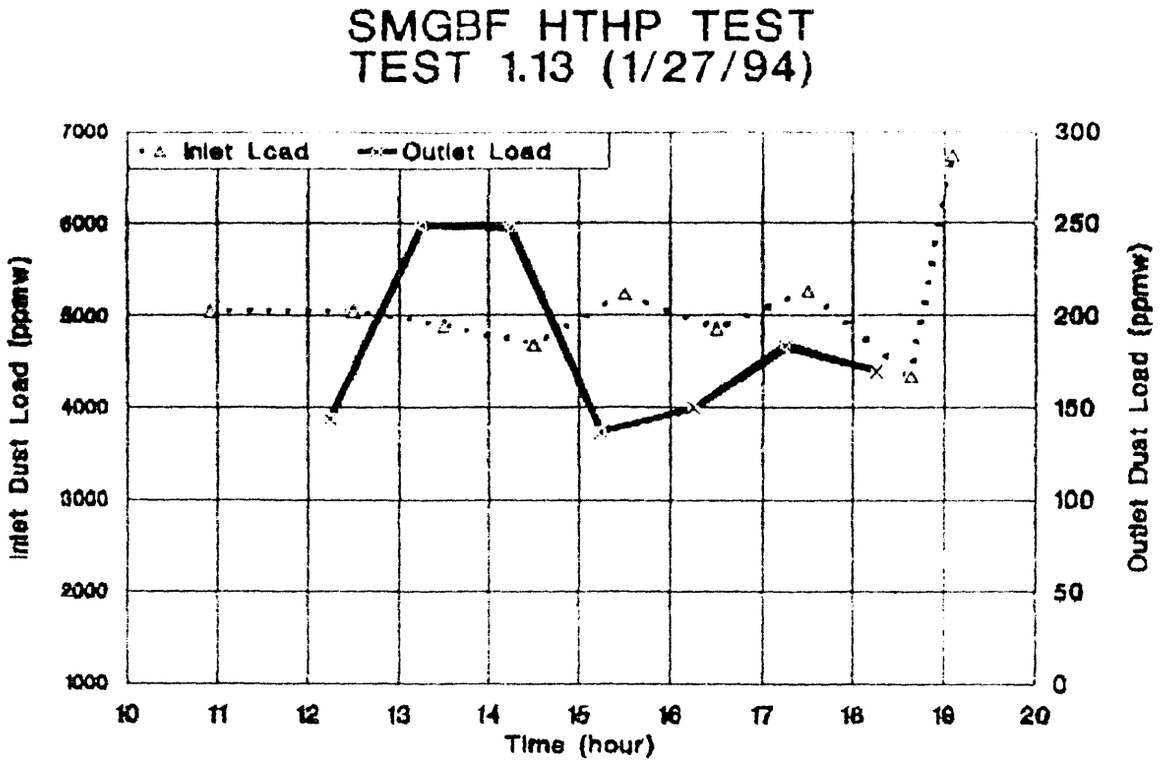


Figure C39 — Test 1.13 (1/27/94) velocity and pressure drop.

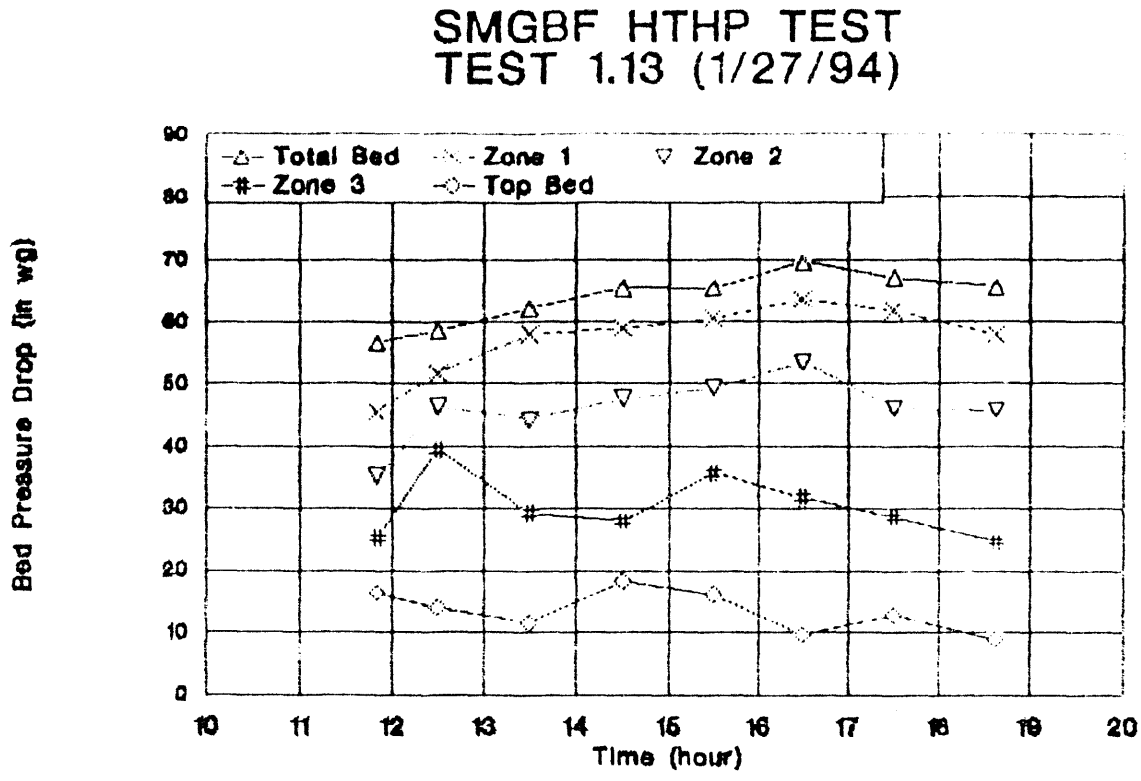


Figure C40 — Test 1.13 (1/27/94) dust loads.

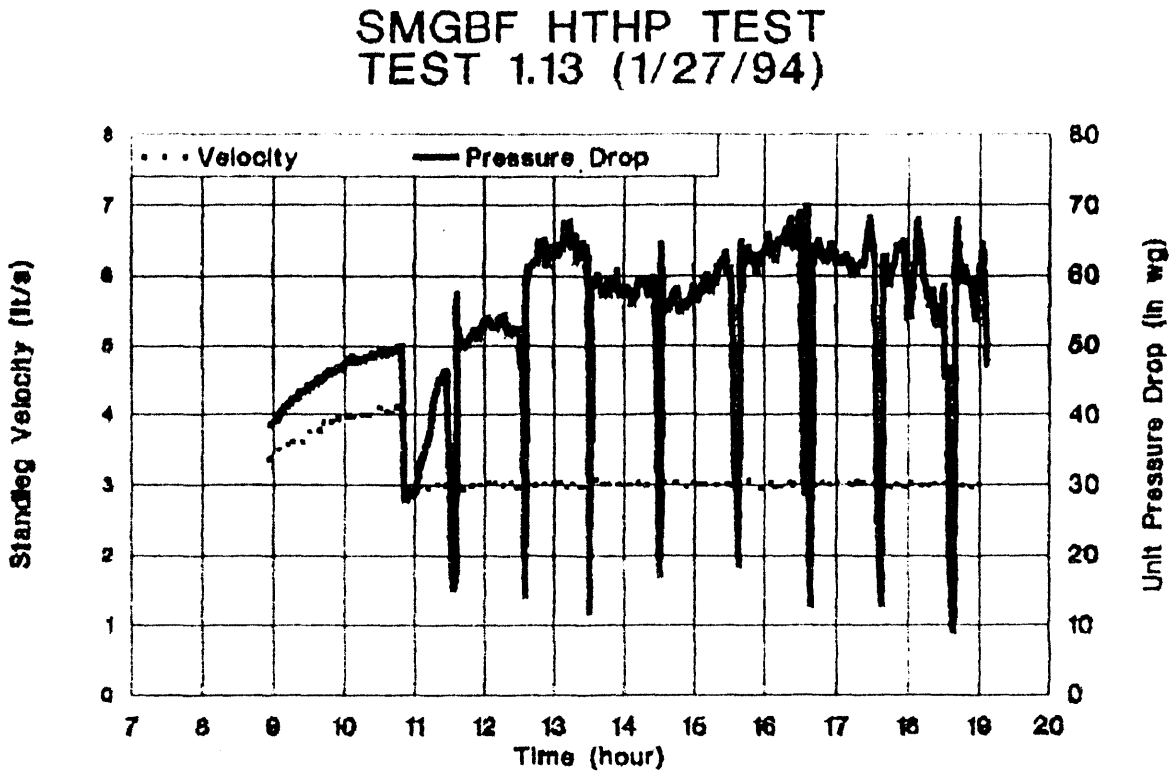


Figure C41 — Test 1.13 (1/27/94) pressure drop profiles.

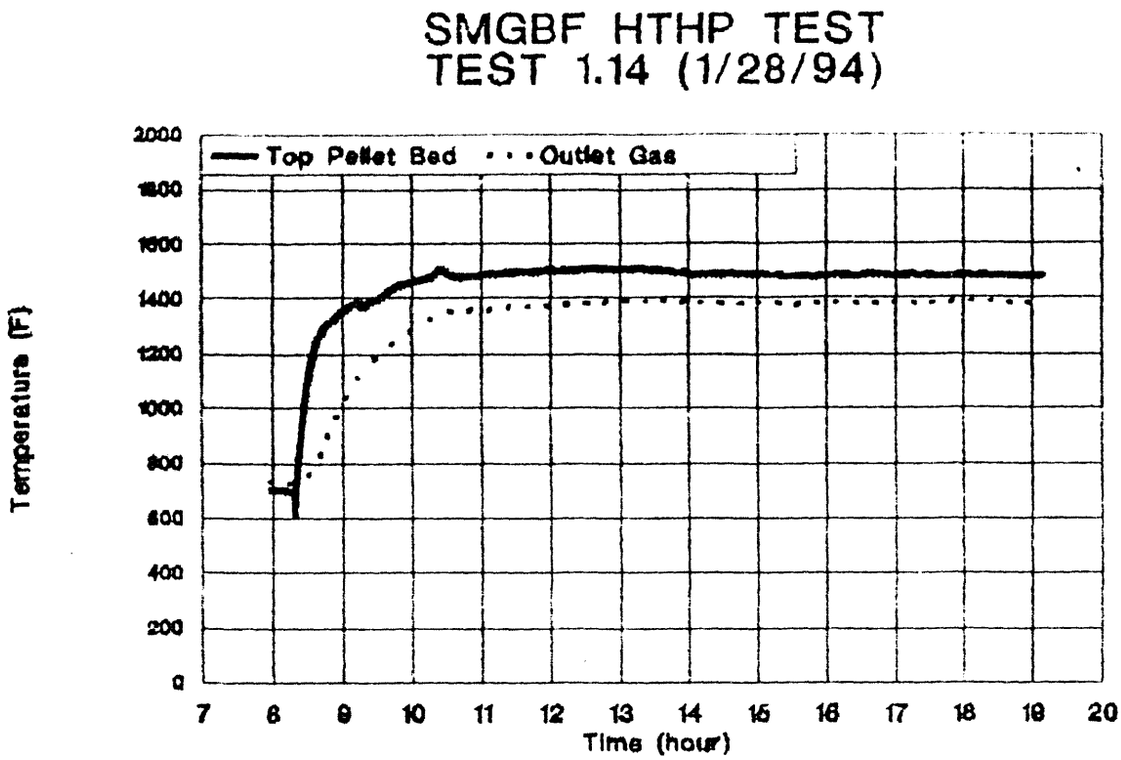


Figure C42 — Test 1.14 (1/28/94) temperatures.

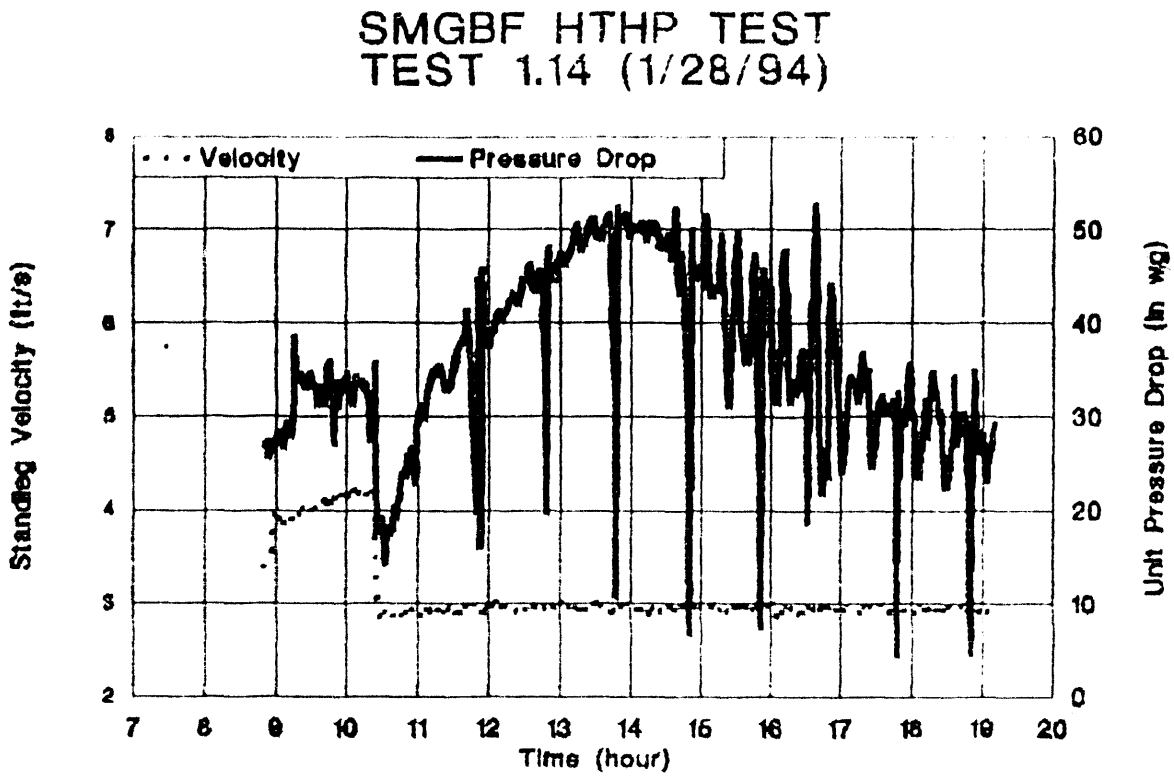


Figure C43 — Test 1.14 (1/28/94) velocity and pressure drop.

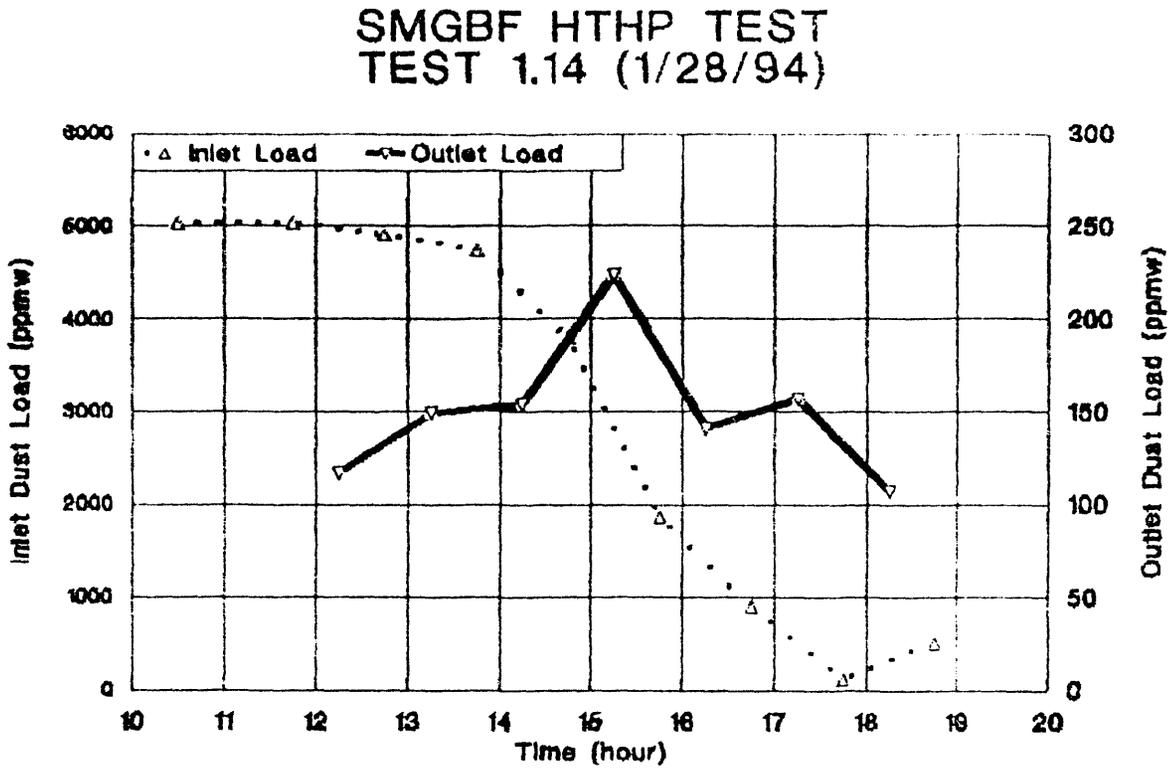


Figure C44 — Test 1.14 (1/28/94) dust loads.

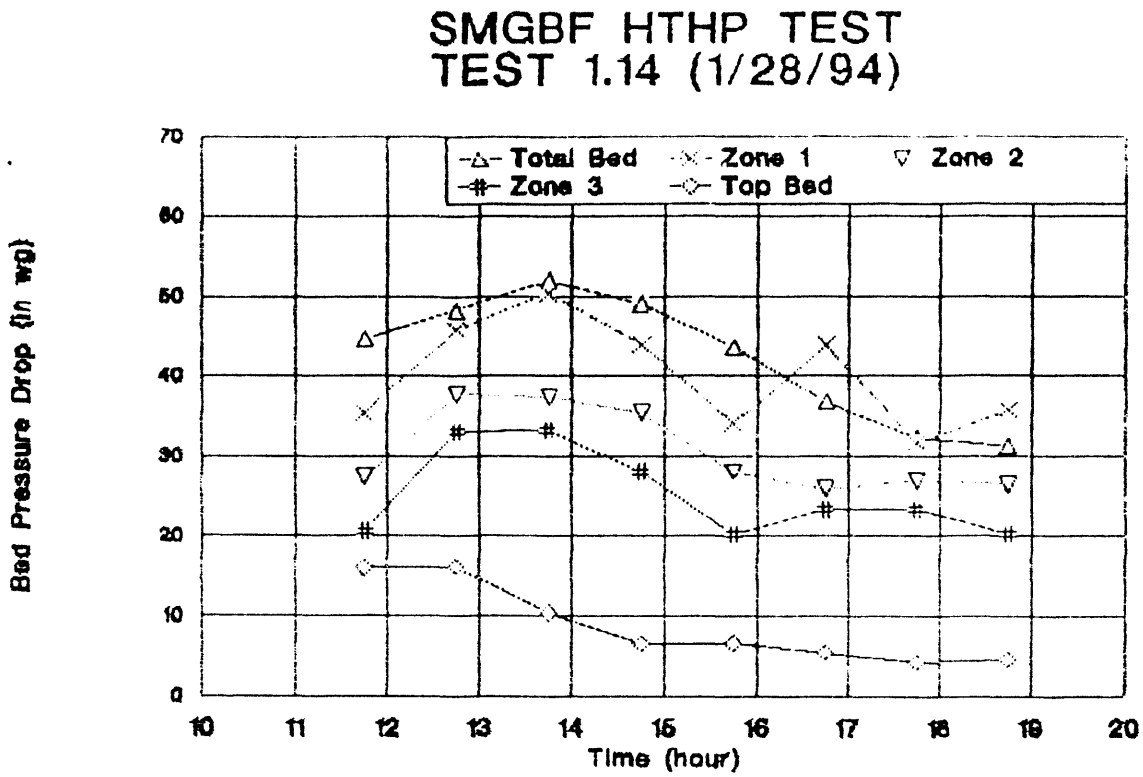


Figure C45 — Test 1.14 (1/28/94) pressure drop profiles.

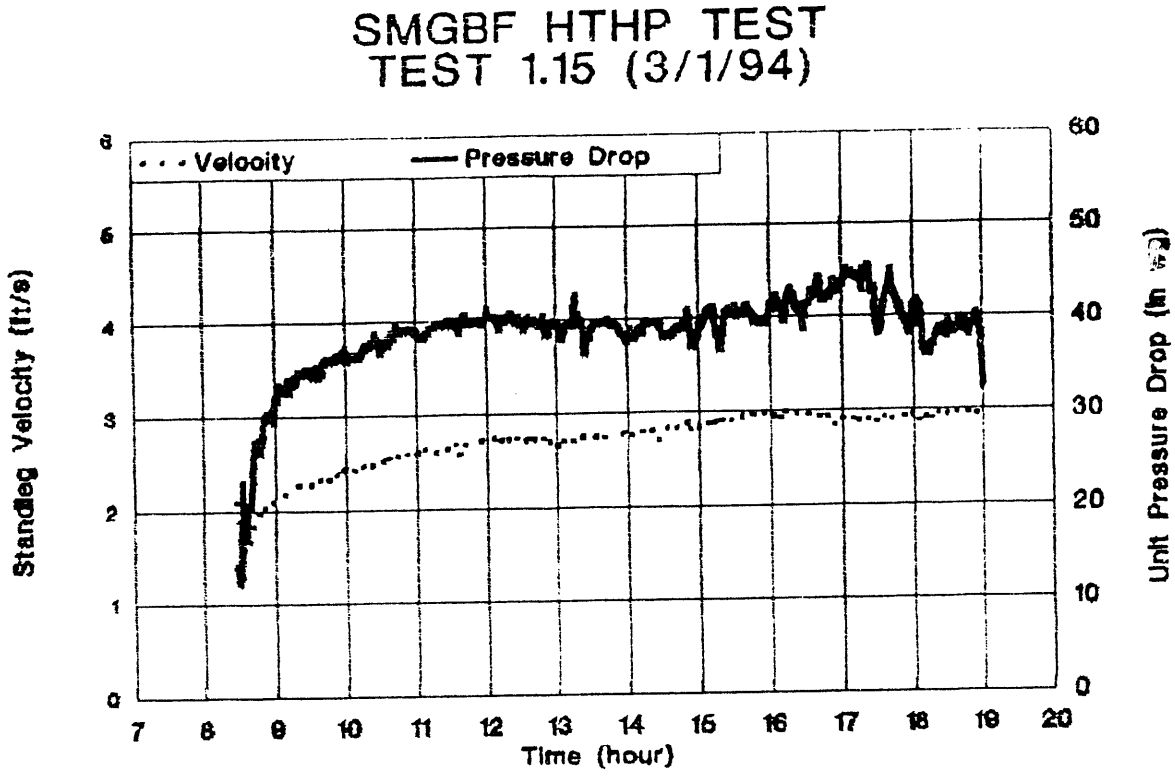


Figure C46 — Test 1.15 (3/1/94) temperatures.

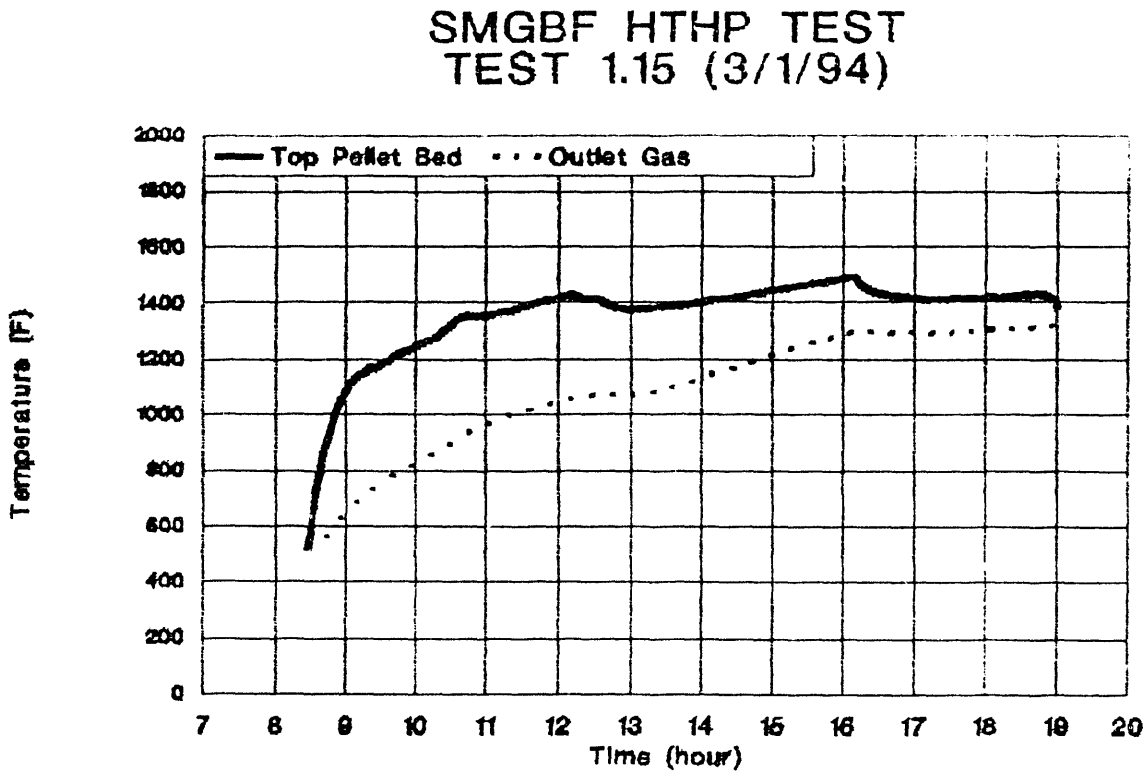


Figure C47 — Test 1.15 (3/1/94) velocity and pressure drop.

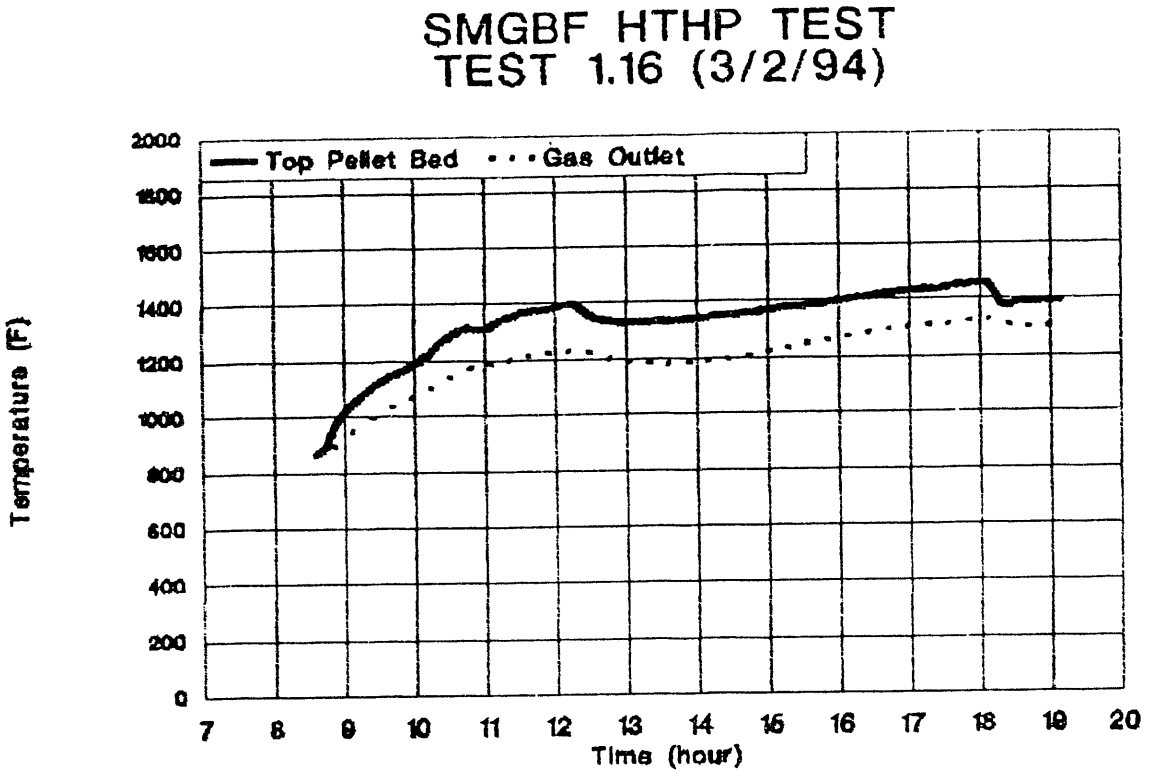


Figure C48 — Test 1.16 (3/2/94) temperatures.

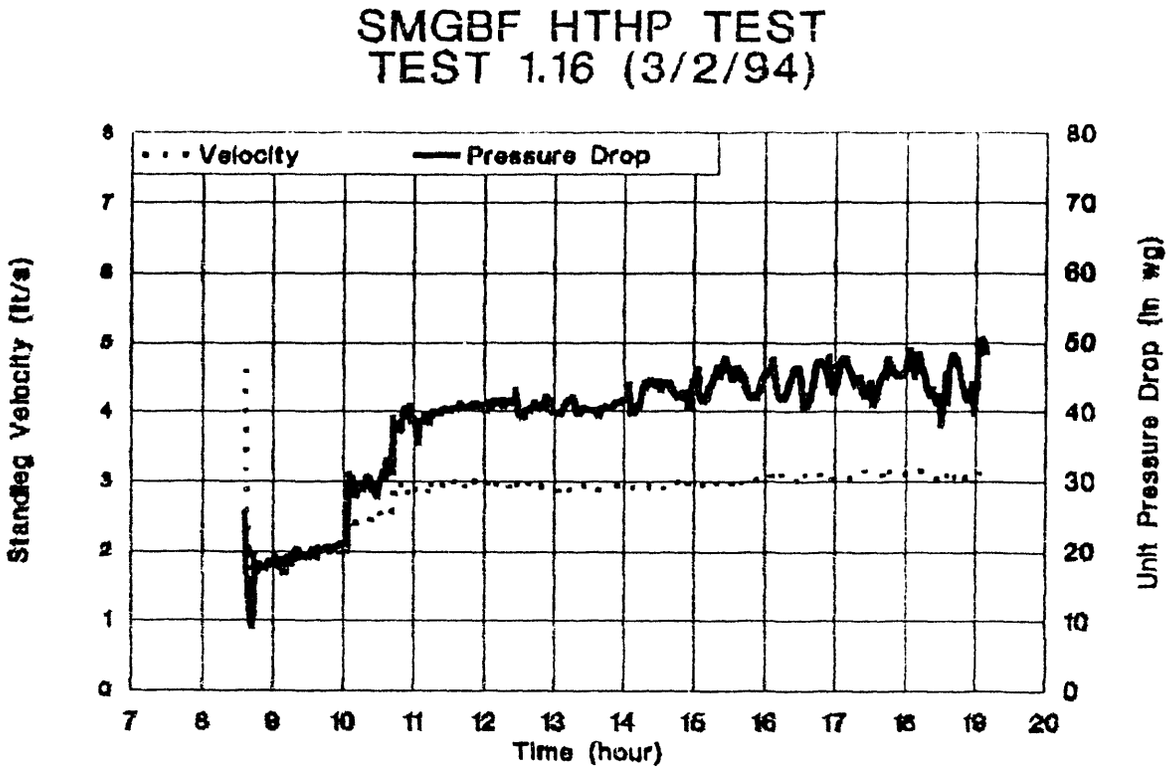


Figure C49 — Test 1.16 (3/2/94) velocity and pressure drop.

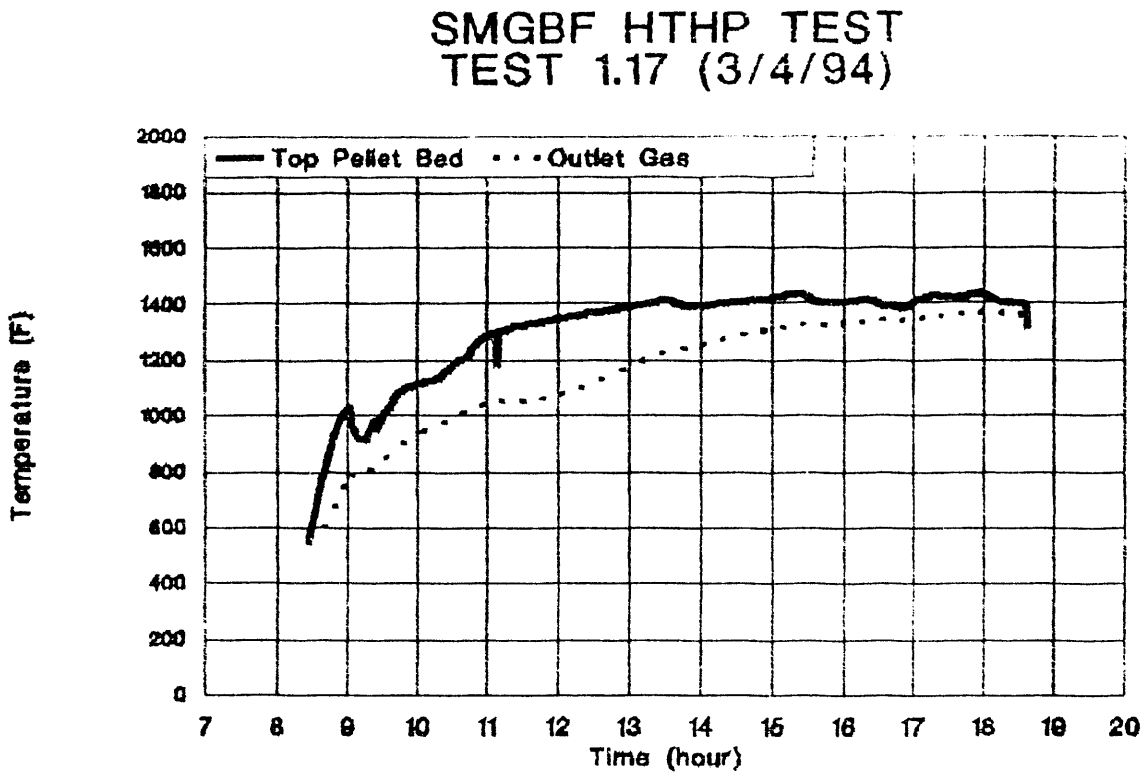


Figure C50 — Test 1.17 (3/4/94) temperatures.

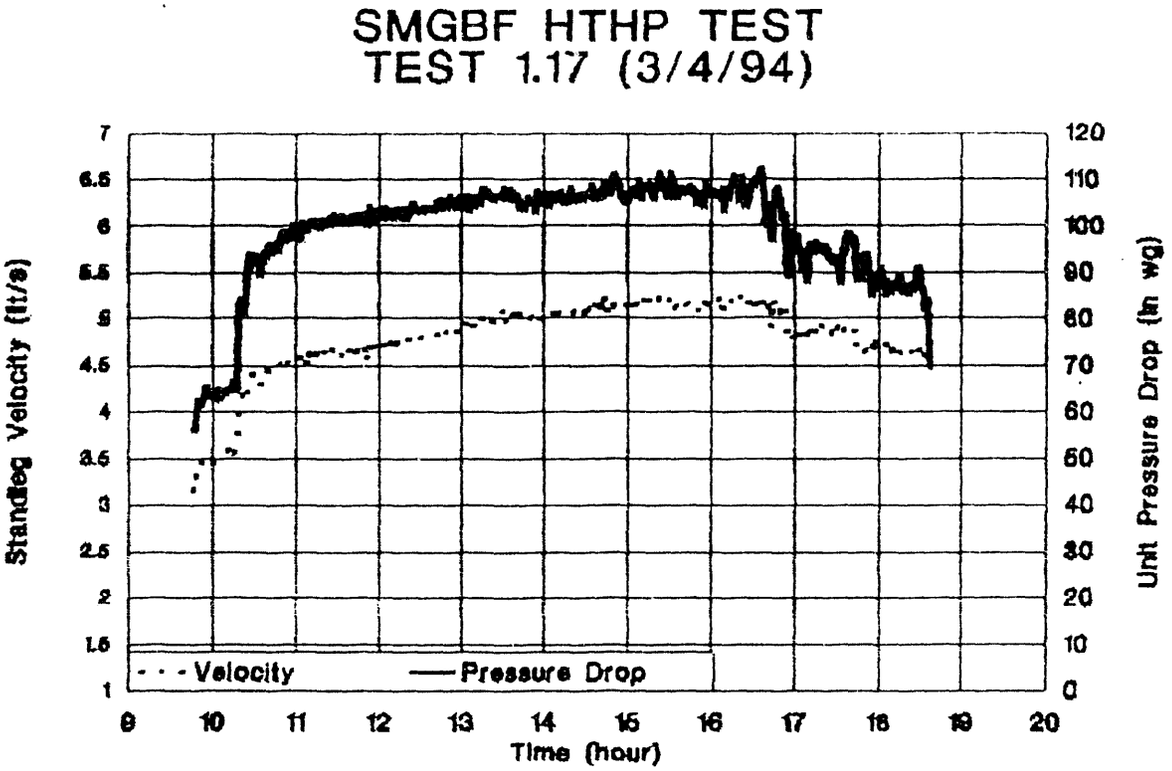


Figure C51 — Test 1.17 (3/4/94) velocity and pressure drop.

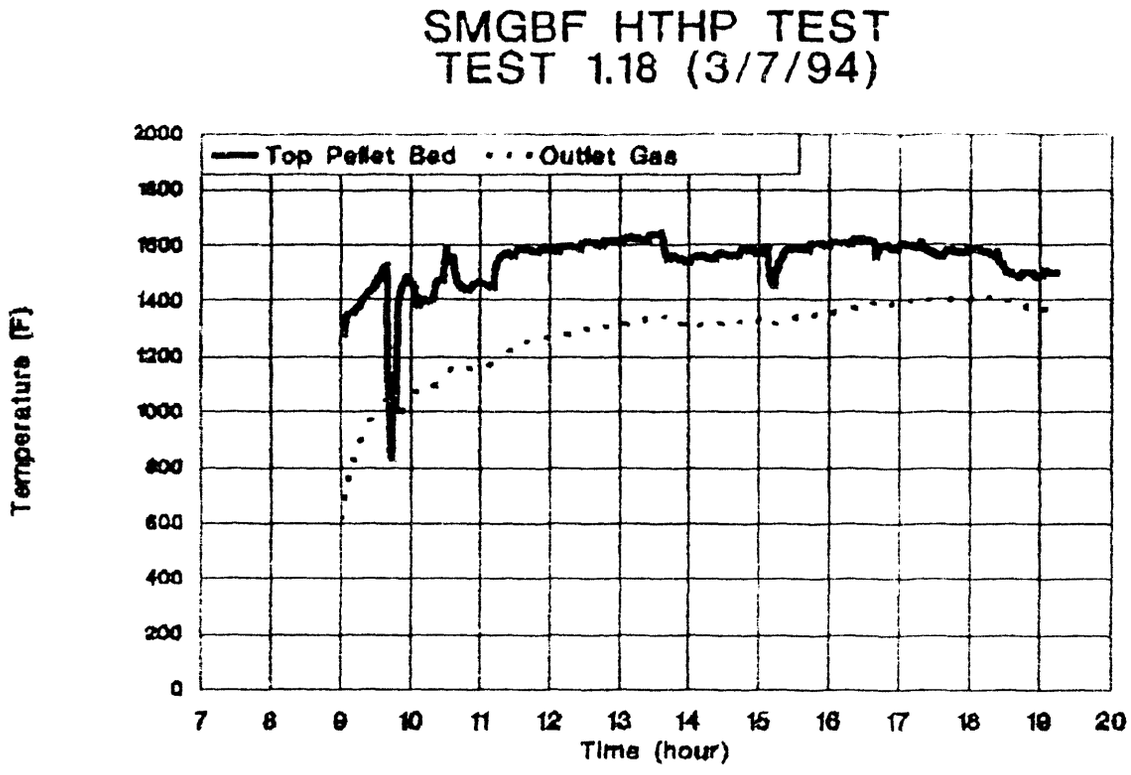


Figure C52 — Test 1.18 (3/7/94) temperatures.

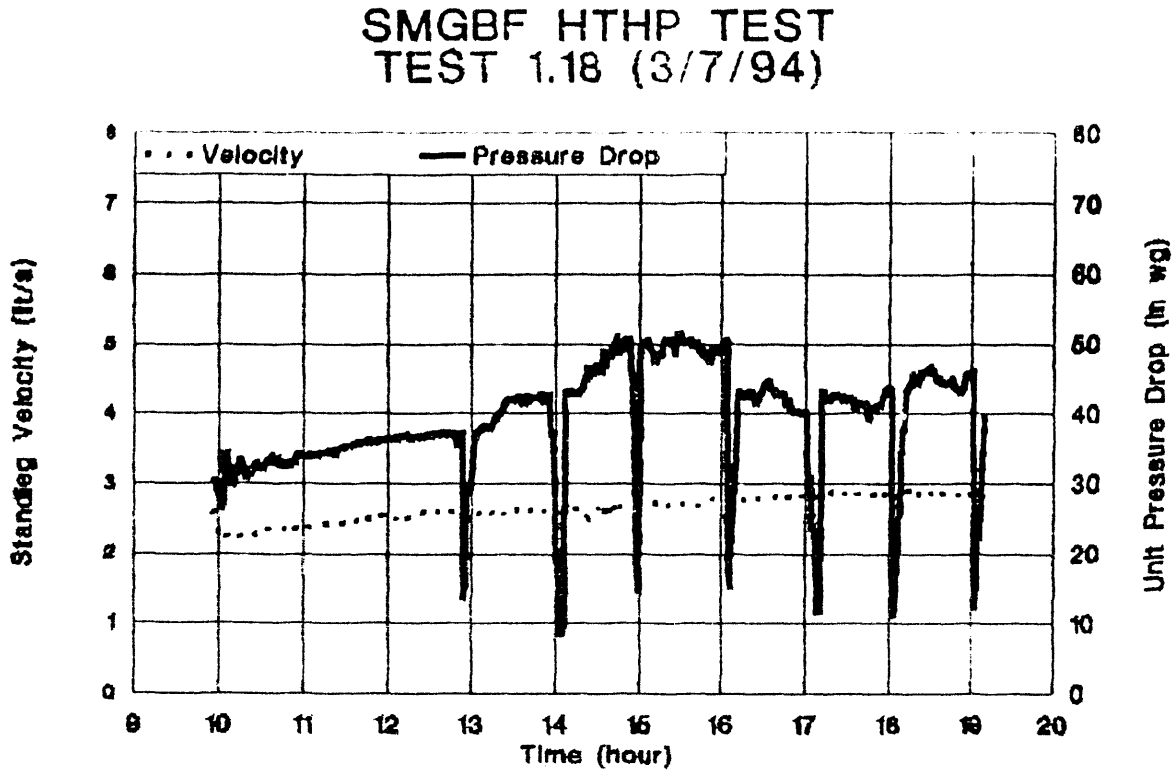


Figure C53 — Test 1.18 (3/7/94) velocity and pressure drop.

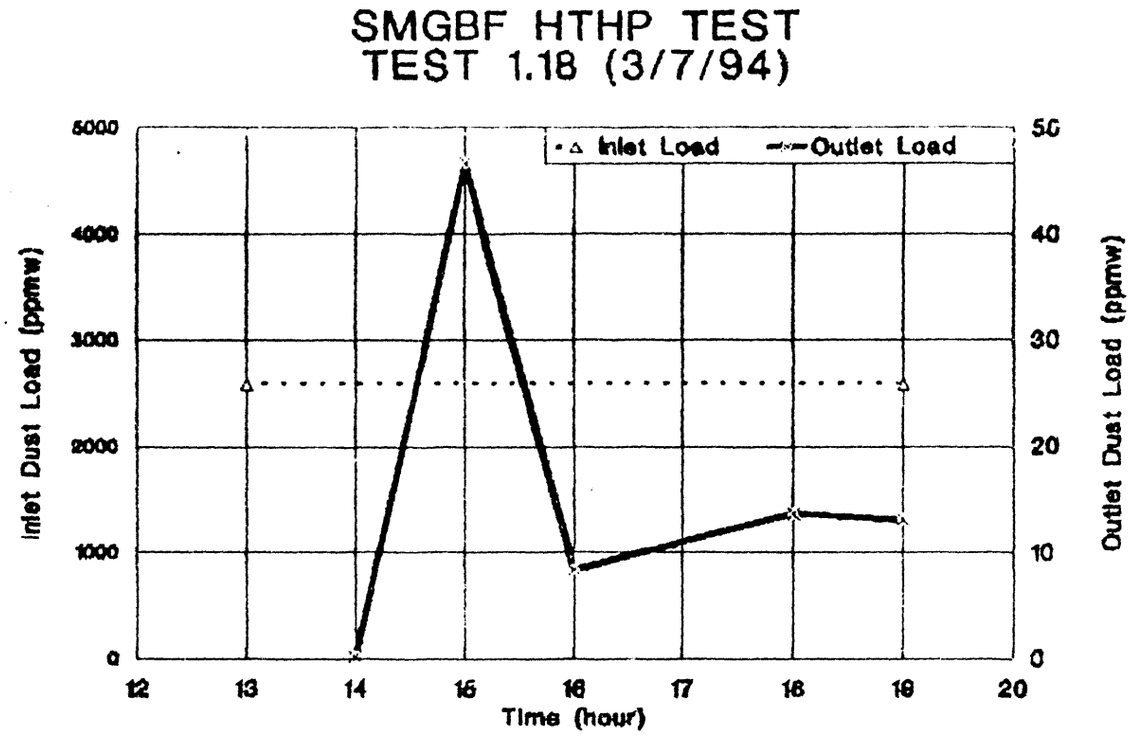


Figure C54 — Test 1.18 (3/7/94) dust loads.

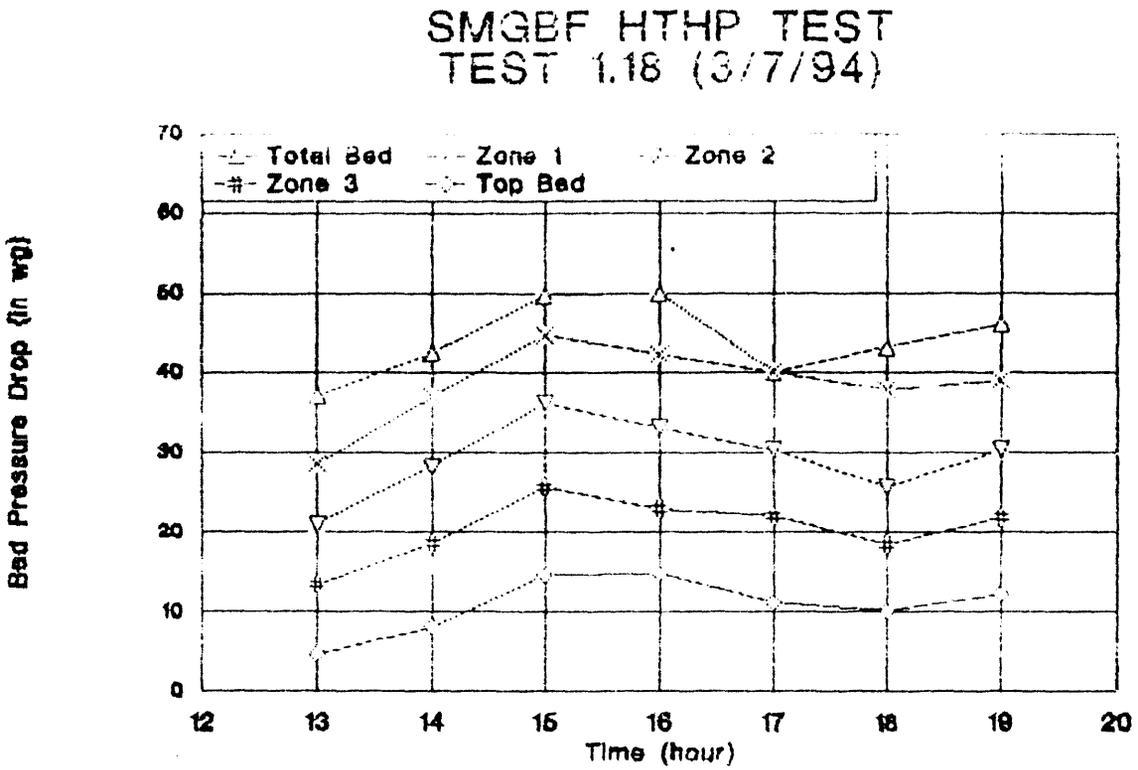


Figure C55 — Test 1.18 (3/7/94) pressure drop profiles.

DATE
FILMED
8/10/94

END