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# EFFECT OF FEED ATOMIZATION AND VESSEL CONFIGURATION ON FINES FORMATION AND ENTRAINMENT FROM FLUIDIZED-BED CALCINERS

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# Effect of Feed Atomization and Vessel Configuration on Fines Formation and Entrainment from Fluidized-Bed Calciners

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## Abstract

Minimal fines formation and entrainment from the fluidized-bed calciner vessel of the NWCF is desirable to maximize waste throughput. This report summarizes the results of pilot-plant and WCF efforts in the areas of feed nozzle design and operation and calciner and baffle design.

# Summary

Fines and granules are produced during fluidized-bed calcination of liquid radioactive wastes. Fines are generated by attrition of larger bed particles and spray drying of atomized feed droplets. Some of the fines have sufficient residence time in the bed to provide seed particles for the particle growth; the remainder are elutriated from the bed or withdrawn with the product. Methods which were tested to reduce the generation and entrainment of fines during the calcination process are discussed in this report.

A pneumatic flat-faced feed atomizing nozzle has proven adequate for feed introduction, bed particle size control, and seed particle generation. Other pneumatic nozzle types (the extended divergent, long extended convergent, and short extended convergent) did not control bed particle size. Testing of a single-fluid pressure nozzle and the combination nozzle and cyclone fines return jet was discontinued before completion. However, no further testing to improve nozzle operating characteristics is presently justifiable, as the flat-faced nozzle has proven adequate.

Limited tests confirmed that a cylindrical fluid bed with an expanded vapor space results in lower entrainment rates than a conventional cylindrical fluid bed. A reduction of the superficial gas velocity in the expanded vapor space by a factor of 3.2 reduced entrainment by a factor of 8. Double "venetian blind" baffles in the calciner vapor space were 20% more effective in suppressing fines entrainment than single "venetian blind" and fan baffles. Submerged baffles increased bed particle attrition and subsequent fines entrainment. The New Waste Calcining Facility will have a cylindrical calciner vessel with an expanded vapor space containing a double "venetian blind" baffle.

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# I. Introduction

The reprocessing of spent nuclear fuel at the Idaho Chemical Processing Plant (ICPP) generates radioactive waste solutions. The volume and mobility of these liquid wastes are reduced by fluidized-bed calcination to fines (<150 μm diameter) and granular particles at the Waste Calcining Facility (WCF). Ideally fines would be coated with feed solution, grow into granules, and be drained from the bed as product. However, part of the fines are elutriated from the fluid-bed and entrained with the off-gas. Part of the fines are not removed from the off-gas by the cyclone and are collected in the off-gas scrubber system. Reducing the amount of fines going to the off-gas scrubber system reduces the scrubbing solution recycle rate and increases the calciner net throughput.

Fines are produced in the fluid-bed calciner by: 1) the mechanical impact and fracturing (attrition) of the particles against vessel surfaces and other particles, 2) the thermal shock as cold feed solution is injected onto the hot bed particles using pneumatic atomizing nozzles, and 3) the spray drying of liquid feed droplets. The external-mix pneumatic nozzle shown in Figure 1 has been demonstrated in the WCF[1] and pilot plant calciners to meet the following requirements:

1. Adequate coating of moving particles within the fluidized bed to provide continual growth of those particles until they leave the calciner as product.
2. No serious agglomeration of bed particles.
3. Minimum production of particles small enough to be elutriated with the effluent calciner gases.
4. Production of sufficiently small "seed" particles to provide nuclei for particle growth to stabilize the mean diameter of bed particles at an acceptable value.
5. No caking in the bed, on the vessel walls, on the calciner internal appurtenances, or on the nozzle itself.
6. No erosion of exposed equipment surfaces or of the nozzle itself.
7. Acceptable feed introduction characteristics over a wide range of feed flow rates.
8. Minimum use of atomizing air to minimize the volume of gas requiring cleanup.
9. Minimum pressure requirements for feed solution.
10. Capable of handling suspended fine solids from the recycled quench and scrubbing solution.
11. Long, trouble-free life in remote operation.

Other types of nozzles tested did not adequately meet the above requirements.

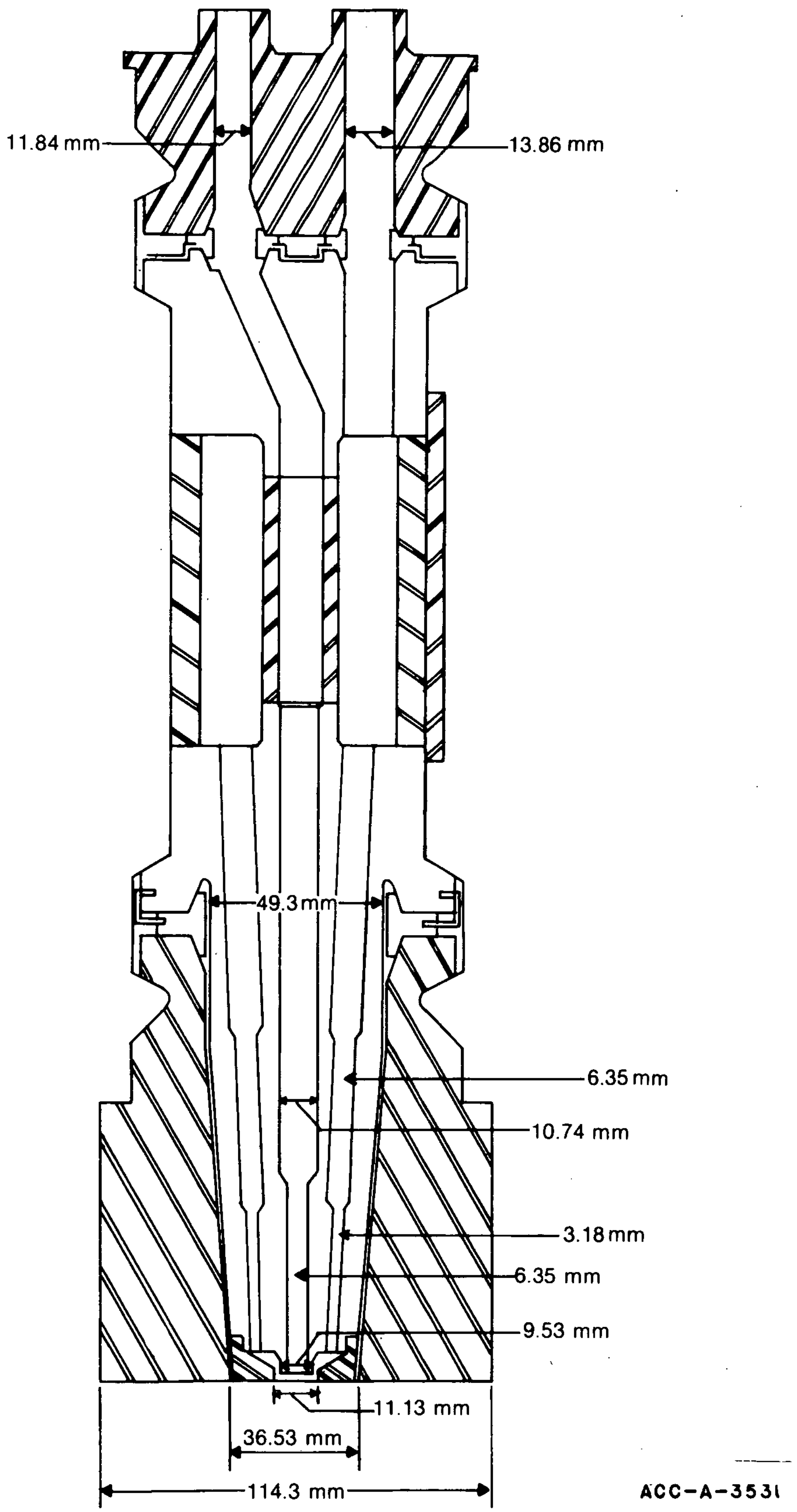


Figure 1. NWCF External Mix, Flat-Faced, Pneumatic Atomizing Nozzle

Control of the mass mean particle diameter (MMPD) of bed particles to between ∿ 0.3 and 0.6 mm is desirable to maintain good fluidization quality and minimize elutriation. The volumetric nozzle air ratio (NAR) of atomizing air (at the metered temperature and at the pressure in the fluid-bed vapor space) to waste feed can be varied and is used as a means for controlling the bed MMPD. Several other variables such as waste feed type and concentration, bed particle attrition resistance, fuel nozzle design and operation (when in-bed combustion is used for heating) and degree of fluidization, also affect the MMPD, but are not generally used for particle size control during operation.

The following variables affect particle entrainment from the calciner vessel: gas velocity, viscosity, and density; particle size distribution, density, and shape; vessel dimensions; and devices used to suppress entrainment. Because of the many variables involved, quantitative prediction of entrainment for scale up of equipment is difficult.

Zenz[2] proposed the following explanation for particle entrainment. Bubbles of gas pass upward through the bed at velocities greater than the superficial fluidizing velocity. When the bubbles erupt at the bed surface, particles are thrust into the vapor space at varying velocities. The intermittent high-velocity bursts of gas impose an irregular, time-dependent velocity profile over the cross section of the vessel at the bed surface. The velocity profile becomes progressively more stable with increasing height in the vapor space. The velocity profile becomes stable at a height in the vapor space referred to as the transport disengaging height (TDH). At TDH, all entrained particles having a terminal velocity greater than the superficial velocity will have dropped back into the bed, and the remaining particles will be elutriated. The TDH increases with the superficial gas velocity, since the rate of bubble eruptions increases. A proposed method for reducing the TDH in the NWCF is to increase the bed cross-sectional area with increasing height thereby decreasing the superficial gas velocity with height.

A tapered vessel of increasing cross-sectional area with increasing height was proposed to maintain an approximately constant superficial velocity through the bed, as additional gases are produced at the feed and fuel nozzle locations.

A cylindrical vessel with an expanded upper section to decrease the superficial velocity in the vapor space was also proposed. As the superficial velocity decreases, a larger fraction of particles will have a terminal velocity greater than the superficial velocity and fall back into the bed.

Baffles installed in the vapor space of a vessel with an insufficient TDH were proposed to decrease entrainment by deflecting particles with terminal velocities greater then the superficial velocity back into the bed. However, Zenz[2] reports that tests with baffles near the bed surface are relatively ineffective, since bubbles tend to push material through the baffle slats. A "fan" shaped baffle was proposed to be more efficient than a "venetian blind" baffle. The "fan" baffle swirls the gas stream, thereby subjecting the particles to centrifugal forces to create a cyclone effect. A double "venetian blind" baffle with the second set of plates placed perpendicular to the flow produced by the first set of plates was also proposed to be more effective than the single "venetian blind" baffle.

Baffles installed below the surface of the bed were suggested to break up massive bubbles and reduce the violence of the erupting bubbles. However, it is reported by Zenz[2] that the TDH is not related to the size of the bubbles bursting at the bed surface. The greater frequency of small bubble eruptions tends to increase the distance required for velocity profile stabilization to the same distance required for large bubbles erupting more violently but less frequently. Also submerged baffles tend to inhibit top-to-bottom particle mixing.

The results of waste feed atomization nozzle tests, vessel shape tests, and baffle design and location tests are discussed in subsequent sections of this report.

## II. Effects of Feed Atomizing Nozzles on the Operation of Fluid-Bed Calciners

Feed atomizing nozzles injecting liquid waste into the fluid-bed calciner 1) cause a temperature depressed zone, 2) control average bed particle diameter, and 3) generate fines.

### 1. Temperature Depressed Zone

Temperature depression caused by the nozzle spray zone was measured in the 61-cm square pilot-plant calciner.[1] Use of the Type 1/2-J pneumatic atomizing nozzle made by Spraying Systems Company causes a temperature reduction of up to 350°C in a zone that extends approximately 30 to 45 cm in front of the nozzle. Some particles undergo thermal shock in this zone. Beyond that distance from the nozzle, the normal bed temperature prevails. Aluminum nitrate feed solution was used; feed rates varied from 80 to 150 L/hr; NAR values ranged from 300 to 860.

### 2. Average Particle Diameter

Particle production occurs from the fracturing of larger particles by mechanical impact or thermal shock and by spray drying. Particle growth takes place by either of two mechanisms: 1) agglomeration of two or more smaller particles to make a larger particle, or 2) a buildup of layer upon layer of solidified feed material around particles in the fluid bed. Particles below a certain size and particle density have an insufficient residence time in the bed prior to elutriation and do not receive a coating of feed solution. Particles of sufficient size and density do become coated and grow or are fractured into smaller particles. Dependence upon the effects of the nozzle air for average bed particle size control and for the production of "seed" particles has been successfully demonstrated in the WCF and pilot-plant calciners. However, many other factors influence the average bed particle size which prevents a direct correlation to NAR values. The other factors involved are: feed composition and concentration, particle attrition resistance, vessel size, nozzle size and physical condition (eroded or corroded), and the effects of the fuel nozzles. NAR values in the WCF have been varied from ∿50 to ∿900 for different types of feed to control the average bed particle size.

### 3. Fines Generation

Because of spray drying and particle fracture from nozzle effects, a significant fraction of WCF product consists of fines entrained from the calciner and separated from the off-gas by the primary cyclone. The vast majority of fines generated in the fluid-bed calciner can be directly attributed to the effects of pneumatic feed atomization and the fuel combustion nozzles. Only minor generation of fines is caused by the fluidizing air. Test were conducted in the 61-cm square calciner[1] to determine the feed nozzle effects on particle attrition. Introduction of high velocity atomizing air to a fluidized alumina bed caused a several-fold increase in attrition and entrainment over that obtained with no nozzle air and no feed. The introduction of feed solution results in an additional increase in bed entrainment. Particle fracture caused by thermal shock and spray drying explain the latter increase in bed entrainment. The effects of the additional gases from atomizing air and feed decomposition products and the resulting increase in superficial gas velocity on entrainment was not discussed.

## III. Results of Nozzle Configurations Tests

Several types of pneumatic atomizing nozzles were tested in the 61-cm square calciner and are illustrated in Figure 2. The spray patterns and liquid droplet size and uniformity produced by these nozzles were not evaluated. Only the operating characteristics of the nozzles in the calciner were reported.

The standard flat-faced nozzle 2a has been demonstrated to be satisfactory for introducing feed solution to fluid-bed calciners. Under proper operating conditions, the nozzle produces the necessary particle attrition to provide the seeds which are required for new particle growth. The MMPD of the fluid bed is controlled when calcining different types of feed solutions by regulating NAR values. Nozzle orifice sizes have proven adequate for atomizing feed solution containing undissolved solids.

The boron modified flat-faced nozzle 2b had similar fines generation rates and bed MMPD control as the standard flat-faced nozzle. However boron carbide was easily fractured and was not recommended for use in calciner applications.

The extended divergent nozzle 2c mixes atomizing air and liquid feed solution internally. The MMPD of the alumina fluid bed could not be controlled with adjustments in NAR values during the test. For this reason the extended divergent nozzle was not recommended for use in calciner applications.

The long extended convergent nozzle 2d mixes atomizing air and liquid feed solution externally. Again, the MMPD of the alumina fluid bed could not be controlled, and the use of the nozzle was not recommended.

The short extended convergent nozzle 2e caused bed caking and was not recommended for use in calciner applications.

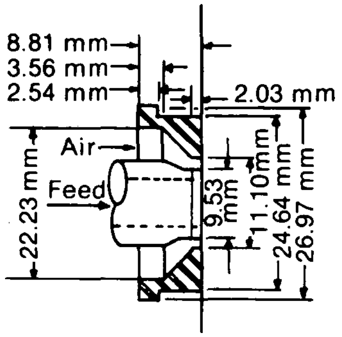
Test results of a single fluid pressure nozzle were inconclusive as the nozzle corroded and eroded excessively during the test. However, the nozzle was not recommended for further testing since a pressurized feed system, prone to wear and failure, would be necessary.

Plugging occured in both air and feed lines during testing of a combination nozzle and cyclone fines return jet. The object in using this combination was to trap cyclone fines in the feed solution and thereby reduce the fines content of the stored product. However, testing was abandoned before sufficient development work could be done, and the combination nozzle could not be recommended without further testing.

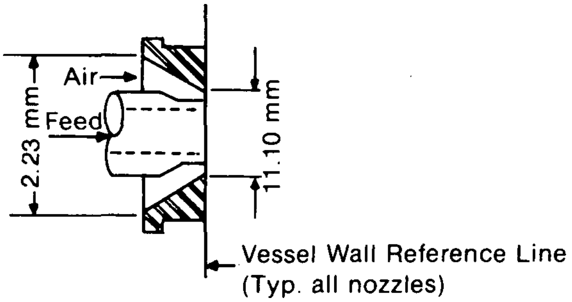
Description

Pertinent Dimensions
(Cross Section)

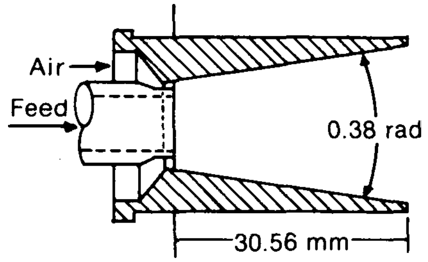
Standard Flat - Faced Cap.
External Air-Liquid Mixing.



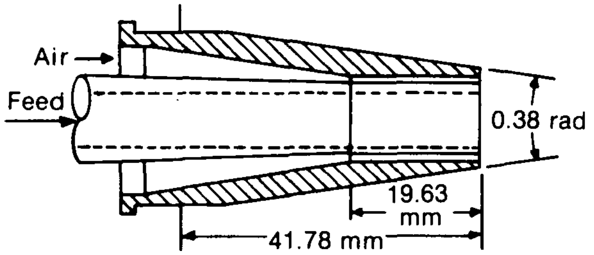
Boron Carbide, Modified,
Flat-Faced Cap. External
Air-Liquid Mixing.



Extended Divergent Cap.
Internal Air-Liquid Mixing



Long Extended Convergent
Cap. External Air-Liquid
Mixing.



Short Extended Convergent
Cap. External Air-Liquid
Mixing.

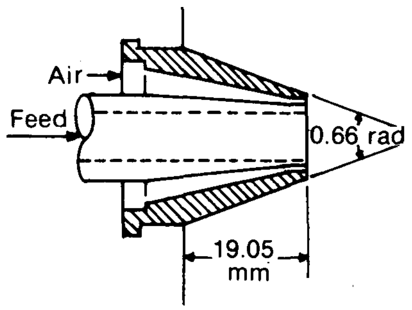


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Figure 2. Description of Feed Nozzle Caps Tested on the Type 1/2-J Feed Nozzle in the Pilot Plant

## IV. Experimental Vessel Configurations

### 1. Equipment Description and Operation

Three fluidized-bed vessel configurations were evaluated with regard to fluidization quality and particle entrainment rates.[3] The vessel shapes, shown in Figure 3, were cylinderical, cylindrical with expanded upper section, and tapered. Alumina calcine was used as bed media in all tests. A constant rate of fines production due to attrition of bed material was assumed during entrainment tests. Particle entrainment rates were evaluated in the pilot plant using only the cylindrical and cylindrical with expanded upper section vessels.

### 1.1 Cylindrical Vessel

A 28-cm diameter plexiglass cylindrical vessel used for fluidization and entrainment studies is shown in Figure 4. The fluidizing air distributor was a perforated metal screen. Air and entrained particles passed through a cyclone for particle removal. The weight of solids collected by the cyclone was used to determine particle entrainment rates. The entrainment rates reported were the average of seven entrainment rates determined for each condition.

### 1.2 Cylindrical Vessel with Expanded Upper Section

The upper section of the 28-cm diameter plexiglass vessel was replaced with an expanded upper section for the next series of tests. The expanded upper section was approximately 1.8 times the diameter of the cylindrical section which would decrease the superficial gas velocity by a factor of 3.2 in the expanded upper section. Particle entrainment rates, expected to be reduced due to the lower superficial gas velocity, were determined in the previously described manner.

### 1.3 Tapered Vessel

A tapered, two-dimensional, plexiglass vessel (Figure 5) was used for a preliminary study of fluidization and particle mixing in a conical vessel. The change in cross-sectional area with respect to height was designed to maintain an approximately constant superficial gas velocity through the bed, as nozzle gases were injected. Fluidizing air entered through a perforated distributor plate. Mixing in the tapered, fluidized bed was studied with the aid of dyed calcine particles. The particles for the test were initially arranged in the vessel as shown in Figure 5.

### 2. Results of Vessel Tests (Fluidization)

The effects of vessel configuration on fluidization quality follow.

### 2.1 Cylindrical Vessel

Adequate fluidization quality in cylindrical vessels has been verified in the WCF and pilot-plant fluidized beds and was observed visually in the cylindrical test apparatus.

### 2.2 Cylindrical Vessel with Expanded Upper Section

The expanded upper section in the vapor space had no effect on bed fluidization quality as observed visually in the test apparatus. From the fluidization quality viewpoint, a cylindrical calciner vessel with or without the expanded upper section was recommended for use in the NWCF.

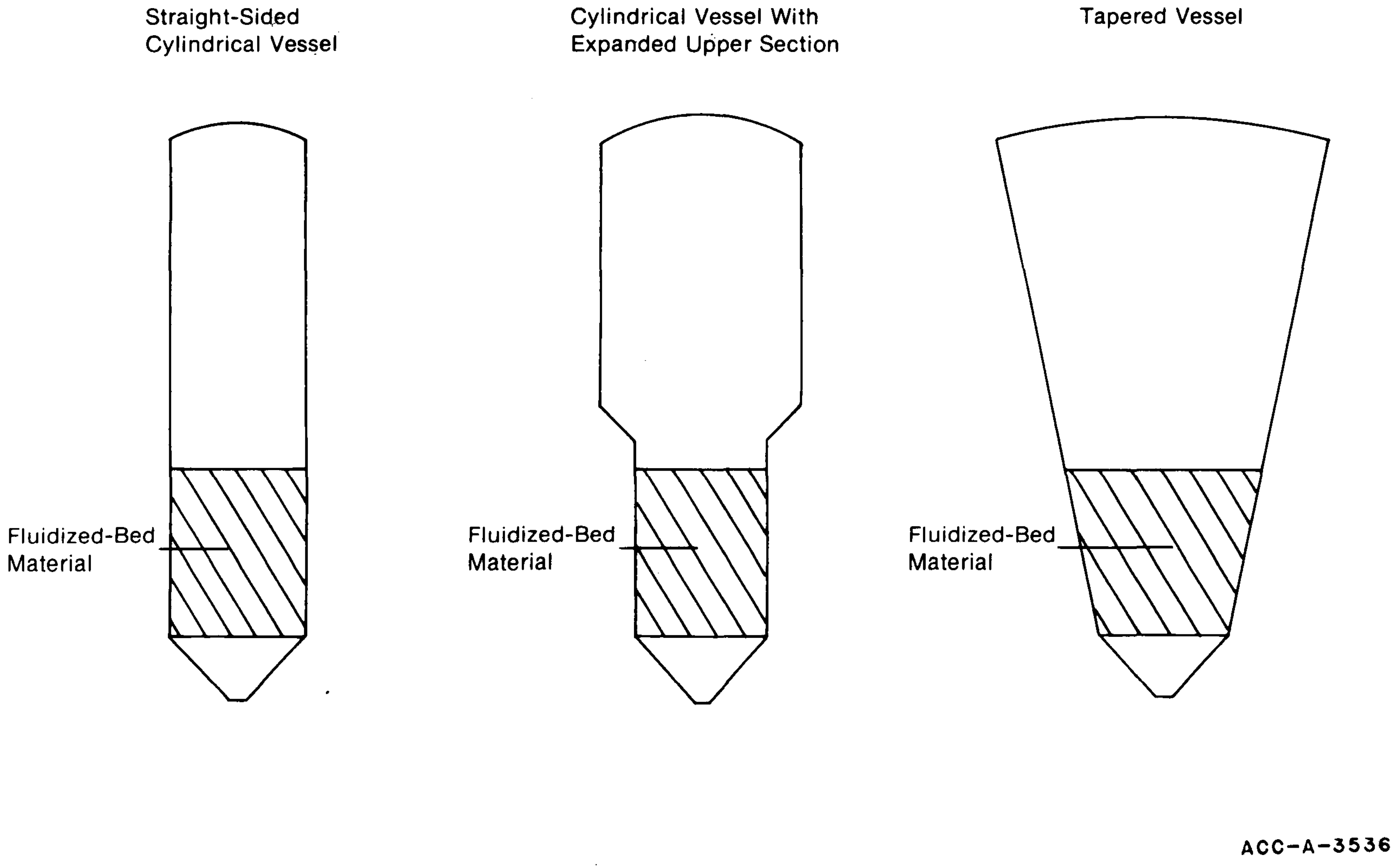

Figure 3. Candidate NWCF Calciner Vessel Configurations

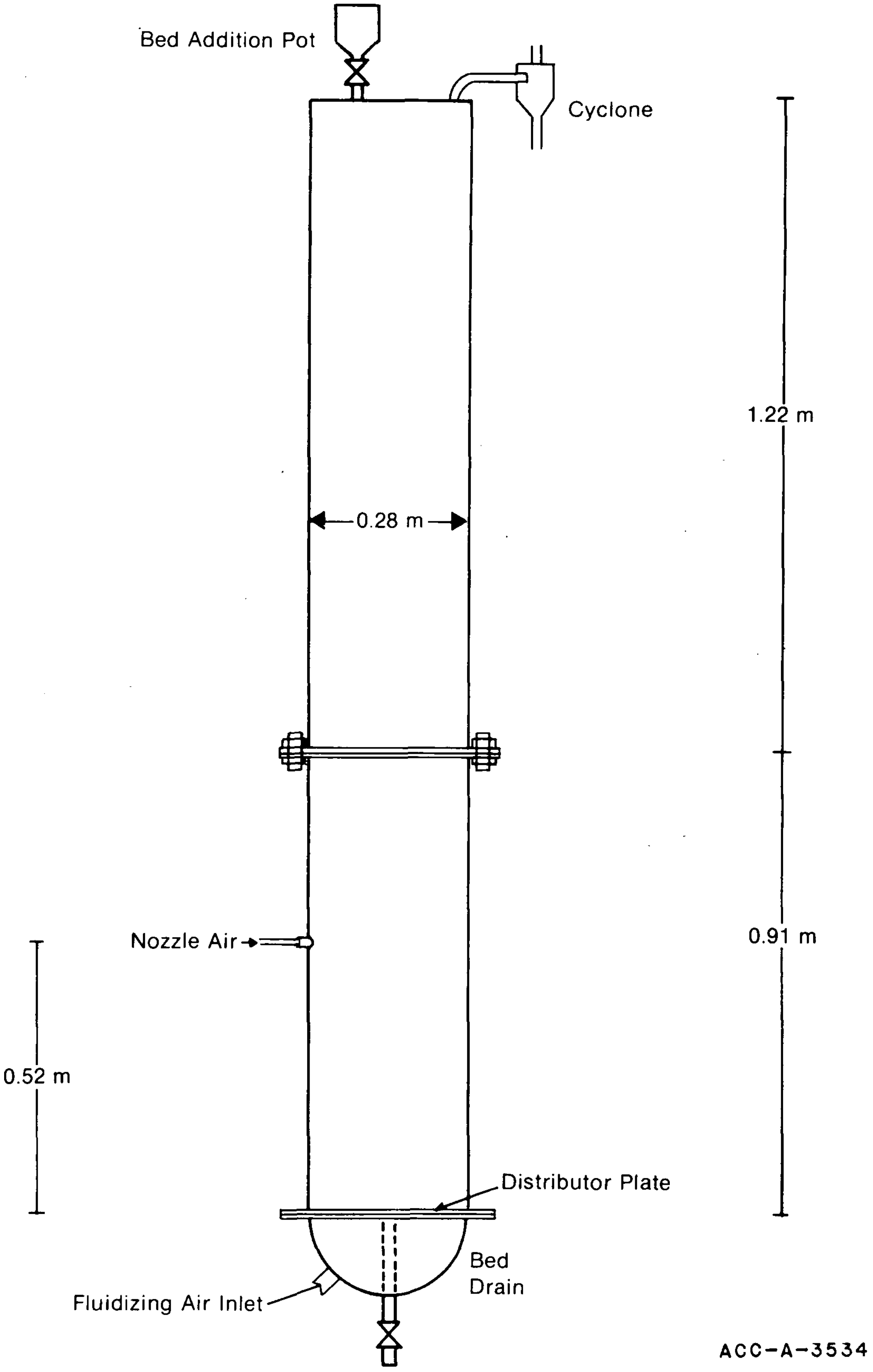

Figure 4. Cylindrical Vessel Test Apparatus

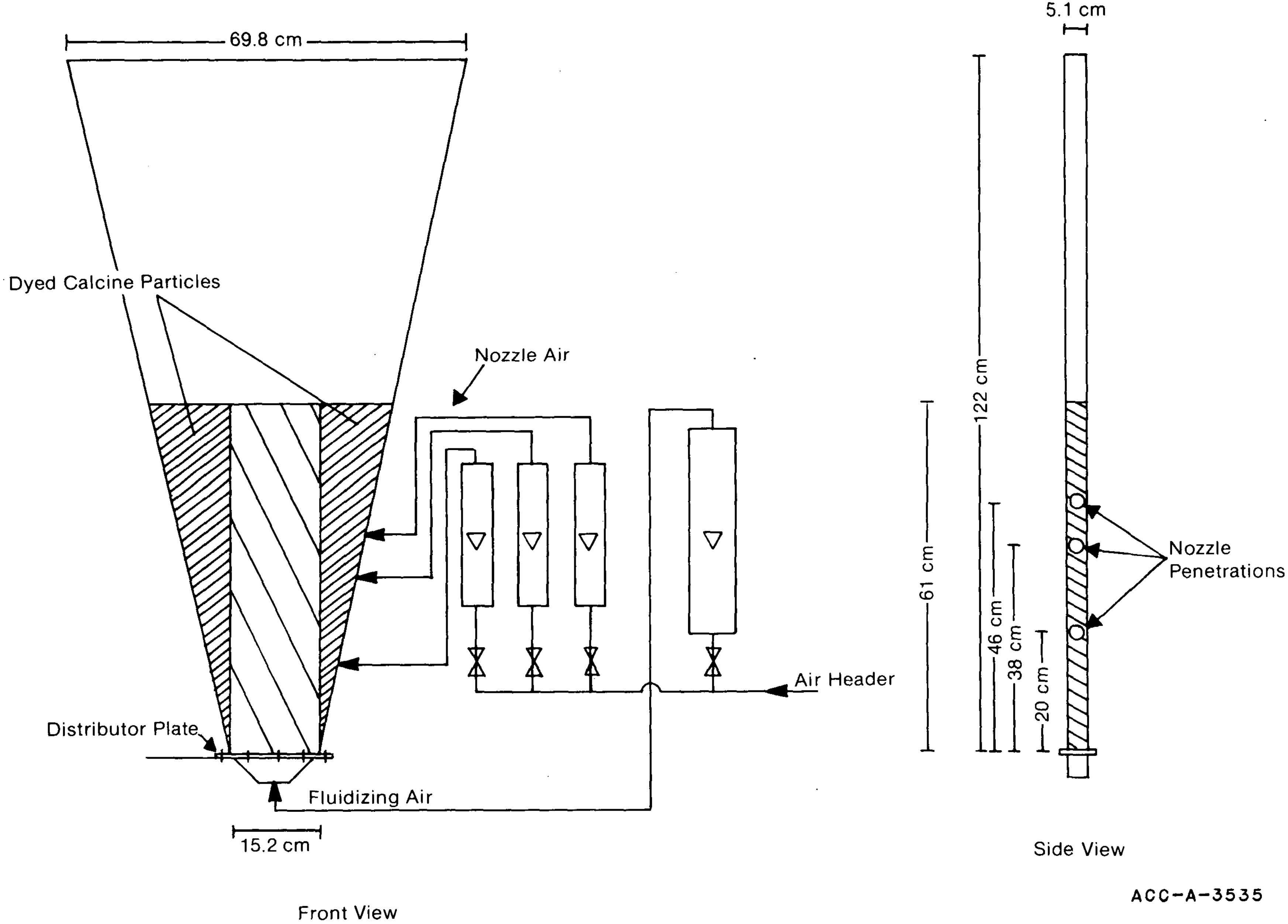

Figure 5. Tapered 2- Dimensional Bed

### 2.3 Tapered Vessel

A run made in the tapered vessel started with dyed calcine near the tapered walls and plain calcine in the middle (Figure 5). The dyed material near the nozzle side mixed almost immediately with the plain material (less than 5 seconds). The dyed material on the side opposite the nozzles took about 45 seconds to mix. Visual observation determined that the poor fluidization near the walls was caused by the fluidizing air channeling through the center of the bed. Because of the potential for poor mixing in a tapered vessel and the increased fabrication costs for a plant-size vessel, further testing of tapered vessels was dropped. A tapered calciner vessel was not recommended for the NWCF.

## 3. Results of Vessel Tests (Entrainment)

The effects of vessel configuration on particle entrainment as deterimined in the pilot plant[3] are described.

### 3.1 Cylindrical Vessel

Particle entrainment studies were conducted at a superficial gas velocity of 1.45 m/s using alumina calcine for bed material. Attrition of the bed material generated fines (at a rate assumed constant) for entrainment rate measurements. Particle entrainment rates averaged 102 grams per hour. Particle size distribution of the entrained fines was not determined.

### 3.2 Cylindrical Vessel with Expanded Upper Section

Test procedures and conditions were the same as for the cylindrical vessel test with exception of the installation of the expanded upper section. Particle entrainment rates averaged 13 grams per hour with the expanded upper section in place. The reduction of the superficial velocity by a factor of 3.2 in the expanded upper section apparently caused particle entrainment rates to decrease by a factor of 8. No attempt was made to determine the particle size distribution of the entrained fines. A cylindrical calciner vessel with an expanded upper section was recommended for the NWCF.

### 3.3 Tapered Vessel

As fluidization quality was poor in a tapered vessel, particle entrainment studies were not conducted.

## V. Baffle Design and Location

A description of test equipment and procedures and the test results of baffles used as entrainment suppression devices are subsequently presented.

### 1. Equipment Description

Three different baffle designs located in the vapor space were tested by different investigators.[3-6] The single "venetian blind" baffle (Figure 6), the double "venetian blind" baffle (Figure 7), and the "fan" baffle (Figure 8) were evaluated. Two other types of screen baffles were tested submerged in the fluidized bed.[3]

### 1.1 Single "Venetian Blind" Baffle

Single "venetian blind" baffles were installed in the 61-cm square calciner[5], the 30-cm diameter calciner[4], the 28-cm plexiglass vessel[3], and the WCF.[6] The slats were set at an angle of $\pi/4$ rad to the direction of flow. Fines were injected into the bed, produced during calcination, or generated by alumina bed attrition.

### 1.2 Double "Venetian Blind" Baffle

A double "venetian blind" baffle was tested in the 28-cm plexiglass vessel[3]. The second set of slats was placed perpendicularly to the first set of slats. Particles passing through the first set of slats would be deflected back by the second set. Fines production was due to the alumina bed attrition.

### 1.3 "Fan" Baffle

A "fan" baffle was tested in the 30-cm diameter calciner.[4] Particles and gas passing through this baffle are swirled to create a cyclone effect. Zirconium fines were recycled to the fluidized bed.

### 1.4 Submerged Baffles

Two types of submerged baffles were tested in the 28-cm plexiglass vessel to break up massive bubbles formed in the fluidized bed[3]. The two baffles were screens having grid openings of 0.64 cm and 6.4 cm, respectively. The location of the submerged baffles was not reported.

### 2. Test Procedures

### 2.1 "Fan" vs. Single "Venetian Blind" Test in 30-cm diameter Calciner

The baffle tests were conducted with a zirconium bed at a fluidizing velocity of 0.76 m/s. Fines were continually injected into the bed, using an auger-type fines feeding device, to simulate the actual bed particle size distribution.

### 2.2 Single vs. Double "Venetian Blind" Test in 28-cm diameter Vessel

The baffle tests were conducted with an alumina bed at a fluidizing velocity of 1.45 m/s. The baffles were tested in the expanded upper section where the average superfical velocity was 0.46 m/s. The double "venetian blind" baffle was installed at two positions above the bed, 20 cm and 91 cm, to determine the effect of baffle location.

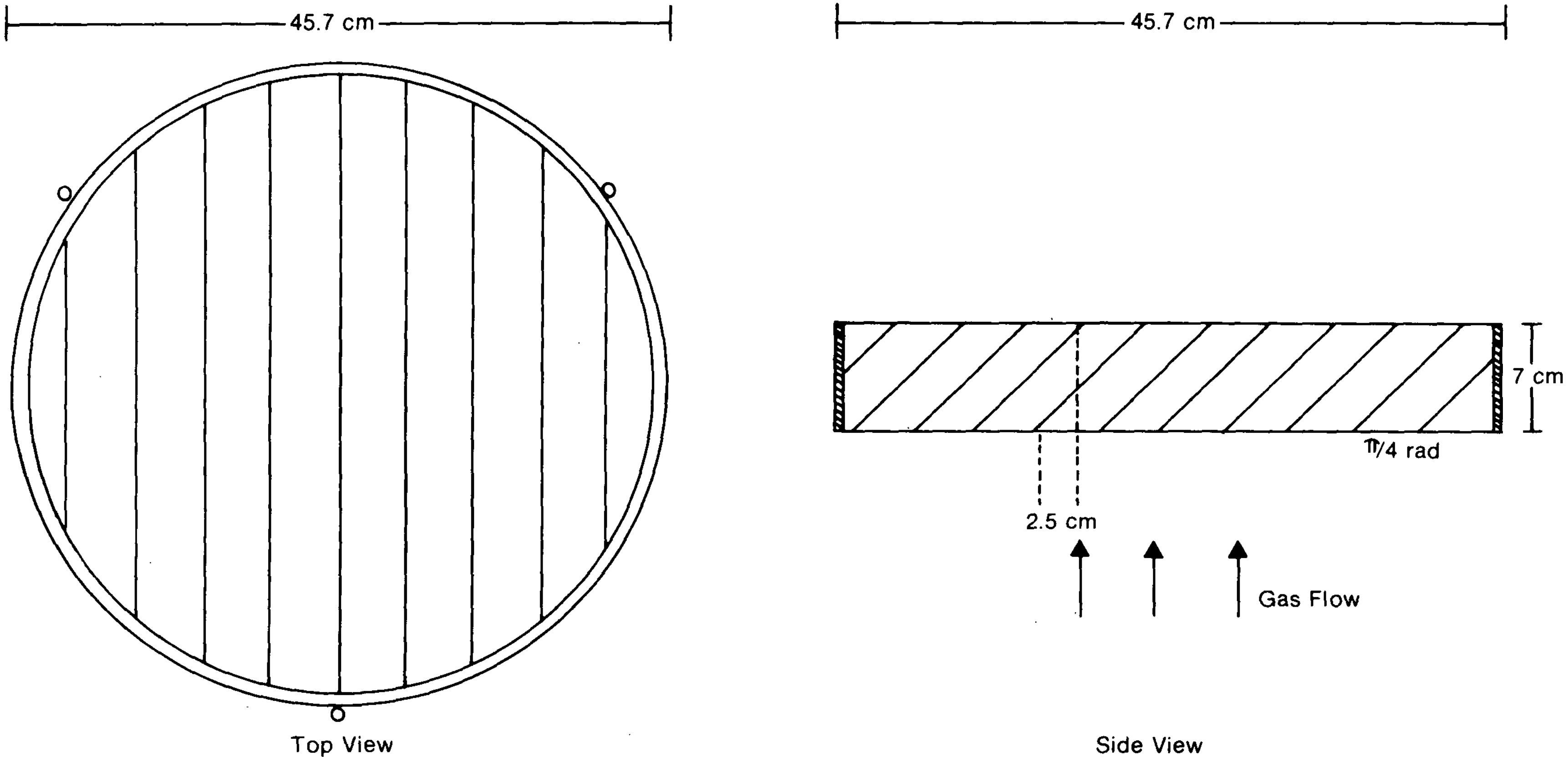

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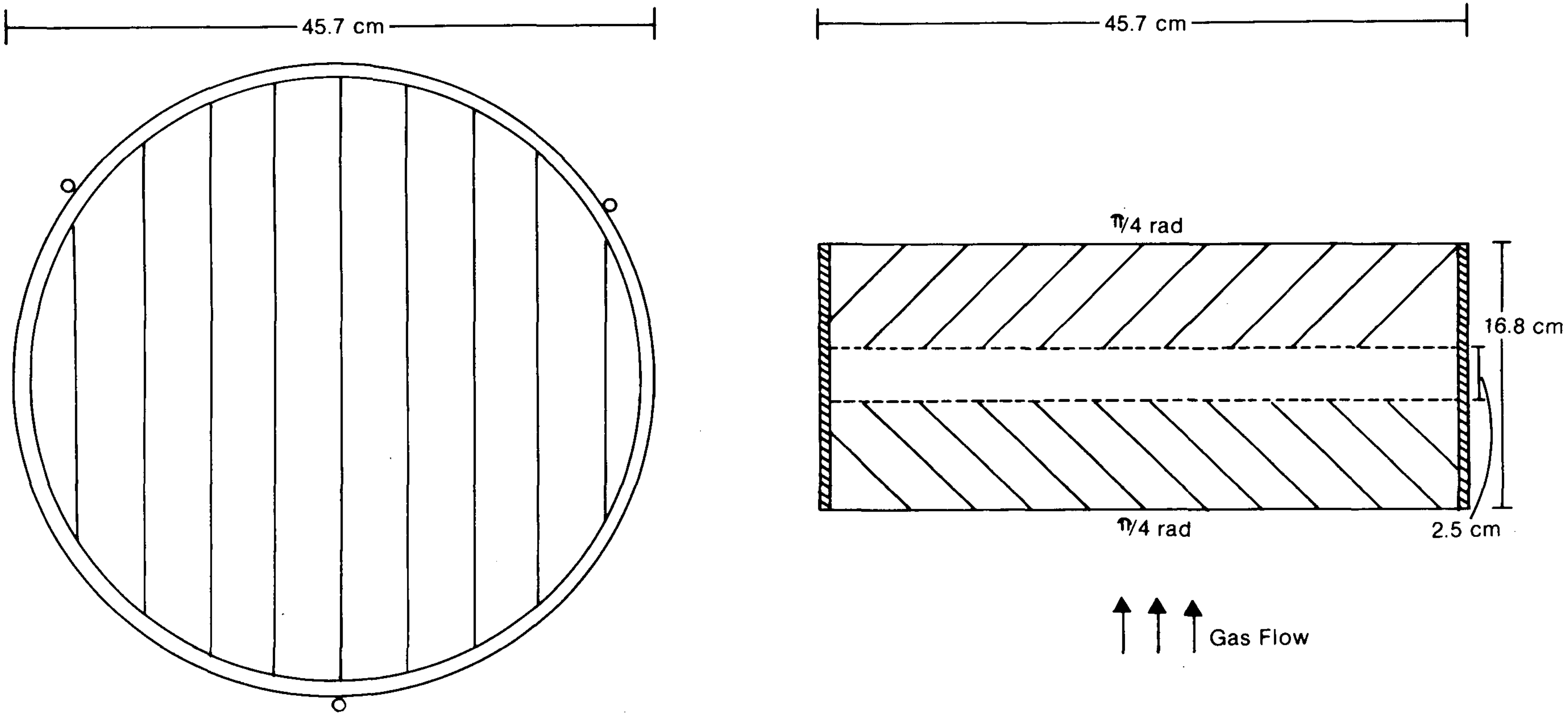
Figure 6. Single "Venetian Blind" Baffle



Top View

Side View

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Figure 7. Double "Venetian Blind" Baffle

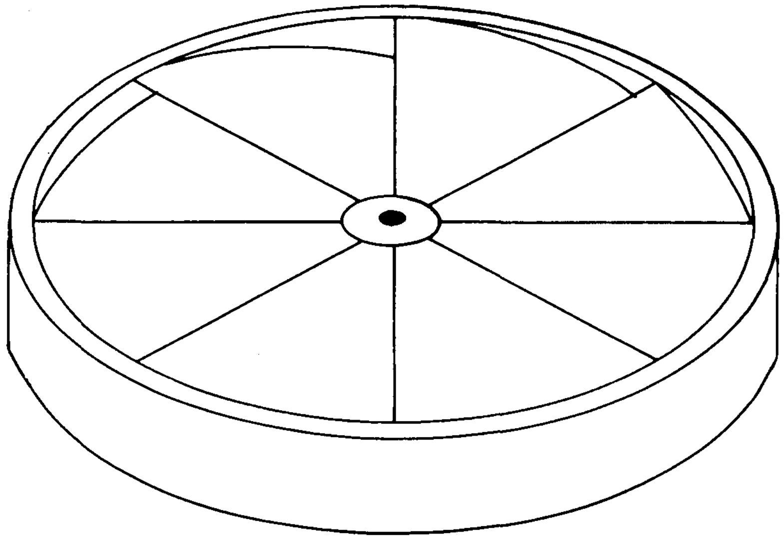

Figure 8. Off-gas Baffle for 30-cm Calciner

### 2.3 Submerged Baffle Tests in 28-cm diameter Vessel

The submerged baffle tests were conducted with an alumina bed at a fluidizing velocity of 1.45 m/s.

### 3. Results of Baffle Tests

The single "venetian blind" baffle was found to be just as effective as the "fan" baffle at reducing entrainment.[4] Entrainment rates from the 28-cm plexiglass vessel with expanded upper section using no baffles, a single "venetian blind" baffle, and a double "venetian blind" baffle were 13, 8.4, and 7 grams per hour, respectively. The double "venetian blind" baffle is approximately 20% more effective than the single "venetian blind" baffle. Entrainment rates were not significantly increased with the double "venetian blind" baffle installed in the lower position as compared to the entrainment rates measured when installed in the upper position.

Results of the submerged baffle tests using the 28-cm plexiglass vessel with expanded upper section showed entrainment to be increased to 11 and 21 grams per hour when using the 6.4 and 0.64 cm grids, respectively.[3] The increase in entrainment was probably due to an increase in attrition of the bed material as the bed buffeted the screens.

A quantitative estimate of the baffle effect on entrainment in the 61-cm square calciner was not possible.[5] Insufficient entrainment data taken before and after installation of the baffle plus the effects of uncontrolled alpha alumina formation (which creates excessive fines) prevented determination of the baffle efficiency.

During "cold" testing of the WCF, excessive fines carryover to the scrubbing system caused feed system restrictions. The combined effect of transporting the fines to the calcine storage facility, instead of recycling the fines to the calciner, modifications to the cyclone, and installation of a baffle plate reduced the entrainment rate from ∿330 kg/hr to ∿55 kg/hr[6].

## VI. Discussion of Vessel Configuration and Baffle Test Results

An important parameter in the design of fluid-bed systems is the transport disengaging height (TDH). None of the investigators attempted to measure the TDH for their apparatus. TDH can be determined by increasing the distance between the apparent surface of the fluid-bed and the off-gas outlet until the rate of entrainment becomes constant as the distance increases. The size distribution of the entrained particles also becomes constant as the gas outlet is raised above the TDH. Since TDH is a function of vessel diameter, gas velocity, and particle properties, it is not possible to predict TDH from the literature. Designing the calciner vessel with a vapor space significantly longer than the TDH will increase costs without reducing entrainment. However, placing the off-gas outlet slightly above the TDH would eliminate the need for baffles.

The results of the investigators does not allow predictions of entrainment rates. Only a ranking of the effectiveness of various vessel configurations can be made. Since elutriation of particles with terminal velocitites less then the superficial velocity depends of the particle size distribution of the elutriated material, rates of entrainment can vary if the particle size distribution changes. For this reason the MMPD of the bed and entrained material should be determined for all tests. The attrition produced fines used by Swink[3] could have had different rates of production and size distribution as the alumina particles eroded with time. This makes the magnitude of the relative effectiveness of the various configurations suspect. Assurance should have been made that particles going to the various entrainment suppression devices were consistent with respect to size distribution and rate of production.

## VII. Conclusions

Feed atomization characteristics and vessel and baffle configurations have a major impact on particle carryover rates from fluid-bed calciners. Specific conclusions are:

1. A standard flat-faced 1/2 J nozzle by spraying Systems Company provides adequate feed introduction, bed MMPD control, and bed attrition for seed particles in the calcination process.
2. Seed particles cannot be produced without producing elutriable fines.
3. Inadequate MMPD control and caking were identified as problems with other nozzle types: extended divergent, long extended convergent, and short extended convergent nozzles.
4. Fluidization quality in cylindrical vessels with or without an expanded vapor space has been shown to be adequate. Fluidization quality based on particle mixing experiments in a tapered vessel was observed to be poor.
5. The use of the expanded diameter vapor space causes a reduction in the vapor-space superficial velocity which resulted in a reduction in particle entrainment.
6. Baffles installed in the vapor space reduce particle entrainment when the gas outlet is below the TDH. The double "venetian blind" baffle was more effective in reducing particle entrainment than the single "venetian blind" and "fan" baffles. Submerged baffles caused an increase in particle attrition and subsequent entrainment.
7. A more quantitative assessment of entrainment from the vessel and baffle configurations tested could have been made if the MMPD of the entrained fines had been maintained constant.

## VIII. Recommendations

The results of various studies presented in this report are the bases for the following recommendations.

1. Further studies are needed to define maximum feed nozzle productivity, eg. spray envelope volume to bed volume ratio.

2. Studies are needed to determine the most satisfactory feed nozzle location within the bed.

3. Studies are needed to determine the most satisfactory feed nozzle location and orientation with respect to fuel nozzle.

4. Further nozzle configuration development should be pursued on a low priority basis since feed atomization nozzles presently used in the WCF and pilot-plant calciners have proven satisfactory.

5. Further design and testing of a combined feed nozzle and cyclone fines return jet should be done if a reduction in the fines content in the calcine storage bins is shown to be necessary.

6. Determination of the TDH for vessel shapes of varying sizes using various calcines would be useful for design of future vessels. However, baffles are probably more desirable than large vapor space de-entrainment sections because of limited cell height.

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