# Boiler Modification at the Southeast Resource Recovery Facility (SERRF)

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# Introduction

In 1988 the City of Long Beach contracted with Dravo Corporation for the design, construction, acceptance testing and operation of a 470,000 t/y waste-to-energy facility to serve the needs of the City and surrounding areas with 500,000 population.

The facility, which was completed in 1988, consists of three L. & C. Steinmüller combustion lines, each designed for 460 t/d. A boiler side elevation is shown in Figure 1.

When Dravo Corporation decided to abandon the waste-to-energy business in 1988, the City of Long Beach contracted with Montenay Pacific Corporation for the operation and maintenance of the facility for an initial five-year period. This contract was subsequently extended to the year 2012.

Ever since Montenay took over the operation and maintenance of SERRF, the City of Long Beach, Montenay and Steinmüller have collaborated in facility improvements and modifications to better plant performance and efficiency with the goal to improve revenues for both, the City and Montenay. Some of the major past improvements executed by Montenay at SERRF included:

- Installation of a Wes-Phix ash treatment system as required by California law.
- Installation of an ash screening system to permit the ash to be used as landfill cover and road material.
- Redesign and installation of ammonia injection nozzles in the boilers to enhance NOχ control and ammonia consumption
- Change over from anhydrous to aqueous ammonia in the facility to improve safety.
- Redesign of the turbine nozzle block to increase turbine steam capacity and power output.
- Redesign of the secondary air nozzles in the boilers to improve combustion and reduce CO and NOχ .
- Adding evaporator platens in the third pass of the boilers to increase saturated steam production and to decrease superheater inlet gas temperature.
- Providing saturated steam extraction capability from the boiler drums to the deaerator to reduce turbine extraction and increase power output.
- Replacement of the ash locks in the third pass of the boilers with an improved design to reduce gas bypass and CO emissions.
- Adding separate combustion and cooling air fans for all burners in the boilers to enhance burner stability and secondary air control.

The latest in the long line of improvements implemented in the Long Beach facility is a modification of the gas inlet configuration to the superheaters, which is the subject of this presentation.

# Experience History

The three Steinmüller boilers at SERRF were designed to produce 117,000 lbs/hr. of steam at 650 psig and 750 °F each.

Combustion takes place on an inclined Steinmüller reciprocating grate consisting of two parallel sections and five zones, each with its individual underfire air supply.

The boiler is of the typical European design with a furnace and secondary air supply, two empty radiant passes and a horizontal convection section, where tubes are cleaned by rapping mechanisms. The waterwalls and evaporator platens in the third pass are of welded tube and membrane construction.

Economizer, waterwall and evaporator tubes are low carbon steel, while the original superheater tubes were of SA 213 T12 material, for both the low and high temperature superheater bundles.

The superheater tubes were approximately 2.00" O.D. x 0.200" wall thickness. The wall thickness included significant corrosion allowances.

The pendant superheater tubes are connected to 12 headers (headers 1 through 12) at the top of the convection pass, where the final superheater consists of two pendants and four headers and the initial superheater consists of four pendants and eight headers. The secondary superheater is located at the inlet of the convection pass and is arranged for parallel flow with the gas flow. The primary superheater follows the secondary superheater and is arranged for counter flow.

About three years after start-up, tube failures occurred in the pendant sections of superheater headers one and two in all three boilers, followed by failures in pendants of headers three and four about a year later. Because of the frequency of failures, it was decided to replace the high temperature superheater in steps between 1992 and 1994. The first tube replacement used material of equal specifications as the original material. The low temperature superheater tubes, headers five through eight exhibited a somewhat better life, however also required replacement.

The backend of the low temperature superheater, so far, has not required replacement.

The first high temperature replacement, unfortunately, did not provide any better life than the original tubes. As a matter of fact, they started failing after about two years. The shorter life span was due, in part, to some increase in processing capacity and higher gas temperatures resulting therefrom. Therefore it was decided to employ a better material, SA 213 T22, and a heavier wall thickness (0.220") for the next high temperature superheater replacement. It was expected that the better and thicker material would provide sufficient corrosion and erosion resistance for a 5-year tube life. As it turned out, this tube life expectation was not achieved. As a matter of fact, the second tube replacement did not perform any better than the first tube replacement.

In addition to tube failures, drain lines at the lower headers of the pendants also required replacement. Here the failure mechanism was determined to be caused by erosion.

As a matter of convenience and to improve outage schedules, superheater pendants are being replaced together with their upper and/or lower headers, whenever the tube stubs at the headers require replacement also.

The tube failure history and the superheater replacement schedule is presented in Table 1 for the three boilers at SERRF.

**Table 1: Superheater Tube Replacement**

| HEADER | UNIT 1 | UNIT 2 | UNIT 3 |
|---|---|---|---|
| 1-2 | Tubes Fall 92<br>Tubes Fall 96<br>Drain Lines Spring 98 | Tubes Spring 94<br>Drain Lines Spring 98<br>Tubes Fall 98 | Tubes Fall 92<br>Tubes & Upper Hdrs Spring 98<br>Lower Hdrs Spring 98<br>Drain Lines Spring 98 |
| 3-4 | Tubes Spring 93<br>Tubes Spring 95<br>Fall 97<br>Drain Lines Spring 98 | Tubes Fall 93<br>Tubes Fall 95<br>Tubes Spring 98<br>Drain Lines Spring 98 | Tubes Spring 93<br>Tubes Fall 95<br>Drain Lines Spring 98<br>Tubes Spring 99 |
| 5-6 | 1st Row Hdr 5<br>Tubes Spring 96<br>Drain Lines Spring 98 | Tubes Fall 92<br>1st Row Hdr 5 Fall 94<br>Tubes Fall 96 | 1st Row Hdr 5 Fall 94<br>Tubes Fall 96<br>Drain Lines Spring 98 |
| 7-8 | Tubes Fall 93<br>Spring 97 – Hdr. 7 Only<br>Drain Lines Spring 98 | Tubes Spring 94<br>Drain Lines Spring 98<br>Tubes Fall 98 | Tubes Fall 93<br>Drain Lines Spring 98<br>Tubes Spring 99 |
| 9-12 | No Failures | No Failures | No Failures |
|  |  |  |  |

# Failure Evaluation

## 1. Purpose of Study

In comparison to SERRF, the two other facilities in the U.S., which employ Steinmüller combustion technology and boilers of very similar design, obtained superheater tube life of over six years.

Because of these differences in superheater tube degradation in the three Steinmüller facilities in the U.S., Montenay decided to evaluate the boiler designs of each facility with the intent to determine the root cause for SERRF's poor performance, as far as tube life was concerned, in comparison to the other two facilities.

Because the failed tubes showed very strong evidence of erosion at the top third of the superheater, it was easy to conclude that the gas velocity across the superheater was too high. To prove this point, the facility contracted Carnot to take gas velocity measurements across the boiler convection sections. The test data proved that the average gas velocities across the tube bundles fall within accepted criteria for waste-fired boilers, however, the measured velocity distribution exceeded by far the typically accepted deviation of about ± 30% from the average design velocity. As a matter of fact, velocities more than twice the average were recorded, indicating severe gas flow maldistribution.

Recognition of the distribution problem led to the review and analysis of the design of the superheater inlet section for each of the Steinmüller facilities in the U.S., as well as a comparison of gas velocities upstream and across the superheater bundle.

## 2. Approximation of Velocities

Gas velocities at design conditions were estimated for SERRF (Table 1).
It should be noted that the calculations were performed for 100% load at 80% excess air.

A more typical operating condition at SERRF is 105% load and about 100% excess air. This condition would increase all velocities by: (105/100) x (2.0/1.8) = 1.166 or 16.6%.

See Figure 2 for locations of Point A through Point D.

## Table 2: SERRF Gas Velocities in Superheater

| | |
|---|---|
| Design Capacity | 460 t/d = 38,333 lbs/hr fuel |
| Fuel heating value | 4654 Btu/lb. |
| Excess Air | 80% |
| Total Air | 225,181 lbs/hr or 5.87 lbs air/lb fuel |
| Total gas | 269,017 lbs/hr or 7.02 lbs gas/lb fuel |
| Gas temperature superheater inlet | 1051ºF clean - 1256ºF dirty |
| Gas density at about 1200ºF | 0.0226 lbs/ft.$^3$ |
| Total gas volume | 269,017/0.0226 =11,903,407 ft$^3$/hr<br>= 3,307 ft$^3$/sec |
| Flow area Point A | 17.8' high x 19.4' wide = 346 ft$^2$ |
| Gas velocity at inlet of transition pass #3 to pass #4 | 3,307/346 = 9.6 ft/sec |
| Flow area Point B | 26.3' high x 10.2' wide = 268 ft$^2$ |
| Gas velocity upstream of first superheater | 3,307/268 = 12.3 ft/sec |
| Free flow area across first superheater, Point C | 268 – 77 = 191 ft$^2$ |
| Gas temperature about | 1100ºF |
| Gas density at about 1100ºF | 0.024 lbs/ft$^3$ |
| Total gas volume | 269,017/0.024 = 11,209,041 ft$^3$/hr<br>= 3,114 ft$^3$/sec |
| Gas velocity through first superheater | 3,114/191 = 16.3 ft/sec |
| Free flow area across second superheater, Point D | 268 – 98 = 170 ft$^2$ |
| Gas temperature about | 1000ºF |
| Gas density at about 1000º | 0.0256 lbs/ft$^3$ |
| Total gas volume | 269,017/0.0256 = 10,508,476 ft$^3$/hr = 2919 ft$^3$/sec |
| Gas velocity through second superheater | 2919/170 = 17.2 ft/sec |

For comparison, Montgomery County gas velocities were estimated at the equivalent positions as SERRF, e.g. position "A", "B", "C" and "D" and are given in Table 3.

Montgomery design conditions are 50,000 lbs/hr of fuel at 5000 Btu/lb higher heating value. At 80% excess air, this fuel would require 6.5 lbs of air per lb of fuel, resulting in a total gas flow of 7.5 lbs gas/lb fuel. Temperatures are equivalent to SERRF.

Montgomery County also typically operates at some overload condition and some higher excess air than 80%, so that the same gas velocity correction factor of 1.166 may be applied to the calculated values.

**Table 3: Montgomery County Gas Velocities in Superheater**

| | |
|---|---|
| Total gas flow | 50,000 x 7.5 = 375,000 lbs/hr |
| Gas volume | 375,000/0.0226 = 16,592,920 ft³/lbs<br>= 4609 ft³/sec |
| Flow area point A | 580 ft² |
| Gas velocity point A | 4609/580 = 8.0 ft/sec |
| Flow area Point B | 373 ft³ |
| Gas velocity point B | 4609/373 = 12.4 ft/sec |
| Flow area Point C | 373 – 131 = 242 ft³ |
| Gas volume | 375,000/0.024 = 15,625,000 ft³/hr<br>= 4340 ft³/sec |
| Gas velocity point C | 4340/242 = 17.9 ft/sec |
| Flow area Point D | 242 ft² |
| Gas volume | 375,000/0.0256 = 14,648,437 ft³/hr<br>= 4069 ft³/sec |
| Gas velocity point D | 4069/242 = 16.8 ft/sec |

The Portland facility was designed for 5200 Btu/lb fuel and 90% excess air. This would translate to approximately 7.0 lbs of combustion air per lb of fuel, or 8.0 lbs of gas per lb of fuel. It's processing capacity is 250 t/d or 10.5 t/hr per train.

The design gas velocities are shown in Table 4, where it is assumed that temperatures are similar to SERRF and Montgomery County.

Note that Portland has three different superheater tube lengths, necessitating evaluation of Point E. If Portland were also operating at peak load as SERRF and Montgomery County, the gas velocities would increase by:

$$(105/100) \times (2.0/1.9) = 1.105 \text{ or } 10.5\%$$

## Table 4: Portland Gas Velocities in Superheater

| | |
|---|---|
| Total gas flow | 10.5 x 2000 x 8.0 = 168,000 lbs/hr |
| Gas volume | 168,000/0.0226 = 7,433,628 ft³/hr<br>= 2065 ft³/sec |
| Flow area Point A | 173 ft² |
| Gas velocity point A | 2065/173 = 11.9 ft/sec |
| Flow area Point B | 169 ft² |
| Gas velocity Point B | 2065/169 = 12.2 ft/sec |
| Flow area Point C | 169 – 51 = 118 ft² |
| Gas volume | 168,000/0.024 = 7,000,000 ft³/hr<br>= 1944 ft³/sec |
| Gas velocity Point C | 1944/118 = 16.5 ft/sec |
| Flow area Point D | 194 – 61 = 133 ft² |
| Gas volume | 168,000/0.0256 = 6,562,500 ft³<br>= 1823 ft³/sec |
| Gas velocity point D | 1823/133 = 13.7 ft/sec |
| Flow area Point E | 194 – 67 = 127 ft² |
| Gas volume | 168,000/0.0265 = 6,339,623 ft³/hr<br>= 1761 ft ³/sec |
| Gas velocity point E | 1761/127 = 13.9 ft/sec |

## 3. Data Comparison

Comparison of gas velocities in feet/second at 105% load, 100% excess air is given in Table 5.

### Table 5: Gas Velocity Comparison

| | Point A | Point B | Point C | Point D | Point E |
|---|---|---|---|---|---|
| SERRF | 11.2 | 14.3 | 19.0 | 20.0 | - |
| Montgomery | 9.3 | 14.5 | 20.9 | 19.6 | - |
| Portland | 13.1 | 13.5 | 18.2 | 15.1 | 15.4 |

The above table shows that the design velocities for the boilers of the three facilities are reasonably close as expected.

As a matter of fact, the Portland boiler has the lowest velocities in the tube bundles, which is due to the low capacity of the Portland boiler in comparison to SERRF and Montgomery County. A higher velocity design for a low capacity boiler would result in a very narrow fourth pass, which is impractical to build.

Simple fluid dynamics, as used in the "Presumed Gas Flow Distribution" diagrams, (Figure 3, 4, and 5) as well as Carnot's velocity test data showed that design velocities are not attainable in the boiler convection sections because of flow maldistribution.

Therefore, in order to estimate the real average gas flow velocities, the effective flow areas, as determined form the distribution diagrams were estimated and the gas velocities were calculated based upon the effective flow areas (Table 6 and 7).

### Table 6: Approximate flow area reduction due to gas flow maldistribution:

| | Point A | Point B | Point C | Point D | Point E |
|---|---|---|---|---|---|
| SERRF | 50% | 59% | 58% | 53% | - |
| Montgomery | 38% | 42% | 39% | 35% | - |
| Portland | 50% | 52% | 52% | 53% | 47% |

**Table 7: Approximate average gas flow velocities as expected from gas flow maldistribution for 105% load and 100% excess air in ft/sec.**

| | Point A | Point B | Point C | Point D | Point E |
|---|---|---|---|---|---|
| SERRF | 16.8 | 22.7 | 30.0 | 30.6 | |
| Montgomery | 12.8 | 20.6 | 29.1 | 30.0 | |
| Portland | 19.7 | 20.5 | 27.7 | 23.1 | 22.6 |

This comparison indicates that, due to malidstribution in the flue gas flow entering the superheater and across the superheater, SERRF had the highest velocities of the three U.S. Steinmüller boilers.

A comparison of the estimated actual average gas velocity values with the values measured by Carnot is of little value as Carnot's measurements were taken between the tube banks and the highest velocities causing the erosion problems actually occur within the tube banks.

Only one Point of the Carnot tests, which is reasonably close to Point B of the calculated values, may be used for comparison. Here, Carnot measured 25.6 ft/sec average velocity vs. the calculated value of 22.7 ft/sec.

Carnot's test data are of value only to support the claim of severe gas flow maldistribution, which is proven by the significant difference in gas velocities between the different boiler elevations.

## 4. Evaluation of Data

Erosion is a third power function of gas velocity. Assuming approximately the same flyash loading in the gas stream for all Steinmüller boilers, it stands to reason that SERRF would suffer from higher erosion rates in superheater #2.1, the cooler portion of the finishing superheater, than either Montgomery County or Portland, because of its higher average actual gas velocity through this tube bank.

The effect of the velocity on tube life, neglecting any other possible influences, could be estimated as follows:

Superheater Banks S.H.2.1, Header #1

| | |
|---|---|
| Point C: SERRF | 30 ft/sec |
| Point C: Montgomery | 29.1 ft/sec |
| Point C: Portland | 27.7 ft/sec |

**Assuming Portland to be the base condition with normal erosion caused metal wastage, e.g. "X", then the metal wastage for Montgomery and SERRF would be as high as calculated below:**

**Montgomery:** $(29.1/27.7)^3$ **x X = 1.16 X**
**SERRF:** $(30.0/27/7)^3$ **x X = 1.27 X**

**This shows that the erosion potential of the SERRF Superheater section #2.1 is 27% higher than Portland and 11% higher than Montgomery.**

**For header #2 of S.H.2.1 the following results are obtained:**

Superheater Bank S.H.2.1, Header #2

| | |
|---|---|
| Point D: SERRF | 30.6 ft/sec |
| Point D: Montgomery | 30.0 ft/sec |
| Point D: Portland | 23.1 ft/sec |

**This would indicate erosion potentials for SERRF and Montgomery in comparison to Portland as follows:**

**Montgomery:** $(30.0/23/1)^3$ **x X = 2.2 X**
**SERRF:** $(30.6/23.1)^3$ **x X = 2.3 X**

**Therefore, both Montgomery and SERRF appear to have an erosion potential of more than double the potential for superheater S.H.2.1, header #2 than the Portland facility.**

**For superheater bundle S.H. 2.2, which is the final superheater bank, Portland's gas velocity was calculated at 22.6 ft/sec at Point E. As the flow areas at Point E are equal to Point D for SERRF and Montgomery, their Point D velocities need only be adjusted by gas flow distribution and gas density for the lower temperature.**

**SERRF – Point E:** (1.33 X 20) x (0.024/0.0265) = 24.1 ft/sec
**Montgomery – Point E:** (1.26 x 19.6) x (0.024/0.0265) = 22.4 ft/sec

**These velocities compare to 22.6 ft/sec at Portland. Calculating erosion potential for SERRF versus Montgomery and Portland for superheater bank #2.2 yields the following results:**

**POINT E VELOCITIES: SERRF = 24.1 ft/sec**
**Montgomery = 22.4 ft/sec**
**Portland = 22.6 ft/sec**

**Montgomery: $(22.4/22/6)^3$ x X = 0.97 X or ~ X**
**SERRF: $(24.1.22.6)^3$ x X = 1.21 X**

**The erosion potential for SERRF's superheater bank S.H. #2.2, headers #3 and #4 appear to be 21% higher than either Montgomery or Portland. Using erosion potential values permit a prediction of tube life as a relative value based on the Portland experience, which appears to be better than either Montgomery or SERRF. Here, tube life would be the inverse of the erosion potential.**

**According to the information obtained, Portland had not replaced headers #1 or #2 of the superheater at the time of the study (October 1996). Assuming these tube banks lasted another year, a total life of approximately seven years will have been realized.**

**Using this life as the base, the following life predictions could be made for SERRF and Montgomery:**

| | S.H.#2.1, header #1 | S.H.#2.1, header #2 | S.H.#2.2, headers 3&4 |
|---|---|---|---|
| **Portland** | **7 years** | **7 years** | **6 years** |
| **Montgomery** | **7/1.16 = 6.0 yrs** | **7/2.2 = 3.2 yrs** | **6/1 = 6 years** |
| **SERRF** | **7/1.27 = 5.5 yrs** | **7/2.3 = 3.0 yrs** | **6/1.21 = 5 years** |

**Comparing these values against actual tube life for Montgomery and SERRF, however, do not show a fully satisfactory relationship (Figure 6), proving that other factors influence tube life in the boilers. This becomes especially apparent when comparing the three units at SERRF, whose tube replacement schedule varied significantly from unit to unit, with unit #2 performing somewhat better than the others.**

## 5. Other Failure Mechanisms

It is known that essentially all superheater failures are due to erosion/corrosion. However, it is not known how much either of these two mechanisms contributes how much to the observed metal wastage. One thing is clear, SERRF has in most cases the highest effective gas velocities, however its wastage rates exceed, by far in some areas, the prediction for its reduction in life as a function of these velocities.

Therefore, we must assume that corrosion may play a greater part in tube metal degradation at SERRF than at Montgomery or Portland.

Other factors causing corrosion are, of course, the HCL, $SO_2$, $SO_3$, and CO levels in the flue gas. Although there is a remote possibility that HCL and SO levels may be higher at SERRF, it does not seem very likely as the fuel heating value at SERRF is lower than at Montgomery and Portland, indicating lower plastics and rubber content in the fuel.

CO values, however, are higher at SERRF than at Montgomery. No data on the Portland conditions were available for comparison.

CO is strictly a combustion related contaminant and may stem from the other incidents and problems, many of which have been addressed (see list of boiler modifications in Introduction).

Therefore, in addition to higher gas velocities caused by severe maldistribution of the gas flow, SERRF may also have suffered from higher chemical attack due to the higher CO levels than in the other plants.

Another difference between SERRF, Montgomery and Portland is the ammonia injection for Nox control at SERRF. This was suspect in 1994 to be a contributor to the tube failure mechanism, however detailed chemical and physical analyses by Steinmüller and other laboratories concluded that the ammonia was benign in terms of superheater corrosion.

## 6. Effect Of Cleaning

In 1991, Montenay implemented high-pressure water washing of the convection sections, while the boilers stayed on line, at the SERRF boilers. This is a very effective method to remove ash and slag deposits from boiler tubes and to regain boiler efficiency. Unfortunately, the SERRF boilers did not have enough doors to effectively clean the convection banks completely and often portion of the banks would plug, causing further maldistribution of gas flow and even higher gas velocities.

Additional doors were added over time, however there are still not enough doors to permit full coverage of the surfaces with precise viewing of the washing action, allowing for the possibility that portions of the tubes may be over-cleaned to bare metal, or under-cleaned leaving significant deposits on the tubes. Either case is dangerous from a corrosion point of view. Over-cleaning, which removes the tube metal oxide layer, forces the rebuilding of this layer which wastes base metal. Under-cleaning, which may leave a thick deposit of ash or slag on the tube will increase corrosion attack of the metal as the deposits will absorb corrosive gases such as HCL, $SO_2$, etc., which will condense when in contact with the cooler metal.

Montgomery County started on-line boiler washes essentially right after commercial operation was achieved in 1992. Montgomery also embarked on a program to install sufficient cleaning doors to achieve essentially full coverage.

Portland started cleaning one year after Montgomery, which would place the start of their program in 1993.

SERRF has now cleaned boilers by waterwash for approximately seven years, while Montgomery executed this program for about six years and Portland for about five years. It is interesting to note that all three plants have had tube damage resulting from the water washes. Tube bowing occurred in all plants, a sign of over-cleaning as cold water hit the hot bare metal causing the tubes to bow due to shrinkage. Tube erosion also occurred at all three plants close to the boiler openings, again indicating over-cleaning. Here, over-cleaning could mean too high a water velocity, e.g. too much water, or too long a time period for each cleaning step.

All three plants have employed tube shields close to the doors to protect tubes from erosion due to boiler washing.

## Recommendations For Boiler Modification

The analyses presented in this report prove that SERRF's accelerated superheater failures are caused by the combined effects of erosion and corrosion.

It is believed that corrosion was basically due to the higher CO levels in the flue gas. Therefore, it was imperative to bring the CO level down to the typical values experienced in modern mass-burn facilities, e.g. about 25 ppm, with a maximum of about 50 ppm, when corrected to 7% $0_2$.

It is further believed that erosion/corrosion was attributable to the boiler water wash procedure. Water washing is beneficial; however, to avoid accelerated damage from the washing, it was recommended to reduce the frequency to an absolute minimum of six weeks intervals, to not exceed 10 minutes of washing at any given location and to use water pressures of 5000 psig maximum at the pump. The amount of water should be as low as possible. Cleaning should be stopped before all ash and slag is removed from the tube, so that no bare metal surfaces result from the cleaning.

It was further recommended that all tubes in the first row of any tube bank on either side of the cleaning doors be fitted with SS-shields for erosion protection.

Erosion of the SERRF superheater has been proven to be a result of the high gas flow velocities as caused by severe gas flow maldistribution. As SERRF's design velocities were very similar to the other Steinmüller boilers, it was decided to rectify the distribution problem. The lowering of the third pass back wall would achieve this objective. A lower backwall would closely approach Montgomery County boiler design conditions.

There were two alternatives available.

The first alternate (Figure 7) considered to lower the backwall outlet header to about the same level as the header #2 of superheater 2.1. This would open the inlet flow area to the superheater sufficiently for reduction of gas velocity into the superheater by improved flow admission to the superheater.

The ash hopper wall under the superheater would then also be lowered to meet the new back wall header elevation and sidewall tubes would be lengthened. The resulting flatter angle could, however, present an ash flow problem.

The second alternate (Figure 8) contemplated moving the back wall header lower yet and provide for an ash slide into the third pass as well as into the superheater ash hopper. With this scheme the present ash hopper wall maintained its present angle. This design appeared, by inspection, to be more beneficial for superheater flow distribution, but it certainly would be more expensive, as additional headers and additional hopper wall tubes plus side wall tubes were involved.

Based upon the foregoing study, Steinmüller was contracted to execute a flow model test of the SERRF superheater inlet section to prove the viability of either one of the above alternate design changes.

# Flow Model Test

## 1. Flow Model And Model Variants

For this investigation, an 1/16 isothermal flow model of the boiler was built and operated at sub-atmospheric pressure using ambient air as the flow medium. Figure 9 is a schematic representation of the test rig. Figure 10 is a photograph of the flow model (model of actual boiler).

The model consists of the following main components

- Simplified model of 1st pass
- Model of 2nd and 3rd passes inclusive of ash hopper
- Simplified model of platen heating surfaces and headers installed in 3rd pass
- Transition to horizontal pass
- Model of horizontal pass up to and including 2nd ash hopper
- Simplified model of superheater heating surfaces and headers

The actual conditions plus three modification alternatives were modeled. These variants mainly differ from the actual condition (3rd pass rear wall header at elev. 21.25m) with respect to the position of the header and the resultant enlarged inlet cross-section of the horizontal pass with a modified transition.

| | |
|---|---|
| • Model of Actual condition | 3rd pass rear wall header = 21.25 m.<br>Approx. 32 $m^2$ cross section = 100% |
| • Model Alternate 1 | 3rd pass rear wall header at approx. 19.20 m.<br>Cross section increased by approx. 37%<br>Ash discharged into 1st ash hopper of horizontal pass |
| • Model Alternate 2 | 3rd pass rear wall header at approx. 19.75 m.<br>Cross section increased by approx. 29%<br>Ash discharged into 3rd pass |
| • Model Alternate 3 | 3rd pass rear wall header at approx. 18.80 m.<br>Cross section increased by approx. 45%<br>Short transverse pass |

The flow profiles at the middle of the boiler and close to the side walls were measured. For assessment of the flow profiles to be expected in each case, the following planes were chosen for measurements in the flow model:

- Cross-section to inlet of horizontal pass
- Approach flow to SH 2.1
- Flow profiles in SH 2.1 local to headers 1 and 2
- Outlet flow from SH 2.1

## 2. Transfer Rules

Investigations on the flow configuration and mixing behavior in furnaces and flue gas ducts have been performed in the Steinmüller Flow Laboratory using isothermal models for more than 25 years. Many of these model investigations produced results the transferability of which has been confirmed by the measurements carried out in full-size plants. A prerequisite for transfer of the modeling results to the full-size plant is adequate similarity of the flow fields in model and original. This is the case with geometrically similar flow boundaries and requires that the forces acting on the flow are in the same relation to each other. Furthermore, if several part-flows enter the system in question, the mass and impulse flow relationships must be the same as in the actual boiler.

For this model investigation, the model was run in a condition approximating 100% load of the boiler. The model design was based on the full load flue gas flow of the boiler, e.g.

| | | |
|---|---|---|
| Refuse throughput | 460 | t/d |
| Combustion air volume flow | 225,181 | lb/h |
| Flue gas volume flow | 269,017 | lb/h |

Depending on the degree of boiler fouling, the design flue gas temperature at the inlet to the superheater in the full-size plant varies between 1051ºF and 1256ºF. A temperature of 1200ºF was taken as the basis for model calibration. The throughput for the model was chosen in such a way that the same flow velocities are obtained for the superheater inlet zone in the model as in the boiler.

The heating surfaces of the horizontal pass, the platen heating surfaces in the 3rd pass and the headers installed were modeled in such a way as to provide a similar Reynolds number as far as the approach flow and the pressure drop are concerned.

## 3. Measuring Technology For 3D Velocity Field Measurements

The following measuring methods are applied by the Test and Research Institute of L & C Steinmüller GmbH for investigation of three-dimensional flow fields in isothermal flow models.

1. 3 D velocity measurement of the "Ptrandtl" principle
   probe form. Square tube after Konrad (five-hole probe)

2. 3 D velocity measurement based on
   "hot film manemometry" principle
   probe form. Triple split-film probe

Velocity field measurement using 5-hole probes:

With 5-hole probes the three components of the local velocity vector are determined by measuring three pressure differentials ($p_{total}$-$p_{stat}$, $\Delta p_a$ $\Delta b$) via the holes in the probe head. With the reference method applied here, the differential pressure $\Delta p_a$ is adjusted to zero by rotating the probe shaft and the direction of one velocity vector determined via the probe position. The two other pressure differentials measured with the probe in this position serve to determine the amount of the vector and the angle of approach flow via two calibration curves.

The individual velocity components are then calculated on the basis of the amount and the two angles of the velocity vector.

The pressure differentials from the probe are converted by means of pressure cells into electrical signals, which are recorded and evaluated by a process computer. The probe position in the flow model (approach to measuring point as well as rotation of probe for flow balancing) is adjusted by means of an electromechanical setting mechanism, which is controlled by the process computer.

Velocity field measurement by means of triple split-film probes:

Triple split-film probes are mainly used in flow fields where the angle of the approach flow to the probe exceeds the calibration range of the 4-hole probe.

In this measuring technology a quartz cylinder of approx. 0.4 mm diameter is used as the flow sensor, on which three thin nickel layers are deposited, staggered at an angle of 120°. These three-nickel films are independently maintained at a constant temperature of 160°C by thermostats. Depending on their position in relation to the direction of flow and on the flow velocity, the nickel films transfer heat to the fluid, which is returned to the film in the form of electrical energy. The flow velocity, in terms of amount and direction, can be calculated in each case from the electric current thus returned to the individual films.

With this measuring system, field measurements can be largely automated. Signal recording and calculation of velocity components are computer assisted. The positioning of the probe in the flow model and the rotation of the probe for determination of the main angle of approach is effected by a computer-controlled electromechanical positioner.

## 4. Description of Flow Configuration

The flue gases produced on the grate travel through the three vertical radiation passes and at the end of the 3rd pass are again deflected 90° when entering the horizontal pass. The flue gases emerging from the horizontal pass first pass through the flue gas cleaning systems and then enter the stack.

The flow configuration at the superheater inlet is characterized by the deflection of flue gases towards the horizontal pass. Due to the high upward velocities in the 3rd pass (about 7 to 8 m/s), a non-uniform velocity distribution with possibly considerable local peaks develops at the inlet cross-section of the horizontal pass.

Before entering the superheater banks, the flue gas flow is accelerated by the downstream lateral reduction in boiler cross-section, an effect which generally results in gas velocities being higher here than in the middle of the boiler. This flow restriction, though producing a somewhat more uniform flow profile, also causes an increase in average flue gas velocity by nearly 30%.

Depending on the extent by which the flow is restricted by the tube banks when the flue gases enter SH 1.1, a further increase in flue gas velocity takes place here, which gradually decreases in the downstream heating surfaces due to the cooling of the flue gases.

## 5. Flow Configuration – Actual Condition:

In the actual condition with the plant being operated under design conditions, the highest average flue gas velocity of approx. 2.8 m/s was theoretically determined for the inlet cross-section of the horizontal pass.

The flow profile measured in the isothermal flow model exhibits a considerable imbalance as a result of the deflection. Locally measured peak velocities were as high as 5.5 m/s.

An extensive vortex zone is then formed in the outlet flow from the header above the first ash hopper, the ramifications of which extend to the end of superheater stage 2.2. The flow therefore only covers about 65% of the surface of SH 2.1 (height). The resultant flow profile is similar to that in the transition, the average velocity however being somewhat higher due to the lateral boiler constriction. Local velocity peaks nevertheless reach figures as high as 6.4 m/s even in the middle of the boiler and 8.0 m/s at the perimeter.

Due to further reduction of the cross-section, another increase in gas velocity takes place when the flue gases pass through SH 2.1. The highest flow velocity measured over the entire flue gas path at 10.8 m/s is found close to header #1 in the area of the side walls. The severest wear is thus to be expected here. Flow velocities gradually drop again towards the outlet of SH 2.1.

## Alternate Model 1:

Relocating the 3rd pass rear wall header to elevation + 19.20 m would bring about an increase in cross-section at the horizontal pass inlet of approx. 37% over the actual condition. As the ash discharge in this variant is effected similar to the actual condition, the flow model here also exhibited the spoiler effect noted already in the actual condition with an eddy region at header outlet. The size of this eddy region above the first ash hopper is however distinctly smaller than in the present case so that the flow extends over approx. 75% of the surface of superheater stage 2.1

In consequence the flow velocities measured in the model are considerably lower, not only in the middle of the boiler but also in its perimeter zones. As in the actual condition, the highest gas velocities occur in SH 2.1 above the first header. Locally measured velocity peaks for Alternate 1 are however 7.3 m/s at the middle of the boiler and 8.9 m/s in its perimeter areas, i.e. about 18% lower than those determined in the actual condition.

## Alternate Model 2:

With Alternate 2 the proposed modification which necessitates the smallest increase in horizontal pass inlet flow cross-section as compared to the actual condition (+29%, 3rd pass rear wall header at elev. + 19.75 m) was investigated. As compared with the actual condition and Alternate 1, the header is relocated by approx. 1 to 1.5 m in the direction of the main flow so that ash can be discharged into the 3rd pass.

It can be seen from Figures 11 and 12 that an almost ideal flow around the rear wall header over the entire boiler width is obtained with this configuration. There is no noticeable vortex area at the header outlet. Consequently, there is a good velocity distribution at the inlet to SH 2.1 over about 85% of its surface. This represents an increase in active heating surface area of approximately 20 percent.

The low average approach velocities to the superheater measured in the flow model also corroborate this. These are 3.3 m/s at boiler middle and 5.0 m/s in the perimeter areas. Local velocity peaks in the area of SH 2.1 are again reduced as compared to Alternate 1.

## Alternate Model 3:

Alternate 3 presented an additional modification proposal by Steinmüller, which produces the greatest increase in the horizontal pass approach cross-section compared to the other variants (+45% higher than in the actual condition). The 3rd pass rear wall header would be relocated at about + 18.80 m, so that the cross-sectional height would be approximately the same as the height of superheater stage 2.1. The connection to the 1st ash hopper in the horizontal pass would be by a horizontal tube panel, thus forming a short, transverse pass.

The measurements performed on this flow model revealed that with this alternate a flow configuration similar to that of Alternate 2 can be obtained in the horizontal pass. The mean flow velocities at inlet cross-section were at 2.2 m/s and 1.6 m/s respectively the lowest measured in the test series due to the considerable increase in cross-sectional area.

## 6. Recommendations

Figure 13 provides a summary comparison of the flow configurations established for the individual proposals. Comparison of the flow profiles (Figures 14 and 15) reveals that, compared to the actual condition, all proposed modification alternatives improve flow profiles to the first superheater heating surfaces. The cross-sectional area which, depending on the alternative involved, is increased by approx. 30 to 45%l and results in a general reduction of flue gas velocities into the superheater. This effect is desirable for reasons of wear reduction, as well as the better utilization of the SH 2.1 surface. Local velocity peaks within the superheater are also noticeably reduced.

It can also be clearly seen that Alternates 2 and 3, despite their greatly differing horizontal pass inlet areas, exhibit almost identical flow profiles, not only in the inlet zone of the horizontal pass but also local to superheater 2.1. The reason is the configuration of the transition from the 3rd pass to the horizontal pass, which is very favorable in terms of the deflection of the flue gas flow.

Proceeding from the assumption that the local peak velocities measured in the flue gas passing through superheater stage 2.1 are the decisive factor in terms of tube wear, the erosion rate to be expected, if the modification is implemented in the boiler, can be adequately assessed. It is known from the literature that the erosion rate (E) to be expected is almost proportional to the third power of the gas velocity ($W_{RG}$):

$$E \sim W^3_{RG}$$

| Model Variant | Actual condition | I | II | III |
|---|---|---|---|---|
| $W_{RG.max}$ | 10.8 m/s | 8.9 m/s | 8.2 m/s | 8.9 m/s |
| $W_{RG,rel.}$ | 100 % | 82.5 % | 75.9 % | 82.5 % |
| $(W_{RG.rel}/100)$ | 1 | 0.56 | 0.45 | 0.56 |

It is obvious from the above table that the greatest reduction of flue gas velocity in the superheater is obtained with Alternate 2 as proposed by Montenay. The erosion rate can also be expected to be reduced significantly. Further, a better utilization of SH 2.1 will result. Steinmüller therefore recommends that Alternate 2 be selected for the intended conversion.

## Engineering Details

The implementation of the selected boiler modification, Alternate 2 and the associated manufacturing of boiler parts had to be based on the requirement to reduce the outage time to an absolute minimum. This requirement was translated into the following tasks:

- Fabrication of components and assemblies in the fabrication shops to reduce installation and erection time in the field.
- Providing sufficient tolerances in the fabricated parts to compensate for possible dimensional differences which may be found in the boiler.
- Disassembly of as many parts as possible to gain access to the area to be modified prior to boiler shut-down. Such preparatory work could include lagging and insulation removal and the erection of scaffolding to gain access to the work area, as well as fitting and pre-assembly of external piping.

The above tasks were accomplished by the design of the individual components as follows:

- Fabrication of the new boiler arch consisting of two welded tube panels.
- Fabrication of the new side walls as complete welded tube panels.
- Fabrication of headers and pipes with weld preparation.
- Fabrication of pipe bends with weld preparations to avoid bending in the field.

Another important engineering consideration was the structural integrity of the existing steel structure for the modified design. The boiler support structure and the buckstays had to be analyzed for the new static load as well as for dynamic loads resulting from seismic incidents. The following evaluations were executed:

- Stability of the superheater inlet area, where side walls and boiler rearwalls had to be opened up and buckstays had to be removed.
- Determination of new buckstay requirements.
- Confirmation of adequate seismic resistance for the modified buckstay system.

The successful completion of the first boiler modification in record time at SERRF can surely be attributed in part to the technical detail work described above.

# Results and Conclusion

Based on the results of the Flow Model tests which confirmed Montenay's evaluation, it was decided to implement a modification in all three boilers. Alternate 2 was selected.

The first boiler at the Facility was modified during May 1998, and the results looked very promising. The two remaining units are scheduled to be modified in the latter part of 1998.

Upon completion of the modification of the first unit, an extensive flue gas velocity test was conducted over a three day period. The flow measurements were conducted throughout the superheater region following EPA Method 2 using a 16 foot S-type pitot tube with an attached stainless steel type-K thermocouple. The velocity measurements were performed at various steam load conditions, ranging from the design rate of 117Klbs/hr to 125Klbs/hr.

As predicted from the Flow Model tests, the flue gas distribution had improved significantly after the modification. Flue gas velocities at all three elevations of the superheaters appeared more balanced, at various boiler loads. Also, local peak flue gas velocities of greater than 40 ft/second prior to the modification had dropped to about 26ft/second.

From this modification, the following benefits are expected:

- Increase in superheater efficiency by increasing the effective superheater surface swept by the gas.
- Reduction of tube wear by general reduction of the flue gas velocities and more uniform flow profiles. Superheater tube life is expected to improve by at least two years, bringing it in line with the other Steinmüller plants evaluated.
- Steinmüller has predicted that the boiler capacity could be increased by an additional 5% without negative impacts, thus improving annual MSW throughput capacity by 5%.
- The return on investment is expected to be less than three years.

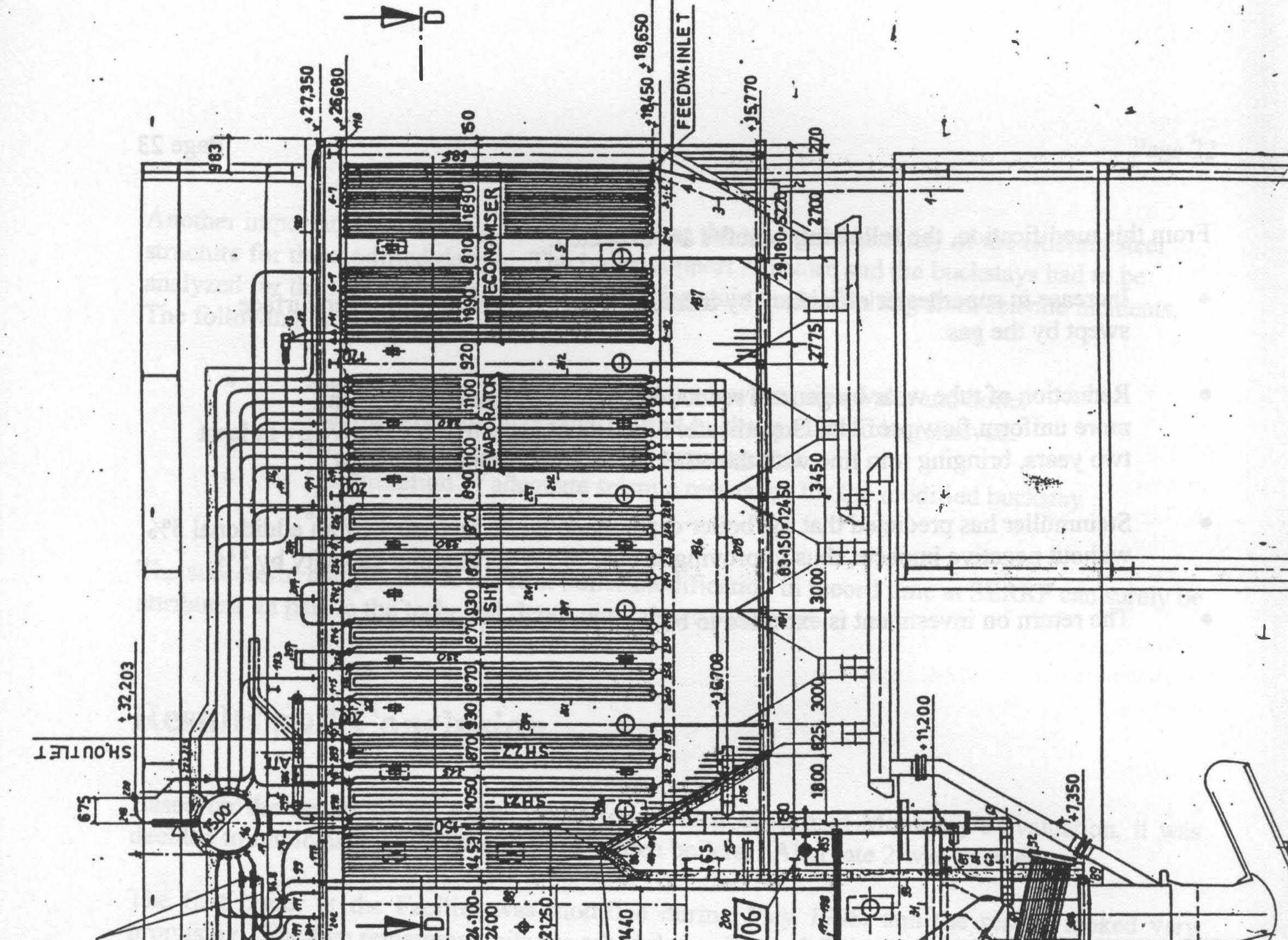

Figure 1:  SERRF Boiler Side Elevation

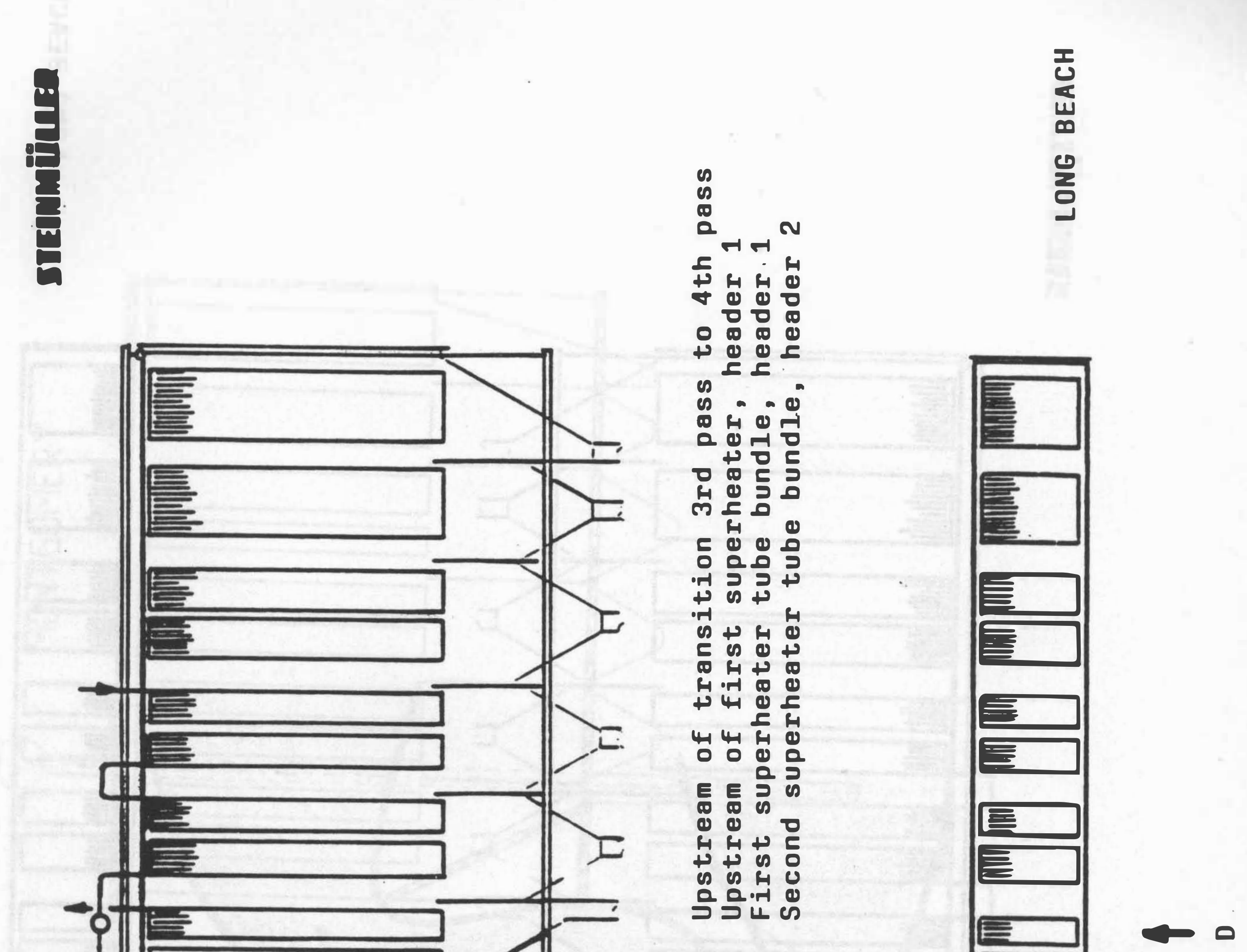

Figure 2: Locations of Point A through Point D

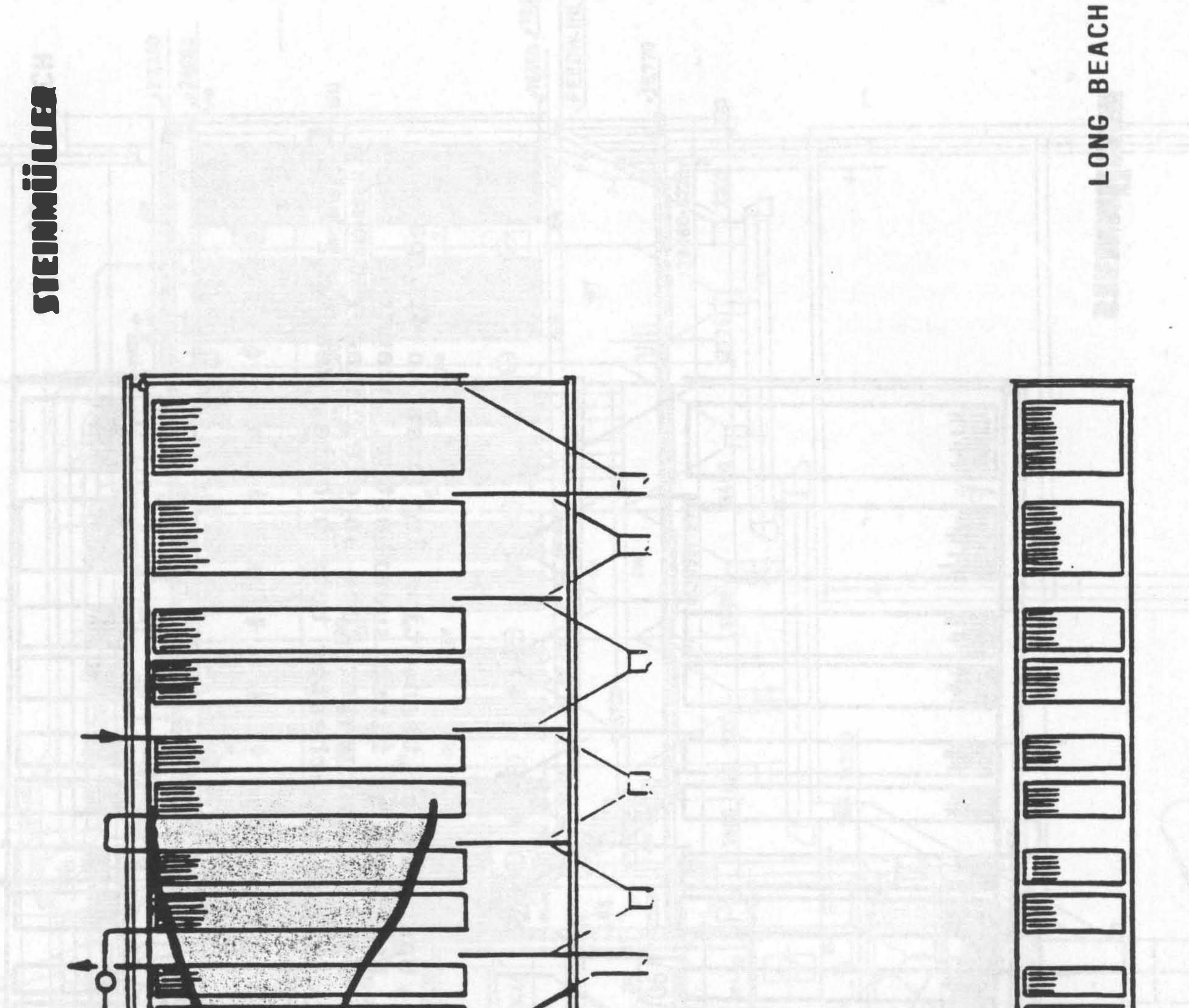

Figure 3: Gas Flow Distribution SERRF

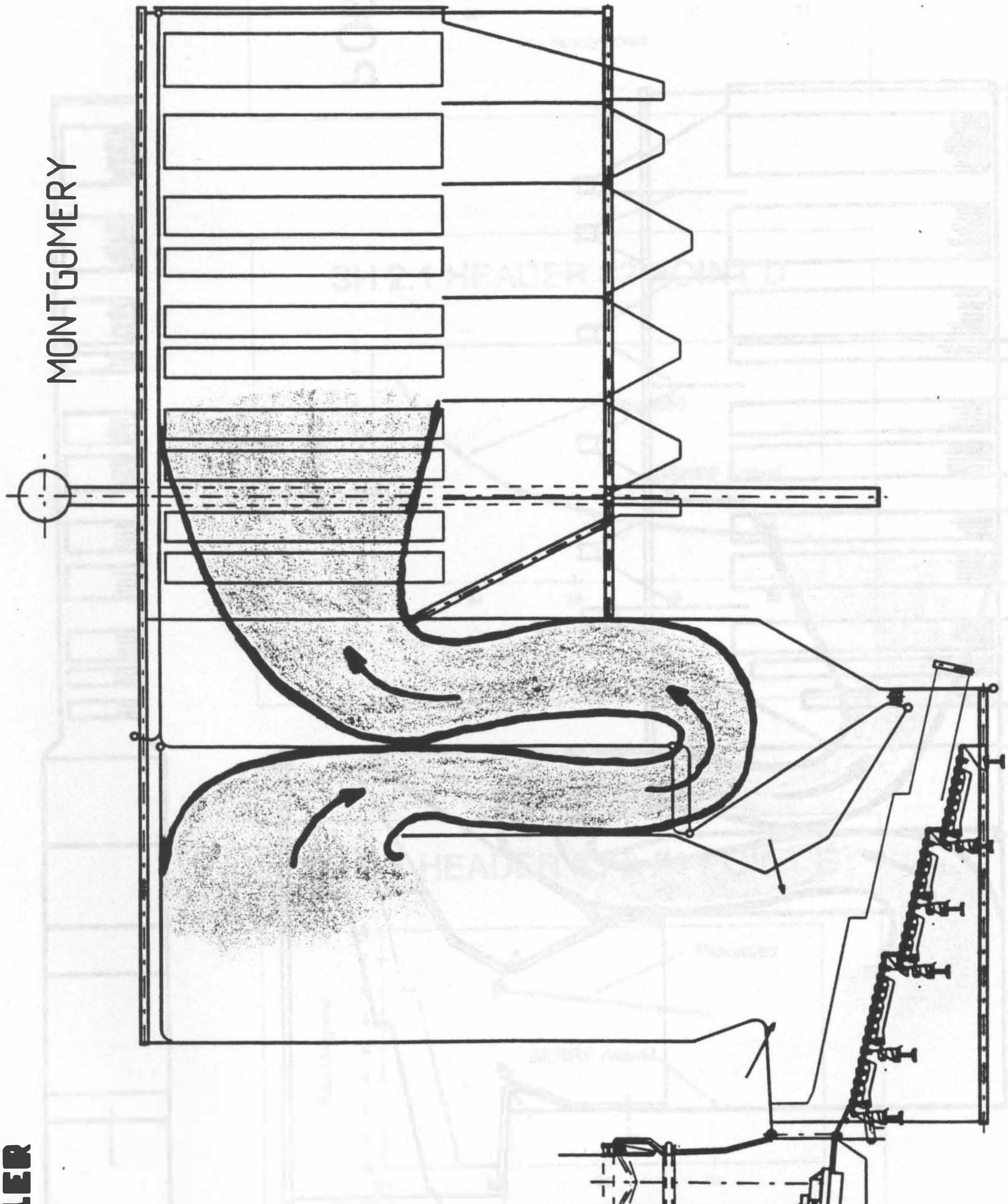

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Figure 4: Gas Flow Distribution Montgomery County

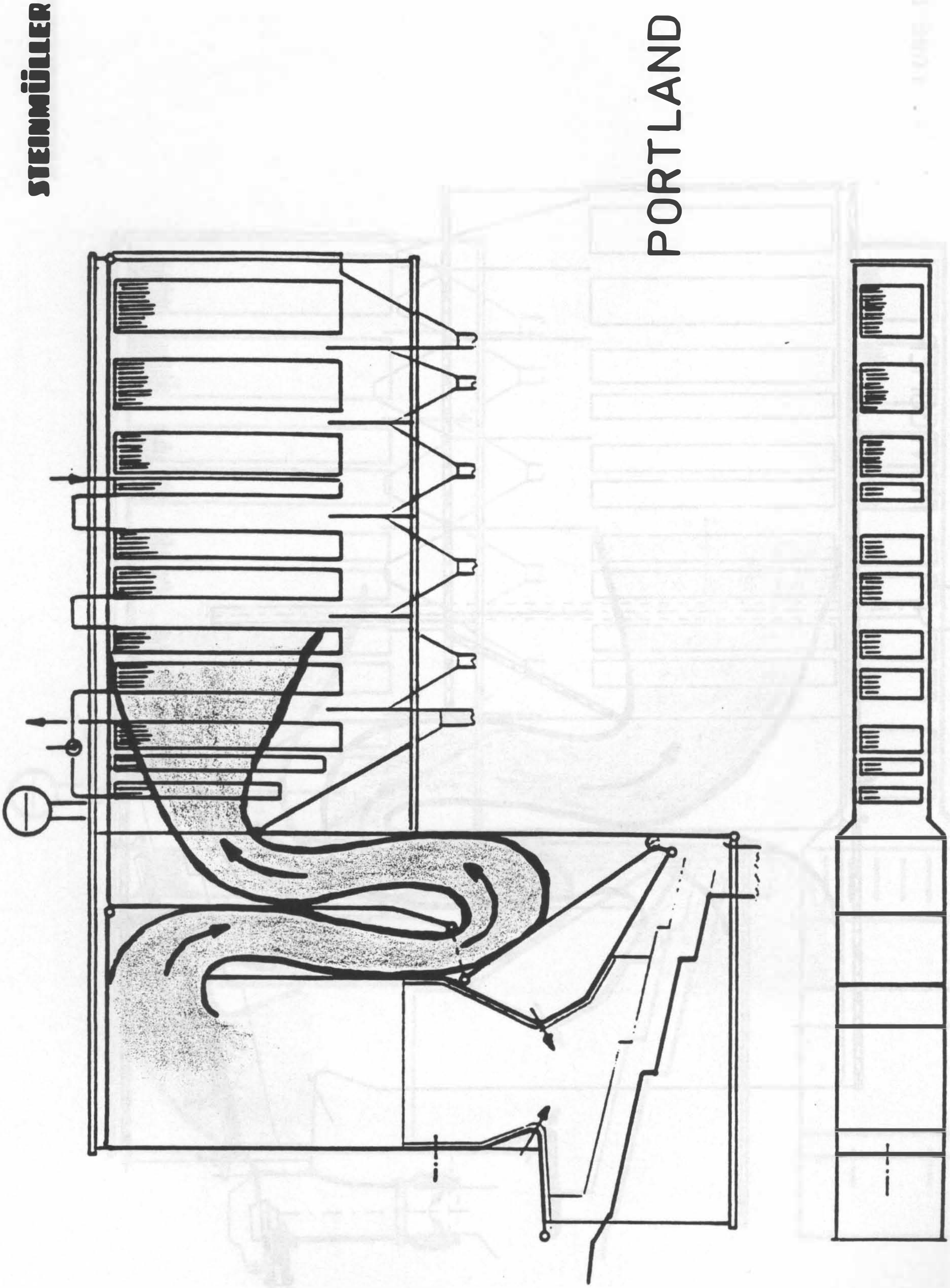
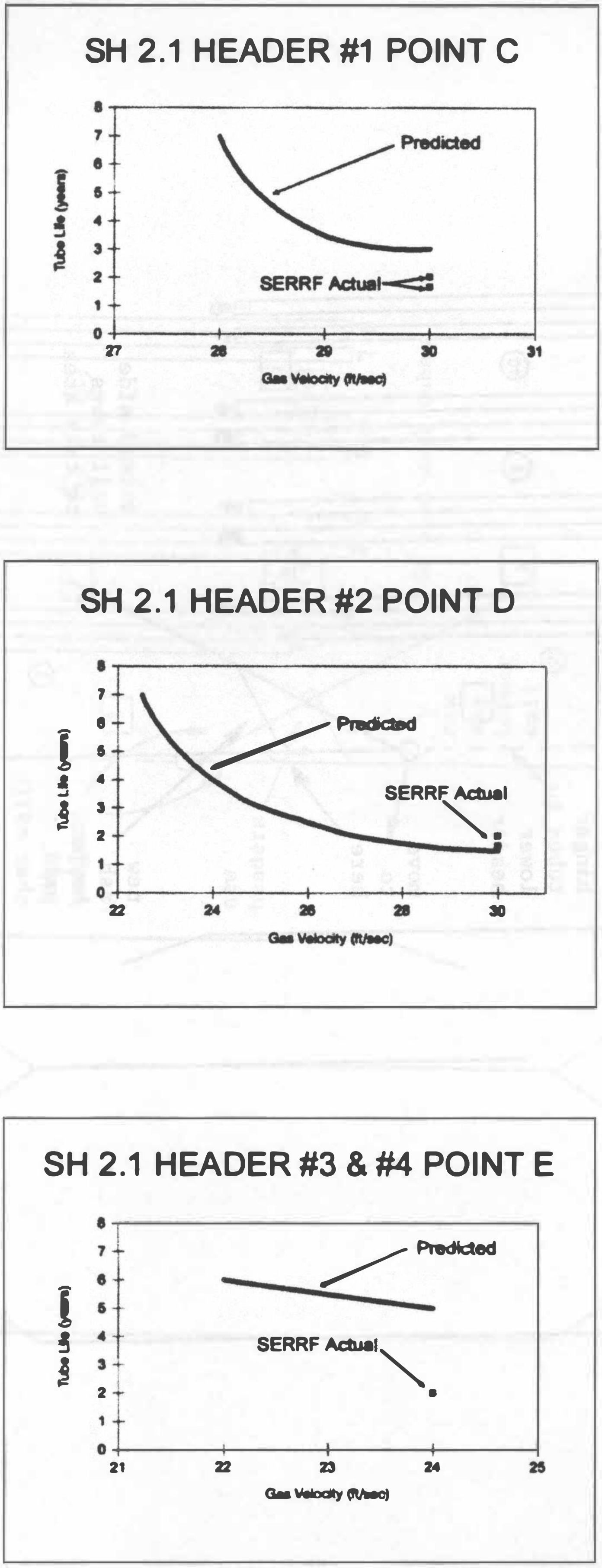


Figure 5: Gas Flow Distribution Portland



SH 2.1 HEADER #1 POINT C

SH 2.1 HEADER #2 POINT D

SH 2.1 HEADER #3 & #4 POINT E

**Fig. 6: Predicted and Actual Tube Life vs. Gas Velocity**

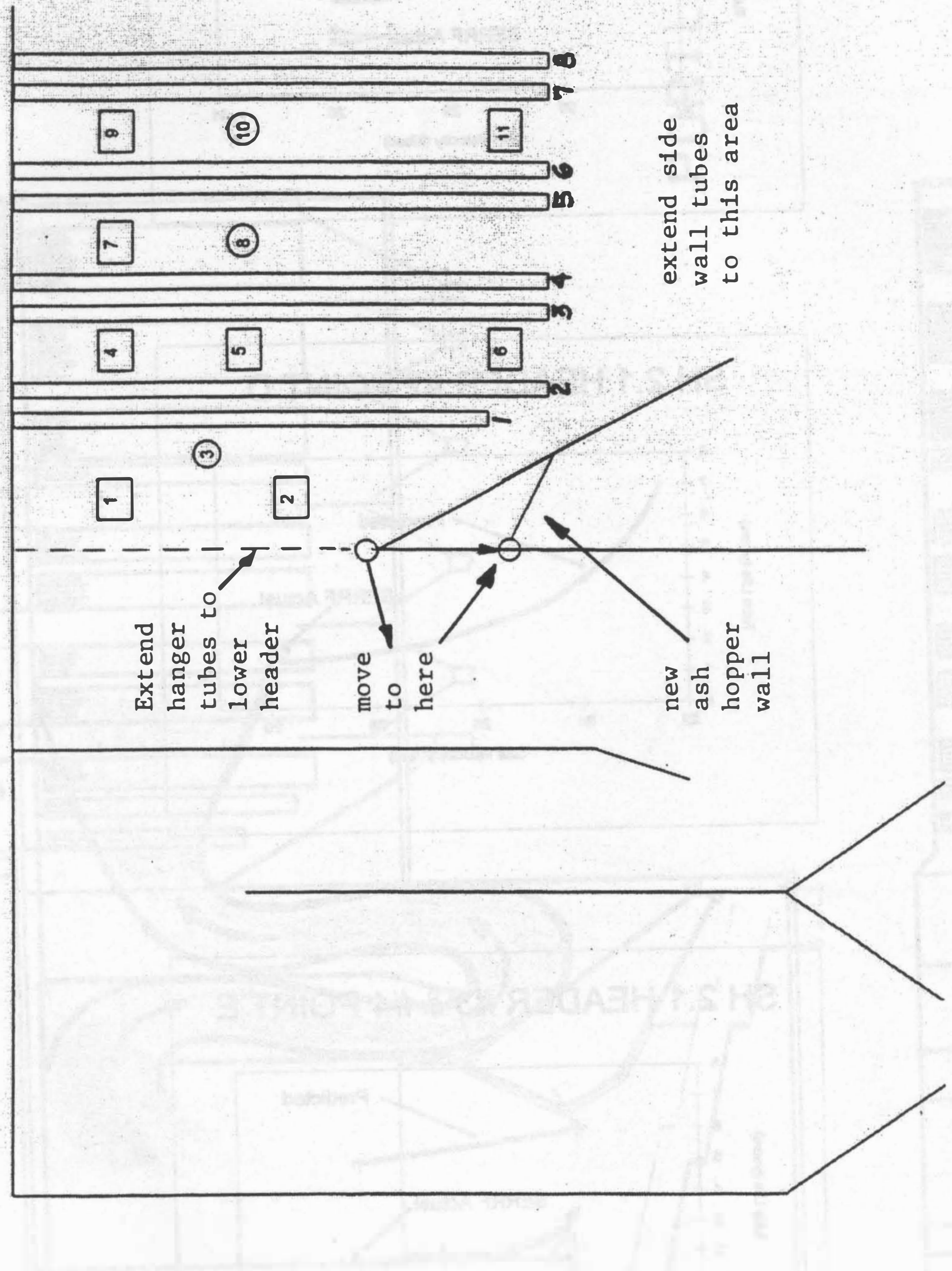


Figure 7: Boiler Modification - Alternate 1

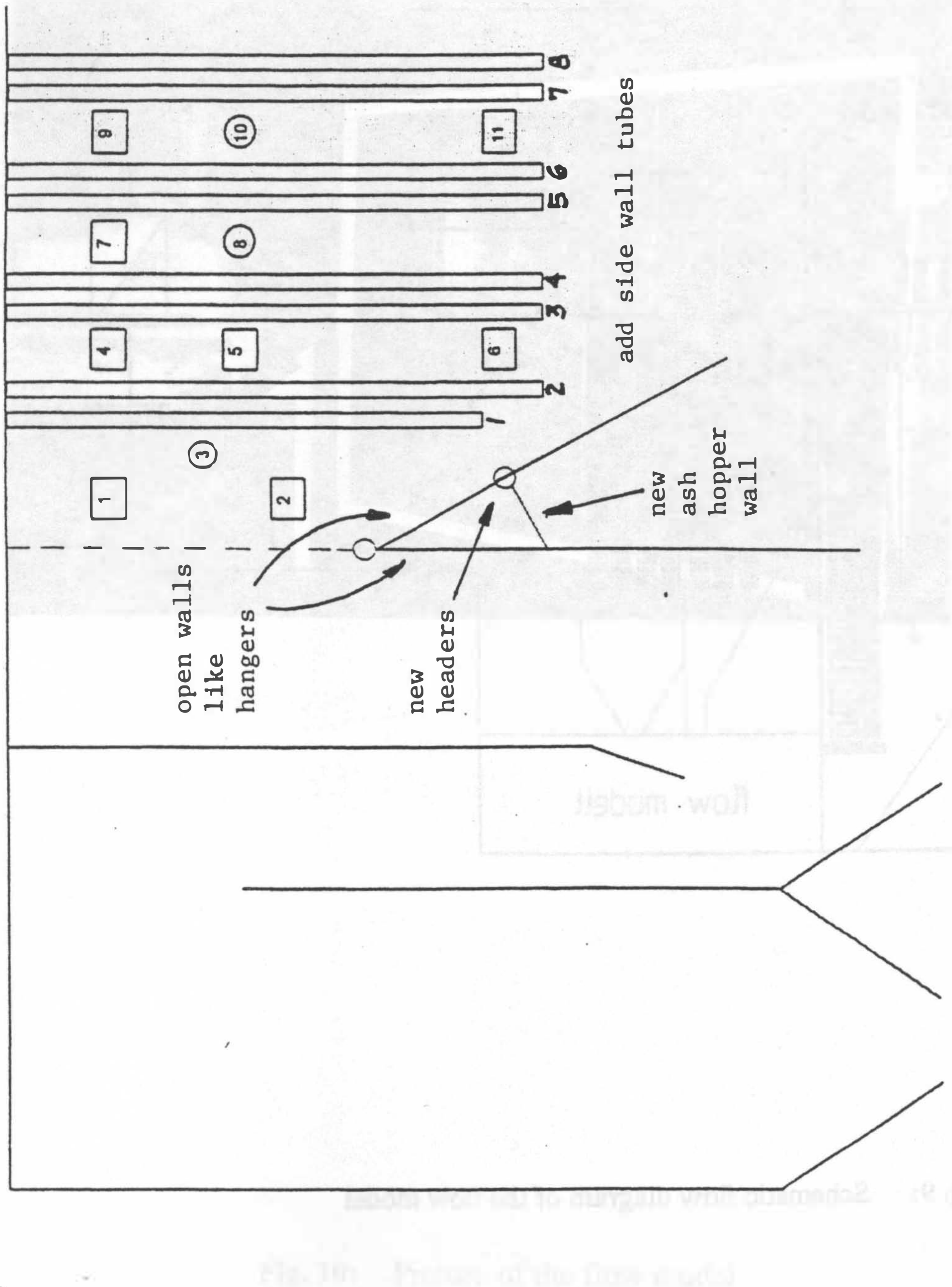


Figure 8: Boiler Modification - Alternate 2

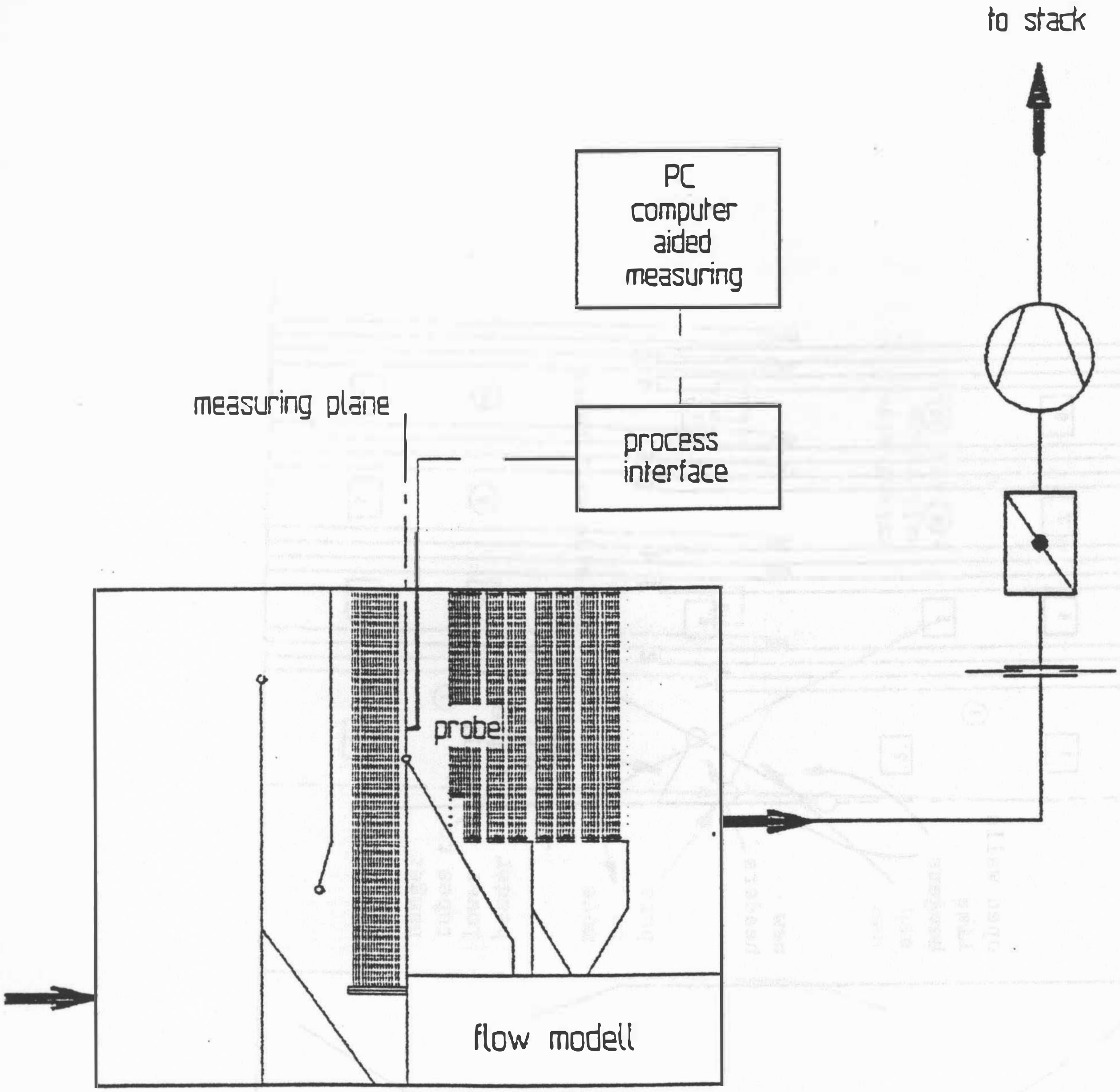


Fig. 9: Schematic flow diagram of the flow model

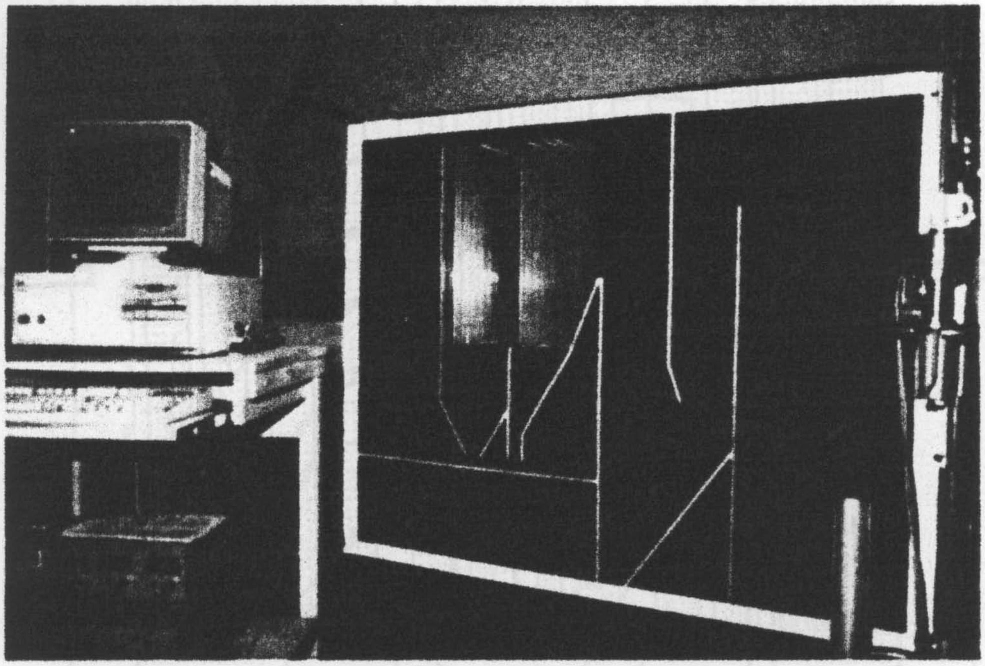


Fig. 10: Picture of the flow model

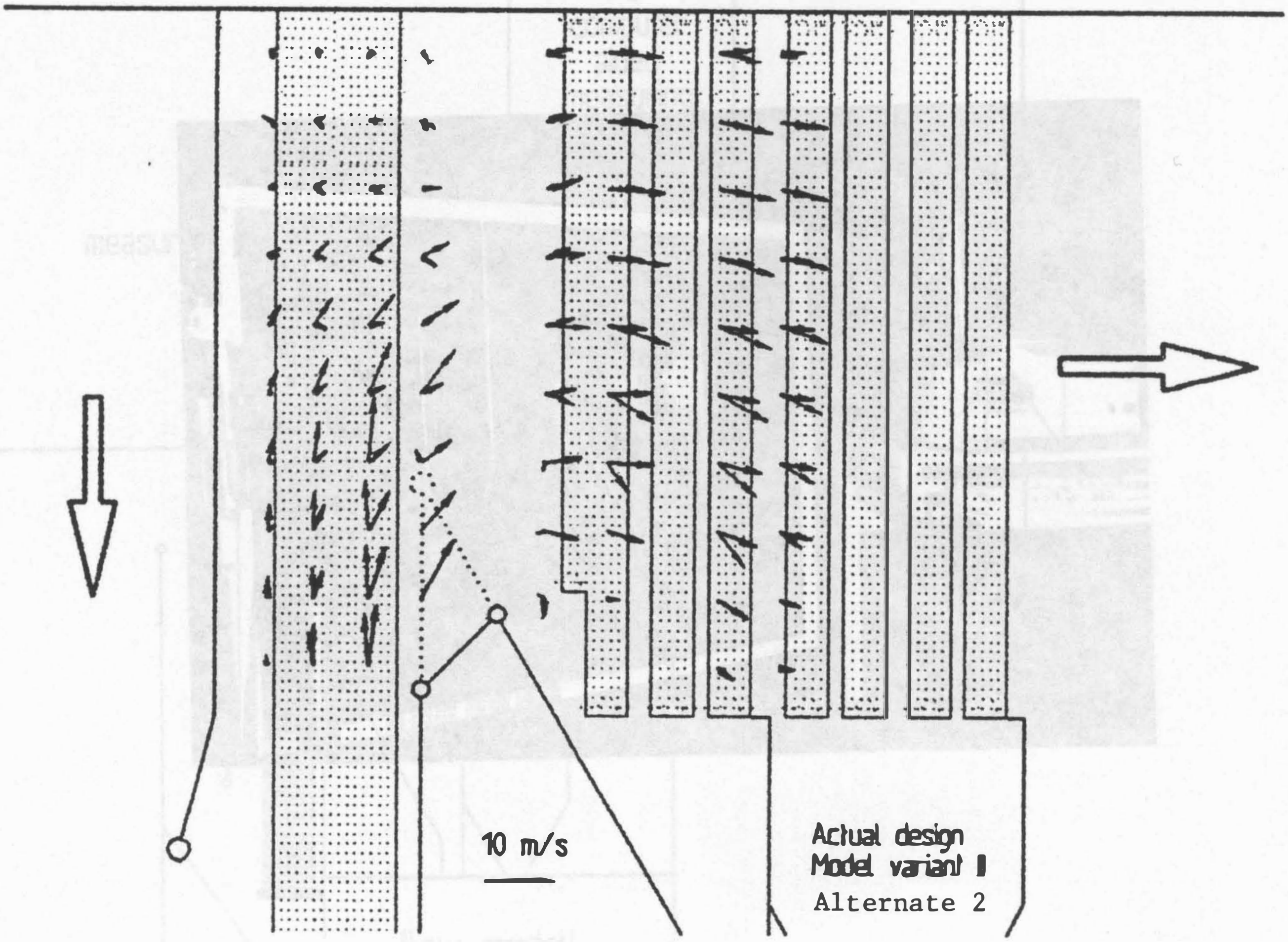


Fig. 11: Comparison actual design - model variant II - Alternate 2
Flow field at the flue gas inlet to the 4. path at boiler mid section
Main components in vektor representation

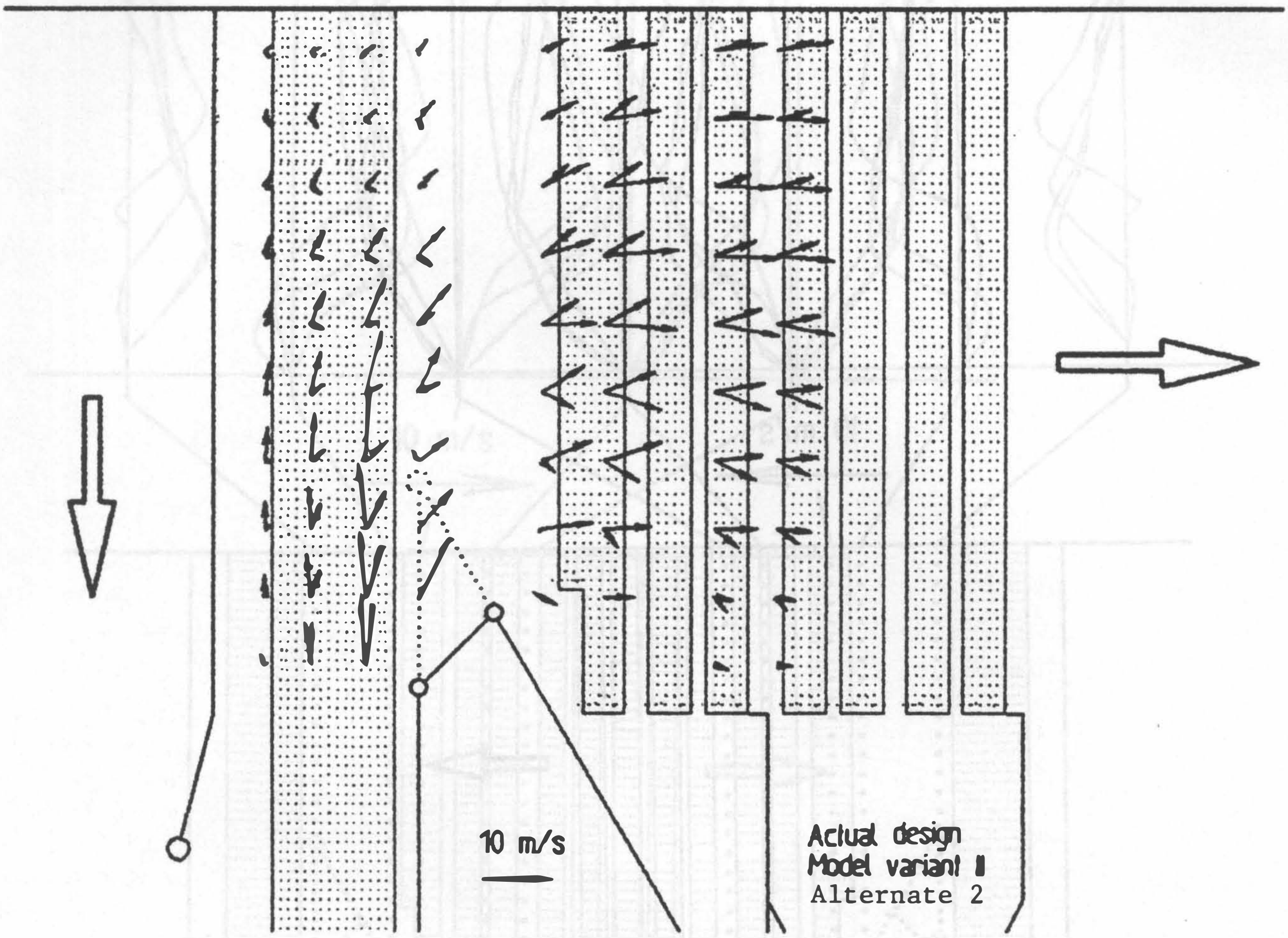


Fig. 12: Comparison actual design - model variant II - Alternate 2
Flow field at the flue gas inlet to the 4. path near boiler sidewalls
Main components in vektor representation

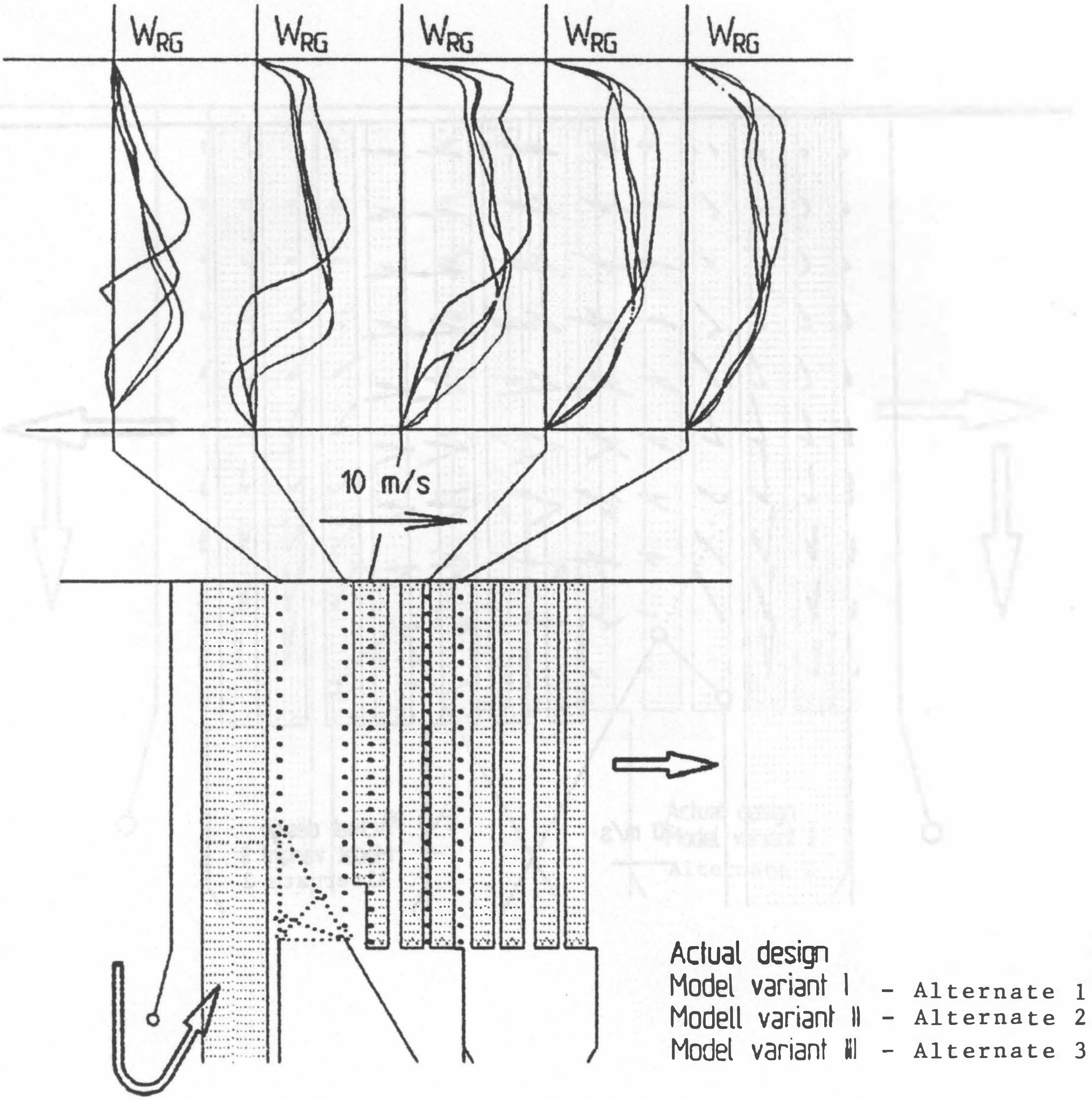


**Fig. 13:** Comparison actual design - investigatet model variants
Flow profiles at the flue gas inlet to the 4. path at boiler mid section

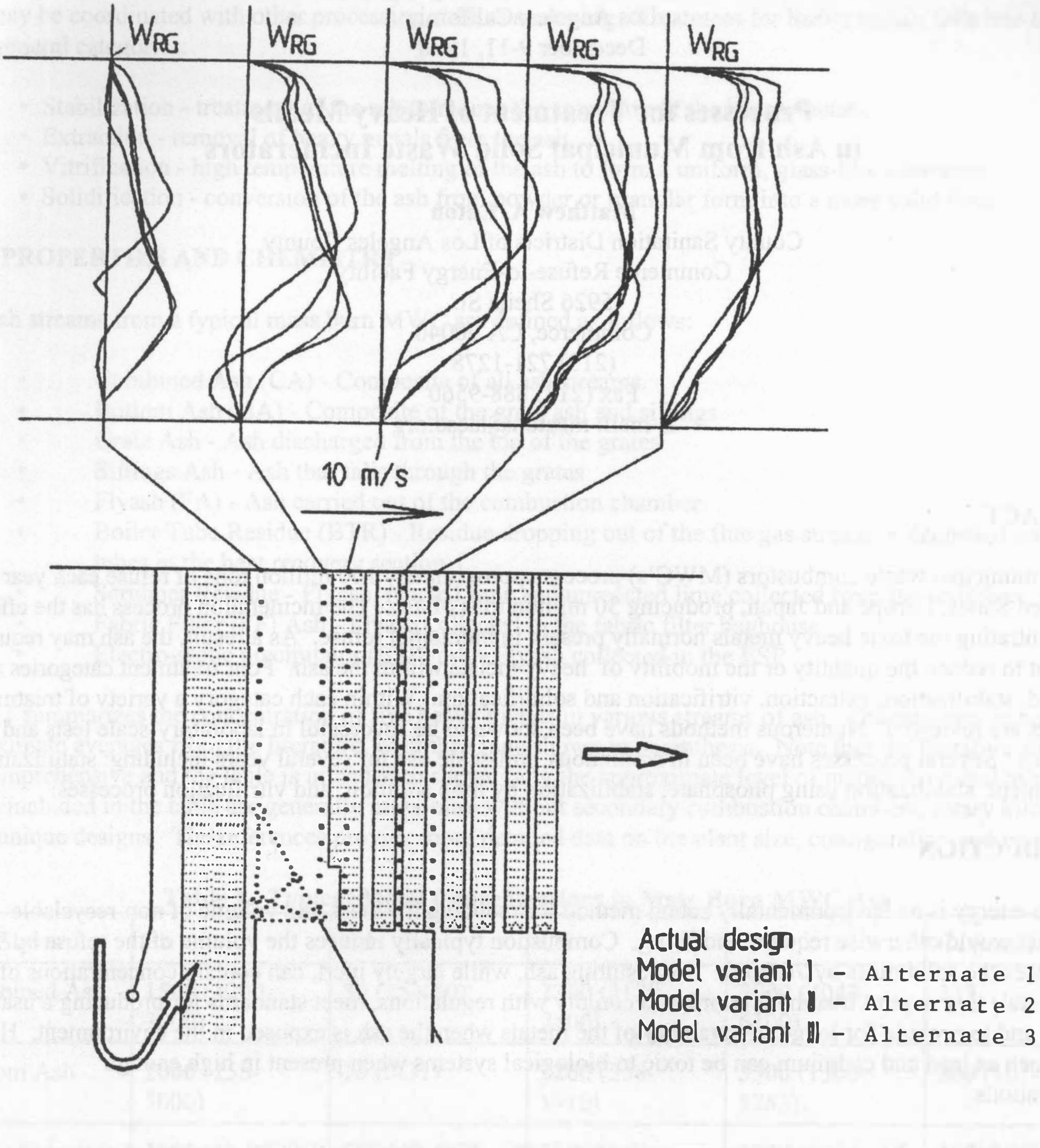


**Fig. 14: Comparison actual design - investigatet model variants** - Alternates
**Flow profiles at the flue gas inlet to the 4. path near boiler sidewalls**