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Moving Granular-Bed Filter Development Program - Option 1 - Component Test Facilities

Topical Report
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ABSTRACT

The Westinghouse Science & Technology Center has proposed a novel moving granular bed filter concept, the Standleg Moving Granular Bed Filter (SMGBF). The SMGBF has inherent advantages over the current state-of-the-art moving granular bed filter technology and is potentially competitive with ceramic barrier filters. The SMGBF system combines several unique features that make it highly effective for use in advanced coal-fueled power plants, such as pressurized fluidized-bed combustion (PFBC), and integrated coal-gasification combined cycles (IGCC).

The SMGBF is being developed in a phased program having an initial Base Contract period followed by optional periods. The Base Contract period was successfully completed and previously documented by Westinghouse. The Option 1 period, "Component Test Facilities", has also been completed and its results are reported in this document. The objective of the Option 1 program was to optimize the performance of the SMGBF system through component testing focused on the major technology issues.

The SMGBF has been shown to be a viable technology in both cold flow simulations and high-temperature, high-pressure testing, and conditions to lead to best performance levels have been identified. Several development activities remain to be complete before the SMGBF can achieve commercial readiness.

EXECUTIVE SUMMARY

The Westinghouse Science & Technology Center has proposed a novel moving granular bed filter concept, the Standleg Moving Granular Bed Filter (SMGBF). The SMGBF has inherent advantages over the current state-of-the-art moving granular bed filter technology and is potentially competitive with ceramic barrier filters. The SMGBF system combines several unique features that make it highly effective for use in advanced coal-fueled power plants, such as pressurized fluidized-bed combustion (PFBC), and integrated coal-gasification combined cycles (IGCC). Both a Once-through-SMGBF system that uses the power plant waste materials as the bed medial, and a more traditional Recycle-SMGBF system that cleans and recycles the bed media have been proposed, each having advantages in certain applications.

The SMGBF is being developed by Westinghouse in a phased program under the United States Department of Energy sponsorship. The second phase of the development program, the Option 1 period entitled “Component Test Facilities”, has been completed and its results are reported in this document.

The objective of the Option 1 program was to optimize the performance of the SMGBF through component testing focused on the major technology issues as well as to accumulate SMGBF performance data that can be used as the basis for future pilot system designs. The focus in this phase of the program was placed on the Recycle-SMGBF system because of its generally greater applicability than Once-through-SMGBF, although the performance data applies as well to Once-through-SMGBF in most cases.

Integrated task efforts were applied in the Option 1 program to:

- Identify and prioritize technical issues,
- develop a test plan,
- produce detailed designs of component test facilities,
- fabricate and install component test facilities,
- conduct the test program.

Given the resources available in the Option 1 program, the following priorities were selected:

- Improve gas-bed media disengaging by advanced design features:
    - improved standleg skirt design
    - addition of a "topping" bed
- Qualify alternative, cheap recycle bed media,
- Qualify the use of partially-cleaned, recycled bed media,
- Consider operation at higher standleg gas velocities for cost reduction.

Test programs were conducted in two test facilities that had been modified from their previous testing configurations used in the initial, Base Contract period of the program: cold flow tests and high-temperature, high-pressure (HTHP) tests.

The parameters varied in the cold flow testing were:

- the SMGBF configuration:
    - bed media recycle mode simulation
    - with and without topping bed
- the skirt design (perforated or solid),
- the bed media/fly ash mass ratio,
- the type of bed media (crushed acrylic or dead-burned dolomite),
- the standleg gas velocity.

The cold flow tests were performed with very low mass feed ratios of bed media-to-dust ranging from about 10 to 20. In the cold flow testing the gas velocity through the standleg was very large relative to the media flow velocity, the ratio of these velocities ranging from 4,000 to 60,000 -- the media bed was very slow moving. Since a fraction of the media feed went directly to the topping bed in the cold flow testing, the feed ratio to the standleg may have been as small as half of the total feed ratio for the unit. Also, the depth of the topping bed used in the Option 1 testing was only 5-inches, substantially less than the 25-inch depth used in the initial program phase cold model testing. These two factors resulted in greater particle penetration in this testing than was obtained during the initial phase testing with a topping bed (e.g., about 24 ppmw versus < 1 ppmw in the initial phase testing). The dust penetration measured was, none-the-less, considerably lower than that obtained without a topping bed (e.g., 21-24 ppmw versus about 60 ppmw in testing with no topping bed at comparable conditions). The cold flow trends identified were:

- Dust penetration was about 20-30 ppmw with acrylic bed media, and 30-60 ppmw with dead-burned dolomite.
- The dust penetration was insensitive to the standleg gas velocity over the range tested.
- The dust penetration was fairly insensitive to the use of a clean topping bed or a recycled, partially cleaned topping bed.

Performance was better with the acrylic bed media than with the dead-burned dolomite media because of the much lower particle density of acrylic (about 1/3 of the dead-burned dolomite density), the acrylic smaller particle size (mean size 3200 micron for acrylic as compared to 5500 micron for dead-burned dolomite) and the much higher volumetric feed rate that resulted with acrylic (volumetric feed ratio of bed media-to-ash ranged from 16 to 35 for acrylic as compared to 5 to 10 for dead-burned dolomite).

The conclusions drawn from the cold flow tests are:

- solid standleg skirts lead to dust penetration slightly better than the specific perforated standleg skirt design tested;
- the SMGBF should be operated with deeper topping beds (deeper than 20-inches) and greater media/ash mass feed ratios (greater than 10) if lower dust penetration is desired;
- dead-burned dolomite is an acceptable bed media under room-temperature conditions;
- operating with partially-cleaned recycle bed media yields dust penetration comparable to that with totally-clean media feed, although the topping bed

feed media should be well cleaned -- this requires a separate feed hopper and recycle system for the topping bed, making this concept more complex than the simple standleg concept;

- operation at high standleg gas velocities is constrained by the pressure drop rather than the dust penetration, the velocity having little influence on the dust penetration over the range of conditions tested.

The HTHP testing was initiated following the completion of the cold flow testing. The objectives of the Option 1 HTHP tests were:

- Demonstrate the HTHP performance of the basic SMGBF design, using a simple standleg (no topping bed) with a solid skirt,
- Demonstrate acceptable fly ash removal performance at commercially acceptable, and representative operating conditions, using
    - dead-burned dolomite as bed media,
    - simulated Recycle-SMGBF by recycling partially-cleaned bed media,
    - parametric values of standleg gas velocity and media/ash feed ratio.

The HTHP unit pressure drops were larger in the Option 1 testing than those measured in the initial, Base Contract phase of testing because the bed media had a smaller size distribution in the Option 1 testing (dead burned dolomite of irregular shape with size range -5/16-inch +8 mesh; mean about 5500 micron) compared to the Base Contract bed media (Aardelite fly ash pellets of fairly spherical shape with size range -1/2-inch +1/8-inch; mean about 8000 micron). The dust penetration was comparable to that measured in the initial, Base Contract phase of HTHP testing (8 to 14 ppmw). Based on the Base Contract test results, it is likely that coarser bed media can be used in practice, decreasing the bed pressure drop while maintaining acceptable dust penetration, although it is generally expected that larger bed media will result in greater dust penetration. Increasing the media-to-ash feed ratio will also result in reduced pressure drop and decreased dust penetration. As in the cold flow testing, the HTHP testing gas velocity through the standleg was very large relative to the media flow velocity, the ratio of these velocities ranging from 15,000 to 120,000.

A summary of the HTHP test results for the test runs having representative, steady behavior is shown in Table S1. While the dust removal efficiency is reported in this table, it is not expected to be as significant a performance parameter as is the dust penetration. If the media-to-ash ratio is maintained constant, the dust penetration should be nearly constant independent of the inlet dust loading, while the dust removal efficiency will increase as the inlet dust load increases.

The use of a cheap bed media, dead-burned dolomite was found to be acceptable in the HTHP tests, corroborating the cold model test results. The recycling of partially-cleaned bed media was also found to result in acceptable dust penetration, consistent with the cold flow testing.

Based on the HTHP tests, with a simple standleg design using a solid skirt, it is estimated that the SMGBF can achieve about 30 ppmw dust penetration at standleg gas velocity up to about 4 ft/s, with media/ash mass feed ratios as low as 10, acceptable for IGCC performance requirements. Likewise, it is estimated that the SMGBF can achieve about 15 ppmw dust penetration at standleg gas velocity up to about 3 ft/s, with media/ash mass feed ratio as low as 20, acceptable for PFBC performance requirements. Operating with larger media/ash feed ratios will reduce the SMGBF pressure drop as well as allow higher standleg gas velocities to be used.

In general, the SMGBF has been shown to be a viable technology in both cold flow simulations and high-temperature, high-pressure testing, and operating conditions leading to "best" performance levels have been identified. It appears that a cheap bed media, such as dead-burned dolomite, and other industrial materials, such as various slags, can be successfully used in the SMGBF, and expensive granular materials, such as alumina beads, are not required. Also, it appears that partially-cleaned bed media can be recycled to the SMGBF and still achieve good particle penetration, although the topping bed may need to have a clean source of bed media.

It seems clear that ceramic barrier filters can operate at comparable pressure drops with much lower dust penetration than granular bed filters, assuming that the ceramic filter elements are durable. The only technique tested by Westinghouse in this program for the SMGBF to approach the dust penetration of ceramic barrier filters is to use a topping bed design, making the SMGBF module design more complex. Several development activities remain to be completed before the SMGBF can achieve commercial readiness.

Table S1 - SMGBF High-Temperature Test Results

Conditions:

- simple standleg with solid skirt; no topping bed
- recycle of partially-cleaned bed media
- bed temperature: 700 - 750°F
- pressure: 100 psig
- bed media: dead-burned dolomite
- fly ash: Tidd PFBC filter ash

Inlet Dust (ppmw)	Media/Ash Mass Ratio	Standleg Gas Velocity (ft/s)	Pressure Drop (in-wg)	Dust Penetration (ppmw)	Dust Removal Efficiency (%)
1100	12	2.0-2.5	40-50	3-15 (mean 10)	99.1
500-1000	11	3.5-4.5	>200	5-52 (mean 35)	95.3
500-1000	25	3.5-4.5	160-195	5-30 (mean 20)	97.3

1. INTRODUCTION

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

An alternative class of hot gas filtration technology is the moving granular bed filter. These systems are at a lower state of development than ceramic barrier filters, and 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. 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 requirements, 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 has inherent advantages over the current state-of-the-art moving granular-bed filter technology. 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 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 fly ash particles. The cocurrent gas/solids operation also prevents fluidization at the bottom of the standleg and permits high gas flow throughput (3 to 6 ft/s through the standleg), with relatively small ratios of bed media-to-fly ash (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 fly ash re-entrainment. The bed media and captured fly ash 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 design technology, making it cost effective, reliable, and easy to scale to larger capacities.

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 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 filter 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 attrition resistance and 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 acceptable levels of power plant performance. The major system components are:

- the SMGBF modules and their connecting piping,
- the plant solid waste handling system (solids cooling and heat recovery, depressurization, transport),
- the pellet generating 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).

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 if it used ceramic barrier filters for particulate control. The solids handling systems and pellet generating 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 (e.g., high pressure) where they have not been previously demonstrated.

The pellet generating 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),
- Heat bonding.

The pellet generating 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 remove a large 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

- 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 to commercial size;
- capable of dealing with plant solid waste issues;
- higher in particle removal 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 specific gas throughput;
- easier operation and maintenance;

- ability to handle difficult fly ash particles (e. g., sticky particles) and gases (e. g., coking fuel gases);
- can operate at very high temperatures without exotic materials or water-cooled internals;
- can operate with higher reliability, having no high-risk internals;
- more tolerant to process thermal and flow transients and upset conditions.

While these potential advantages have been identified in the Base Contract program, further development, such as that reported here on the Option 1 program is required.

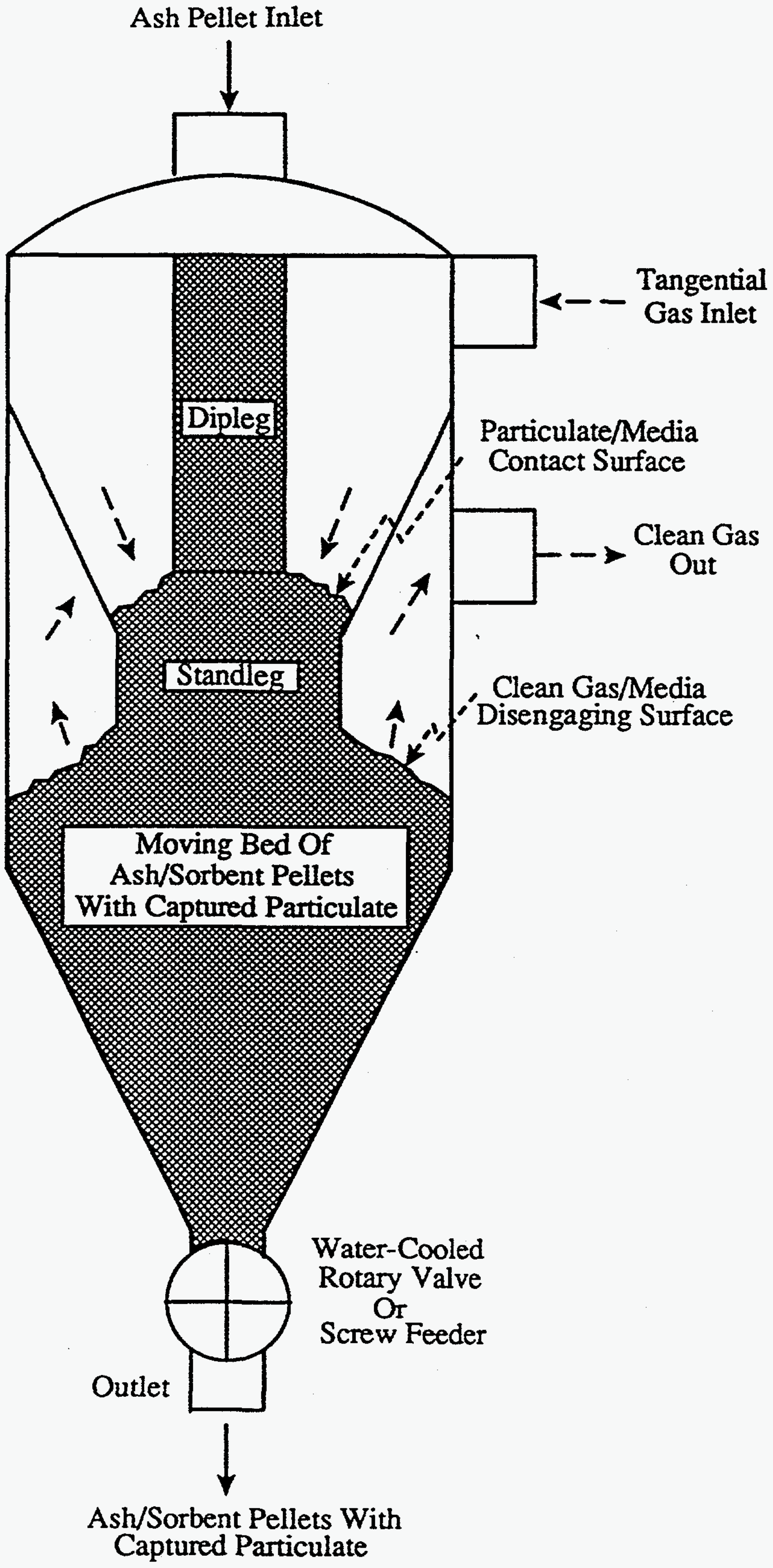


Figure 1.1 - SMGBF Module Schematic

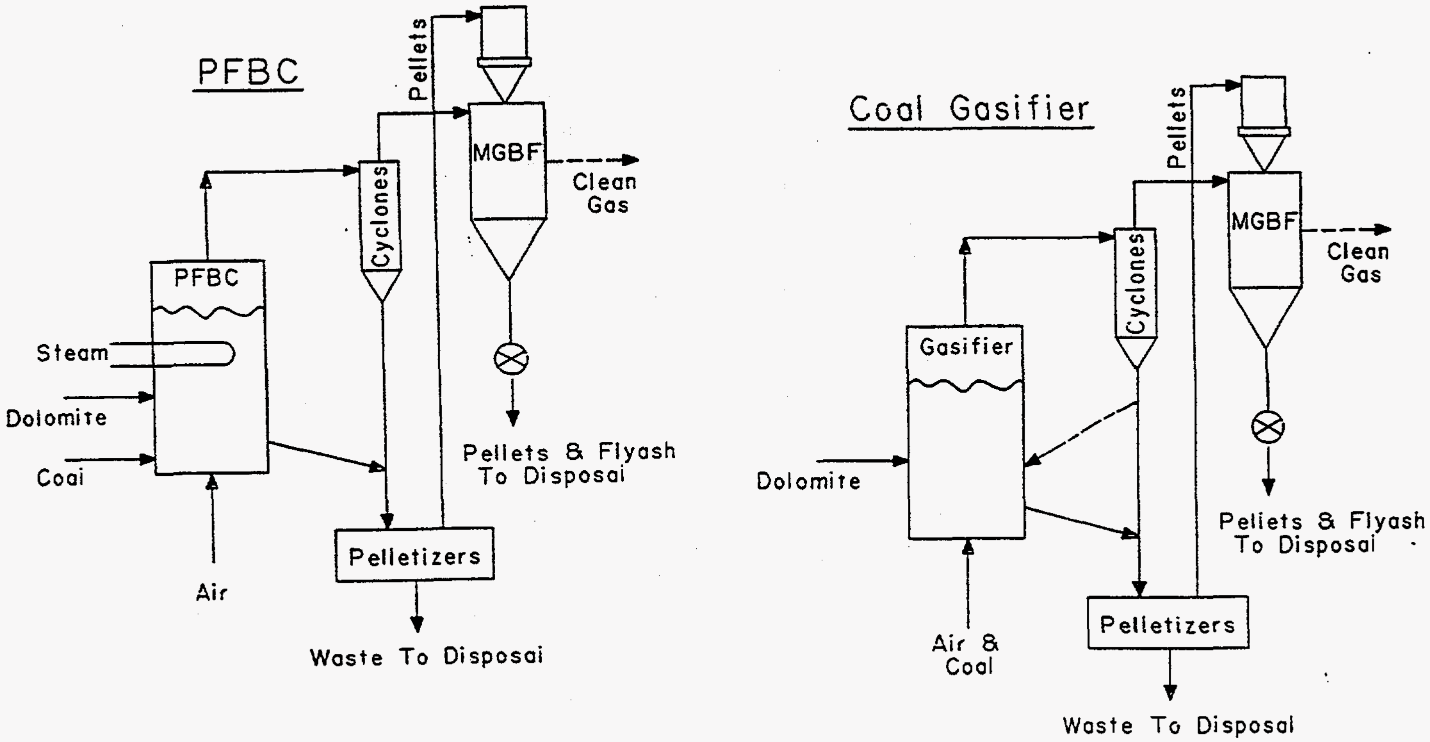


Figure 1.2 - Once-through-SMGBF System Schematic

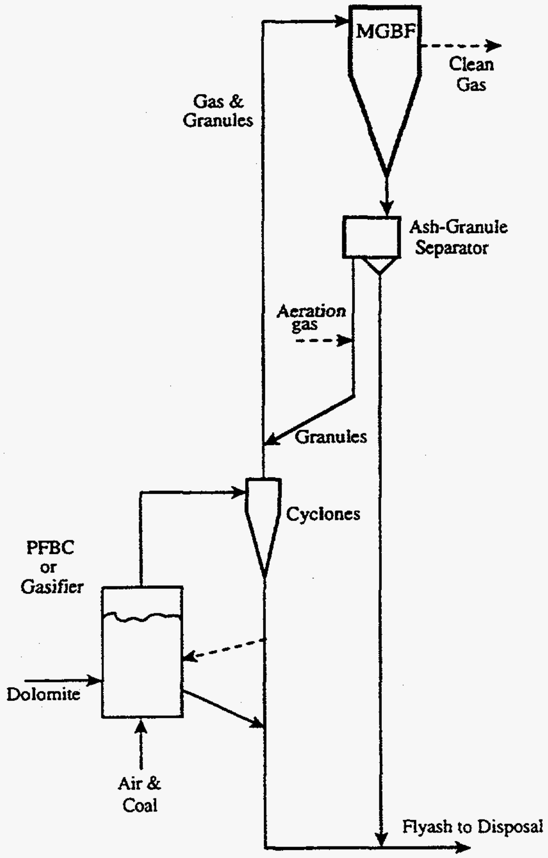


Figure 1.3 - Recycle-SMGBF System Schematic

2. BACKGROUND

The initial, Base Contract period of the program was completed in early 1994 and a Final Topical Report detailing that work was issued by Westinghouse (Moving Granular-Bed Filter Development Program, Base Contact Final Topical Report, R. A. Newby, et al., April 1994, DOE/MC/27259-3797; DE94004149). This section provides a summary of that report as background to the Option 1 Report. The objective of the Base Contract period was to identify and resolve the "barrier" technical issues, thus demonstrating conceptual feasibility. The technical approach applied to achieve the Base Contract objective was to conduct commercial plant conceptual design evaluations, in combination with laboratory and bench-scale testing that focused 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 addressed the two major 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.

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 test program, and a high-temperature, high-pressure (HTHP) test program. The cold flow 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 flow trends were reproducible at HTHP conditions, and to demonstrate the SMGBF performance at small-scale, prototypic conditions. In parallel to the cold flow test program, an effort to identify viable solid waste pelletization techniques, and to test pellet durability was conducted.

A new, cold flow test facility was designed and constructed during the Base Contact period. The SMGBF unit 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 projected 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 Base Contract cold flow model testing was performed with crushed acrylic particles, having an average diameter of about 3800 µm, as the bed media. The acrylic was selected because it had 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 gas 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 the Exxon Miniplant PFBC pilot plant. This was an early PFBC test facility operated by for several years under U.S. EPA sponsorship (Hoke, R. C., et al., Miniplant and Bench Studies of Pressurized Fluidized-Bed Coal Combustion, Final Report, January 1980, EPA-600/7-80-013). Three SMGBF configurations were tested: 1) the simple standleg configuration, 2) a skirt section added at the base of the standleg, and 3) a secondary, or topping bed added as a batch of media 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 about 40 in-wg, and the nominal particle removal performance achieved:

- 97% with the simple standleg configuration (penetration < 200 ppmw),
- 99% with the added skirt section (penetration < 60 ppmw),
- 99.95% with the added batch topping bed (penetration < 1 ppmw).

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 testing was representative of both the Once-through- and Recycle-SMGBF performance capabilities, although it did not include the possibility of dust remaining in the recycled media.

Pelletization studies were performed as part of the Base Contract 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, as well as a standard pellet attrition test rig 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.

An existing HTHP test facility previously used to test ceramic barrier filter elements was adapted to test the SMGBF during the Base Contract period. 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 gas velocity of about 3 ft/s in most of the testing. The standleg was constructed with a solid, unperforated 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 with batch feeding of bed media under conditions simulating a PFBC application:

- temperature of 1500 to 1600°F,
- pressure of 100 psig,
- oxidizing gas,
- 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 conventional 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 uniformly sized and shaped alumina beads resulted in poorer particle removal performance, with outlet loadings of 6 to 250 ppmw. The final series of continuous bed media flow, using pelletized fly ash as bed media, 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 is economically competitive with ceramic barrier filter systems. A conceptual, economic design evaluation was performed to assess this comparison as part of the Base Contract. 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 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 showed 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. 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.

The Base Contract conclusions reached in the test program were:

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

3. PROGRAM OBJECTIVES AND STRUCTURE

The objective of the Option 1 program was to optimize the SMGBF performance by continued testing focused on the major technical issues for the technology. Additional HTHP test data was also compiled that could be used as the design basis for future pilot equipment designs.

The task structure in the Option 1 program was:

- Identify technical issues,
- develop a test plan,
- produce detailed designs of component test facilities,
- fabricate and install component test facilities,
- conduct the test program.

Identification of Technical Issues

This initial task identified, defined, and prioritized the technical issues associated with the SMGBF system following the progress made in the Base Contract work. Technical issues are those issues that must be evaluated to optimize the technical performance of the SMGBF. The technical issues were identified based on the results of the Base Contract testing and commercial evaluation. They were prioritized based on their significance toward improved performance, improved reliability and potentially improved economics.

Test Plan

The objective of this task was to devise a test plan to evaluate the key technical issues identified. Two testing subtasks were defined, one related to filter cold flow modeling, and one related to high-temperature, high-pressure filter testing.

The cold flow tests were to be completed before initiating the HTHP tests.

Detailed Design of Component Test Facilities

The objective of this task was to prepare detailed designs of the component test facilities. The Option 1 testing was based on modifications to the two existing test facilities used during the Base Contract period, the cold flow facility and the HTHP unit.

Fabrication and Installation of Component Test Facilities

The objective of this task was to procure, fabricate, and install the component test facilities. The equipment, as designed and specified to modify the two existing test facilities, was procured and fabricated.

Test Program

The objective of this task was to conduct the testing of the component test facilities in accordance with the test plan and evaluate the test data. The test plan called for first conducting the cold flow model tests in support of the subsequent HTHP unit tests so that the HTHP testing could benefit from the cold flow test results.

4. TECHNICAL ISSUES AND PRIORITIES

The SMGBF technology is grouped into two categories: system component technology, and SMGBF module technology. Table 4.1 lists the major system component technologies, their potential technical issues, and the nature of their resolution. The resolution column lists either conclusions that can be drawn from past studies, or the activities that would be required to be completed to resolve the issues.

Separate listings are shown for the Once-through-SMGBF and the Recycle-SMGBF systems. Many of the potential technical issues for the system component technologies are of limited concern, or have been partially resolved based on the evaluations performed during the Base Contract period. Others are major issues requiring engineering evaluation, and/or modeling, and/or testing evaluations.

The SMGBF module itself consists of the following major components:

- media feed hopper
- media feed dipleg
- dirty gas inlet nozzle
- cone and standleg section
- gas-media disengaging section
- media/fly ash discharge cone and nozzle
- clean gas outlet nozzle

Each of these vessel components is designed by the application of engineering techniques in the areas of gas and particle flow and materials handling. In general, the flow of pellets through hoppers, diplegs, standlegs, and nozzles is a relatively well developed technology for which reliable engineering design criteria have been developed. The less easily quantified aspects of the module design and performance estimates relate to the dust flow and accumulation within the moving bed of media, the media-dust particle interactions (cohesion, attrition of agglomerates, etc.), and especially the dust removal efficiency and losses in the vicinity of the gas-media disengaging section. Engineering materials issues and mechanical design are relatively easy to assess and reliable selections can be made.

Table 4.2 lists the design aspects involved in the characterization of the SMGBF module, the key issues and uncertainties, and the nature of their resolution. They apply equally to both Once-through- and Recycle-SMGBF. Special design features have been identified in the Base Contract program to modify the gas-media disengaging section for optimum particle removal performance:

- addition of a skirt, or screen section at the standleg base,
- addition of a secondary, or topping bed surrounding the standleg base,
- installation of low resistance fiber filter (e.g., Battelle ceramic fiber filter) above the disengaging section,

and these were key considerations for the Option 1 program.

Table 4.3 lists the technical issues identified and ranks them according to priority, with 1 being the highest priority, and 5 being the lowest. They are listed both as SMGBF module issues and SMGBF system issues, and they are ranked separately for each of these categories. The issues listed in Tables 4.1 and 4.2 are identified as key if they potentially can lead to improved performance or economics, but not if it they are just academic explorations. The issue must also be of major importance at this point in the SMGBF development -- that is, for example, not all engineering design issues that can be resolved by standard engineering evaluations are considered to be of high priority at this time. The issues ranked as 1, 2 or 3 in Table 4.3 were considered in the development of the Option 1 Test Plan.

The key technical issues are seen to be those related to module scaleup, optimization of the Once-through pelletization process, the Recycle-SMGBF system ash-granule separation and granule transport components, and the particle removal performance of the SMGBF. Alternatives for resolving the issues are also listed in Table 4.3, and were the basis for the development of the Option 1 Test Plan. Included are mathematical modeling, engineering evaluation, cold flow testing, HTHP testing, laboratory testing and vendor testing. In many cases, multiple resolution options need to be applied.

Given the resources available in the Option 1 program, the following priorities were selected:

- Improved gas-bed media disengaging by advanced features
    - improved skirt design,
    - topping bed,
- Qualification of alternative, cheap recycle bed media,
- Qualification of the use of partially-cleaned, recycled bed media,
- Consideration of operation at higher standleg gas velocities for cost reduction.

The focus was placed on the Recycle-SMGBF system because of its generally greater applicability.

Table 4.1 - SMGBF System Component Technologies and Issues

ONCE-THROUGH-SMGBF

TECHNOLOGY	ISSUES	RESOLUTION
Media transport	Mechanical or pneumatic technique selection	Mechanical favored for pellet durability
Media pressurizing	Alternatives to lock hopper systems	Lock hoppers acceptable from process evaluations
Media feeding and distribution	• Ability to control • Uniformity of distribution	• Limited concern • Limited concern
Media flow control and conveyors	High temperature valve and conveyor reliability	Limited concern using water-cooled valves
Media cooling and heat recovery	Commercial techniques vs. developmental concepts	Commercial are acceptable from process evaluations
Media/ash depressurization	Developmental techniques vs. lock hopper techniques	Lock hoppers acceptable from process evaluations
Pelletization	• Adapt commercial techniques to high pressure • Apply high temperature techniques • Sensitivity to solids properties and size, binder and water content, and curing technique	• Requires significant development effort • Requires significant development effort • Testing required
System integration	• Sufficient pellet/fly ash ratio • Minimize process gas cooling • Effective arrangement of multiple modules	• Pellet recycle and process evaluation • Process evaluation of options • Engineering of options
Solids size reduction	High temperature techniques (e.g., air-jet) vs. low-temperature commercial	Commercial acceptable from process evaluations

Table 4.1 - SMGBF System Component Technologies and Issues (Continued)

RECYCLE-SMGBF

TECHNOLOGY	ISSUES	RESOLUTION
Media transport	• Mechanical or pneumatic technique selection • Granule attrition	• Pneumatic favored • Limited concern with specified granules
Makeup media pressurizing	Alternatives to lock hopper systems	Lock hoppers acceptable from process evaluations
Media feeding and distribution	• Ability to control • Uniformity of distribution	• Requires engineering evaluation and testing • Testing required
Media flow control reliability	Dense-phase aeration	• Nonmechanical valves favored • Testing required
Granule-ash separation	Adapt commercial to high pressure and temperature	Requires engineering evaluation and testing
Ash depressurization	Developmental techniques vs. lock hopper techniques	Lock hoppers acceptable from process evaluations
System integration	Effective arrangement of multiple modules	Engineering of options

Table 4.2 - SMGBF Module Design Technologies and Issues

DESIGN ASPECT	ISSUES/UNCERTAINTIES	RESOLUTION
Media flow: - standleg - hopper - nozzle	• Impact of dust accumulation and agglomeration • Flow distribution to top of vessel	• Design criteria limited to clean systems • Major issue for Recycle-SMGBF
Gas flow	• Local fluidization in disengager • Flow uniformity through standleg • Pressure drop estimation • Tangential or radial inlet flow	All require modeling and testing
Dust flow	• Dust accumulation patterns and plugging • Dust re-entrainment at disengaging zone	All require modeling and testing
Media-dust interaction	• Dust agglomeration/ adhesion on pellets • Dust agglomerate formation • Pellet cohesion/clinkers	All require modeling and testing
Media operating mode	Continuous media flow vs. On-Off flow	Requires modeling and testing
Materials selection	Refractory vs. high-alloy internals	Engineering of options
Mechanical design	Options to support internals	Engineering of options
Particle removal performance	• Special features to minimize dust penetration • Standleg length/velocity • Outlet zone velocity • Media/dust feed ratio • Media size and shape	All require modeling and testing

Table 4.3 - Prioritized list of Issues and Approaches to Resolve

ONCE-THROUGH-SMGBF

ISSUE	RANK	RESOLUTION
Module Design		
Scaleup to large capacity	1	• Mathematical modeling • Cold flow unit probing
Improved particle removal features (skirt design, baffles, topping bed, fiber filter)	1	• Cold flow unit testing • Engineering evaluation
Optimized pellet shape and size distribution	3	• Mathematical modeling • Cold flow unit testing • HTHP testing
System Design		
System integration (layout, multiple modules, power plant integration)	5	Engineering evaluation
Optimized pellet fabrication durability (size reduction, water and binder content, mixing, curing)	2	• Vendor tests • Laboratory tests • HTHP unit tests
Optimum pellet/ash ratio	3	Cold flow testing
Pellet environmental performance	3	• Laboratory testing • Engineering evaluation
Pellet byproduct use	5	• Laboratory testing • Engineering evaluation
On-Off pellet feed vs. continuous	5	• Cold flow testing • HTHP unit testing

Table 4.3 - Prioritized list of Issues and Approaches to Resolve (Continued)

RECYCLE-SMGBF

ISSUE	RANK	RESOLUTION
Module Design		
Scaleup (gas flow, granule flow distribution)	1	• Mathematical modeling • Cold flow unit probing
Improved particle removal features (skirt design, baffles, topping bed, fiber filter)	3	• Cold flow unit testing • Engineering evaluation
Optimized granule shape and size distribution	3	• Mathematical modeling • Cold flow unit testing • HTHP testing
Pneumatic transport of granules to SMGBF top bed	2	• Cold flow unit testing • HTHP testing
System Design		
System integration (layout, multiple modules, power plant integration)	5	Engineering evaluation
Ash-granule separation	2	• Engineering evaluation • Cold flow test
Optimum granule/ash ratio	3	• Cold flow testing • HTHP testing • Mathematical modeling
Media circulation and flow control	3	• Cold flow testing • Mathematical modeling
On-Off pellet feed vs. continuous	5	• Cold flow testing • HTHP unit testing

5. TEST FACILITIES

The details of the cold flow and HTHP test equipment and test facilities have been presented in the Base Contract Final Report (Moving Granular-Bed Filter Development Program, Base Contact Final Topical Report, R. A. Newby, et al., April 1994, DOE/MC/27259-3797; DE94004149). A description is provided here of the modifications made to the equipment and facilities to conduct the Option 1 test program.

5.1 Cold Flow Facility

Figure 5.1 is a layout drawing of the original SMGBF cold flow model constructed and tested during the Base Contract period. The central view of the vessel shows the vessel cross-sectioned internals. The dirty gas enters tangentially at the vessel aluminum top piece, and an optional radial inlet is also available. The bed media enter through a dipleg arranged axially at the top of the vessel. The gas flows cocurrently downward with the bed media through the Plexiglas cone section, then through the 1 ft diameter standleg section at a maximum design superficial velocity of 6 ft/s. At the exit from the standleg the gas turns to flow upward, disengaging from the bed media, and exits radially from the vessel. An alternative gas outlet is shown in the bottom Plexiglas section to provide flexibility for the outlet location. Use of this alternative gas outlet requires the two Plexiglas sections to be rearranged.

The Plexiglas standleg in the original unit was supported by a ring located at the tip of the standleg, and this ring had eight holes inserted for the exit gas to pass through. The bed media flows out of the conical bottom of the vessel. The base of the standleg is designed so that alternative features may be added to assist in the disengagement of the gas from the bed media, and/or for limiting local fluidization and fly ash entrainment.

The Plexiglas is 1" thick and the design pressure is 10 psig, at 100°F. Reinforcement beams also support the Plexiglas vessel wall.

The arrangement drawing of the original, Base Contract cold flow facility also shows the bed media feeding and withdrawal equipment arrangement within the high-bay test area. A storage and feed bin is located at the top, and a slide valve is used to shut off the bed media flow from the bin. The Plexiglas SMGBF unit is directly under the bed media feed bin. The conical outlet from the cold model passes bed media into a screw conveyor that loads the bed media into 55-gal drums for storage. The screw conveyor controls the rate of bed media flow through the cold model. The method for loading the bed media into the feed bin is the load-and-lift approach, with the feed bin lowered to the floor level, loaded with bed media dumped from 55-gal drums, and then lifted by hoist to its feeding position above the cold flow model.

The P&ID for the original cold flow model test facility is shown in Figure 5.2. The major components are an air blower system and air supply system; the Plexiglas model; the bed media handling, feeding, and withdrawal equipment, the fly ash feeding system, and the air exhaust system with their associated flow controls and instrumentation for temperature, pressure, and pressure drop measurements. The air exhaust system includes a conventional fabric filter that collects particulate material as a batch collection for the determination of the SMGBF fly ash penetration.

The maximum flow rates of the major process streams in the test program were:

- Air flow: 283 acfm
- Fly ash flow: 6 lb/hr
- Bed media flow: about 100 lb/hr

Several modifications were made to the cold flow facility for the Option 1 test program.

Standleg Configuration

Several standleg configurations have been identified that may significantly improve the SMGBF particle removal performance, or may improve the test data quality, and these were fabricated for testing in Option 1:

- A metal inlet cone and a 3-ft long, metal standleg were provided in place of the original Plexiglas cone and standleg. This eliminated the interference produced by the support ring structure on the original Plexiglas pieces and improves the quality of the model simulation.

- A metal, cylindrical standleg section having 2-ft length was fabricated for use as a potential test parameter.
- A metal, skirt section having no perforations was fabricated, to be used in place of the original perforated skirt section.

Bed Media Recirculation System

The behavior of the granule recirculation system was simulated by setting up an ash-granule separator (sieve vibrator type) used to simulate the Recycle-SMGBF system ash-granule separation behavior. With this the bed media withdrawal was partially cleaned and reused in the testing much as it would be with a continuous recycle system.

Topping Bed Configuration

The topping bed concept has been found to result in great improvements in the SMGBF particle removal performance based on the limited testing performed during the Base Contract period. Special features to allow a continuously-fed topping bed were fabricated. These features are conceptually illustrated in Figure 5.3. Both a top entry and a side entry of the media feed for the topping bed surrounding the standleg skirt were considered. The top entry design (left side of Figure 5.3) was selected because it allowed the main media feed hopper to directly feed both the standleg and the topping bed. A drain pipe was attached to the media feed hopper for that purpose. There was no means to monitor the relative feed split between the topping bed and standleg. The continuous topping bed designed provides a much shallower topping bed depth (5-inches) than was used during the Base Contract period,(25-inches). However, it was expected to be sufficiently deep to provide similar performance improvements.

5.2 HTHP Test Facility

Figure 5.4 is a conceptual layout drawing and P&ID for the auxiliary systems of the SMGBF HTHP test facility. The pressure vessel is a refractory-lined vessel used previously for ceramic barrier filter testing. The pressure vessel head was modified for the Base Contract testing to accommodate the top gas inlet location and the support of the vessel internals. The essential vessel features are identical with those described for the cold model, except the vessel and internals are designed for operation at 1600°F and up to 350 psig pressure. The dirty gas enters tangentially into the vessel. As in the cold model, an alternative radial gas inlet is included in the head. 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 has a 6" diameter in this vessel, so the HTHP unit operates with about 1/4 of the cold model actual volumetric flow. The bed media and collected fly ash pass out through the conical base.

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. The expansion web accommodates the thermal expansion of the materials. The gas seals are located at the cold vessel flange. The vessel was not modified to accommodate a topping bed configuration, although a batch topping bed was tested during the Base Contract period.

Figure 5.5 shows the conceptual arrangement of the major equipment in the HTHP test facility. The HTHP test facility is equipped with two parallel air compressors that can supply a total of up to 1500 lb/hr of air at up to 200 psig. A natural gas compressor supplies the high pressure natural gas for the combustor. The air stream is split between the combustor and fly ash feed. A K-Tron screw feeder contained in a pressure vessel is used to control and measure the fly ash feed rate. Hot combustion gases are generated by a natural gas fired combustor, and fly ash is injected into the combustion products before entering the filter vessel. The fly ash is injected immediately downstream of the combustor, allowing it to be heated before entering the upper end of the SMGBF. A batch loaded, pressurized bed media feed bin is located above the vessel. A high-temperature valve (e.g., water-cooled screw) controls the flow rate of bed media through the unit, and feeds the bed media into a pressurized storage hopper. Water-cooled piping carries the exhaust gas from the vessel to the pressure letdown valve, and the building exhaust.

Provisions for measuring temperatures, pressures and differential pressures are available. A computer based data logging system is used to collect and display the data during testing and to reduce it after the test.

The maximum flow rates of the major process streams in the test program are:

- Gas flow: 71 acfm, or 820 lb/hr
- Fly ash flow: 4 lb/hr
- Bed media flow: about 80 lb/hr

For the Option 1 testing, the following changes were made to the HTHP facility:

- An enlarged, higher capacity bed media feed system was procured and installed, allowing several days of operation to be completed without refilling.
- Provisions were made for feeding of recycled bed media after partial cleaning.

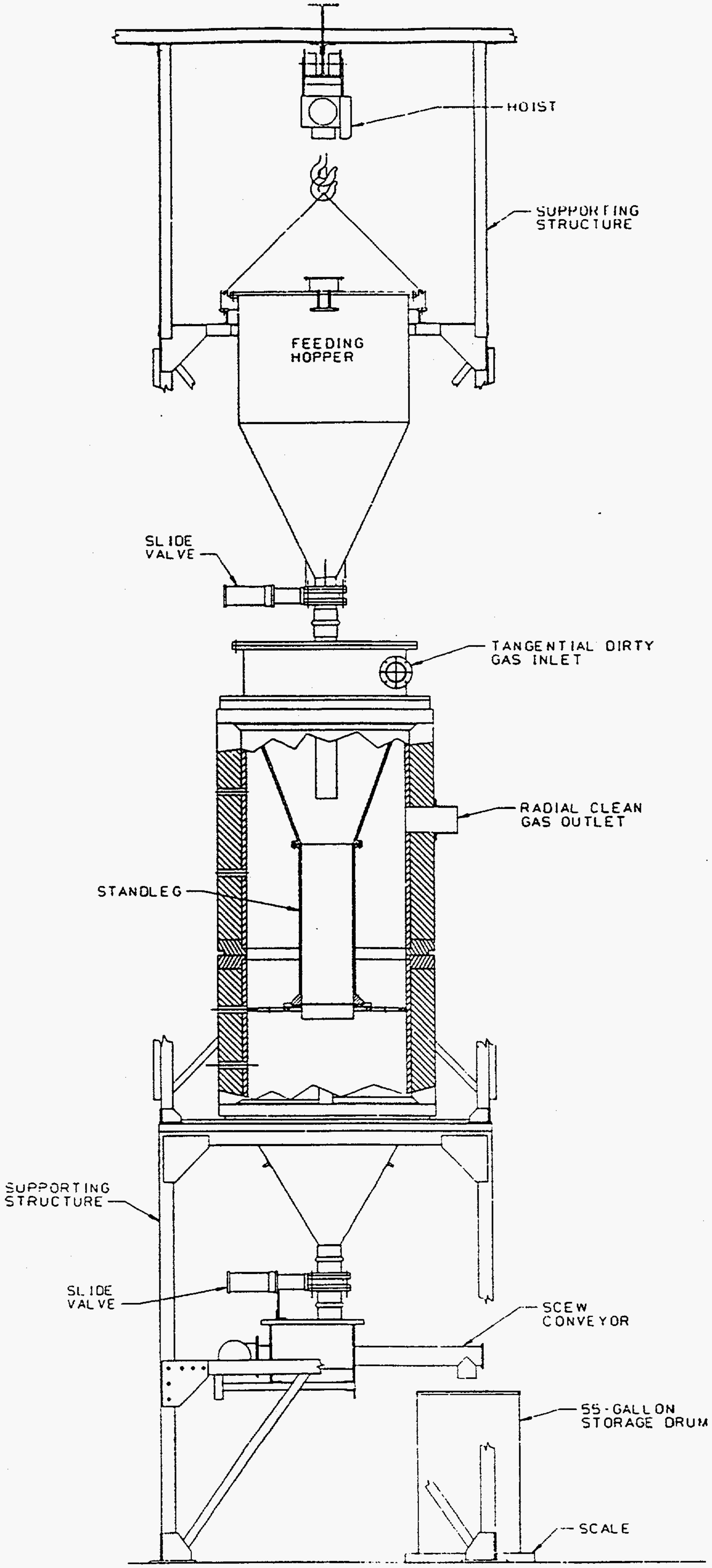


Figure 5.1 - Cold Flow Model Layout

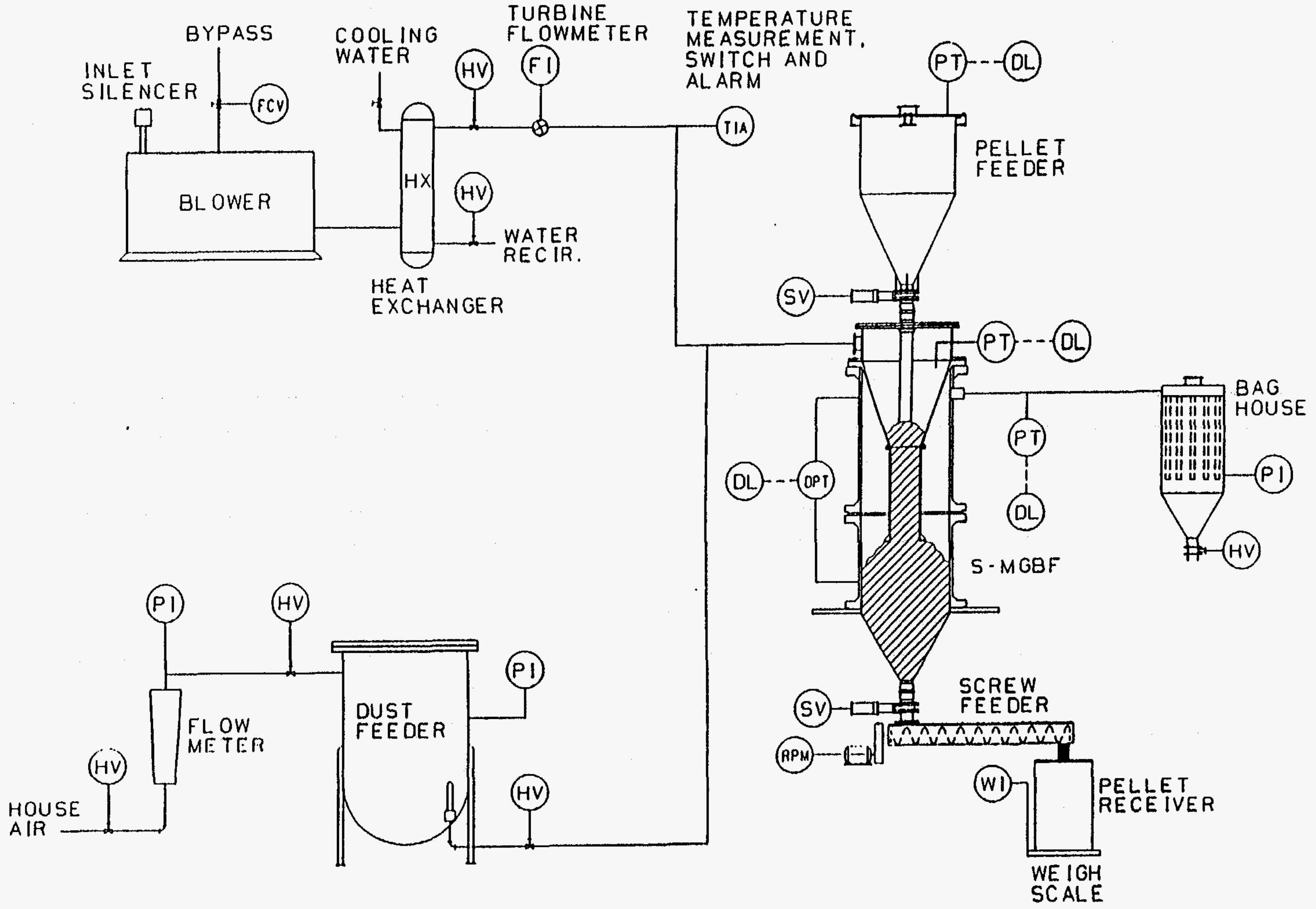


Figure 5.2 - Cold Model System P&ID

VARIATIONS OF CONFIGURATION FOR STANDLEG WITH INNER AND OUTER BEDS

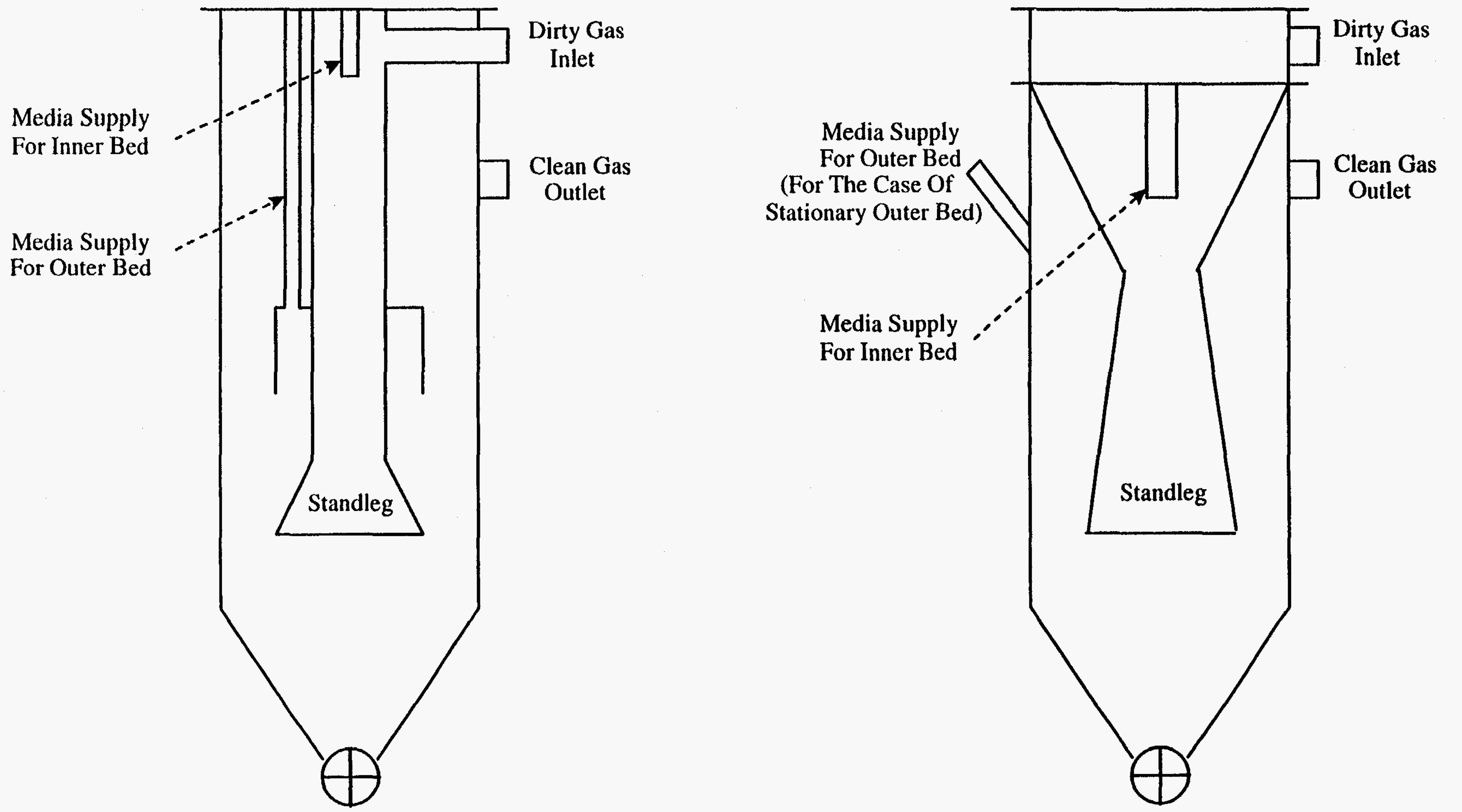


Figure 5.3 - Topping Bed Concept and Media Supply Configuration

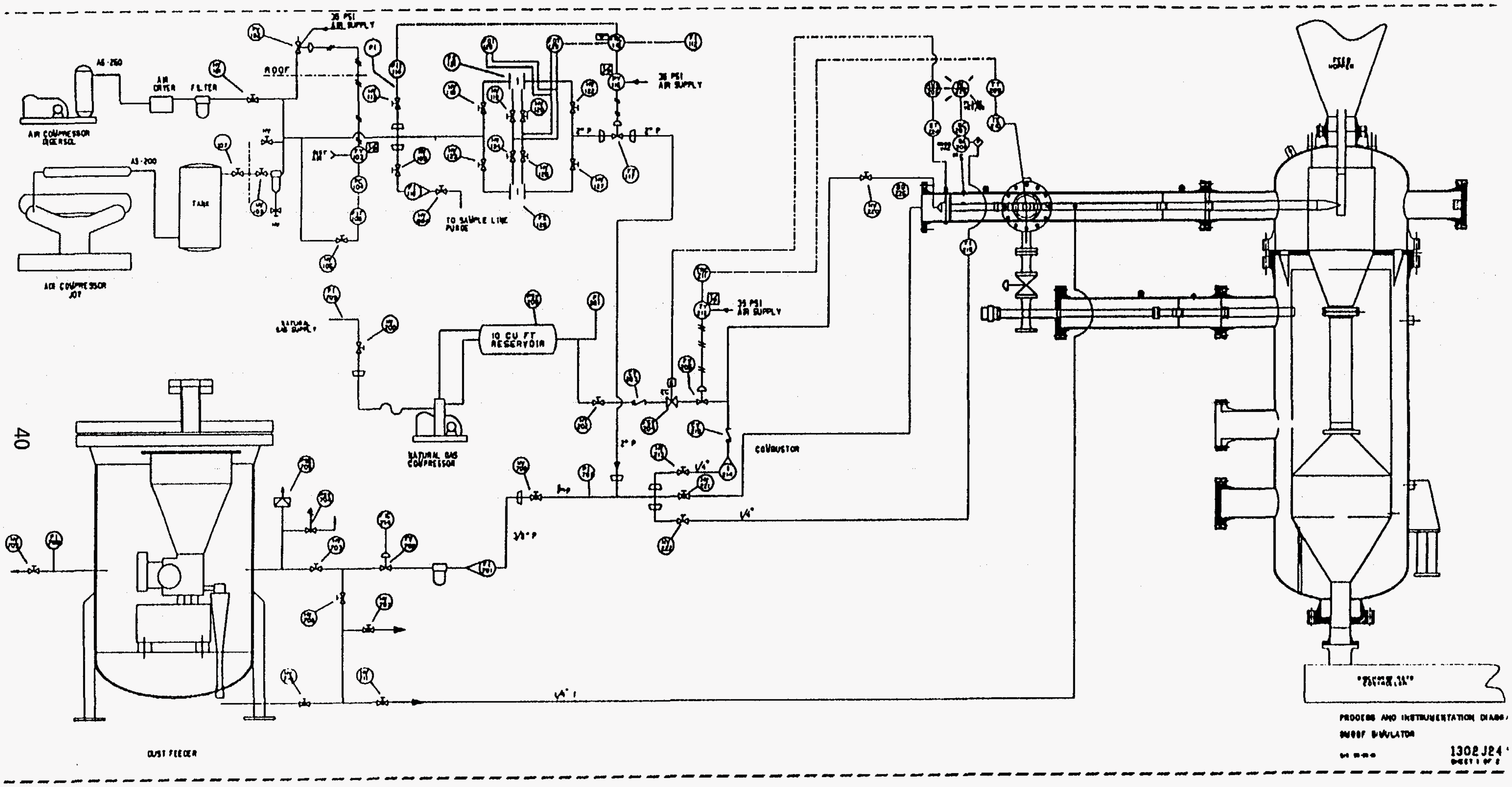


Figure 5.4 - HTHP Unit Conceptual Layout and P&ID

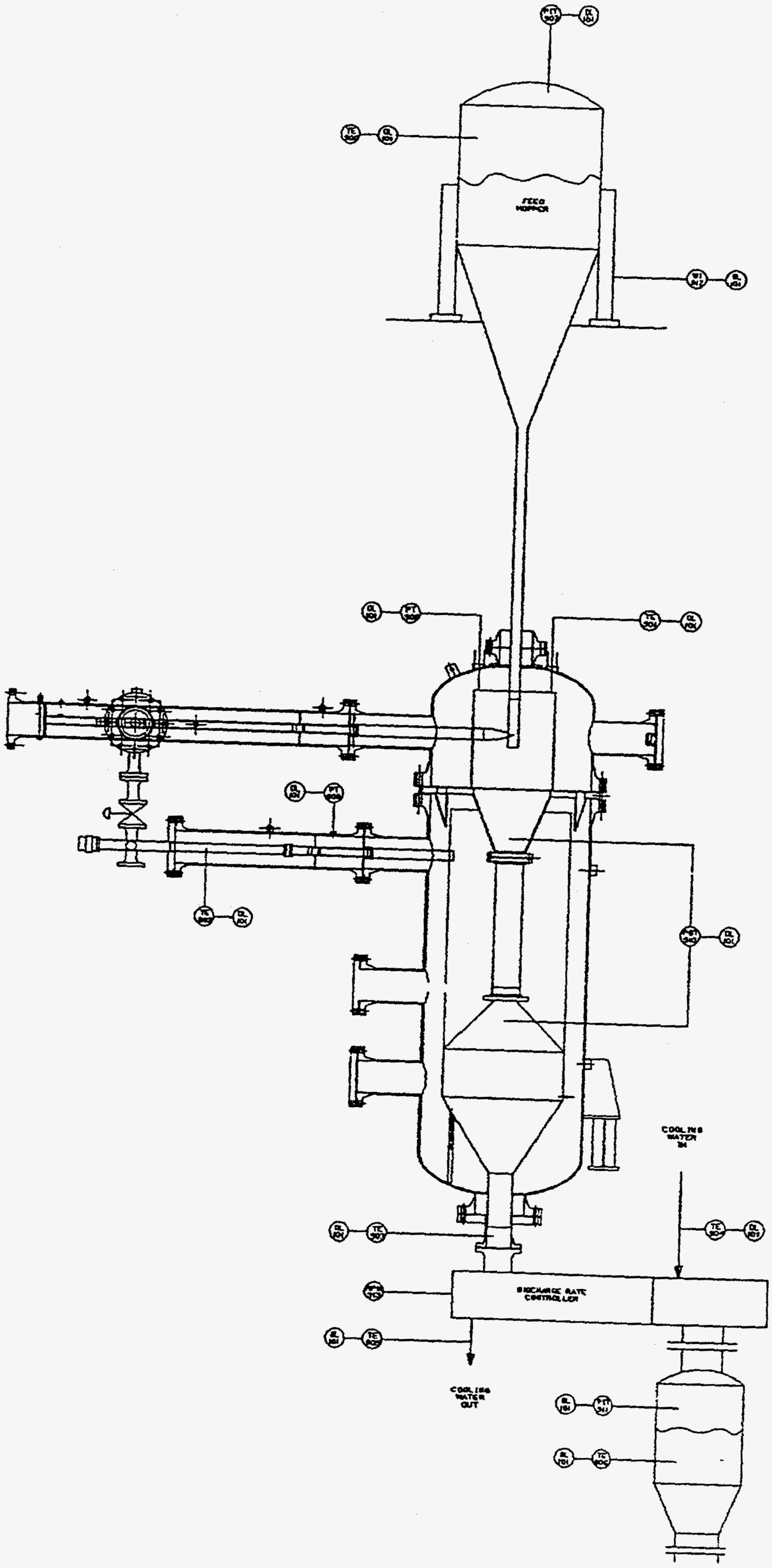


Figure 5.5 - HTHP Facility Arrangement and P&ID

6. COLD FLOW TESTING

6.1 Objectives, Parameters and Procedures

The Option 1 cold flow tests were performed to:

- test the effectiveness of advanced SMGBF design features,
- characterize the performance of alternative bed media,
- characterize the performance of partially-cleaned, recycled bed media,
- characterize SMGBF performance at higher standleg gas velocities.

The parameters varied in the testing were:

- the SMGBF configuration,
  - bed media recycle mode simulation
  - with and without topping bed
- the skirt design (perforated or solid),
- the bed media/fly ash mass ratio,
- the type of bed media (crushed acrylic or dead-burned dolomite),
- the standleg gas velocity.

The gas velocities selected for the testing cover the range of permissible parameters based on economic competitiveness with ceramic barrier filters. The bed media to fly ash mass flow ratios represent values that can be economically achieved in PFBC and IGCC applications, although they are much lower than normally used in granular bed filters.

The operating and design conditions were limited as outlined below:

- pressure: 15 psia
- temperature: less than 100°F
- Operating modes: recycle mode simulation
- Gas face velocities: 3 to 7 ft/s through the standleg
- Media/fly ash mass ratio: 9 to 15

- Inlet fly ash loading: 2200-6500 ppmw
- Bed media material: crushed acrylic and dead-burned dolomite,
- Fly ash material: PFBC fly ash

The gas flow, solids flows (fly ash and media), and pressure drop across the standleg were continuously monitored. The fly ash mass rate delivered was determined through mass balance on the loss-in-weight dust feeder. The gas flow was measured with a turbine flow meter and the bed media flow determined from the weight gain in the 55-gal drum located at the outlet of the screw feeder. From those measurements, the fly ash loading, the standleg gas velocity, and the moving bed velocity can be derived.

The primary test program consisted of tests with fly ash injection. The fly ash collection efficiency was evaluated by the difference between the fly ash delivered and the fly ash collected in the exhaust gas baghouse. Similarly, the fly ash loading in the inlet gas can be calculated from the fly ash delivered and the gas flow rate.

Before testing, the fly ash feeder was calibrated with the fly ash to be used in the tests. The screw feeder for bed media flow control was also calibrated by feeding bed media into a 55-gal drum on a weight scale. The air flow into the cold flow unit was measured with a calibrated turbine flow meter.

The testing was performed with PFBC fly ash from the Exxon Miniplant and was the same fly ash used in the Base Contract cold model testing. Two bed media were used, the same acrylic media tested in the Base Contract cold flow testing, and a commercial dead-burned dolomite. The significant physical properties of these test materials were:

Fly ash (PFBC): mass-mean size 3-6 μm, aerated bulk density 47 lb/ft^3;
Acrylic media (crushed): mass-mean size 3500-3900 μm, particle density 69-74 lb/ft^3;
Dead-Burned dolomite: mass-mean size 5500 μm, particle density 215 lb/ft^3.

6.2 Test Results

The first cold flow test was completed in August 1994 employing the standard standleg configuration with a conical skirt at the bottom and no topping bed. The skirt was constructed from a perforated sheet with holes 0.117 in diameter staggered on 0.156 in centers and an open area of 51%. The superficial standleg gas velocity was 3 ft/s and the bed material was clean, crushed acrylic. The test lasted more than 5 hours. The total bed material drained was 215 lb and the total dust delivered was 18.3 lb, making a bed media/dust ratio of approximately 12. Dust penetration was worse than the case where the conical skirt had no holes. This design feature was eliminated from further consideration.

A core sampling device consisting of two concentric tubes with a 19-mm slit cut along the length of both tubes was fabricated and a core sampling technique was developed to explore the distribution of fly ash within the media bed. The sampling device is 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 miss-aligned such that no bed material can drop into the tube. With the sampling tube positioned at the desired location, the inner tube is rotated to align both slits and allow bed material to drop into the sampling device. Again, the tube is rotated to close off the slits and the tube is withdrawn. The bed material is withdrawn from the tube in sections of 51 mm intervals and the concentration of fly ash determined by sieving through a 120 mesh screen.

Core samples were taken during tests with the acrylic media, for configurations with and without the topping bed in operation. The probe was inserted at a location several inches below the standleg exit height after the media bed had operated long enough to reach a steady-state condition. Figure 6.1 displays the sampling results for the two cases, showing the dust concentration (wt% ash in the media) as a function of the fractional distance from the vessel centerline. With no topping bed in operation, the dust concentration is highest at the radial location of the outer wall of the standleg, but a substantial dust concentration exists throughout. The standleg results in a much more uniform concentration of ash across the media bed, with the concentration a the outer wall of the standleg reduced compared to the case with no topping bed. Since dust reentrainment occurs primarily at the location at the outer wall of the standleg, the topping bed promotes a dust concentration profile that results in reduced ash penetration.

A qualification test was also run with dead-burned dolomite as an alternative bed media, using the standard standleg design with a solid skirt that was tested in the Base Contract period. Dust penetrations were as low as they had been with the crushed acrylic bed media, qualifying the dead-burned dolomite for additional testing.

A series of cold flow tests with a continuously fed, topping bed of clean acrylic material was started during January 1995. The acrylic material was partially cleaned using a vibrating separator and was used as the topping bed in the following series of tests with no degradation in performance. The vibrator removed about 90% of the fly ash from the bed media, operated in a high-throughput mode.

The next cold flow test series, using dead-burned dolomite as bed media, was started in April, 1995, repeating the major test points performed with acrylic media. Performance with the dead-burned dolomite was at the same levels as the acrylic media, operating at standleg gas velocities exceeding 6 ft/s. The cold flow test program was completed in May, 1995.

The cold flow test results are summarized in Table 6.1. The filtration and pressure drop performance of the granular bed is sensitive to the relative volumetric flows of bed media and fly ash. Larger ratios of media volumetric flow over the fly ash volumetric flow should result in lower pressure drops and lower dust penetrations. With a fixed ratio of media-to-ash volumetric flows, the dust penetrations should be independent of the inlet dust loading to the granular bed filter, and the dust removal efficiency should increase as the inlet loading increases. Thus, the dust removal efficiency is not a meaningful performance measure.

The cold flow tests were performed with very low feed ratios of bed media-to-dust, especially since a portion of the media feed went directly to the topping bed. The feed ratio to the standleg may have been as small as half of the total feed ratio for the unit. In these tests, the gas velocity greatly exceeded the media velocity, the velocity ratio being 4,000 to 60,000, providing conditions for effective ash particle impaction on the media particles.

The depth of the topping bed used (5-inches) was substantially less than used in the Base Contract cold flow testing (25-inches), and resulted in greater particle penetration in this testing than was obtained during the Base Contract cold flow testing with a topping bed (e.g., about 24 ppmw versus < 1 ppmw in the Base Contract testing). The dust penetration measured was, none-the-less, considerably lower than that obtained without a topping bed (e.g., 21-24 ppmw versus about 60 ppmw in testing with no topping bed at comparable conditions).

The trends identified were:

- Dust penetration was about 20-30 ppmw with acrylic bed media, and 30-60 ppmw with dead-burned dolomite.
- The dust penetration was insensitive to the standleg gas velocity.
- The dust penetration was fairly insensitive to the use of a clean topping bed or a recycled, partially-cleaned topping bed.

Performance was better with the acrylic bed media than with the dead-burned dolomite media because of the much lower particle density of the acrylic (about 1/3 of the dead-burned dolomite density), the acrylic particle smaller particle size, and its much higher volumetric feed rate that resulted (note the volumetric media/ash ratios listed in Table 6.1).

Figures A.1 through A.27, in Appendix A, display the test data for each of the tests summarized in Table 6.1. Three figures are shown for each of the tests. The first plots the cumulative bed media weight withdrawn from the filter vessel, and the cumulative dust feed mass, against time. This graph shows the uniformity of the bed withdrawal and dust feeding during the tests. The second figure for each test point shows the standleg pressure drop plotted against time. Finally, the dust collection efficiency and dust penetration is plotted against time. In most cases, the tests appear to have closely approached steady-state conditions.

The conclusions drawn from the cold flow tests are:

- solid standleg skirts lead to dust penetration slightly lower than obtained with the specific perforated standleg skirt design tested -- alternative perforation configurations were not explored;
- the SMGBF should be operated with deeper topping beds and greater media/ash mass feed ratios if lower dust penetration is desired;

- dead-burned dolomite is an acceptable bed media under room-temperature conditions -- the dust penetration was larger than in the acrylic bed media tests because of the dead-burned dolomite larger particle size and its lower volumetric feed rate;
- operating with partially-cleaned recycle bed media yields dust penetration comparable to that with totally-clean media feed. It is still preferable that the topping bed feed media should be well cleaned;
- operation at high standleg gas velocities is constrained by the pressure drop rather than the dust penetration, the velocity having little influence on the dust penetration over the range tested -- it was shown in the Base Contract testing that fluidization of the disengaging surface bed media would not occur at standleg gas velocities at least up to 6 ft/s , exceeding the acrylic particle minimum fluidization velocity of 5 ft/s;
- The topping bed promotes a more uniform distribution of ash within the standleg discharge media, and this results in lower dust penetration than obtained without a topping bed;

Table 6.1 - Cold Model Test Results with Continuous Topping Bed

Bed Media	Test No.	Media-To Dust Ratio* (mass)	Media-To Dust Ratio* (volume)	Standleg Velocity (ft/s)	Pressure Drop (in. H_2O)	Dust Penetration (ppmw)
Clean Acrylic	1	9	18	3.0	27	24
	2	9	18	4.9	57	22
	3	9	18	7.2	115	25
Recycled Acrylic	4	10	20	3.1	39	21
	5	13	26	5.0	70	29
	6	14	28	7.2	119	27
Dead-burned Dolomite	7	12	9	3.3	48	33
	8	8	6	5.0	66	59
	9	8	6	7.0	90	42

*Note: Media feed is split between the standleg and the topping bed.

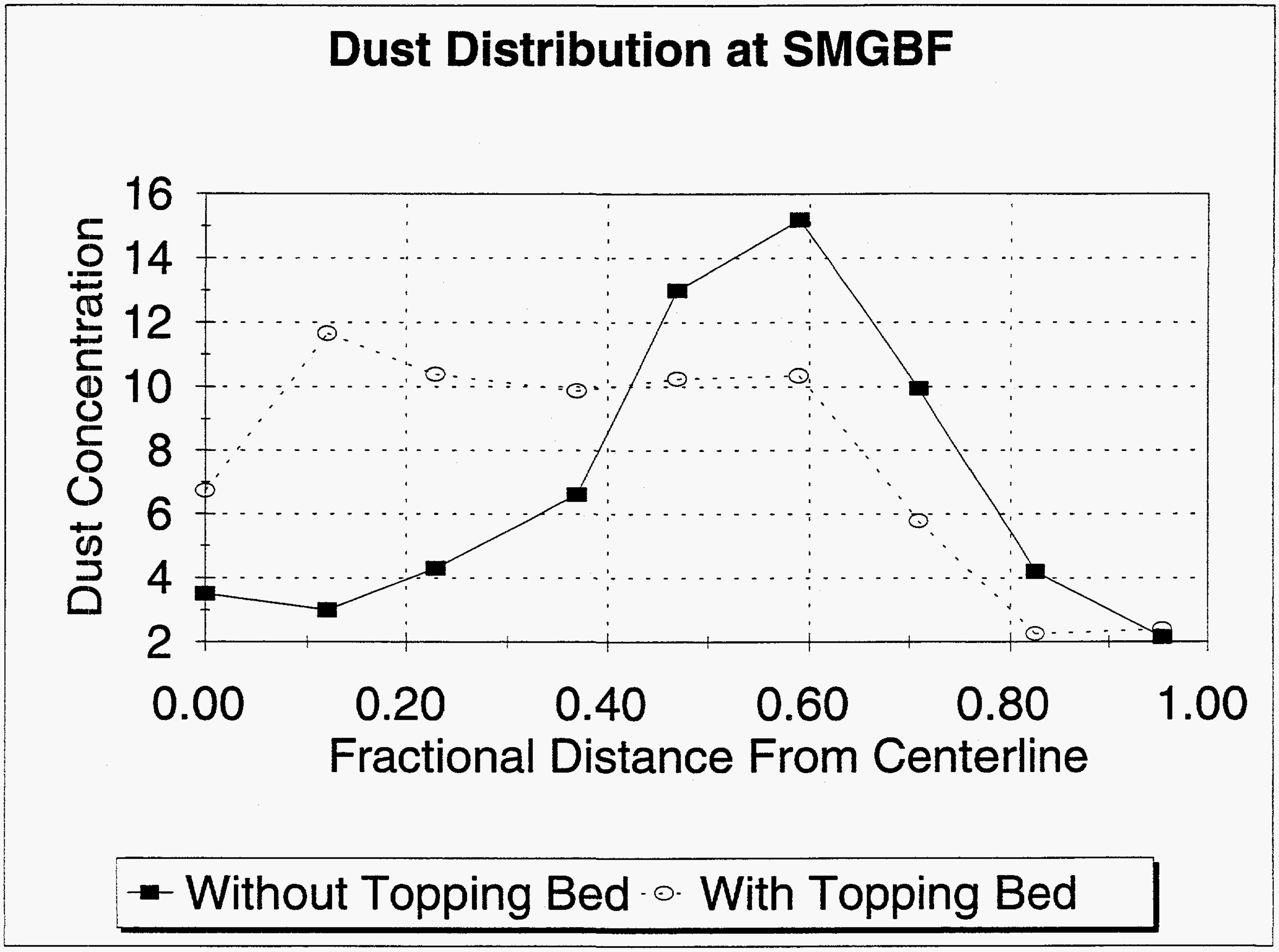


Figure 6.1 - Core Sampling Dust Spatial Distribution

7. HTHP TESTING

7.1 Objectives, Parameters and Procedures

The objectives of the Option 1 HTHP tests were:

- Demonstrate the HTHP performance of the basic SMGBF design, using a simple standleg with a solid skirt,
- Demonstrate acceptable fly ash removal at commercially acceptable, and representative operating conditions, using
  - dead-burned dolomite as bed media
  - simulated Recycle-SMGBF by recycling partially-cleaned bed media
  - parametric values of standleg gas velocity and media/ash feed ratio

The primary test program consisted of tests with fly ash injection representative of the Recycle-SMGBF operating modes. Five HTHP tests were completed. Standleg gas velocities up to 6 ft/s and media-to-ash mass flow ranges similar to the cold model tests were used. The fly ash inlet loadings ranged from 500 to 1100 ppmw in the five tests. As in the cold flow tests, the gas velocities were much larger than the media velocities, with the gas-to-media velocity range being 15,000 - 120,000.

The HTHP equipment was modified to improve the general test operation of the facility. The HTHP testing was performed using PFBC fly ash injected into the HTHP gas stream. The HTHP test system was operated under oxidizing conditions, but at temperatures more representative of gasification than of PFBC. The basic concept feasibility, primarily based on particle penetration, pressure drop, and operability were demonstrated at representative conditions using economically-limited test variables.

All gas flow, bed media flow, fly ash flow rate, pressure drop across the standleg, and key temperatures were monitored. The fly ash delivered was determined through mass balance on loss-in-weight dust feeder. The gas flow was measured with a turbine flow meter, and the average bed media flow determined from the weight change of the bed media collection hopper over the duration of each run. From those measurements, the fly ash loading, the gas face velocity, and the media/ash feed ratio were derived.

Pressure drop across the standleg and the absolute pressure at dirty gas inlet and clean gas outlet was measured with pressure transducers and recorded for further analysis. The fly ash penetration was evaluated by isokinetic sampling of the outlet gas stream.

All of the Option 1 HTHP testing was performed with commercial dead-burned dolomite, a cheap, highly available bed media material. This was the same material tested in the Option 1 cold flow testing. Its mass-mean diameter was about 5500 μm and its particle density about 214 lb/ft^3. Two fly ashes from PFBC testing were used in the HTHP testing. A very fine Grimethorpe PFBC filter fly ash (mass-mean diameter 1-3 μm, bulk density 24 lb/ft^3) was used as well as a coarser Tidd PFBC filter fly ash (mass-mean diameter 25-30 μm).

This material was subjected to high-temperature attrition testing to quality it for HTHP testing. These tests were performed in the same attrition rig that had been used in the Base Contract Program to test bed media ash pellets. Its design and operation was described in the base Contract Final Report (Moving Granular-Bed Filter Development Program, Base Contact Final Topical Report, R. A. Newby, et al., April 1994, DOE/MC/27259-3797; DE94004149). The dead-burned dolomite was subjected to rotary attrition testing conducted at standard test conditions for 1800 revolutions with no baffle in the unit. Testing was performed both at room temperature and at 1500°F. The test results are listing in Table 7.1, showing that very little attrition loss occurred, and losses were not increased by increased temperature. These results were comparable to attrition results obtained in the Option 1 testing for the HTHP bed media Aardelite (commercial fly ash pellets) where the losses ranged from 0.2 to 12.5% over a range of test conditions in the attrition rig.

7.2 Test Results

HTHP testing started in July 1995, following conversion of the equipment, installation of a new bed media feed hopper, and high-temperature attrition testing of the dead-burned dolomite. A simple standleg with a solid, conical skirt was tested using dead-burned dolomite as bed media. The dead-burned dolomite had the same particle size distribution as that used in the cold model testing. Testing was performed in 5 campaigns, two being at room-temperature conditions, and three being at high-temperature conditions. Table 7.2 outlines the main features of the test campaigns, listing nominal test conditions. Table 7.3 summarizes the test performance and provides comments on observations made. Figures 7.1 - 7.15 are plots of test data from the runs, showing a record of media/ash mass feed ratio, pressure drop and inlet and outlet dust loading for each test. A total of about 335 hours of high-temperature testing was completed, as well as about 172 hours of cold testing.

The initial run conditions were:

- bed temperature - 1000°F
- pressure - 100 psig
- inlet dust loading - 1000 ppmw
- standleg gas velocity - 3 ft/s
- bed media-to-ash mass ratio - 10-15.

One-hundred (100) hours of accumulated, high-temperature test time were completed with the outlet dust loading ranging from 0.1 to 5 ppmw. As in all the HTHP tests, the pressure drop varied significantly from day to day due primarily to variations in the fly ash feed rate and media withdrawal rate. The unit pressure drop increased continuously throughout the first test run. A blockage in the bed media flow occurred, stopping the test. The unit was inspected and blockages in the media feed line and the standleg were found. They appeared to result from condensation of moisture that occurred at the hot-cold interface of the bed media feed pipe. Because of these blockages the test results from this run are probably not representative of steady, normal operation.

The unit was cleaned out and refilled with dead-burned dolomite. In Test 2, 140 hours of cold flow tests in the HTHP unit were performed in September, 1995, and options to prevent condensation were assessed. In this test, the same conditions were use as in the prior HTHP tests, but with the filter held at room temperature. Media flow through the unit was smooth and continuous. Dust outlet samples were collected and ranged from 5 to 35 ppmw during the bulk of the test. The high dust penetration in this cold test is higher than that obtained in the first, hot test, but the temperature difference is probably less significant to the penetration differences than the blockages occurring in the first test. The pressure drop was relatively stable throughout this run. The term "stable" is used to describe a pressure drop record that did not show a long term trend to increase or decrease, even though the pressure drop fluctuations were sizable compare Figures 7.2 and 7.5).

HTHP tests resumed during October, 1995. The same conditions used previously were applied in Test 3. Condensation was eliminated by using a constant nitrogen purge through the media feed hopper. During October and November 1995, more than 120 operating hours were compiled, with outlet dust loadings of 3-15 ppmw. On November 17, testing was halted and the unit was cleaned out after a blockage of the vessel hopper drain nozzle occurred. The unit was refilled with dead-burned dolomite.

In December, 1995 the test conditions were changed to test higher standleg gas velocities (up to 6 ft/s). A short cold test was first performed (Test 4). The particle penetration was relatively high and the bed pressure drop exceeded the instrument capability (200 in-wg). Hot testing resumed in Test 5 at a lower standleg gas velocity range of 3.5 to 4.5 ft/s. Particulate removal continued to be good, although not as good as at lower standleg gas velocities. In January, the media-to-ash feed ratio was doubled and operation continued at the high standleg gas velocity. This resulted in reduced dust penetration, and lower pressure drop.

All HTHP testing was completed in January, 1996. The unit was drained and inspected and found to be free of any agglomerates and mechanically in good condition.

The minimum performance goals for the HTHP unit testing were estimated based on typical PFBC and IGCC process performance calculations and representative emission standards. The minimum performance goals interpreted for PFBC and IGCC (air-blown gasifier) applications, are:

	PFBC	IGCC
pressure drop (psi)	3-4	6-9
dust penetration (ppmw)	< 20	< 100

Turbine protection standards may be more stringent than the emission standards for particulate, depending on the turbine design.

The HTHP unit pressure drops were larger than those measured in the Base Contract testing because the bed media had a smaller size distribution in the Option 1 testing (dead-burned dolomite of irregular shape with size range -5/16-inch +8 mesh; mean about 5500μm) compared to the Base Contract bed media Aardelite fly ash pellets of fairly spherical shape with size range -1/2-inch +1/8-inch; mean about 8000 μm). The dust penetration was comparable to that measured in the Base Contract HTHP testing (8 to 14 ppmw). It is likely that coarser bed media can be used, decreasing the bed pressure drop while maintaining acceptable dust penetration based on the Base Contract test results. General granular bed filter testing suggests that coarser media will probably result in greater ash penetration

The use of a cheap bed media, dead-burned dolomite was found to be acceptable in the HTHP tests, corroborating the cold model test results. The recycling of partially-cleaned bed media was also found to result in acceptable dust penetration.

Using the simple standleg design with a solid skirt, the SMGBF can meet IGCC performance requirements at standleg gas velocity up to about 4 ft/s, with media/ash feed ratios as low as 10. Likewise, the SMGBF can meet PFBC performance requirements at standleg gas velocity up to about 3 ft/s, with media/ash feed ratio as low as 20. Operating with higher media/ash feed ratios will reduce the SMGBF pressure drop as well as allow higher standleg gas velocities to be used. The HTHP test results seem to differ from the cold flow test in two respects:

- The dust penetration measured in the HTHP tests seemed to show more sensitivity to standleg gas velocity than was found in the cold flow tests.

- The HTHP testing indicates that higher media/ash feed ratios will result in lower dust penetration, where this was not observed in the cold flow tests.

No explanations for these differences between the HTHP tests and the cold flow tests have been identified, except to note that these are approximate trends shown by the data that may relate to many of the other differences in the tests other than those due to the primary variable. All of the testing was will PFBC fly ashes, and no testing with IGCC fly ashes were performed. No significant differences in SMGBF with IGCC fly ash would be expected due to morphology differences that might exist between PFBC and IGCC fly ashes.

Table 7.1 - Dead-Burned Dolomite Attrition Test Results

Attrition Conditions: 70°F for 1800 revolutions

Size (in.)	Original Sample		Sample After Attrition	
	Weight (gm)	Weight %	Weight (gm)	Change in Weight %
> 0.25	10.27	29.07	8.26	-5.69
0.25-0.11	24.97	70.68	26.36	3.93
0.11-0.066	0.09	0.25	0.22	0.37
0.066-0.033	0	0	0.07	0.20
< 0.033	0	0	0.24	0.68
Total	35.33	100	35.15	

Attrition Conditions: 1500°F for 1800 revolutions

Size (in.)	Original Sample		Sample After Attrition	
	Weight (gm)	Weight %	Weight (gm)	Change in Weight %
> 0.25	10.92	30.78	10.14	-2.20
0.25-0.11	24.48	69.00	24.49	0.03
0.11-0.066	0.05	0.14	0.19	0.39
0.066-0.033	0.02	0.06	0.08	0.17
<0.033	0.01	0.03	0.27	0.73
Total	35.48	100	35.17	

Table 7.2 - HTHP Campaign Characteristics

Test No.	Date	Bed Media/ Ash type	Duration (hr)	Inlet dust (ppmw)	Temperature (°F)	Pressure (psig)	Media/ash mass ratio (mean)	Standleg gas velocity (ft/s)
1	7/18/95 - 8/4/95	DB dolomite/ Grimethorpe PFBC	96	900	1000-1100	100	15	2.5-3.0
2	9/6/95-10/6/95	DB dolomite/ Tidd PFBC	145	1100	75	20	13	2.7-3.7
3	10/10/95-11/16/95	Recycled DB dolomite/ Tidd PFBC	115	1100	750	100	12	2.0-2.5
4	12/5/95-12/8/95	Recycled DB dolomite/ Tidd PFBC	27	500	70	20	10	6.0
5	12/11/95-1/31/96	Recycled DB dolomite/ Tidd PFBC	110	500-1000	700	100	11, 25	3.5-4.5

Table 7.3 - HTHP Test Results

Test No.	Dust Penetration (ppmw)	Pressure Drop (in-wg)	Comments
1	0.1 - 5 mean 3*	55 - 170	Pressure drop generally increased after first 25 hours. Blockage found in bed.
2	1 - 3 (initial period when media/ash very high) 5 - 35 (mean 20*) remainder of test	38 - 90	Pressure drop uniform over test
3	3 - 15 (mean 10*) Rises to 40 at end	40 - 50 (first 60 hours) 80-200 (remainder)	Pressure drop rises after 60 hours Blockage found in unit
4	50 - 155	> 200	High pressure drop, high dust penetration results from high gas velocity and low media/ash ratio
5	5 - 52 (mean 35*) first 40 hours 5 - 30 (mean 20*) remainder after doubling media/ash ratio	> 200 160 - 195	Benefits of higher media/ash ratios shown

*: time-averaged values

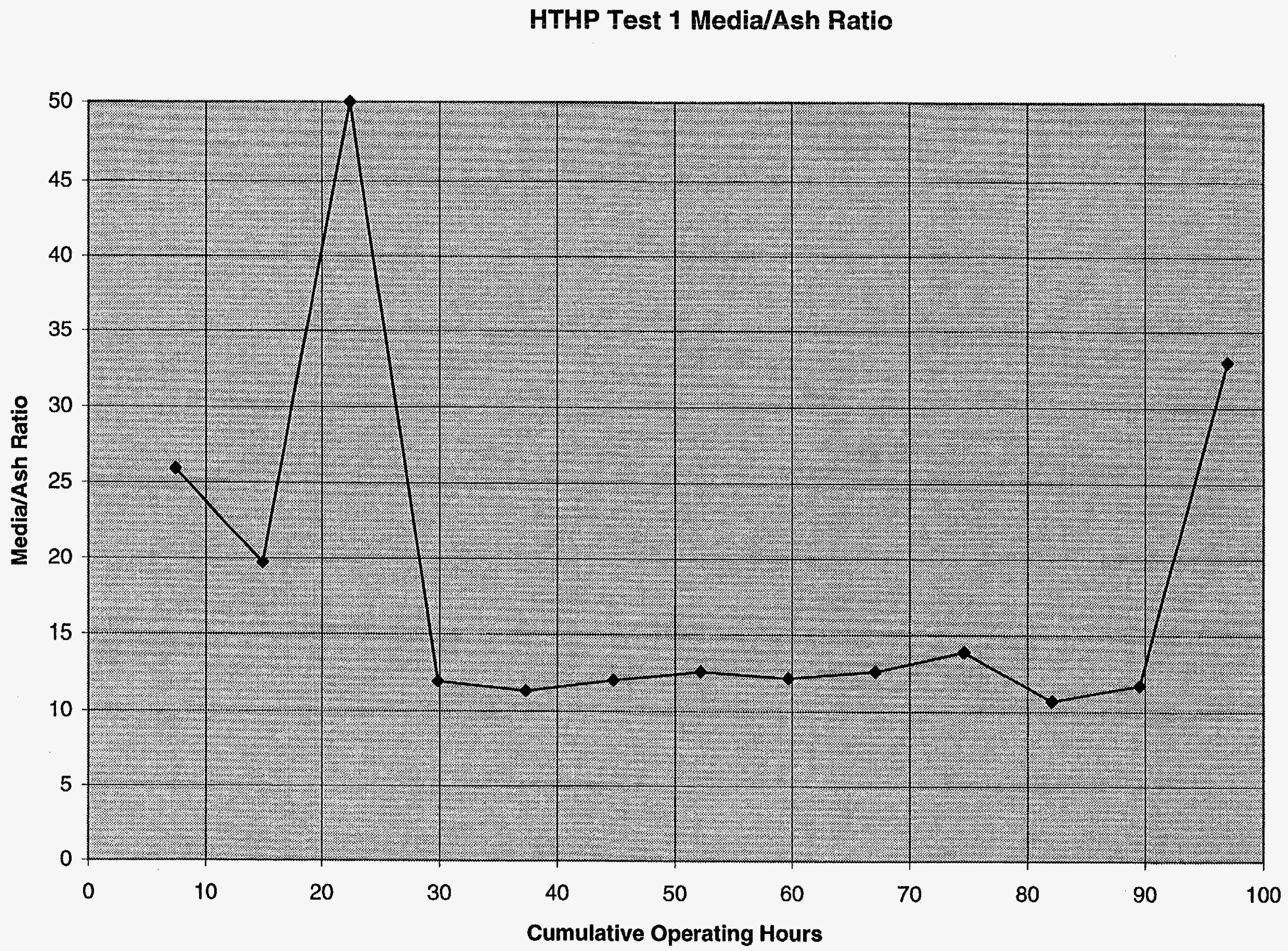


Figure 7.1 - HTHP Test 1 Media/Ash Ratio

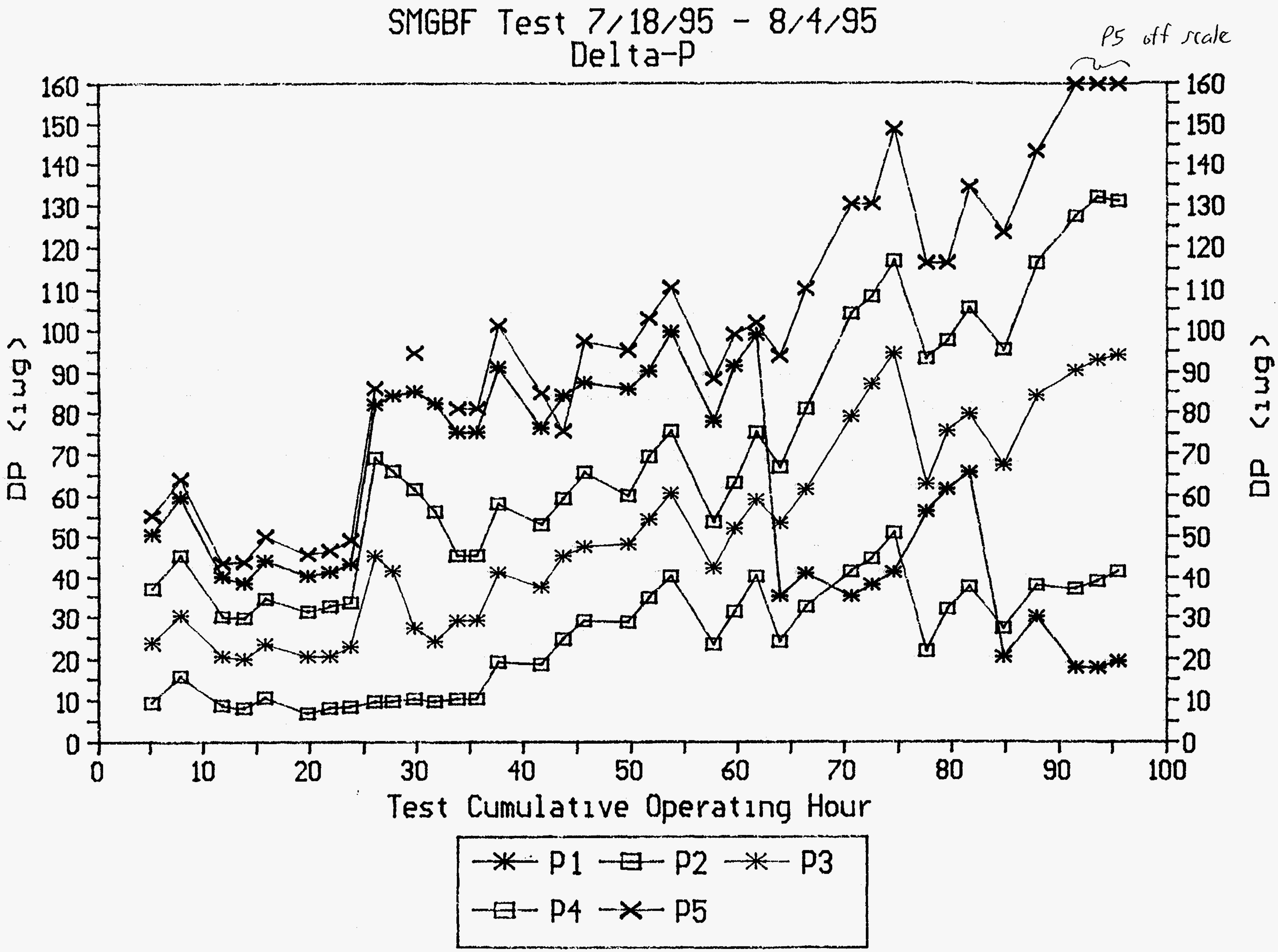


Figure 7.2 - HTHP Test 1 Pressure Drop Profiles

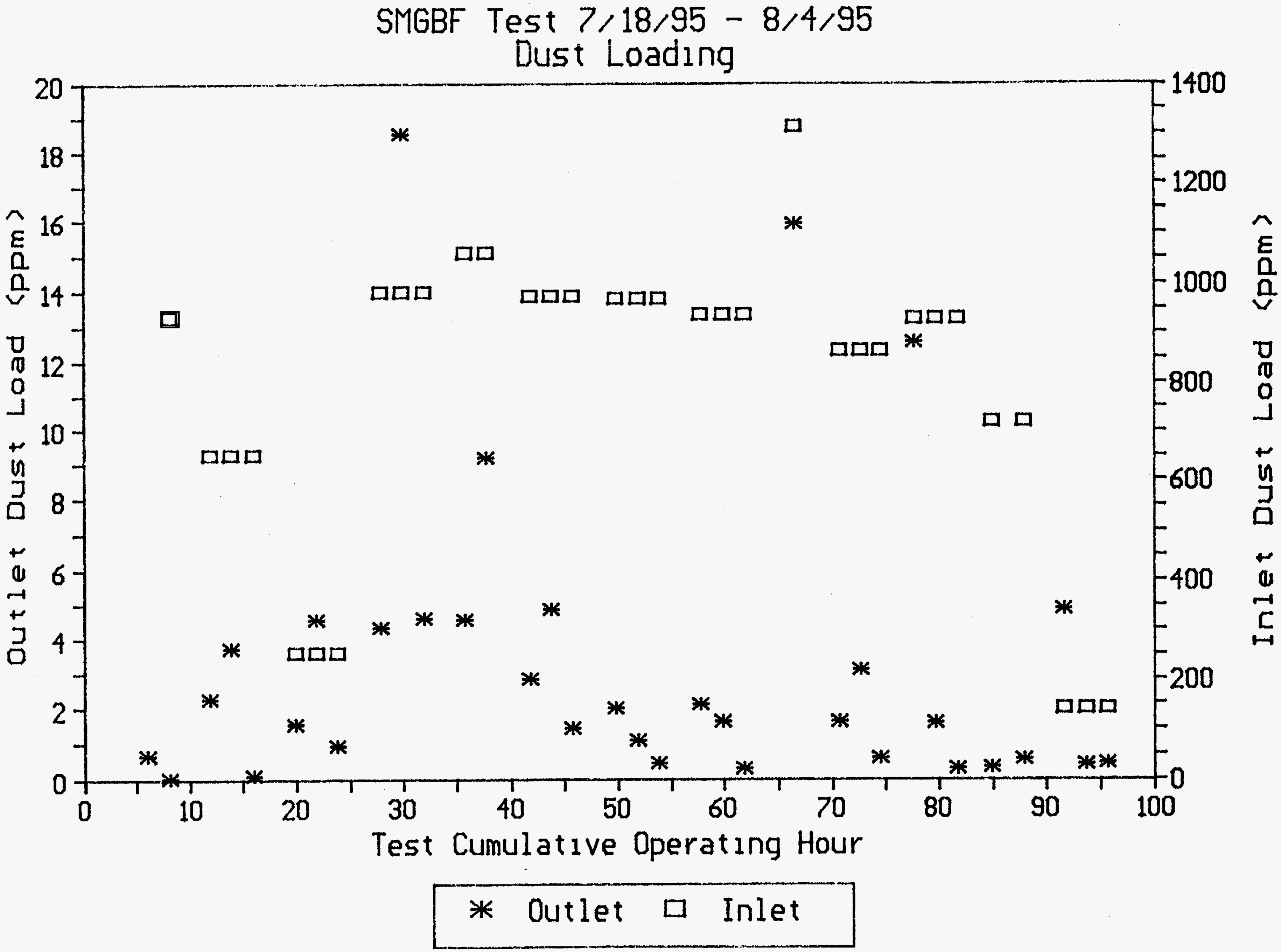


Figure 7.3 - HTHP Test 1 Inlet and Outlet Dust Loadings

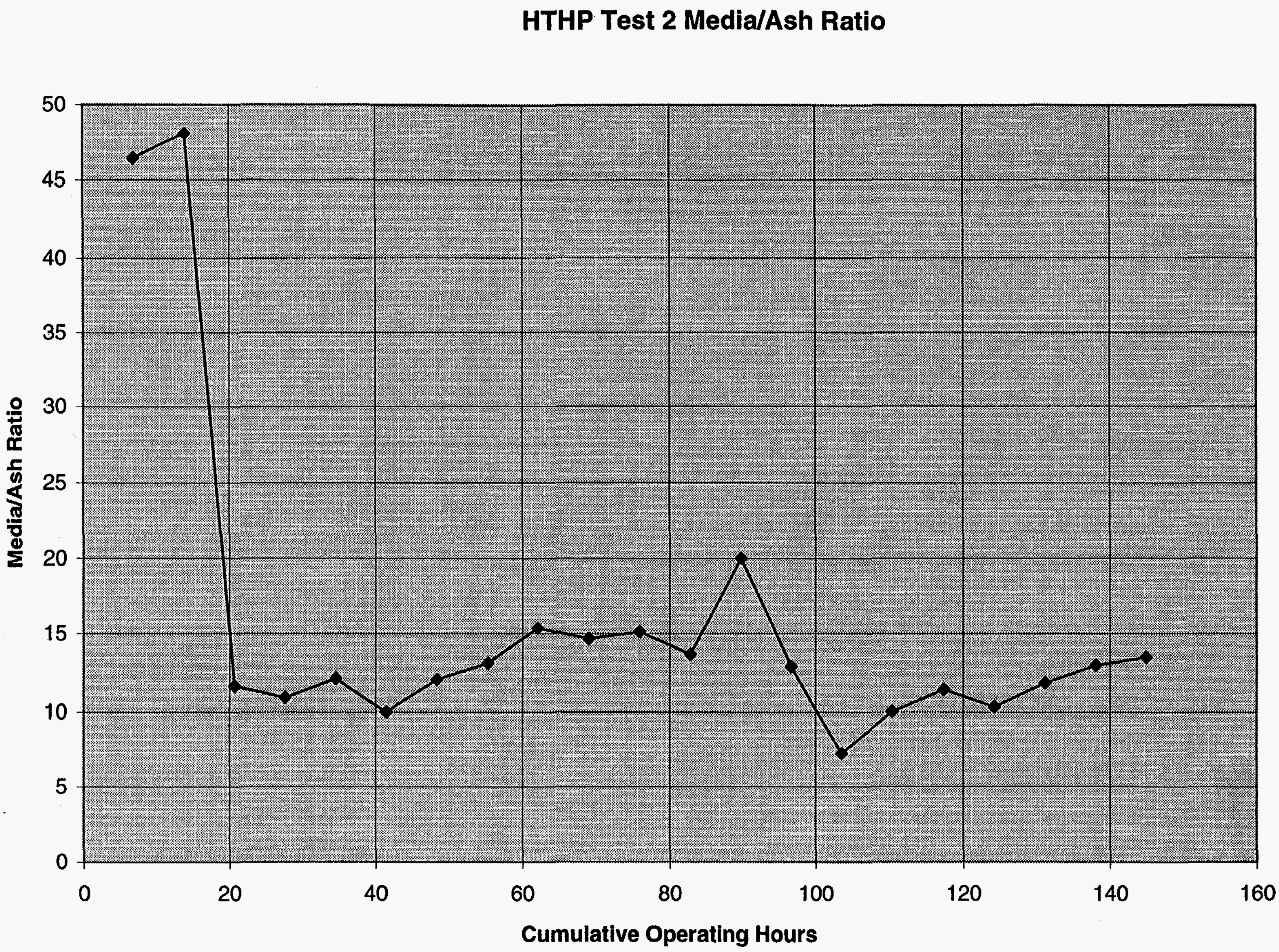


Figure 7.4 - HTHP Test 2 Media/Ash Ratio

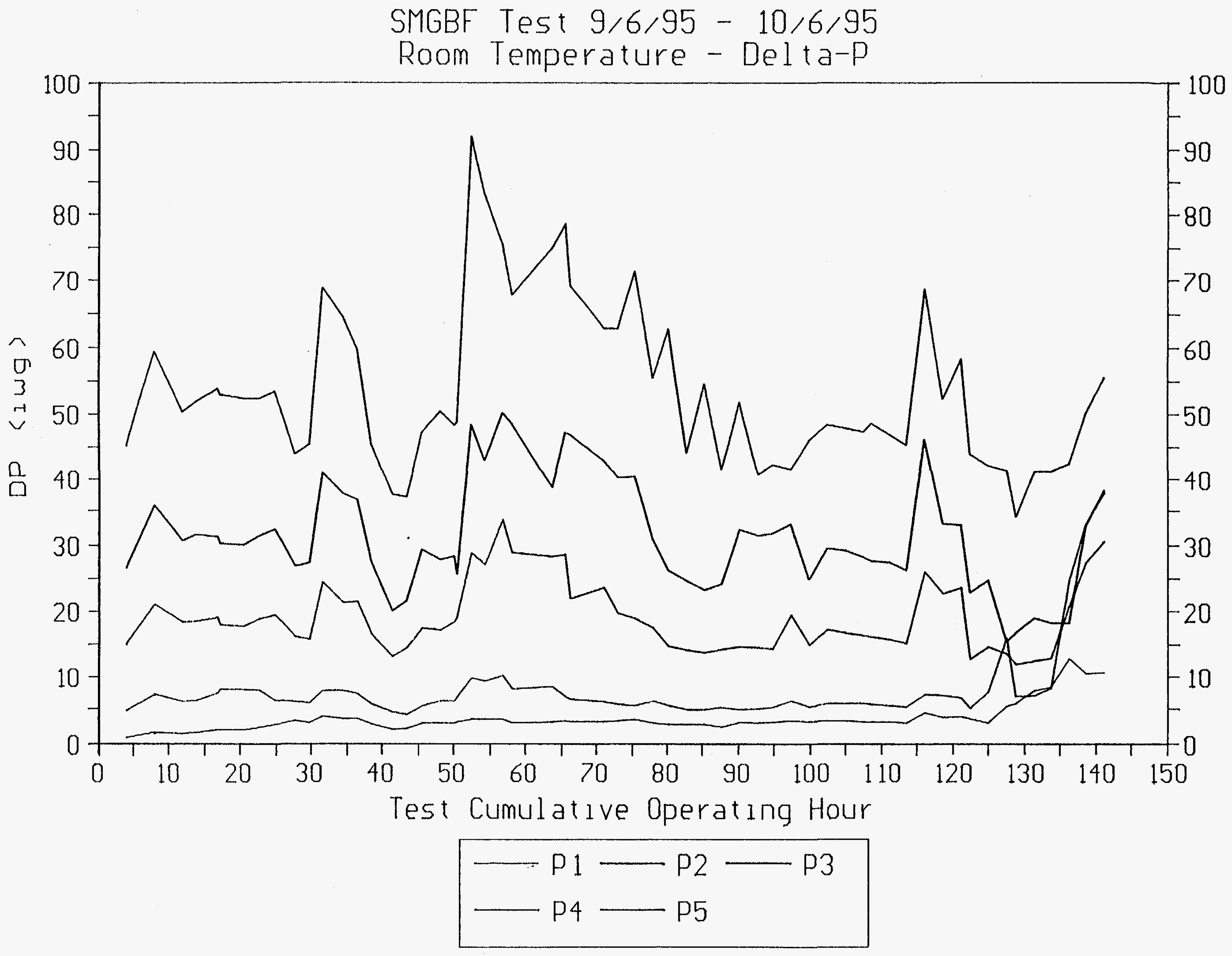


Figure 7.5 - HTHP Test 2 Pressure Drop Profiles

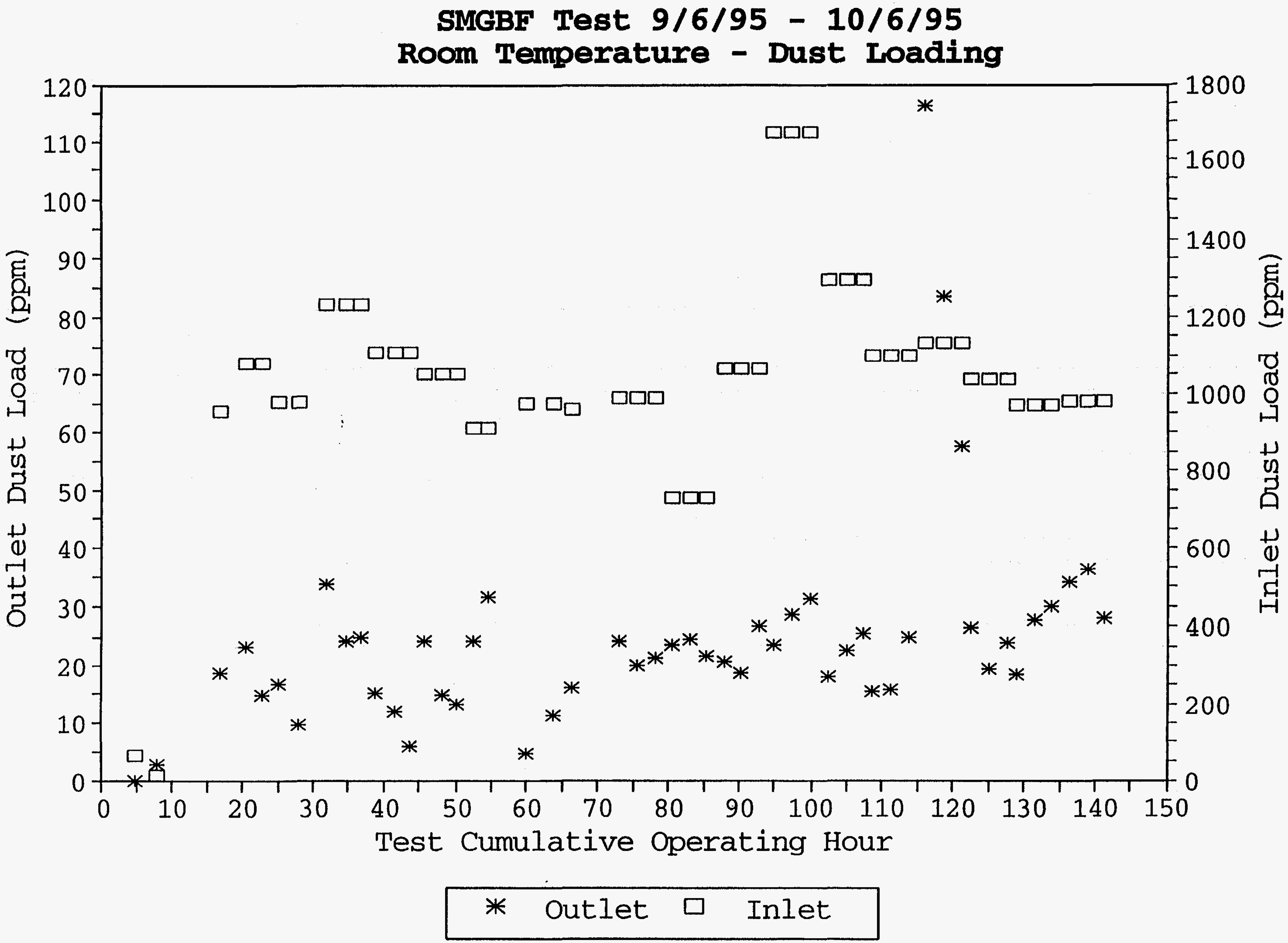


Figure 7.6 - HTHP Test 2 Inlet and Outlet Dust Loadings

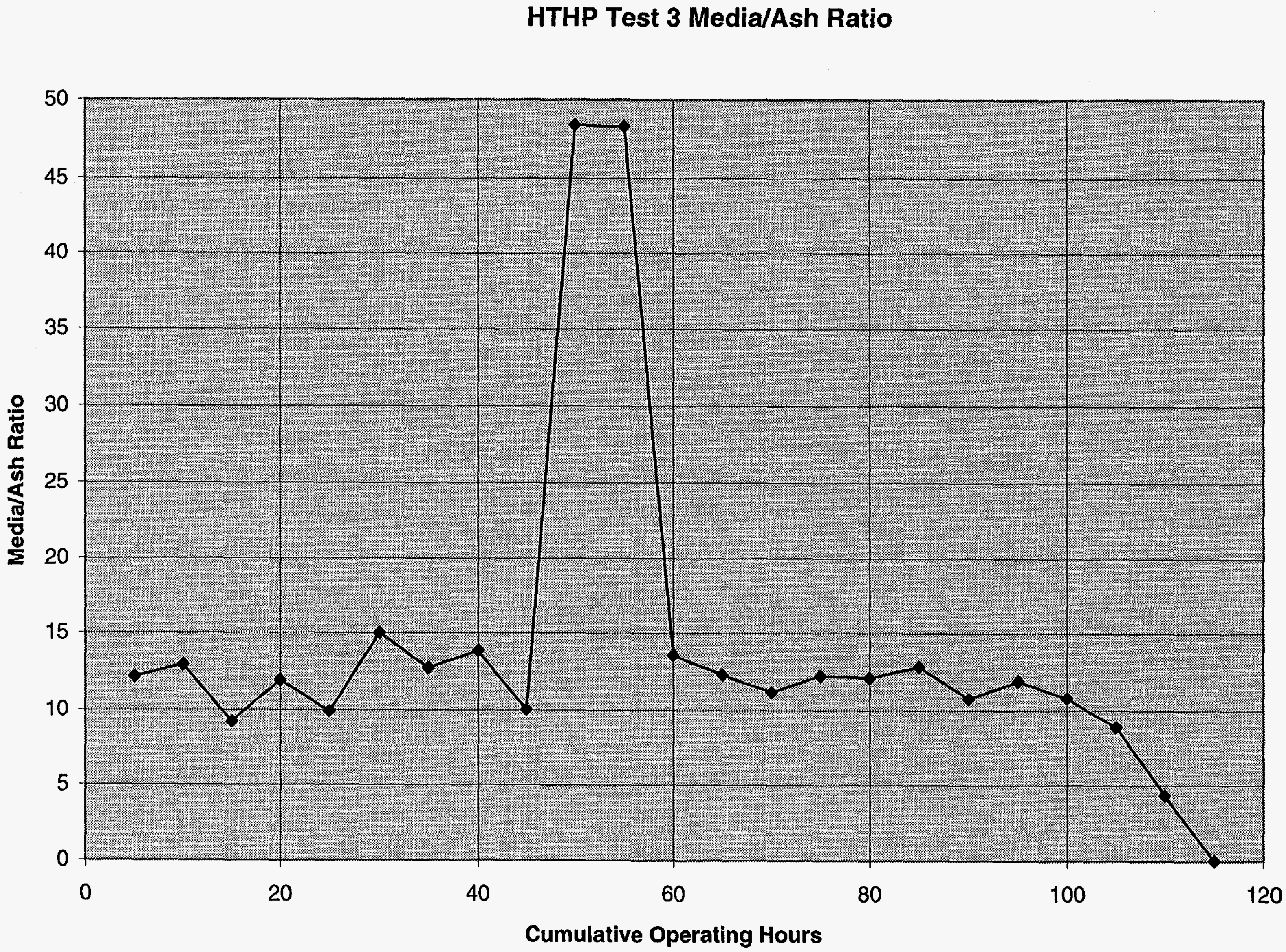


Figure 7.7 - HTHP Test 3 Media/Ash Ratio

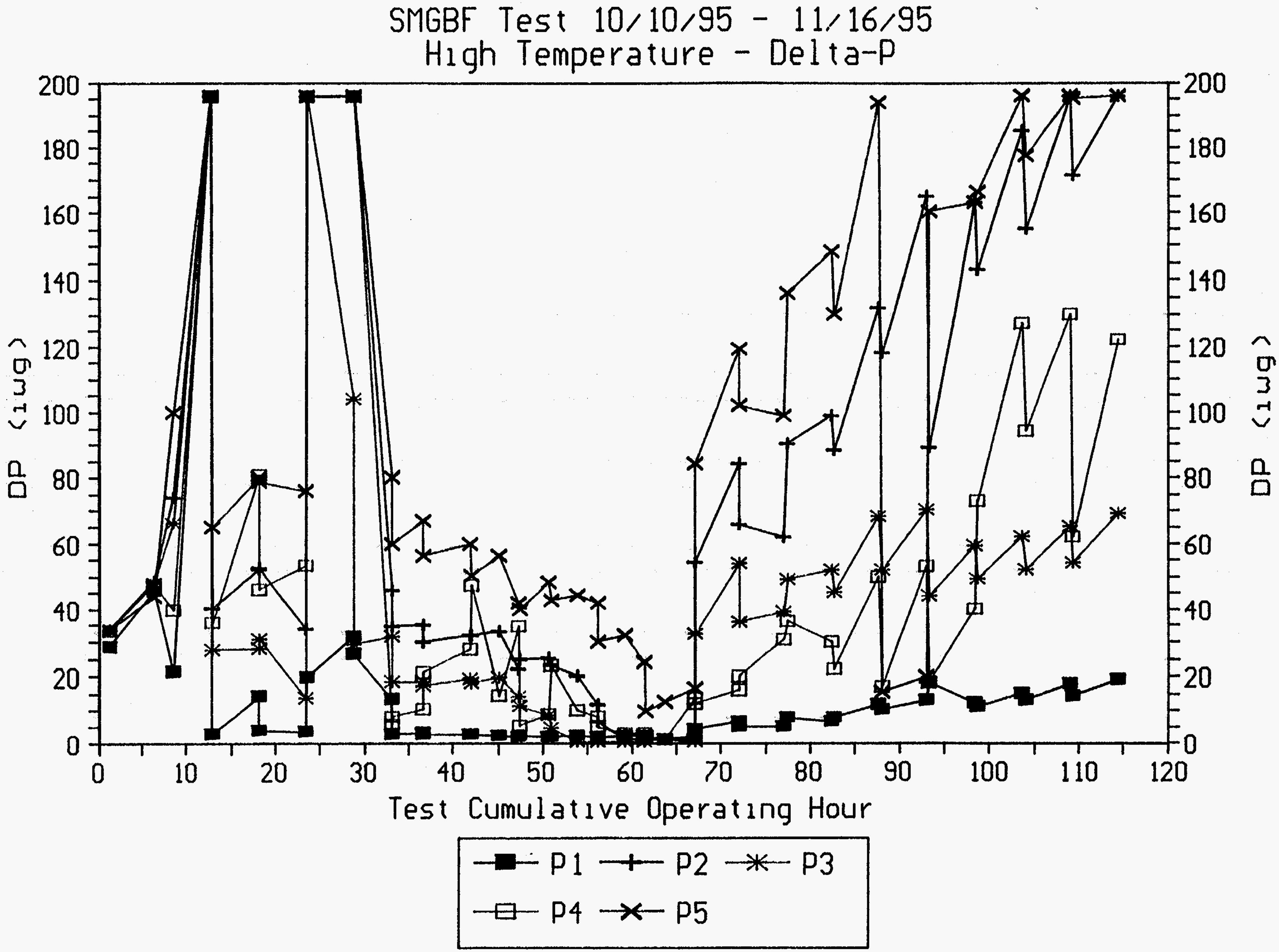


Figure 7.8 - HTHP Test 3 Pressure Drop Profiles

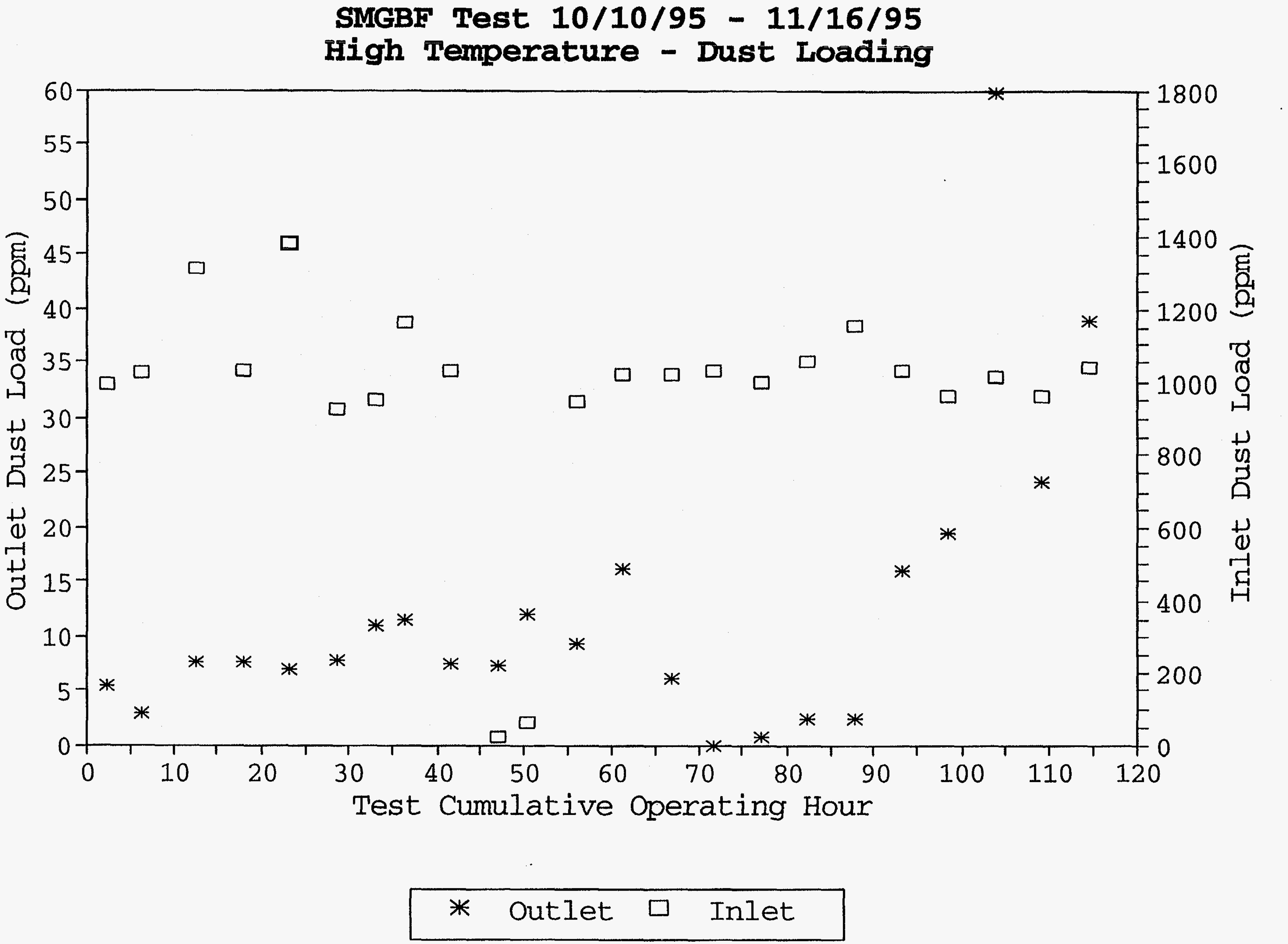


Figure 7.9 - HTHP Test 3 Inlet and Outlet Dust Loadings

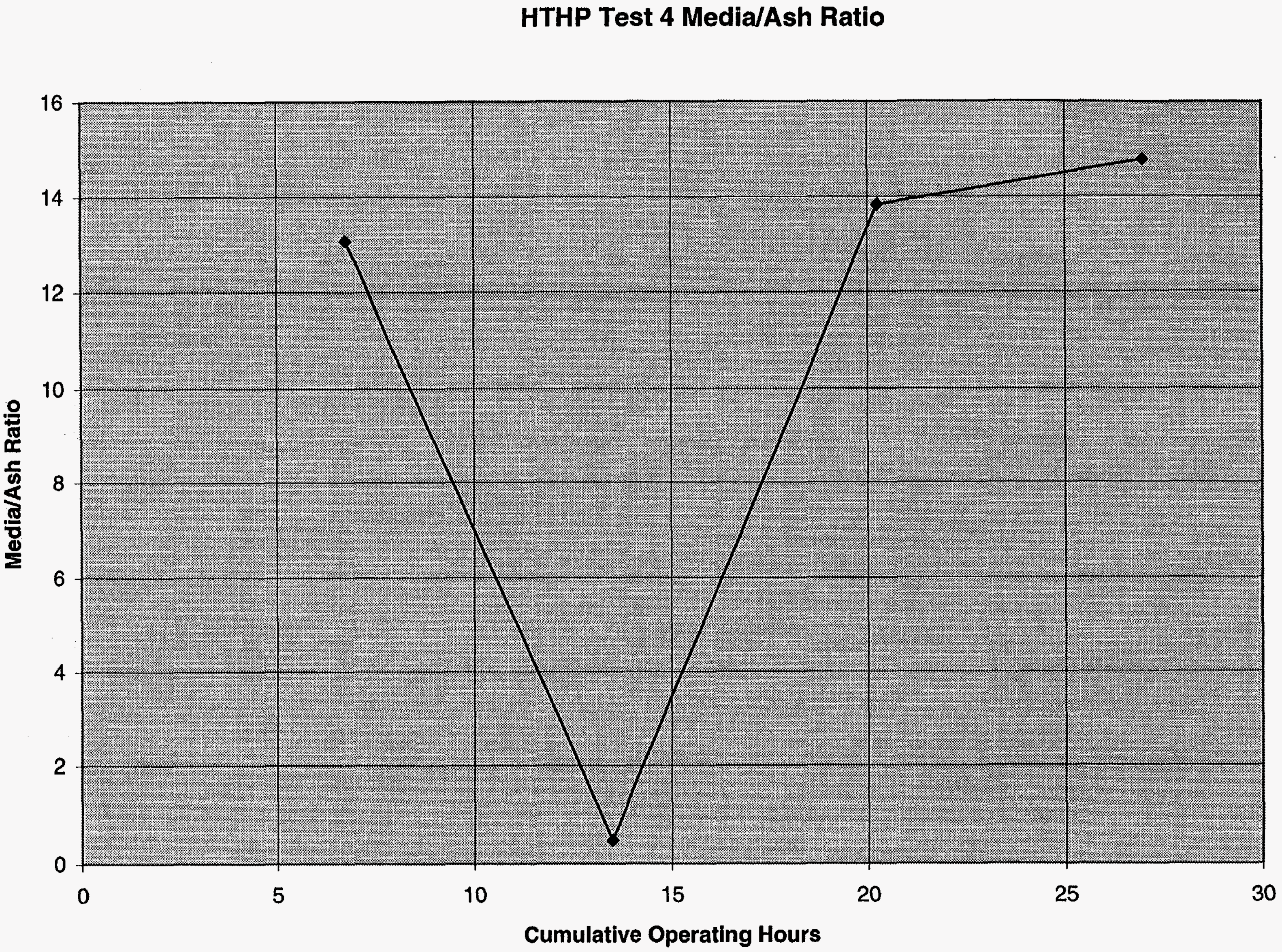


Figure 7.10 - HTHP Test 4 Media/Ash Ratio

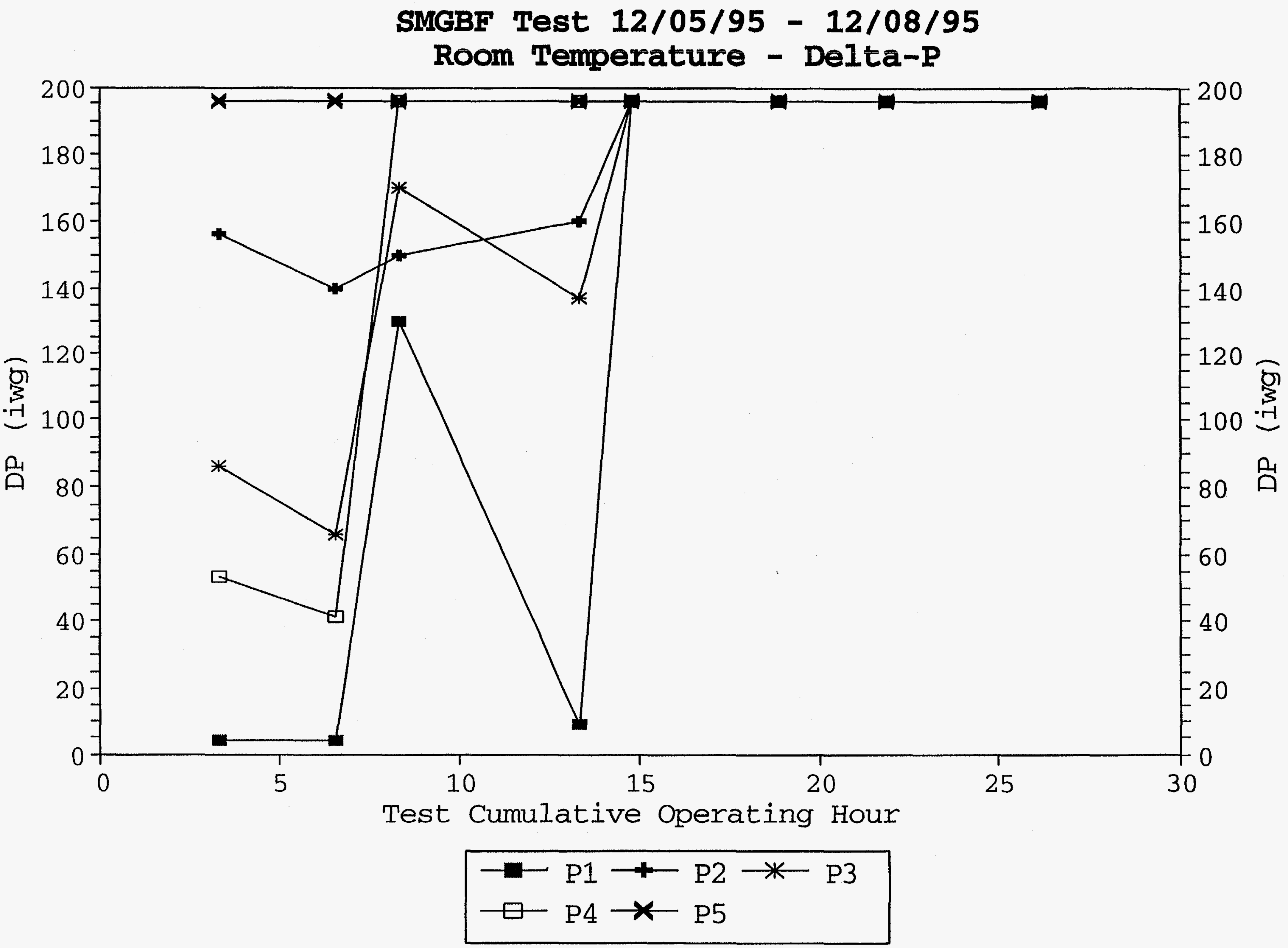


Figure 7.11 - HTHP Test 4 Pressure Drop Profiles

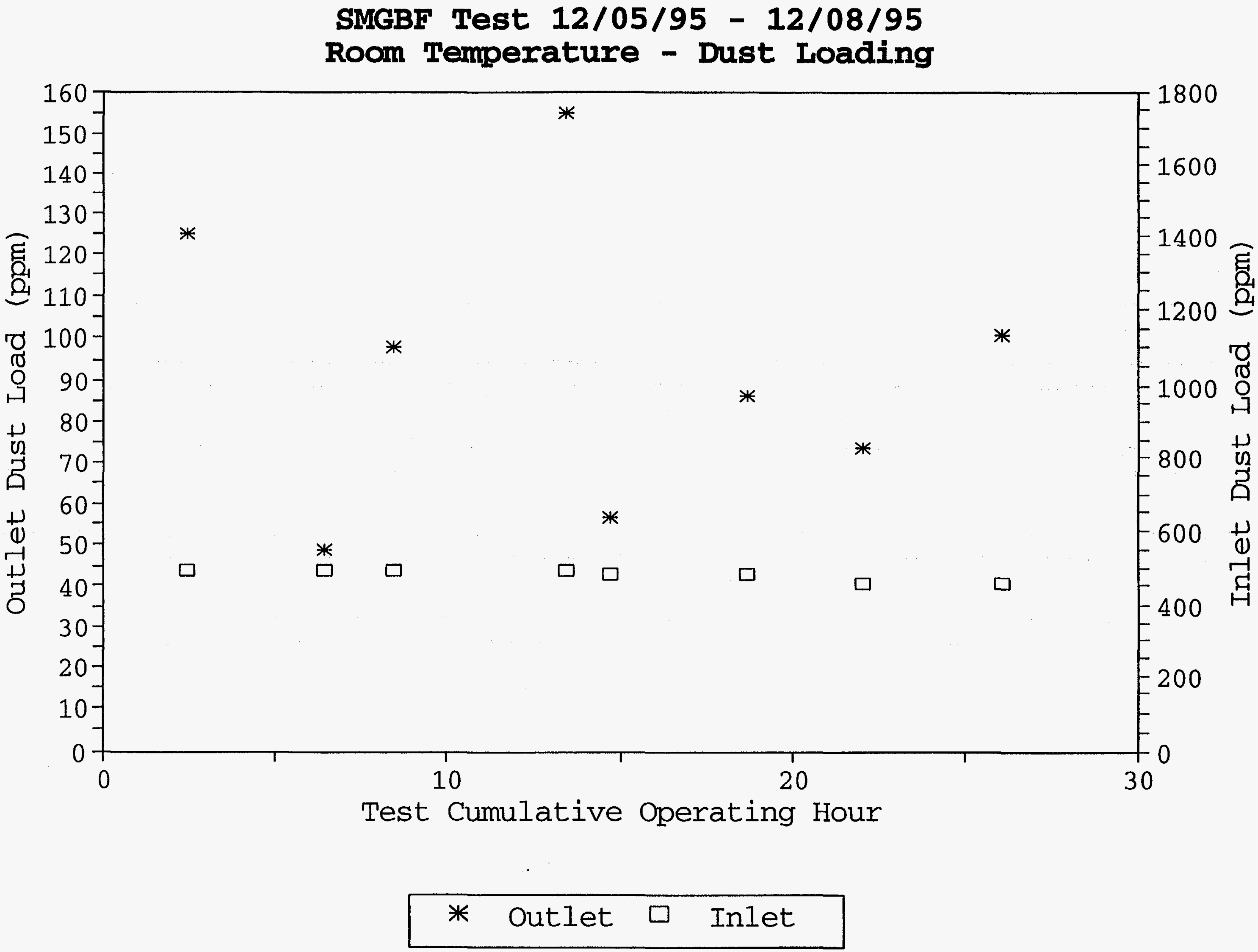


Figure 7.12 - HTHP Test 4 Inlet and Outlet Dust Loadings

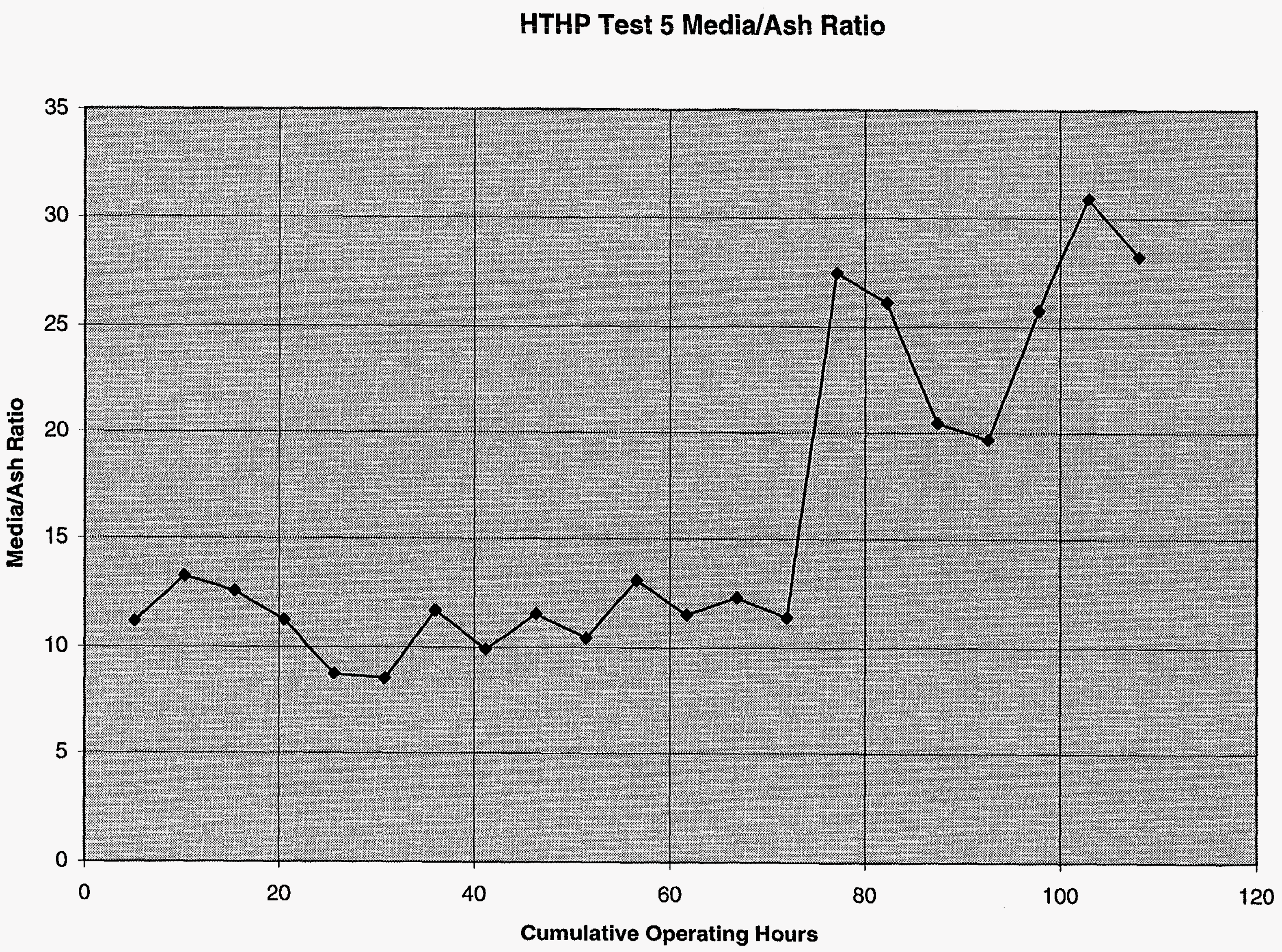


Figure 7.13 - HTHP Test 5 Media/Ash Ratio

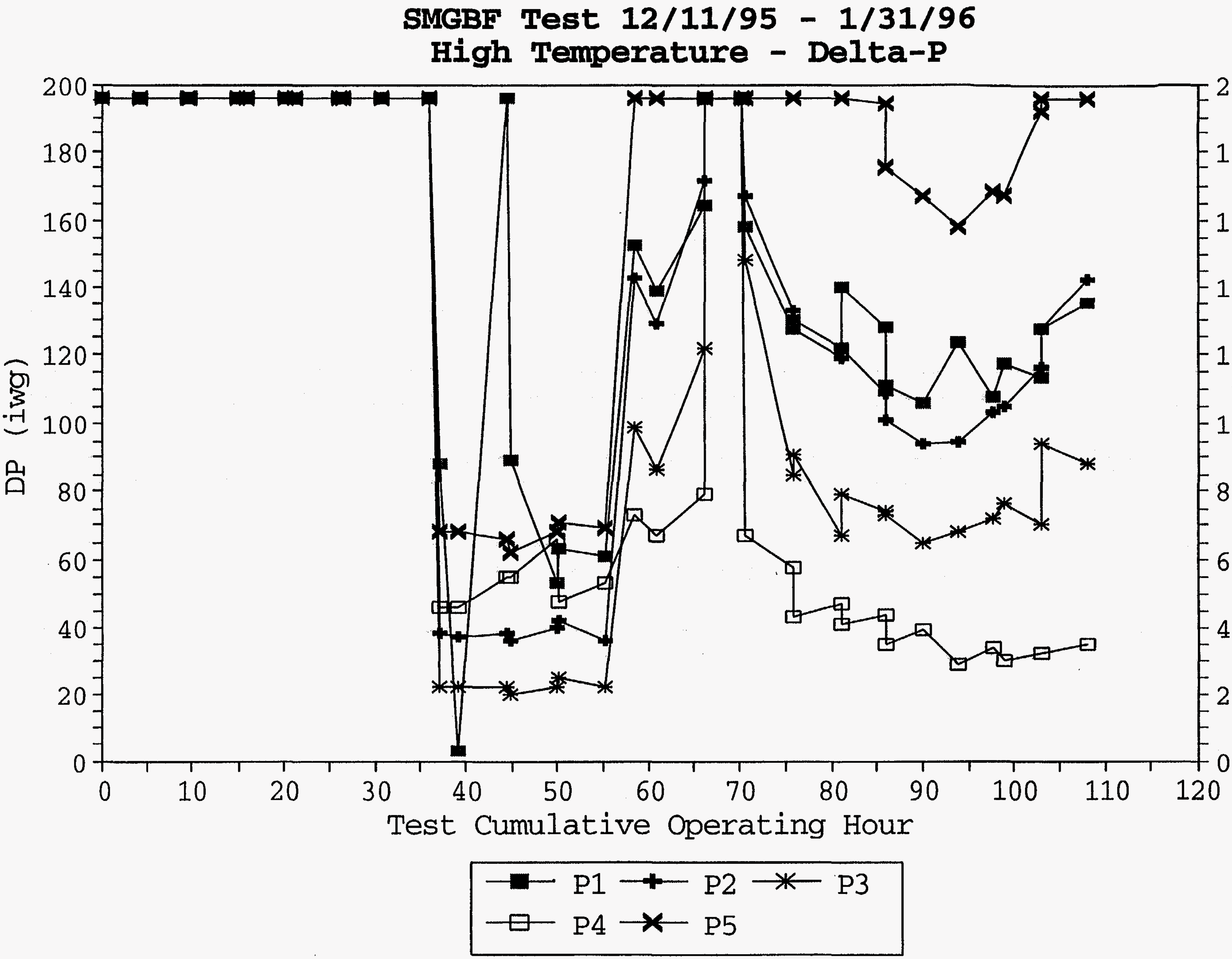


Figure 7.14 - HTHP Test 5 Pressure Drop Profiles

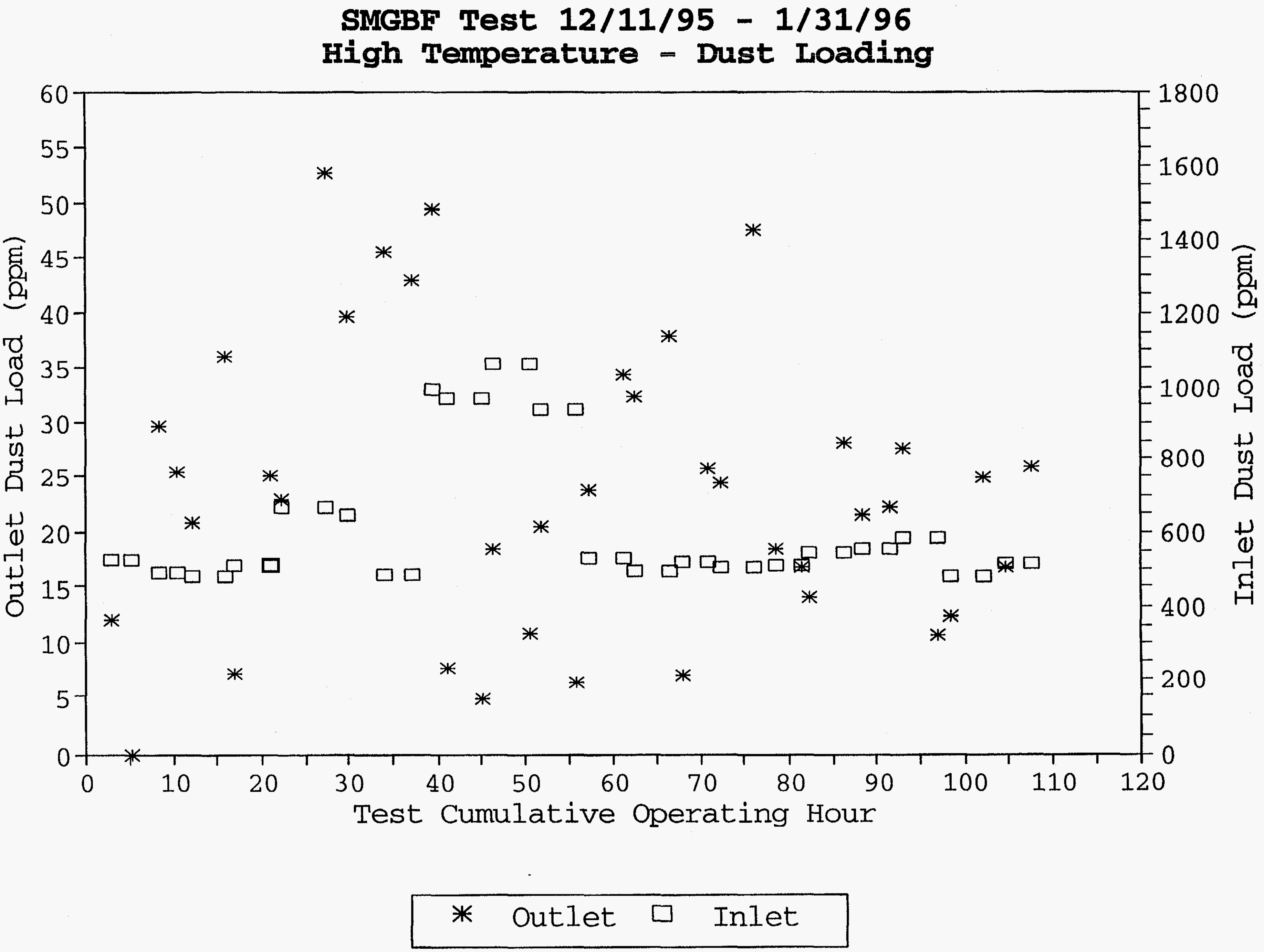


Figure 7.15 - HTHP Test 5 Inlet and Outlet Dust Loadings

8. CONCLUSIONS AND RECOMMENDATIONS

Extensive cold flow testing and HTHP testing was conducted in the Base Contract program and in the Option 1 program. The Base Contract work has been previously reported (Moving Granular-Bed Filter Development Program, Base Contact Final Topical Report, R. A. Newby, et al., April 1994, DOE/MC/27259-3797; DE94004149). This document reports the results of the Option 1 testing, but also draws upon key observations made in the Base Contract testing. The interpretation of the Option 1 tests is directed primarily toward the technical issues identified for the Recycle-SMGBF system, while the Base Contract dealt with many aspects of Once-through-SMGBF.

The cold flow testing was carried out at a scale approaching 1/3-rd of the commercial standleg diameter, and the test measurements can be scaled to high-temperature, high-pressure conditions, and full-scale dimensions using engineering modeling. The HTHP testing was at a smaller scale than the cold flow testing (a factor of 2 smaller in standleg diameter), and can be interpreted directly with respect to dust penetration and pressure drop. Key parameters in the testing were the standleg gas velocity, the media-to-ash mass feed ratio, the characteristics of the bed media, and features of the gas-media disengaging interface. System operability and reliability were also assessed in the testing.

Using a simple standleg design with a solid skirt, it is estimated that the SMGBF can satisfy IGCC performance requirements for dust penetration (about 30 ppmw) and pressure drop (about 6 psi) at standleg gas velocities up to about 4 ft/s, and with media/ash mass feed ratios as low as 10. Likewise, it is estimated that the SMGBF with a simple standleg and solid skirt can satisfy PFBC performance requirements for dust penetration (about 15 ppmw) and pressure drop (about 4 psi) at standleg gas velocities up to about 3 ft/s, and with media/ash feed ratio as low as 20.

Operating with larger media/ash mass feed ratios will reduce the SMGBF pressure drop as well as allow higher standleg gas velocities to be used. The dust penetration measured in the HTHP tests seemed to show more sensitivity to standleg gas velocity than was found in the cold flow tests. The HTHP testing also indicated that higher media/ash mass feed ratios will result in lower dust penetration. The HTHP testing implies that larger media size may be used without a reduction in dust removal performance, but this needs further verification.

The test results show that a cheap bed media, such as dead-burned dolomite or industrial slags, can be successfully used in Recycle-SMGBF and expensive granular materials, such as alumina beads, are not required. This conclusion, together with test results from the Base Contract program, implies that Once-through-SMGBF using pelletized waste materials can also be successful if the pellet attrition characteristics are similar to the cheap bed media tested.

The test data shows that partially-cleaned bed media, with as little as 90% ash removal in the recycle system, can be recycled to the SMGBF and still achieve good particle penetration performance. This capability exists because the recycled bed media is introduced at the dirty gas inlet in the SMGBF configuration. If a topping bed is used to achieve very low dust penetration, the topping bed may require a clean source of bed media.

Ceramic barrier filter systems can operate in IGCC and PFBC applications with acceptable pressure drops and with lower dust penetration (< 3 ppmw) than can be achieved by the SMGBF using a simple standleg and skirt, assuming that the ceramic filter elements are durable. The only technique that Westinghouse has identified and tested for the SMGBF to approach the dust penetration capabilities of ceramic barrier filters is to use a topping bed design. The topping bed should be have a depth of about 20-inches and should have a clean source of recycle media. The Base Contract cold flow testing showed that the topping bed configuration could achieved dust penetration less than 1 ppmw, but this has not been verified in HTHP testing.

It is recommended that development of the SMGBF technology be continued. The next step in the development calls for the installation and operation of the Recycle-SMGBF technology at a flexible test facility that can provide either a PFBC, Second-Generation PFBC, or IGCC gas cleaning environment. Testing should focus on generating long-term performance and operability data at nominal design and operating conditions selected from the results of the Option 1 testing. The testing should also incorporate an integrated bed media recycle system, with an option to also test the Once-through-SMGBF system using off-site pelletization of waste materials from the test facility.

APPENDIX A - COLD FLOW TEST DATA

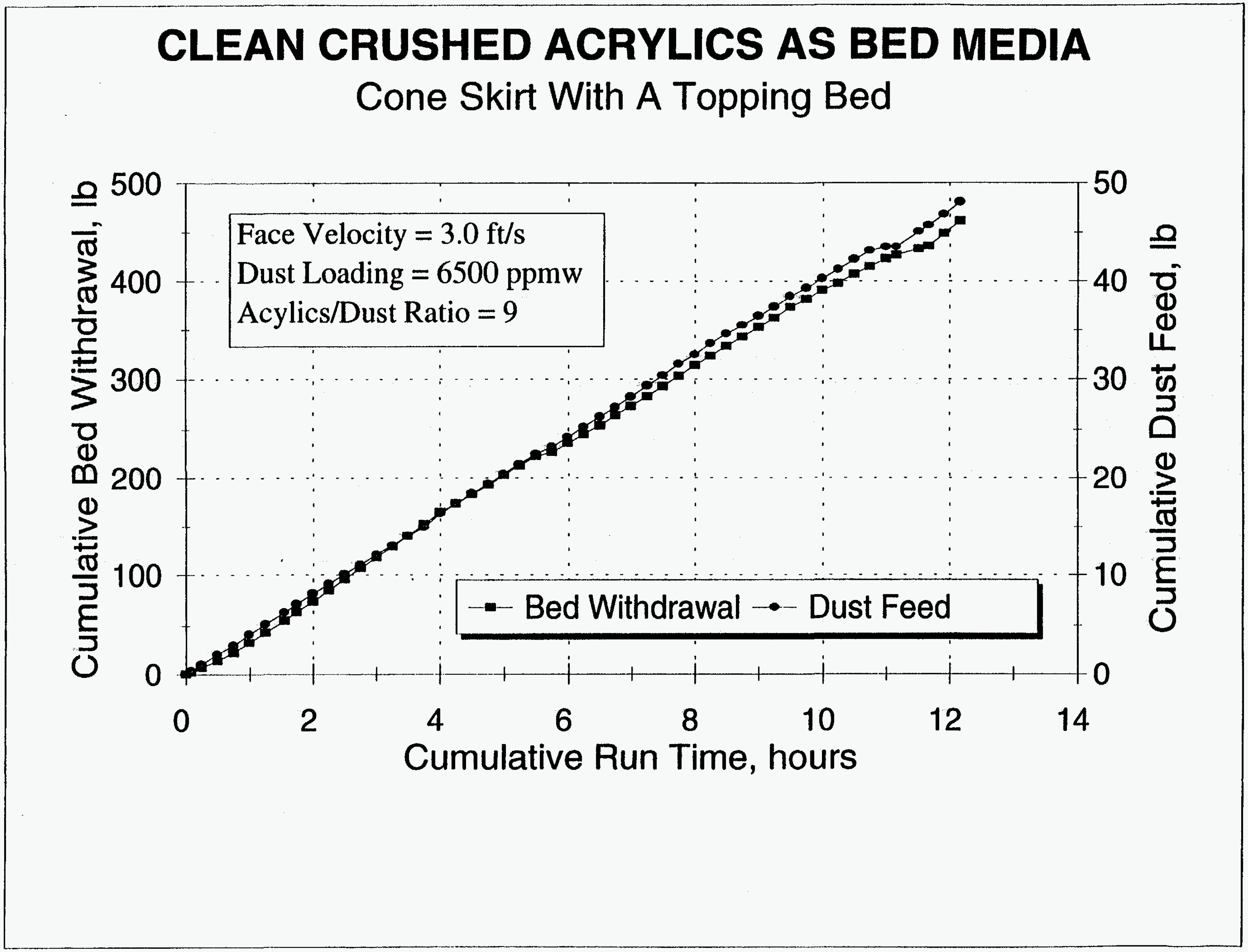


Figure A1 - Cold Flow Test 1 Bed Withdrawal Record

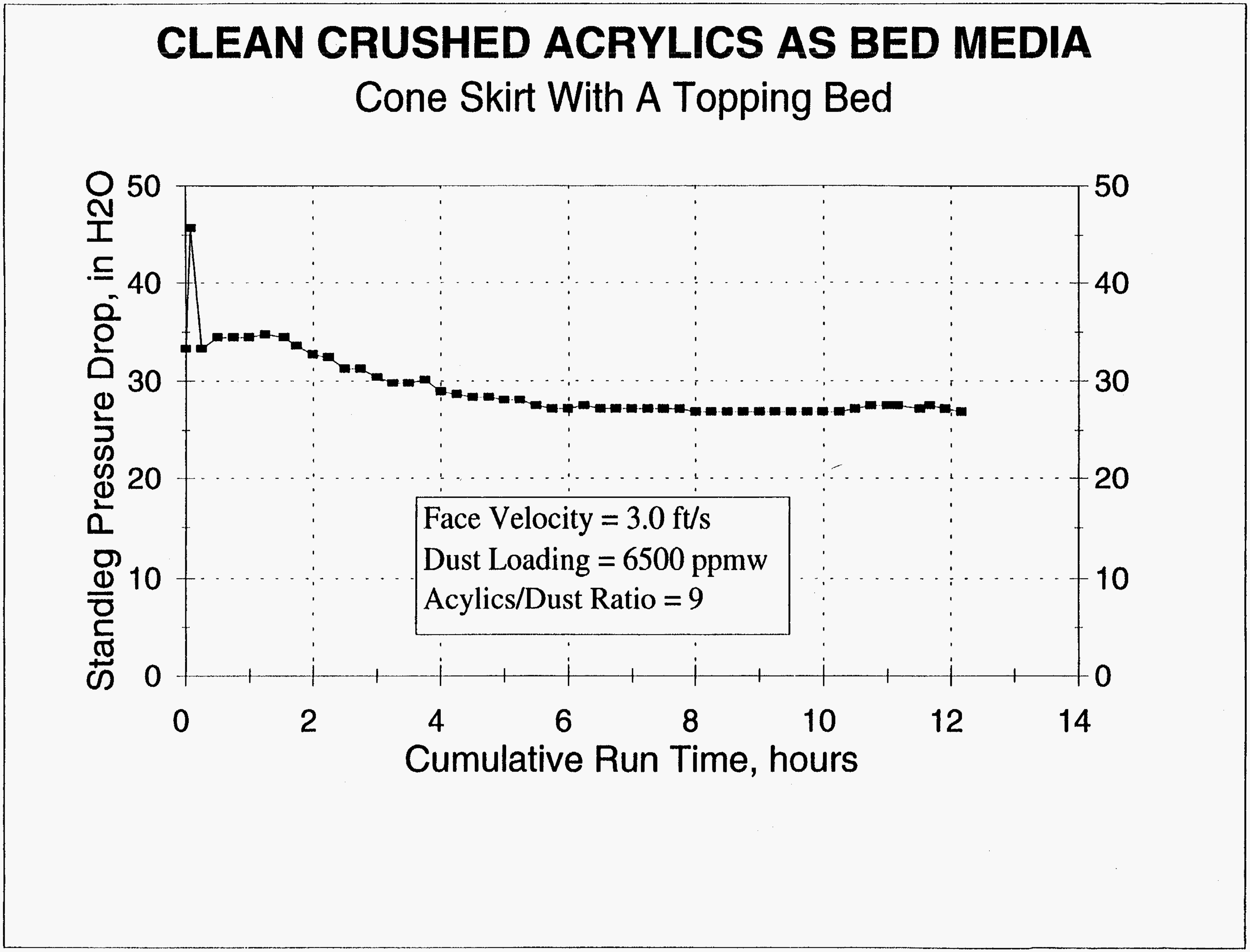


Figure A2 - Cold Flow Test 1 Bed Pressure Drop Record

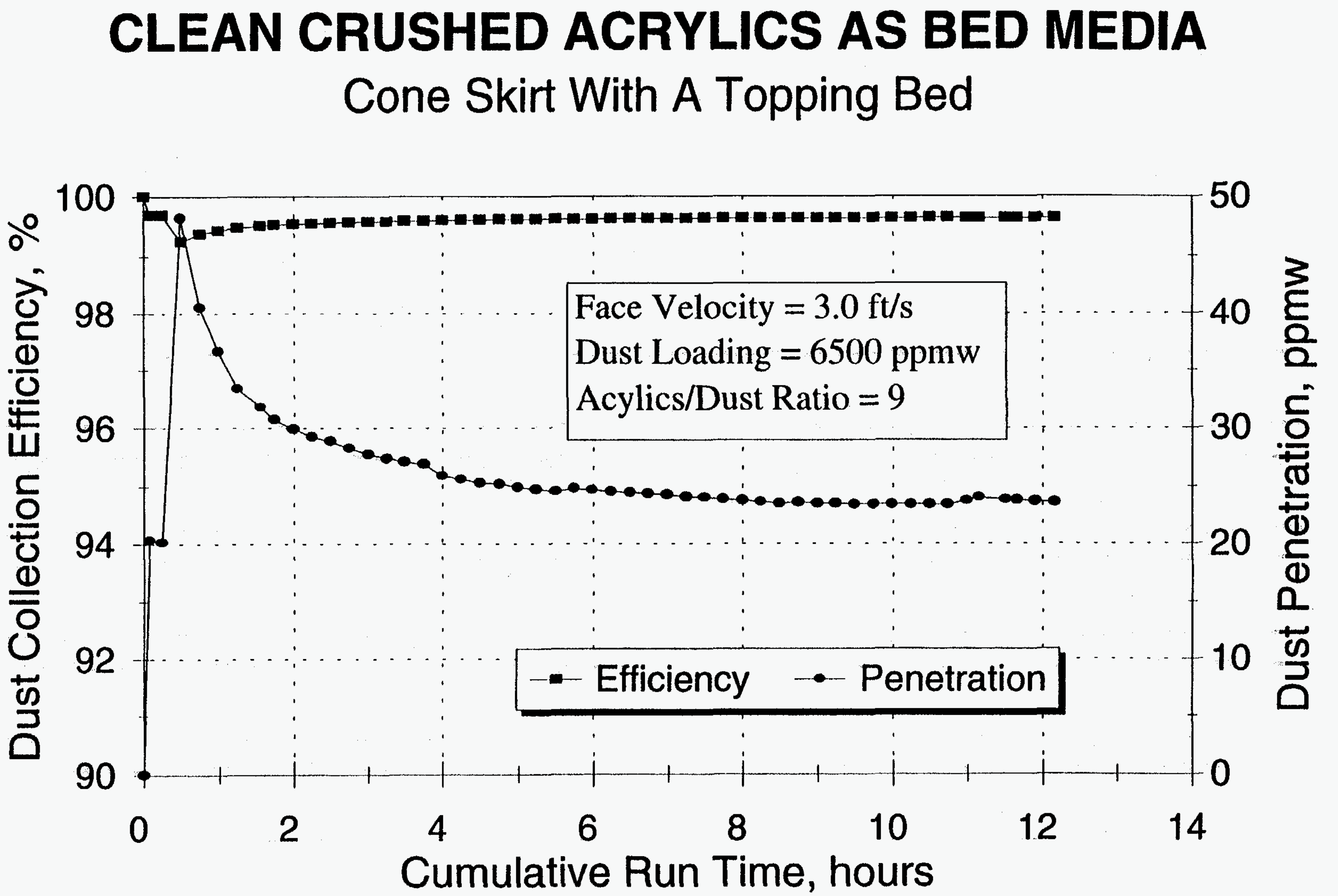
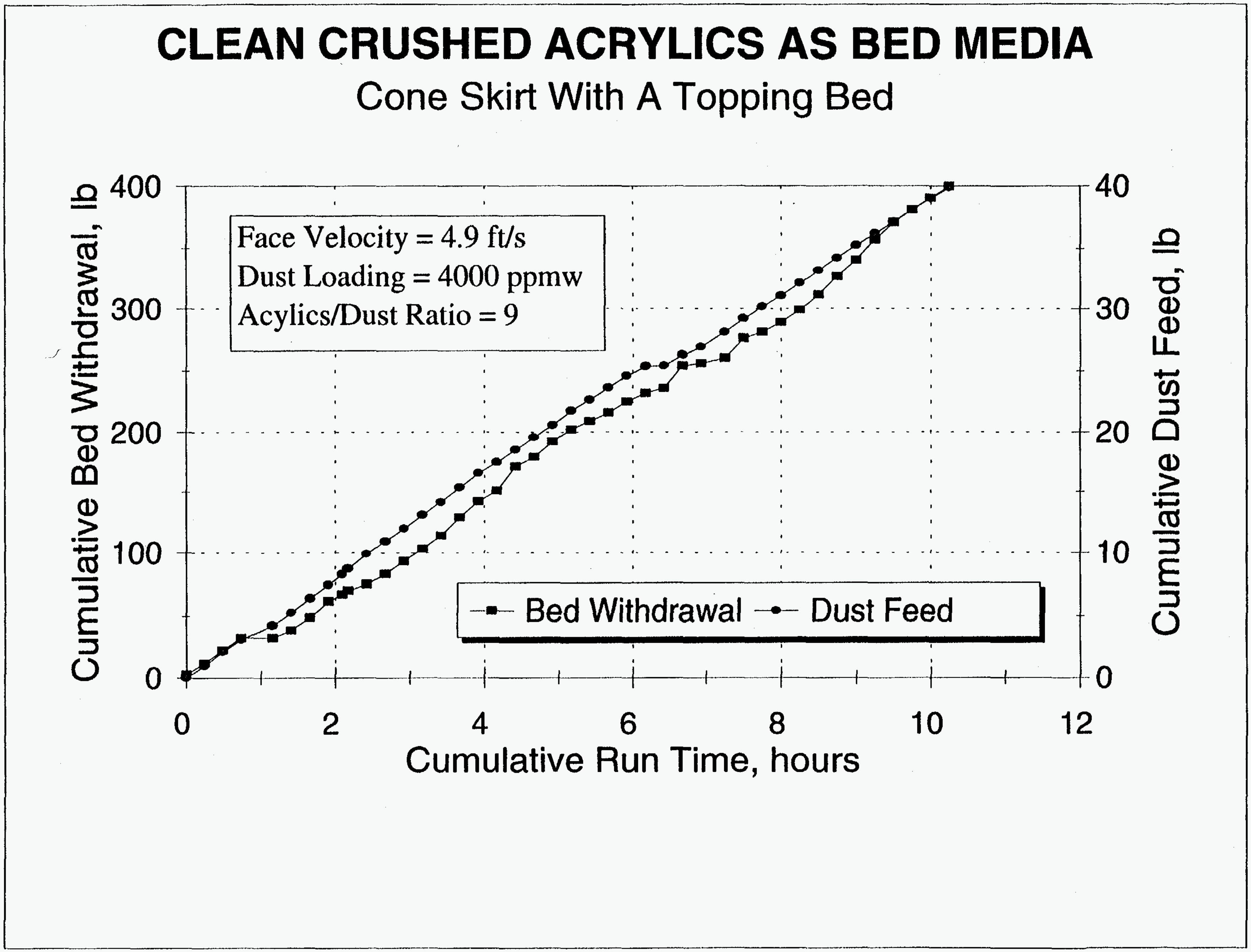


Figure A3 - Cold Flow Test 1 Dust Penetration Record



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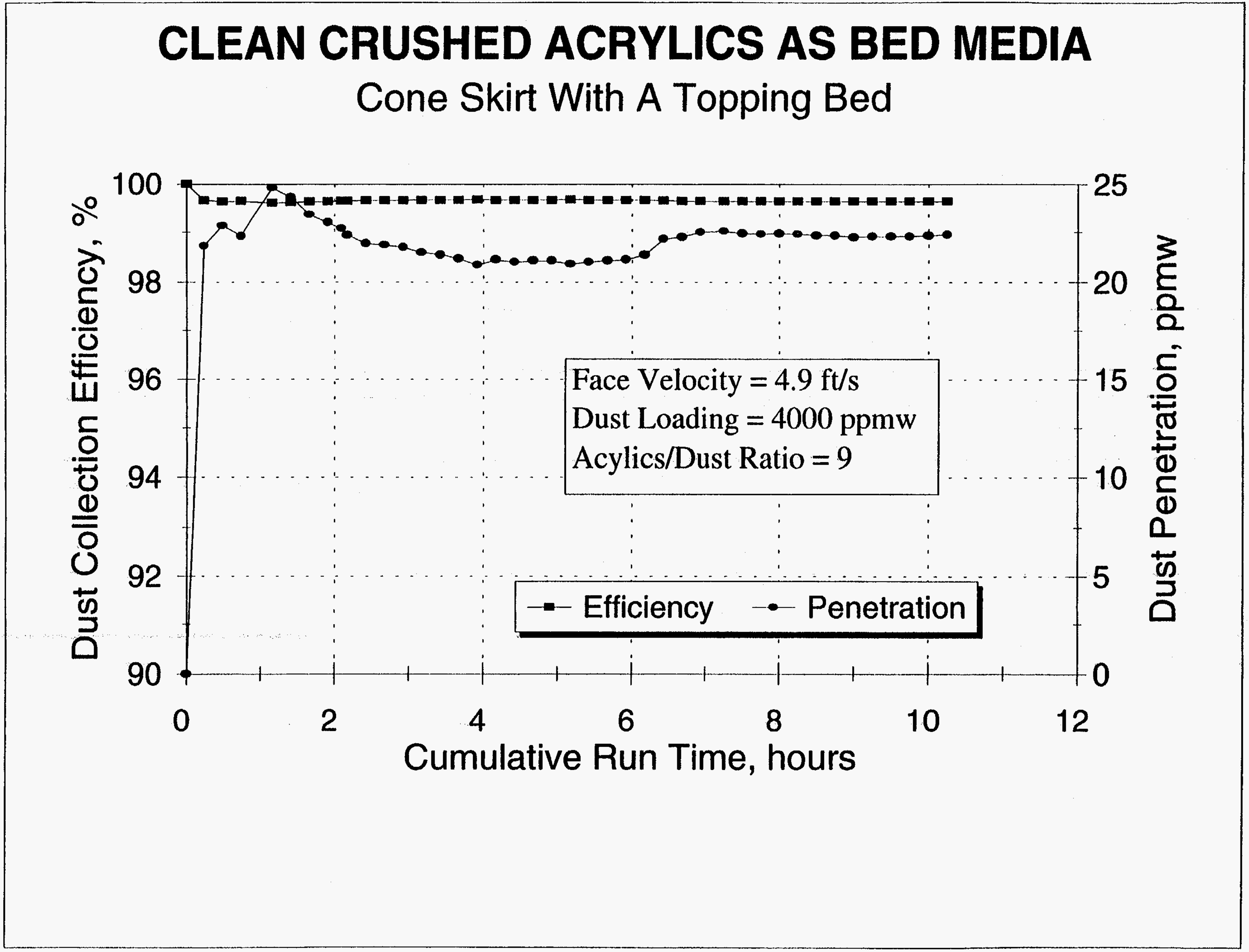


Figure A5 - Cold Flow Test 1 Bed Pressure Drop Record

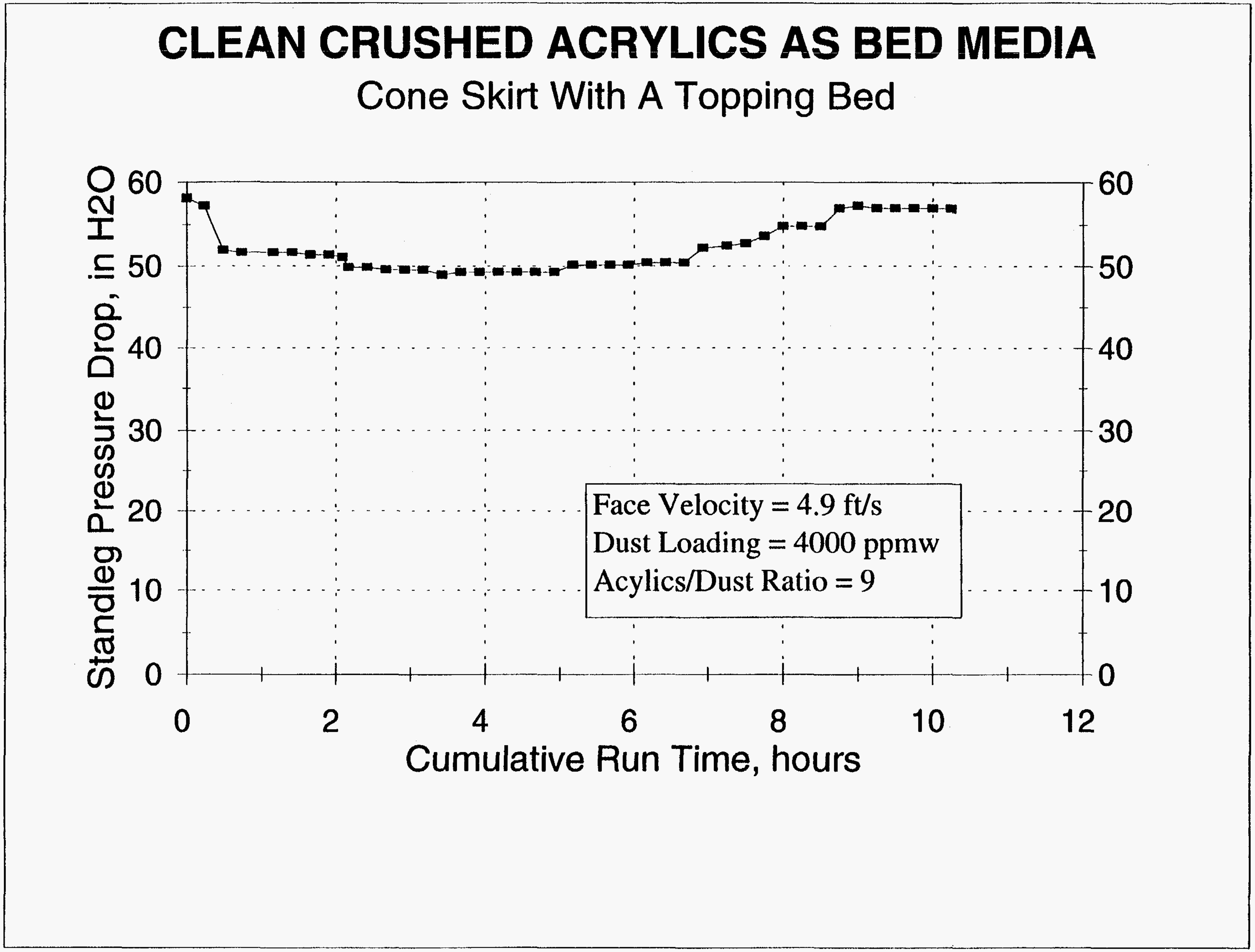
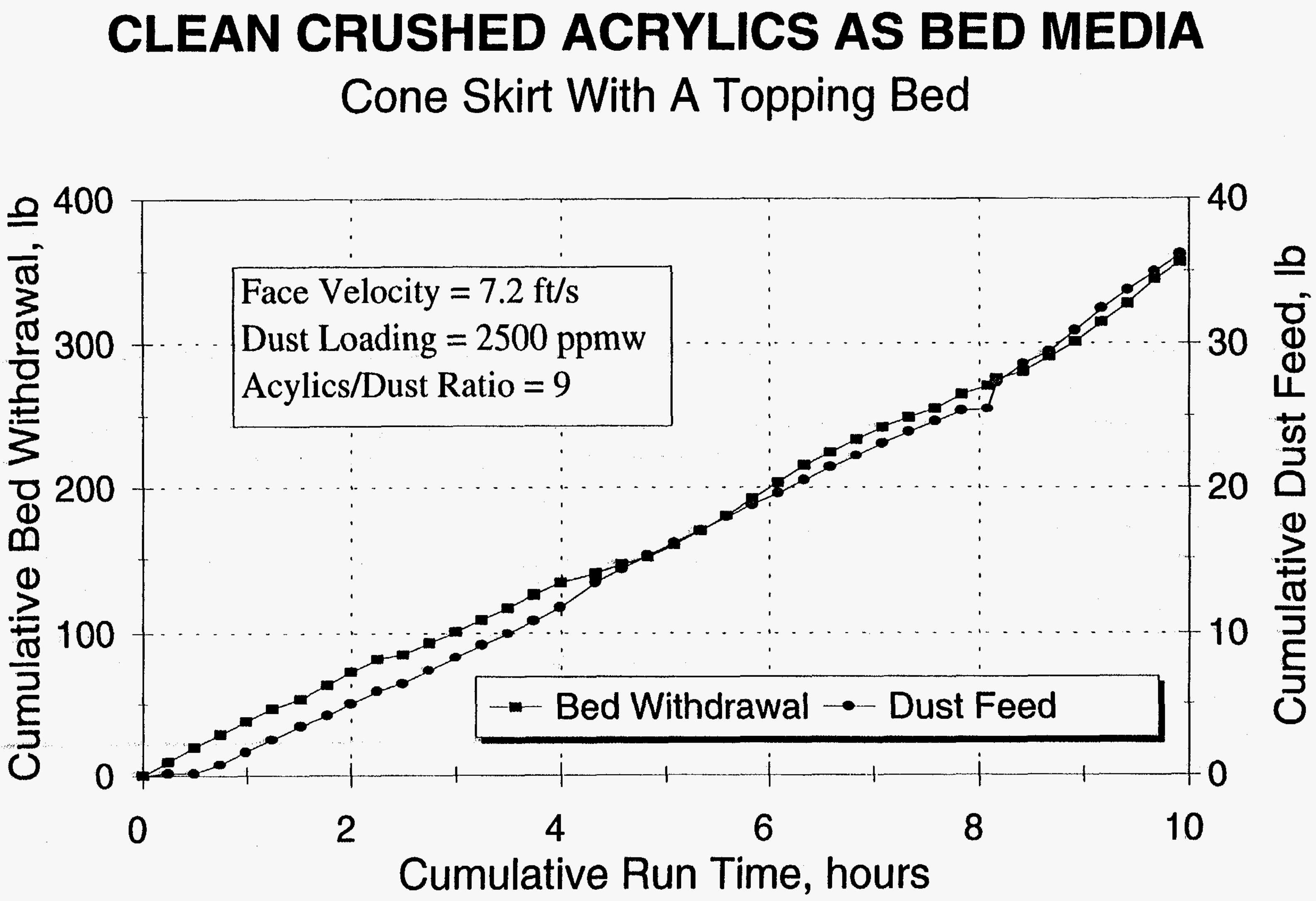


Figure A6 - Cold Flow Test 1 Dust Penetration Record



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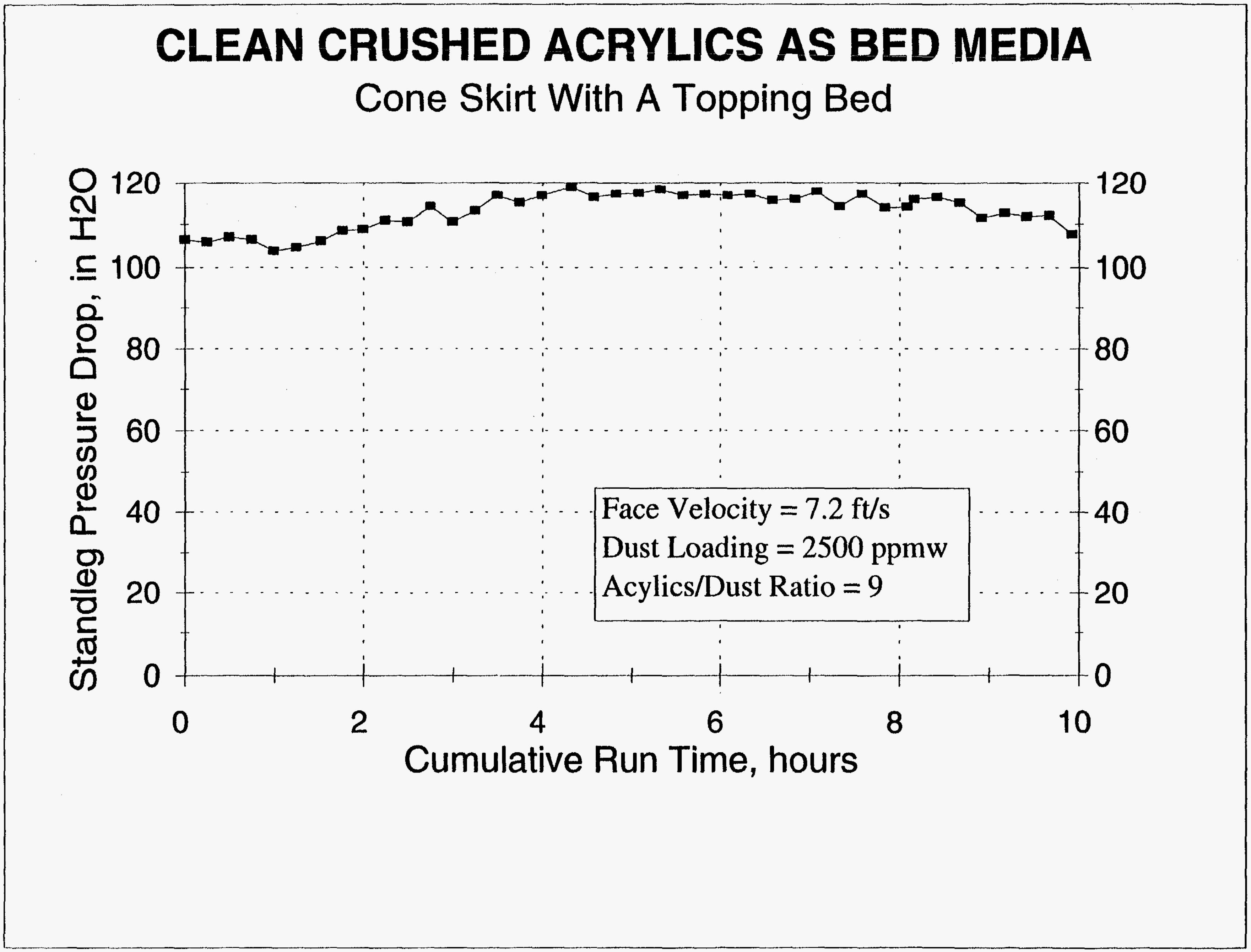


Figure A8 - Cold Flow Test 1 Bed Pressure Drop Record

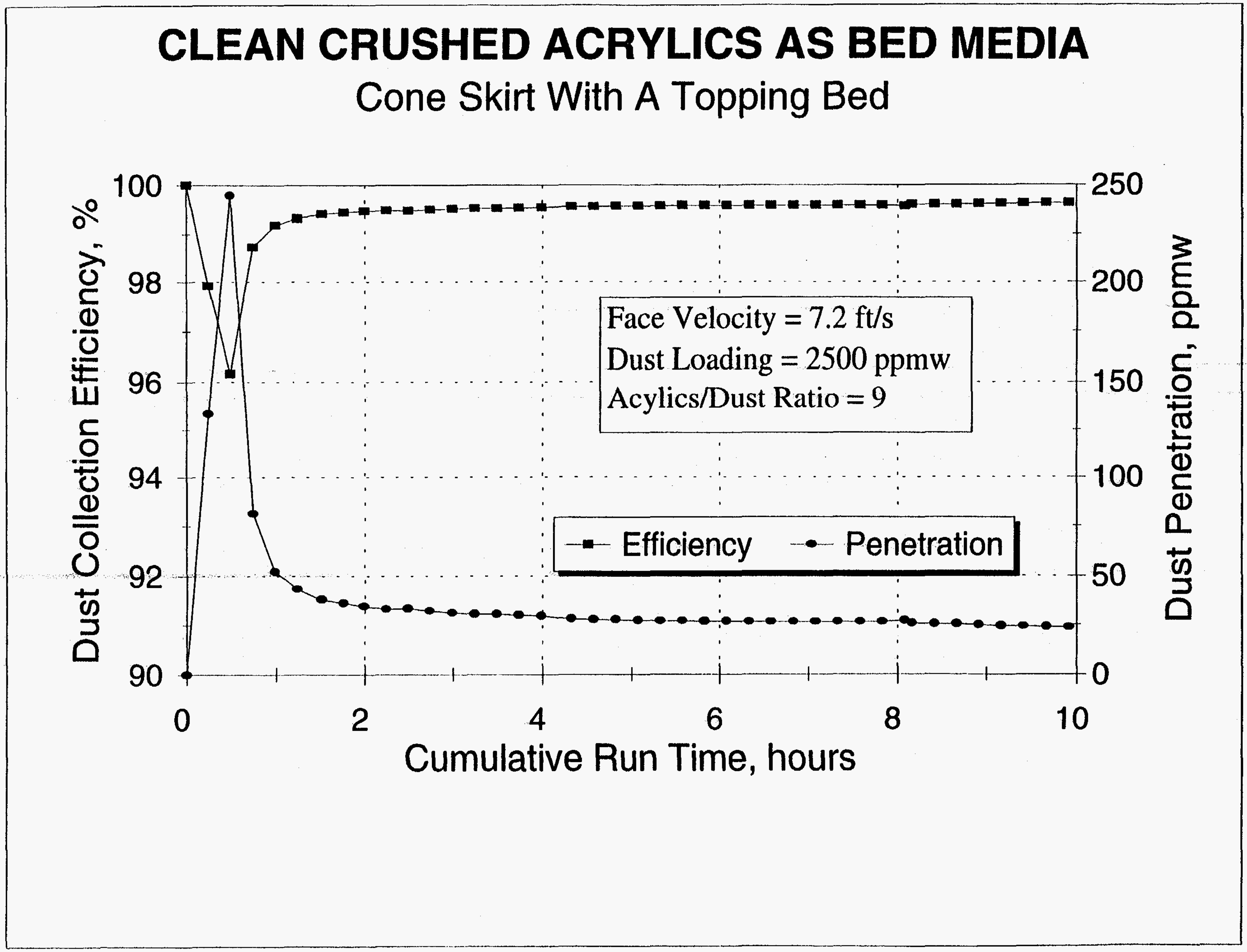


Figure A9 - Cold Flow Test 1 Dust Penetration Record

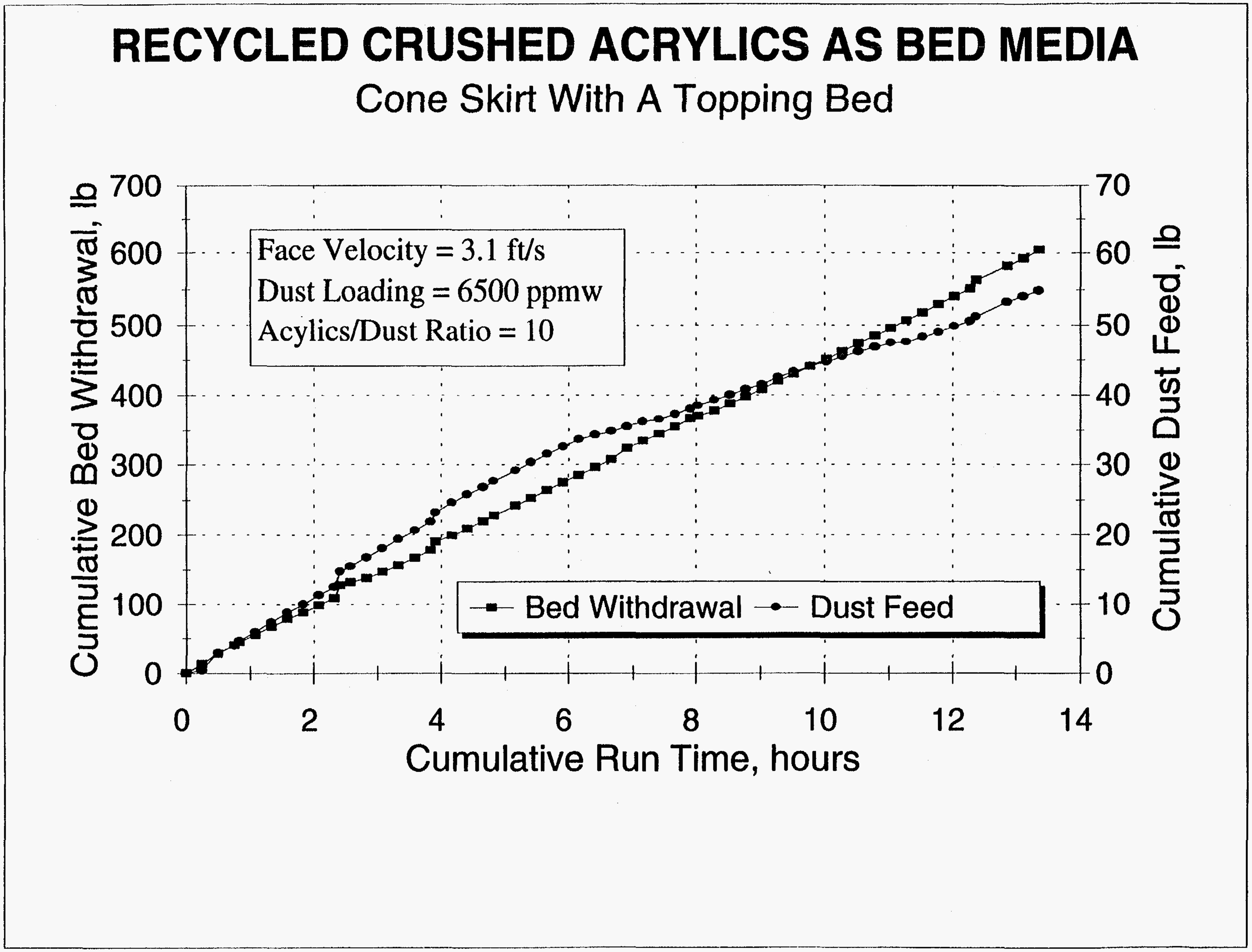
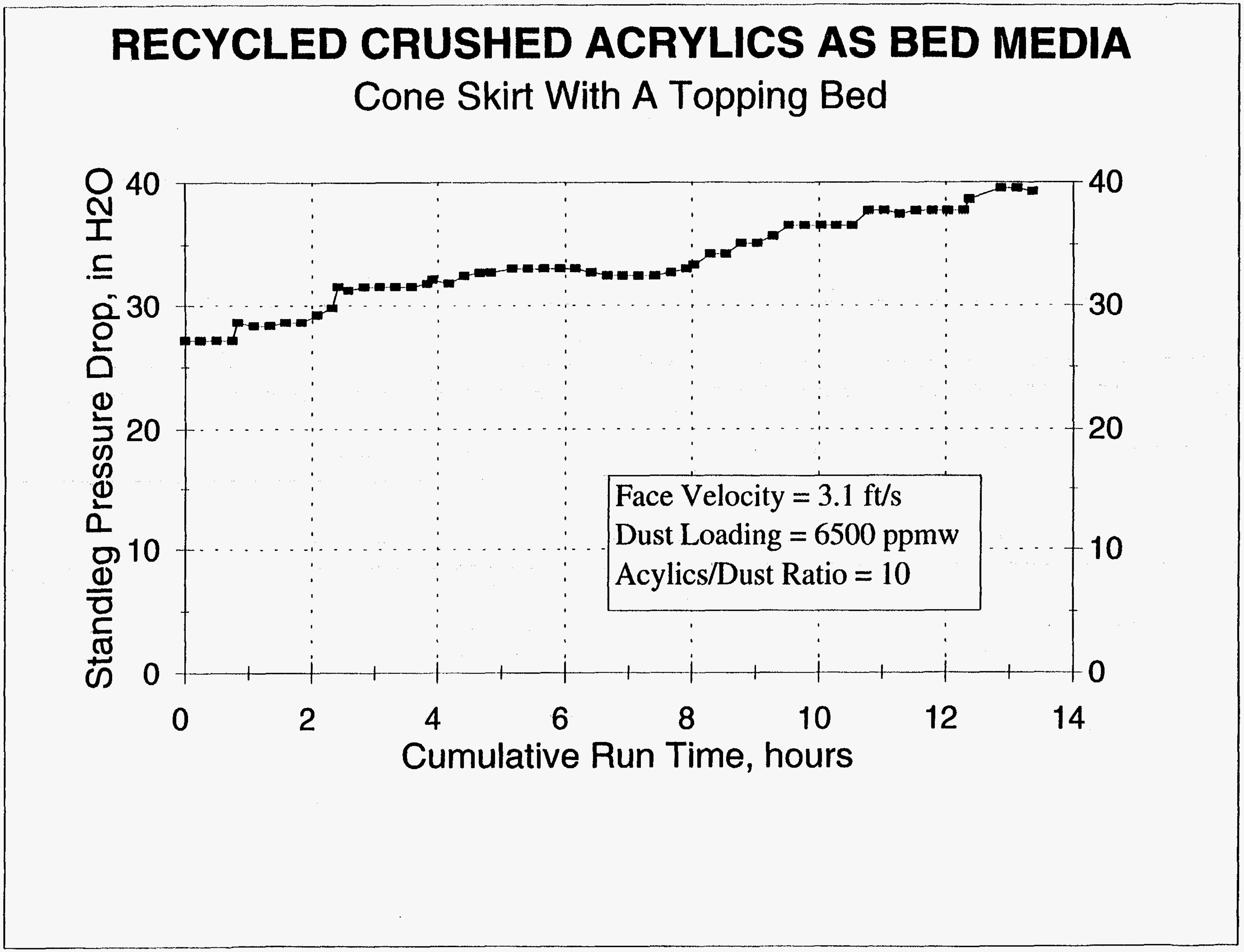


Figure A10 - Cold Flow Test 1 Bed Withdrawal Record



RECYCLED CRUSHED ACRYLICS AS BED MEDIA

Cone Skirt With A Topping Bed

Figure A11 - Cold Flow Test 1 Bed Pressure Drop Record

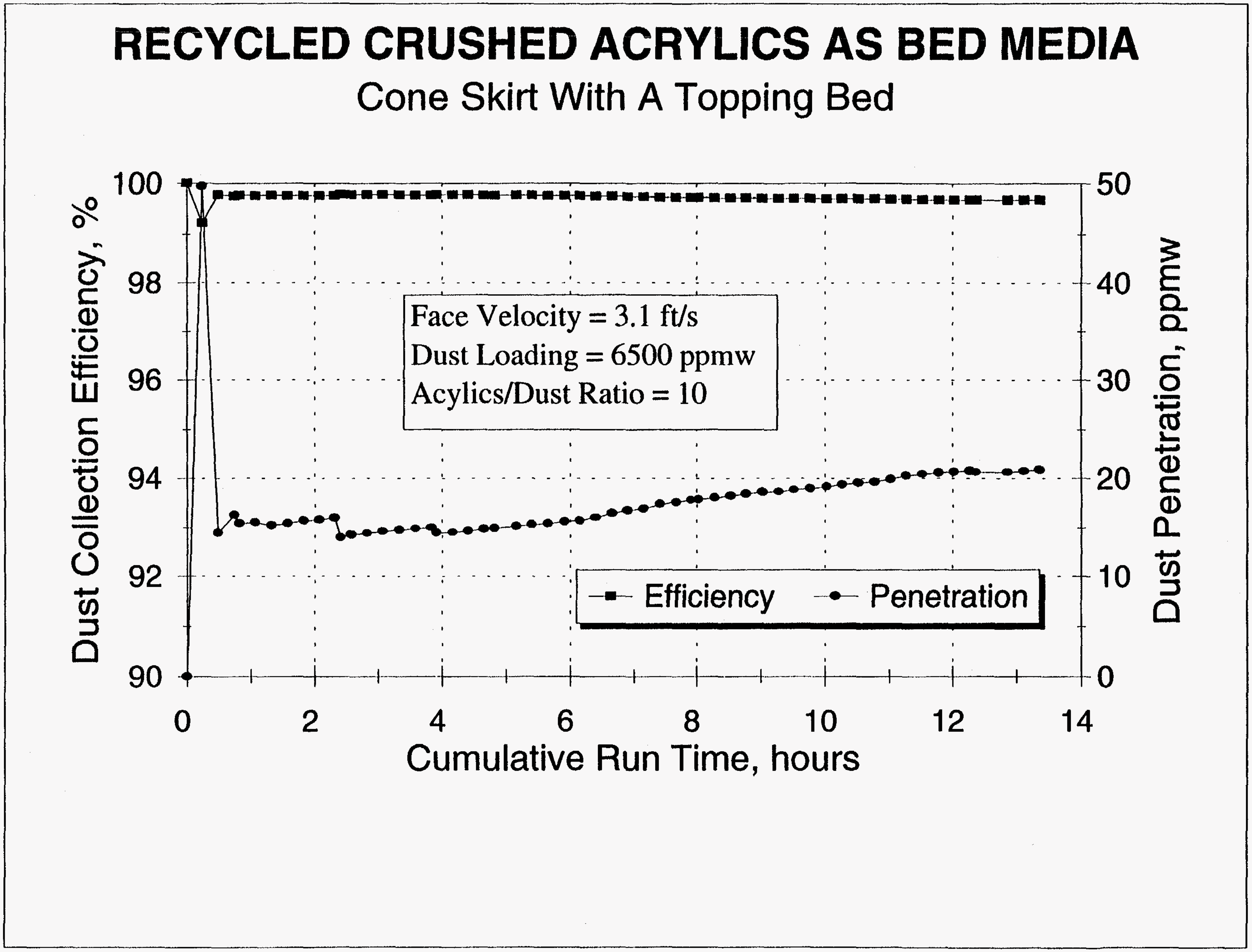


Figure A12 - Cold Flow Test 1 Dust Penetration Record

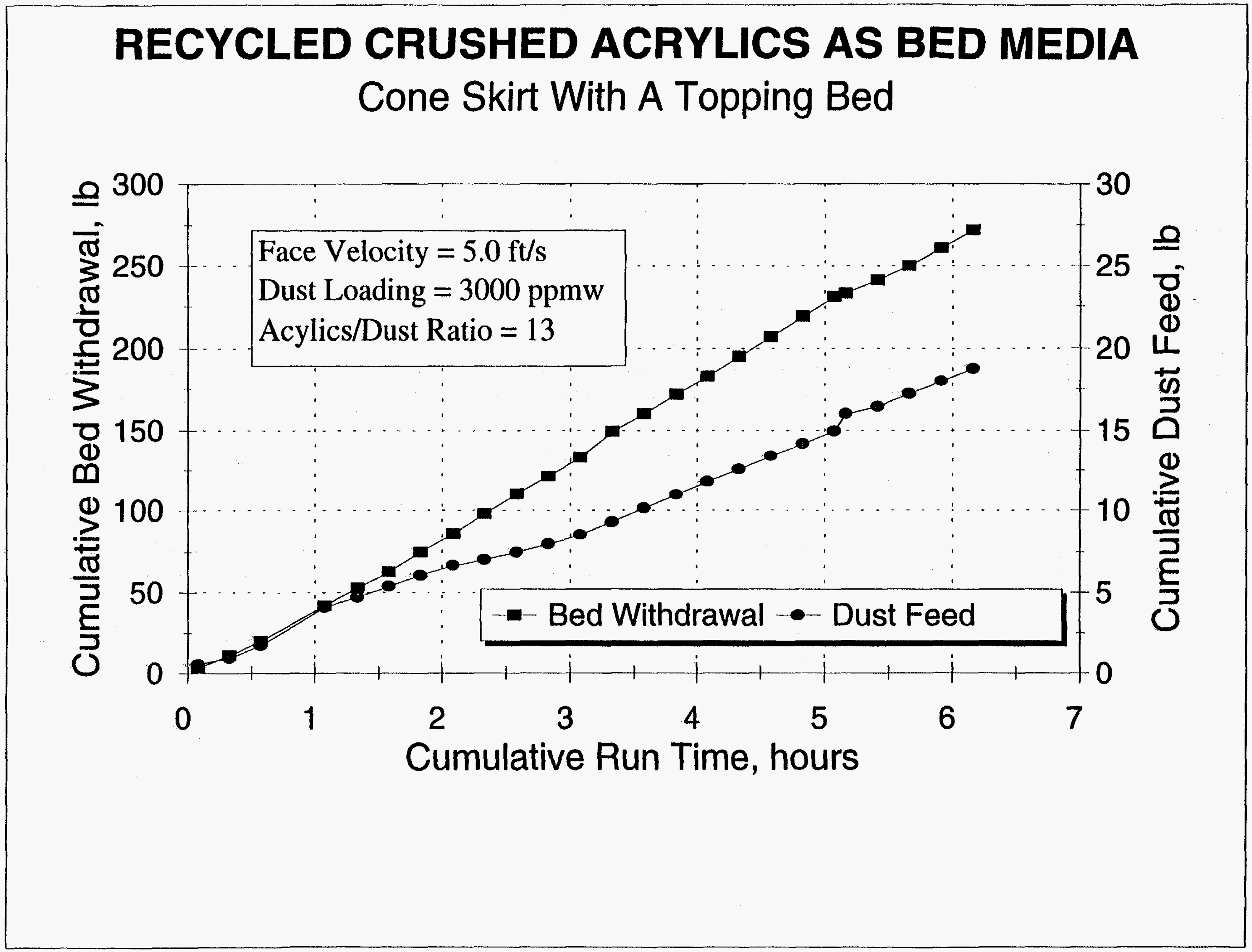


Figure A13 - Cold Flow Test 1 Bed Withdrawal Record

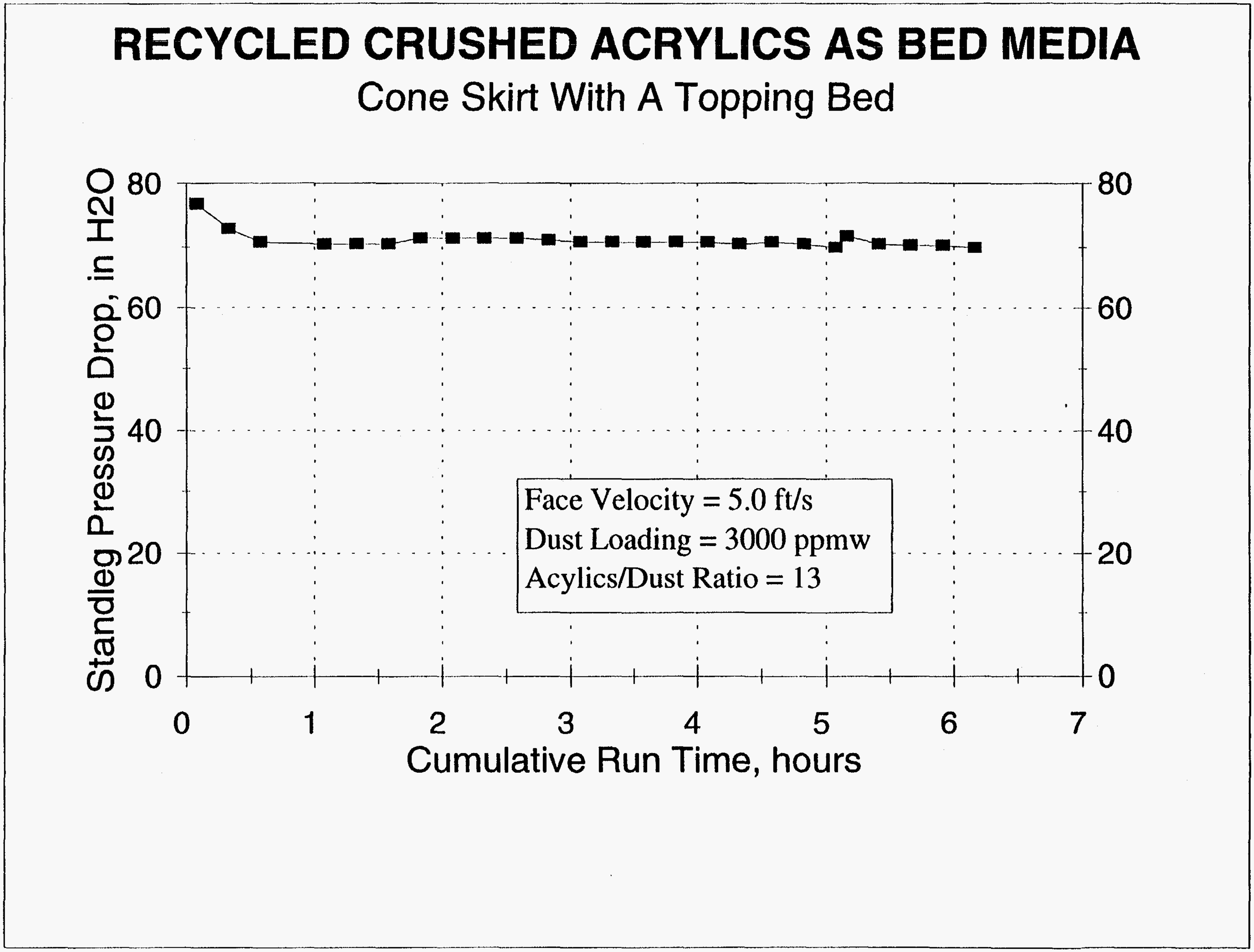


Figure A14 - Cold Flow Test 1 Bed Pressure Drop Record

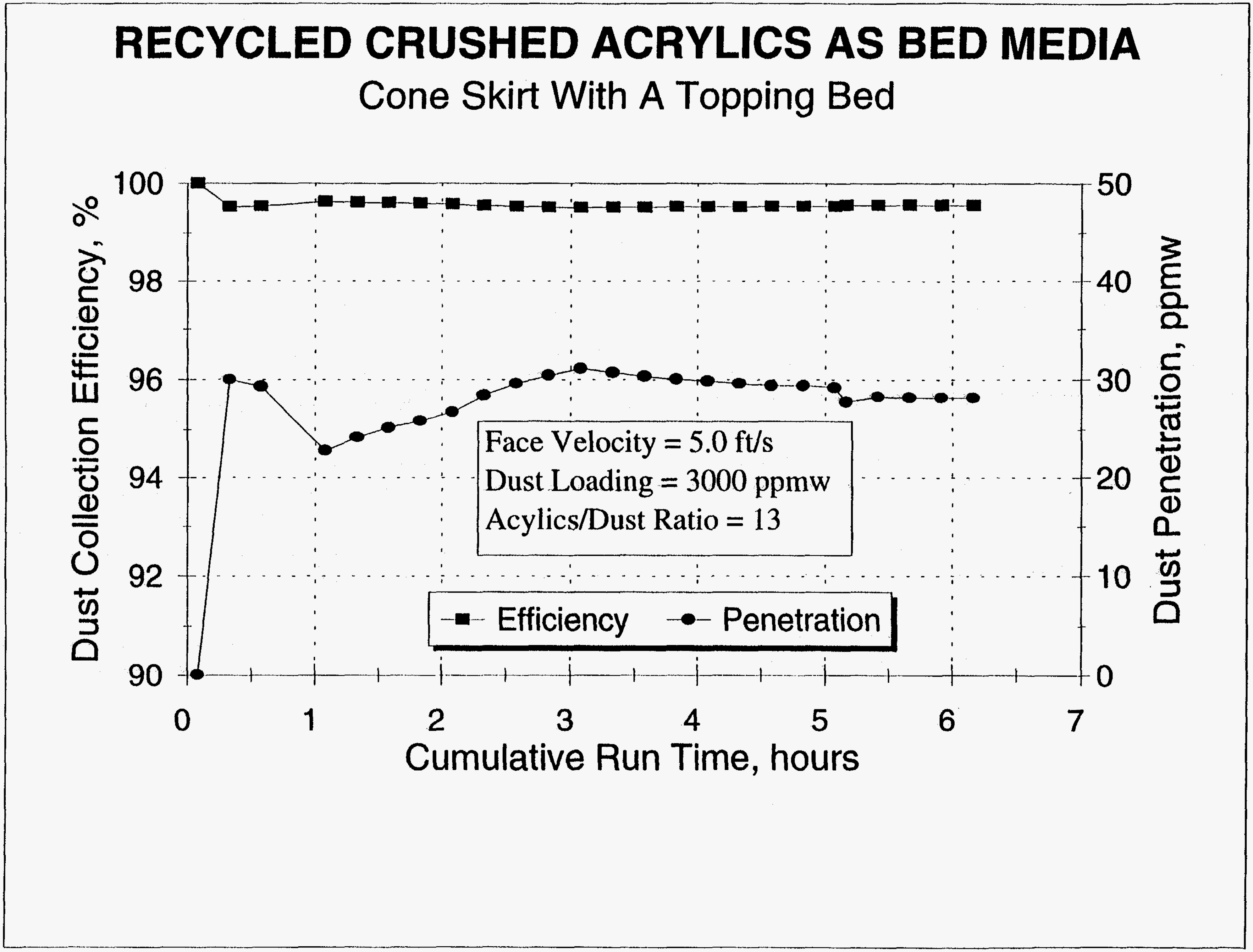


Figure A15 - Cold Flow Test 1 Dust Penetration Record

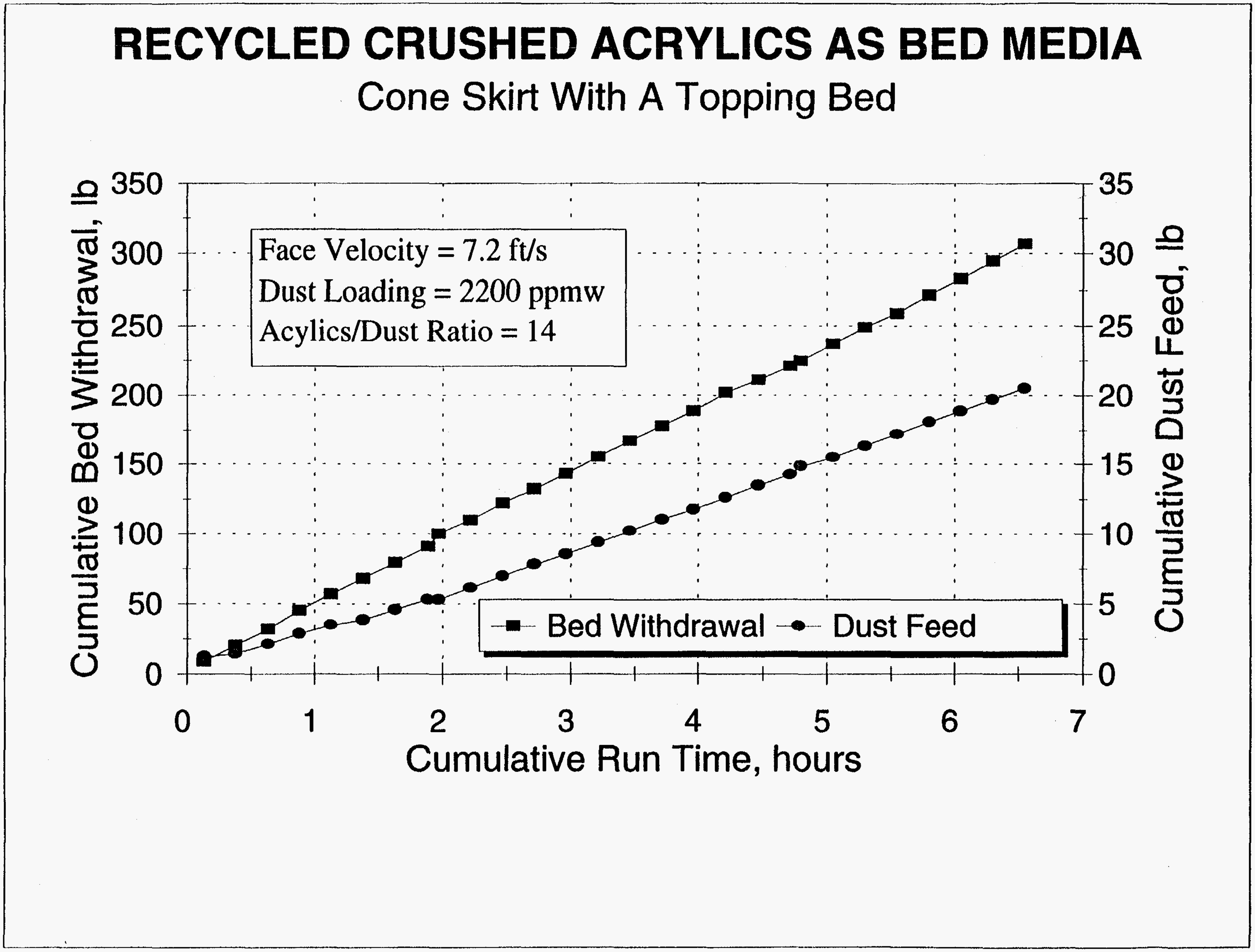


Figure A16 - Cold Flow Test 1 Bed Withdrawal Record

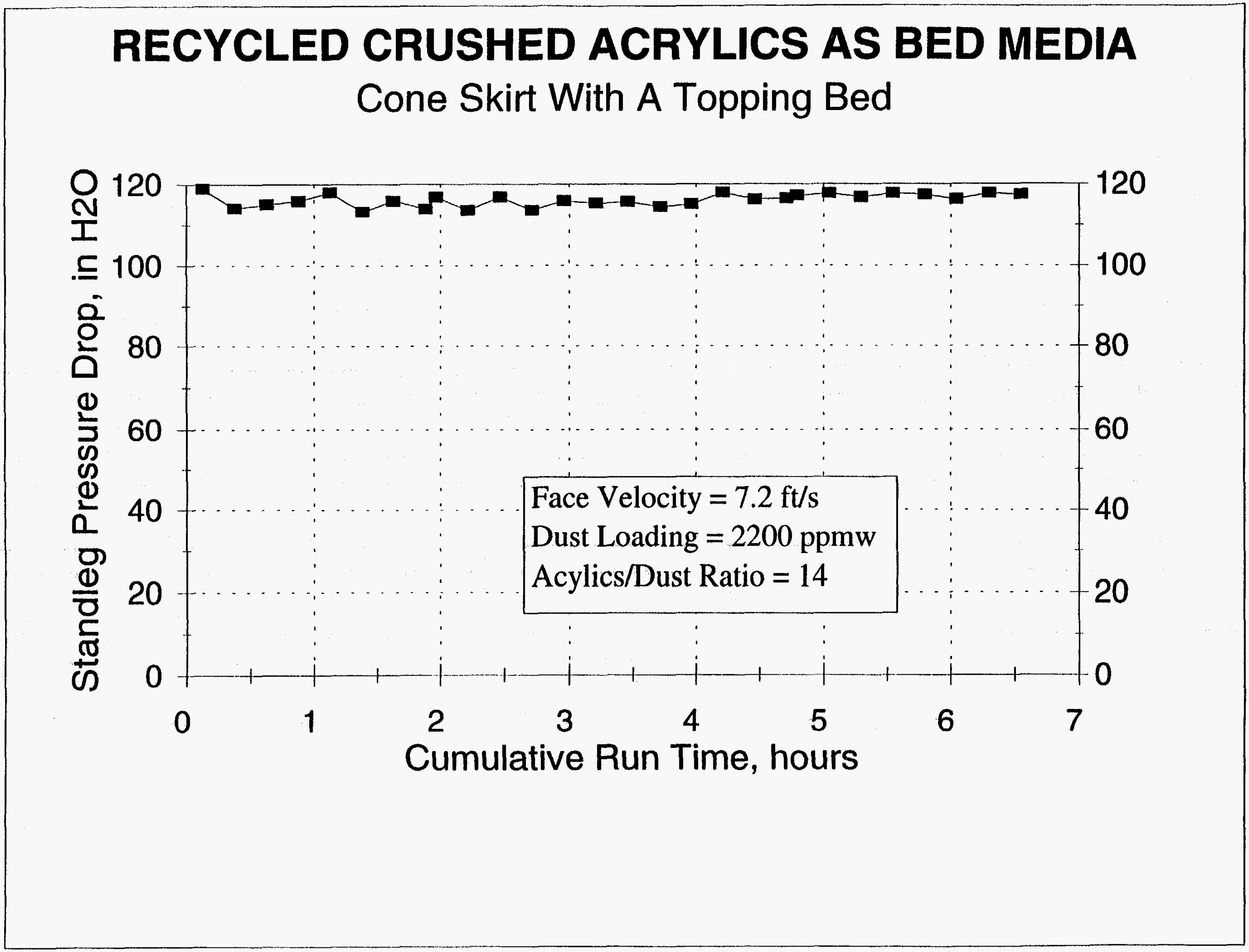


Figure A17 - Cold Flow Test 1 Bed Pressure Drop Record

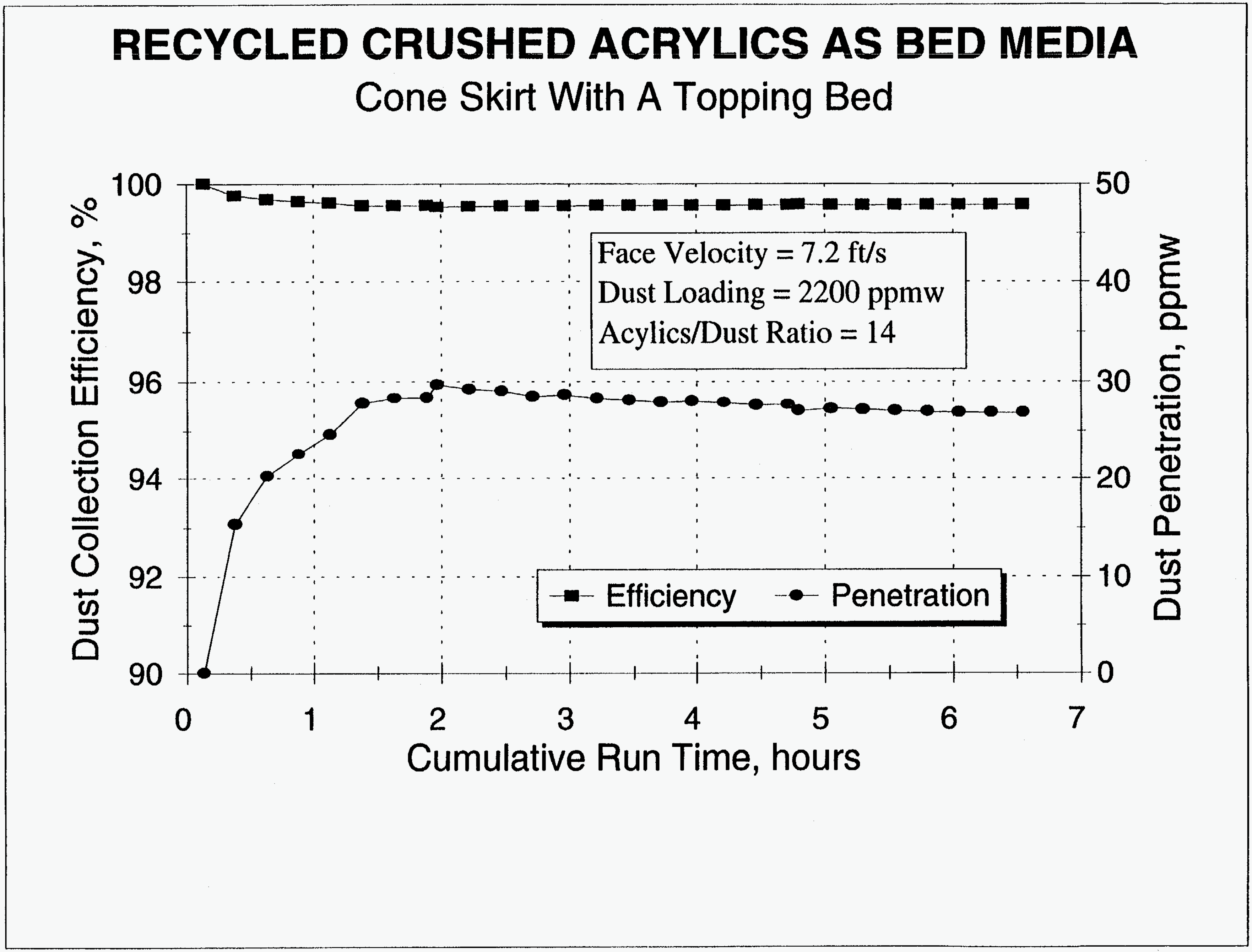


Figure A18 - Cold Flow Test 1 Dust Penetration Record

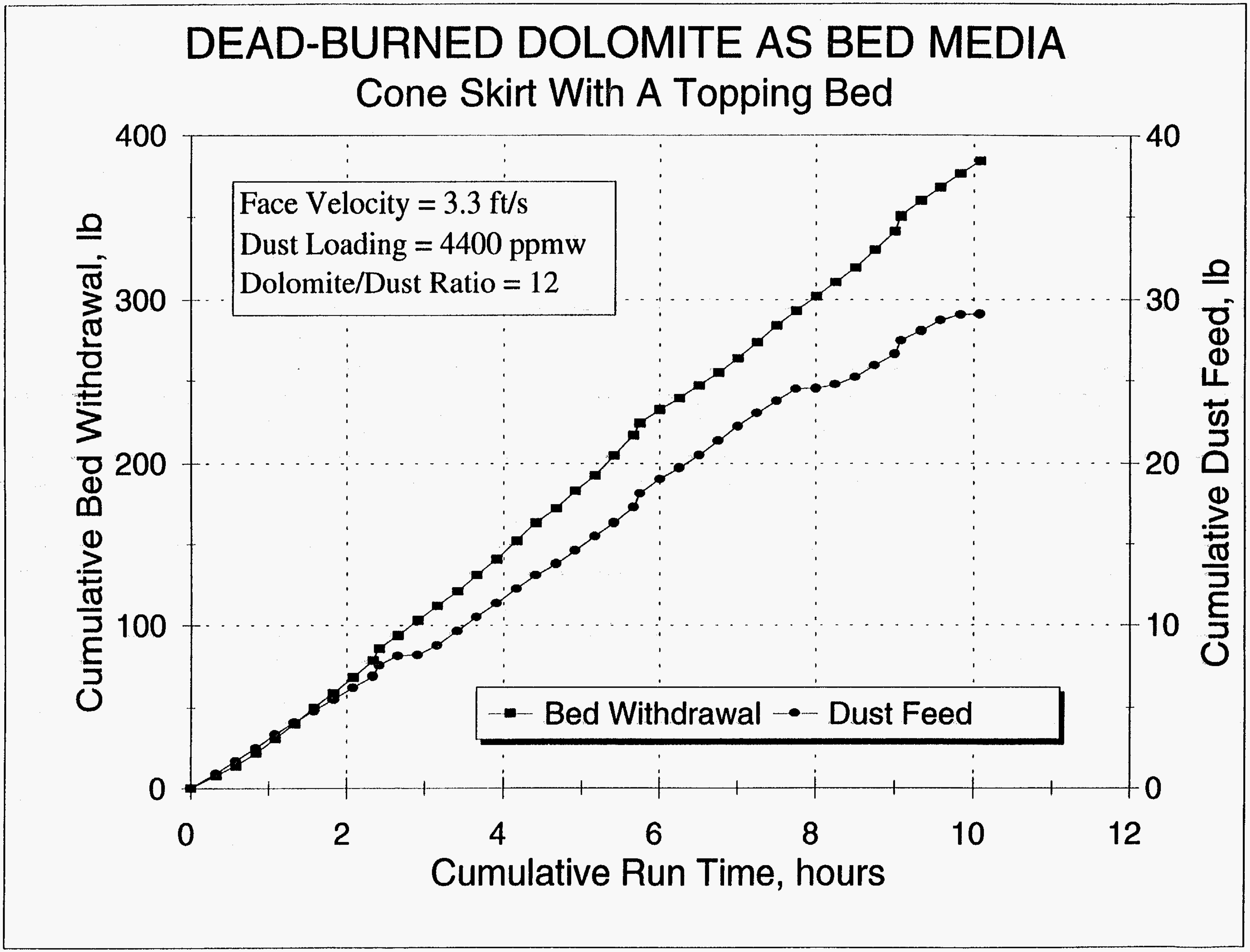


Figure A19 - Cold Flow Test 1 Bed Withdrawal Record

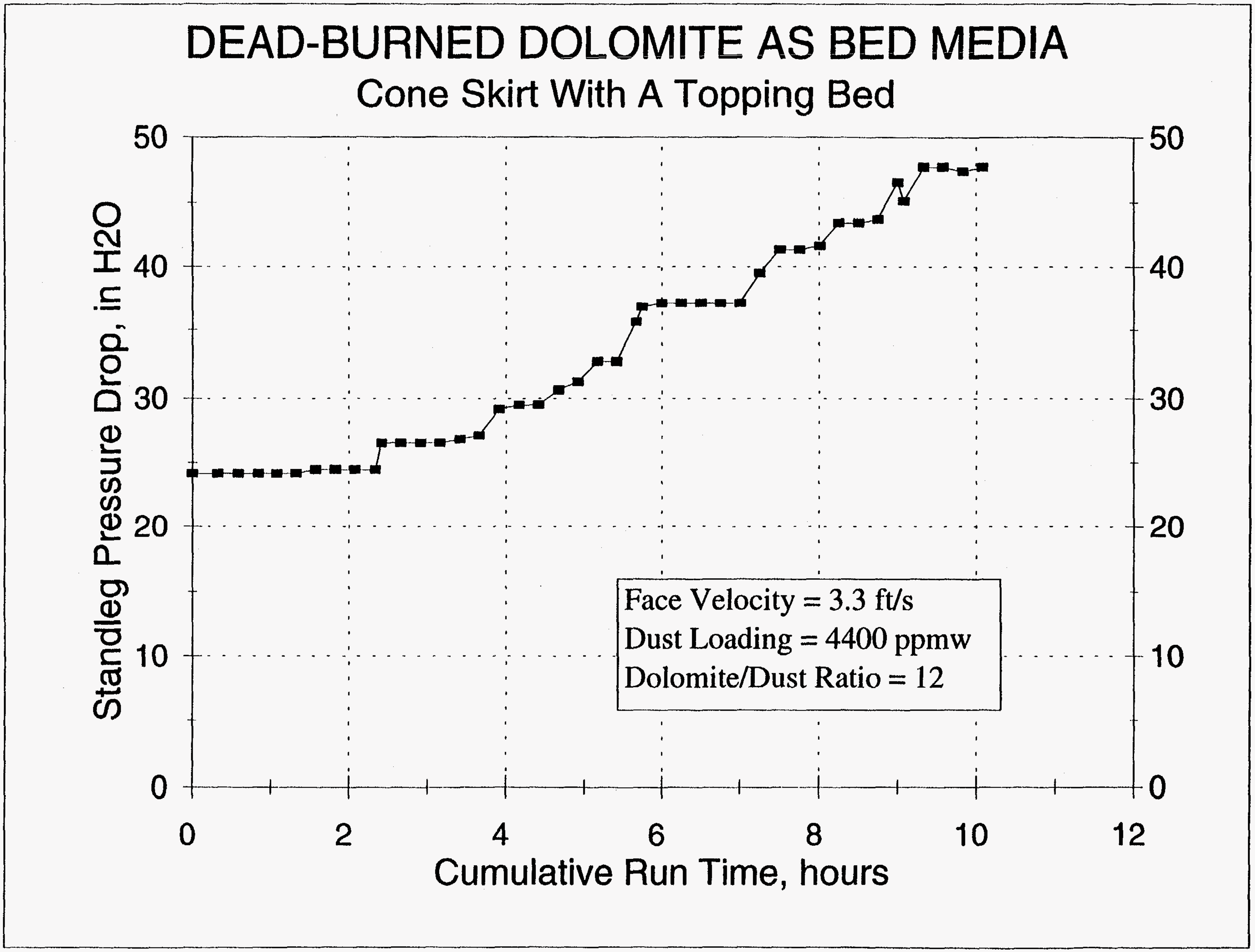


Figure A20 - Cold Flow Test 1 Bed Pressure Drop Record

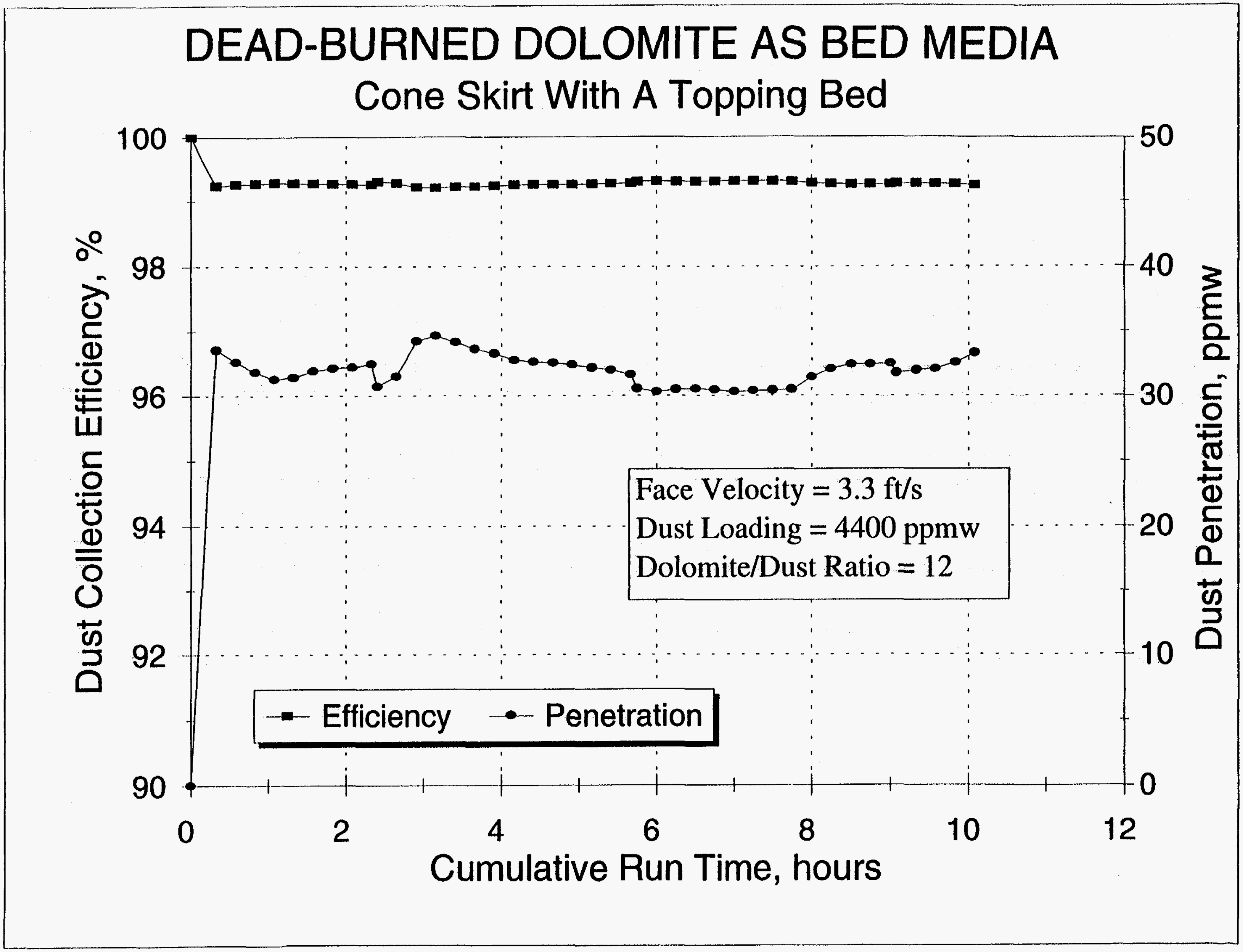


Figure A21 - Cold Flow Test 1 Dust Penetration Record

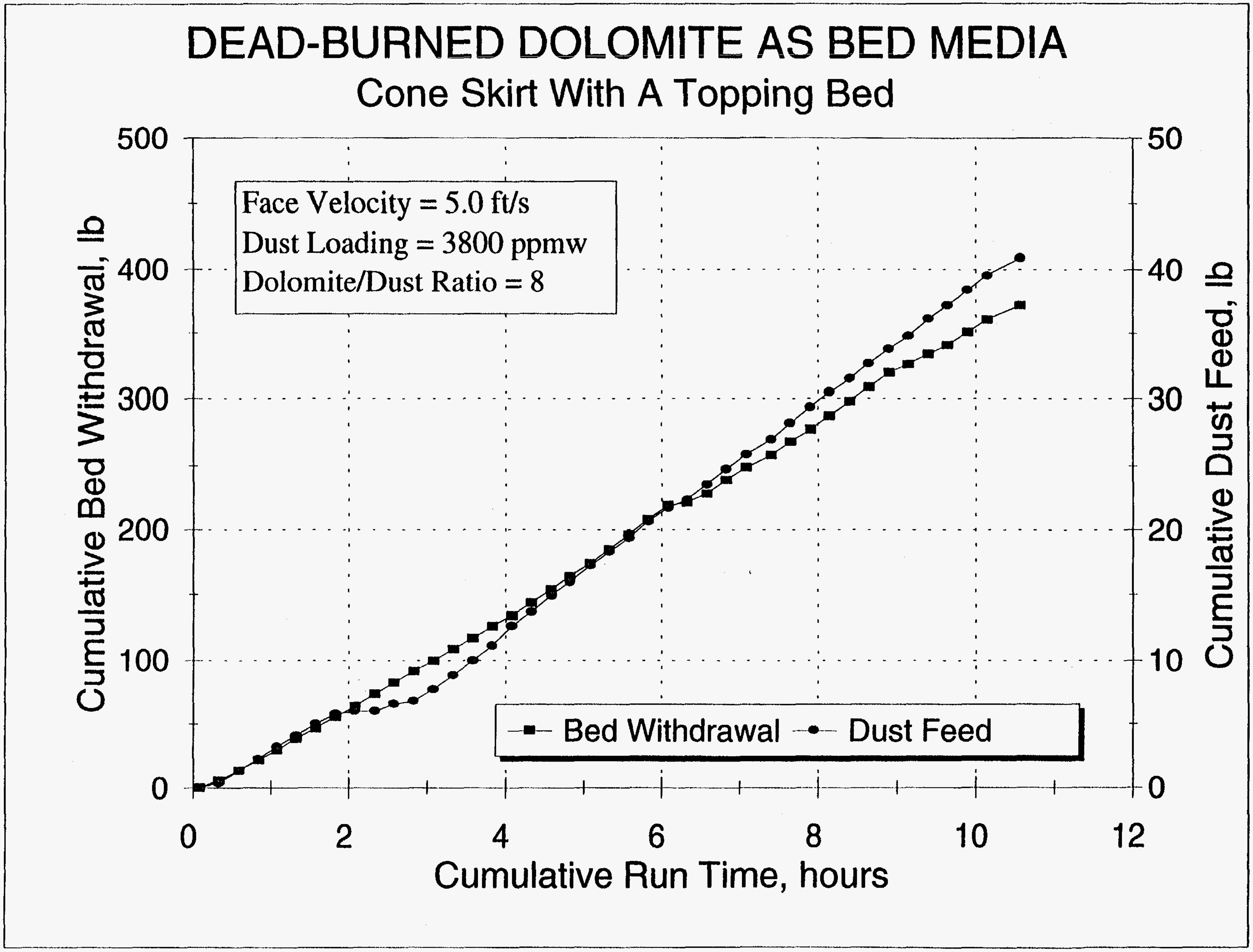


Figure A22 - Cold Flow Test 1 Bed Withdrawal Record

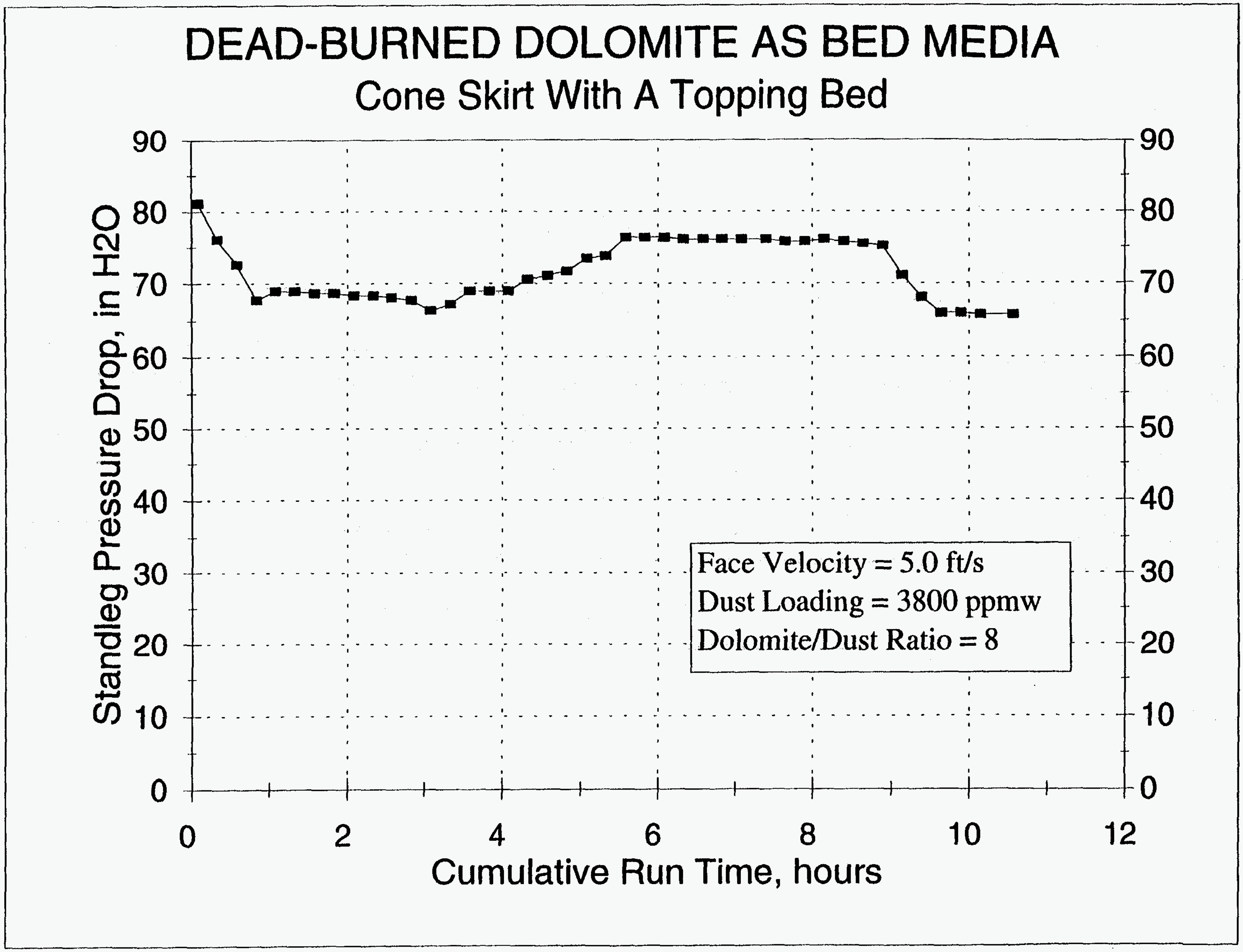


Figure A23 - Cold Flow Test 1 Bed Pressure Drop Record

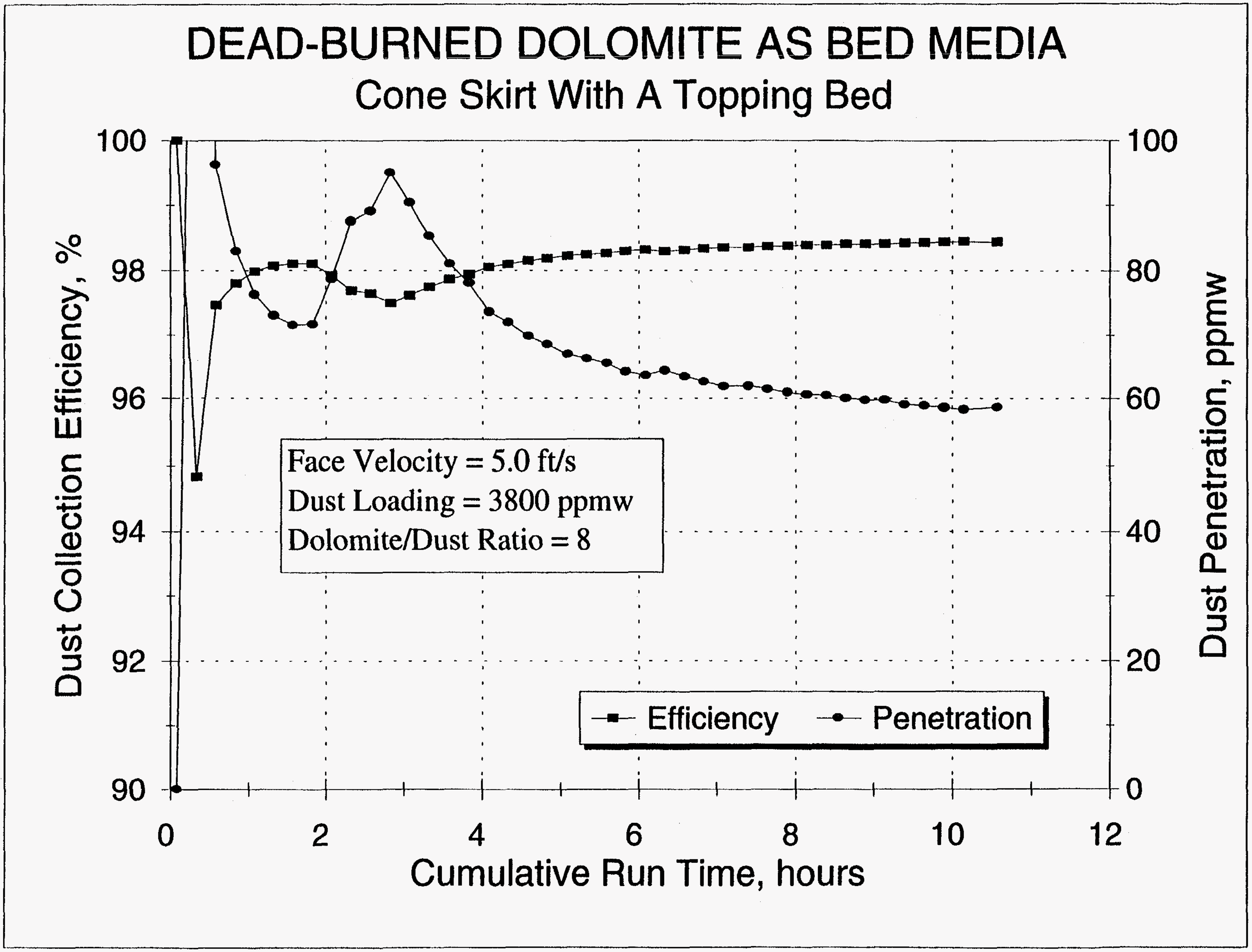


Figure A24 - Cold Flow Test 1 Dust Penetration Record

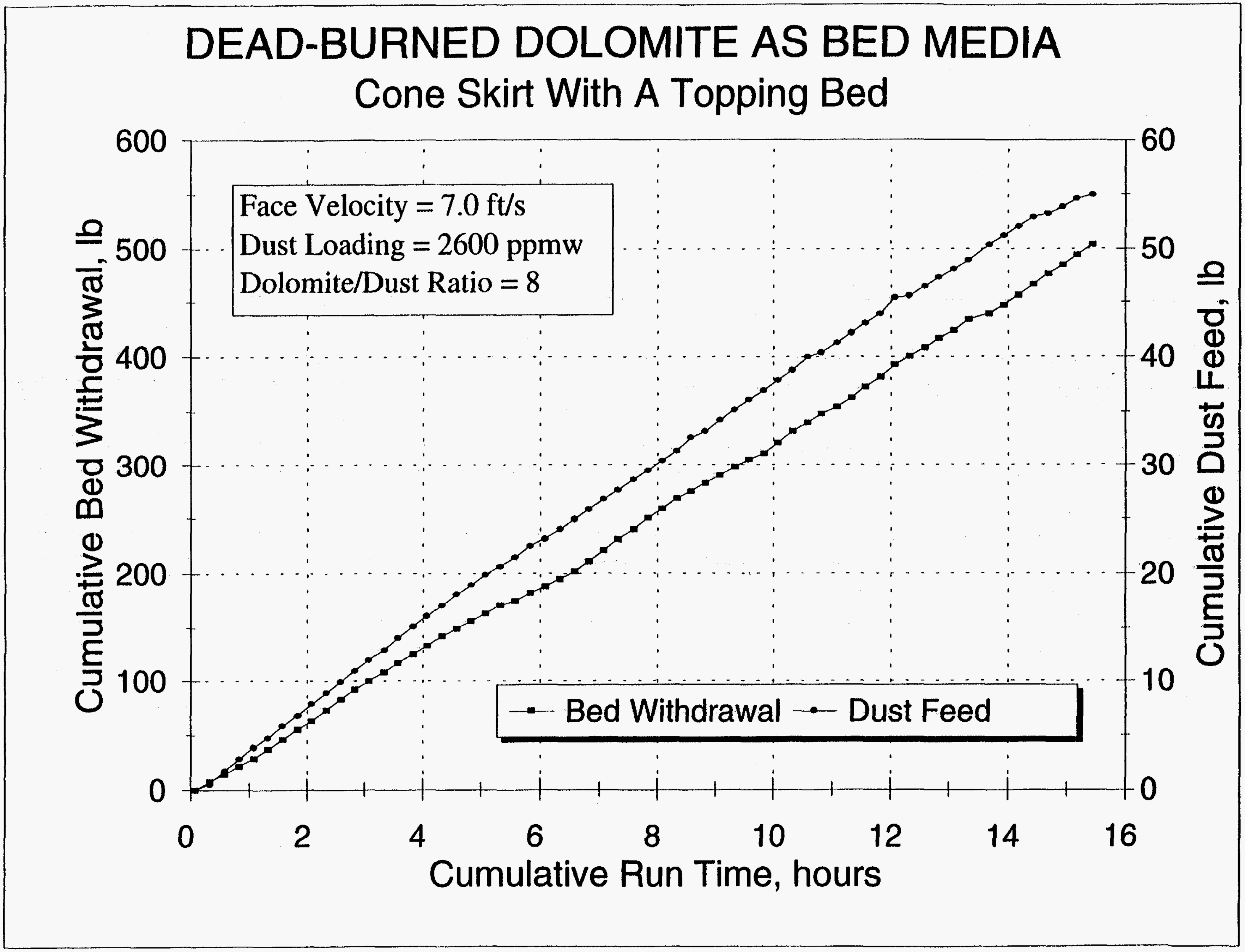


Figure A25 - Cold Flow Test 1 Bed Withdrawal Record

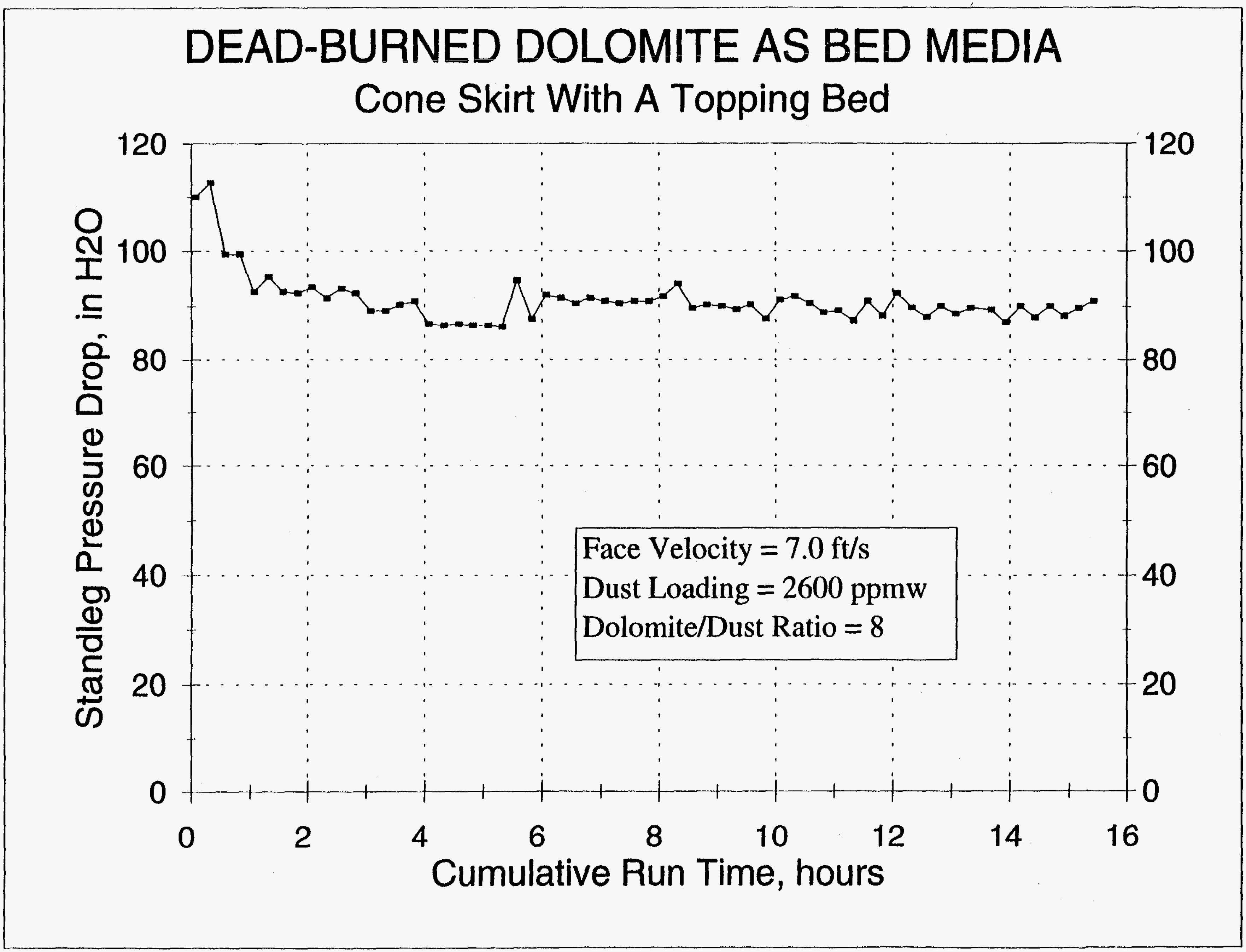


Figure A26 - Cold Flow Test 1 Bed Pressure Drop Record

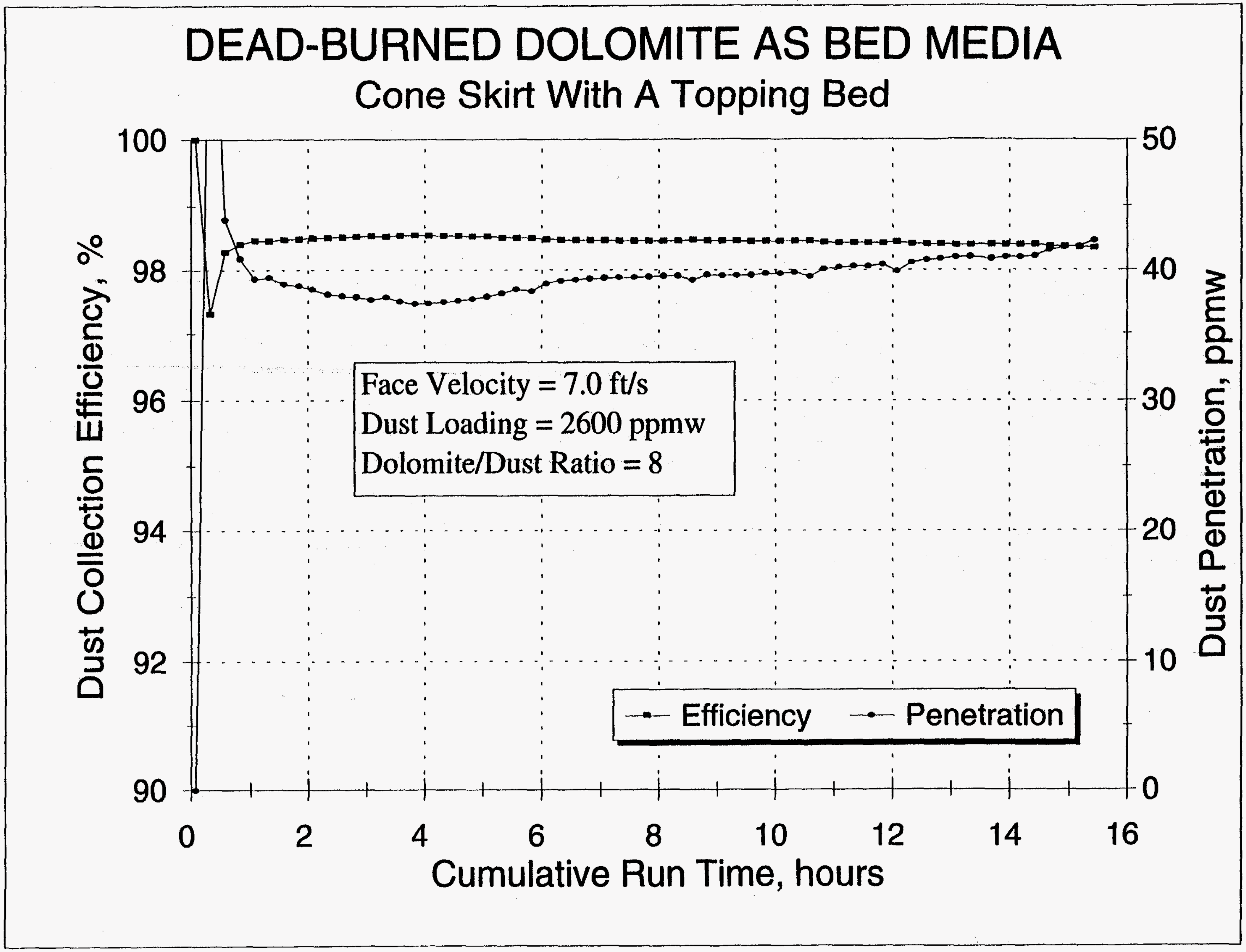


Figure A27 - Cold Flow Test 1 Dust Penetration Record