# Design of a Chimney with GRP Liner for Low and High Temperature Operation

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## Introduction

The addition of a Wet Flue Gas Desulphurization (WFGD) System to an existing coal-fired power plant creates several operational challenges to the plant owner. When the WFGD System incorporates a single absorber/reactor serving multiple power boilers the impact to unit operations makes it desirable to have bypass capabilities. At this plant in the state of Alabama, USA, a single WFGD System will serve three power plant operating units. A new concrete chimney will be built adjacent to the WFGD to discharge the flue gas following the scrubbing operation. The plant owner wished to incorporate bypass capability into the design of the system and, due to the plant arrangement and location of the WFGD, it was decided to include the bypass capability into the design of the new chimney.

This chimney is one of several chimneys being installed by this owner at various power plants in their utility service areas. The owner has selected Glass Reinforced Plastic (GRP), also known as Fiberglass Reinforced Plastic (FRP), for the chimney liners and several of the WFGD vessels on these other units. For this chimney they wanted to maintain the advantages of GRP liners when the WFGD is in operation, while allowing continuous operation in the bypass mode. This resulted in several design features to accommodate both the low and high temperature operation, including a highly ventilated annulus to cool the GRP liner wall and provide an acceptable personnel access temperature in the annulus, and a special high temperature resin for use in the GRP laminate. The chimney also incorporates a large construction opening to accommodate erection of the GRP liner sections with structural components to provide performance equivalent to a similar chimney with a normal sized opening.

## Chimney Arrangement

The General Arrangement of the chimney is illustrated in Figure 1. The overall height of the chimney is 755 ft. (230.1 m) and it will have a single 38.0 ft. (11.6 m) inside diameter GRP liner. The height of the concrete shell is 730.0 ft. (222.5 m), providing liner projection of 25.0 ft. (7.6 m) above the concrete shell. A single inlet breeching duct, 22.0 ft. wide by 52.0 ft. high (6.7 m by 15.8 m), enters the chimney at a sill elevation of 88.1 ft. (26.9 m) above the top of the foundation, which is at grade level. The shell outside diameter is 52.0 ft. (15.85 m) over the upper 415.0 ft. (126.5 m), tapering to 63.0 ft. (19.2 m), which remains constant over the bottom 75.0 ft. (22.9 m).

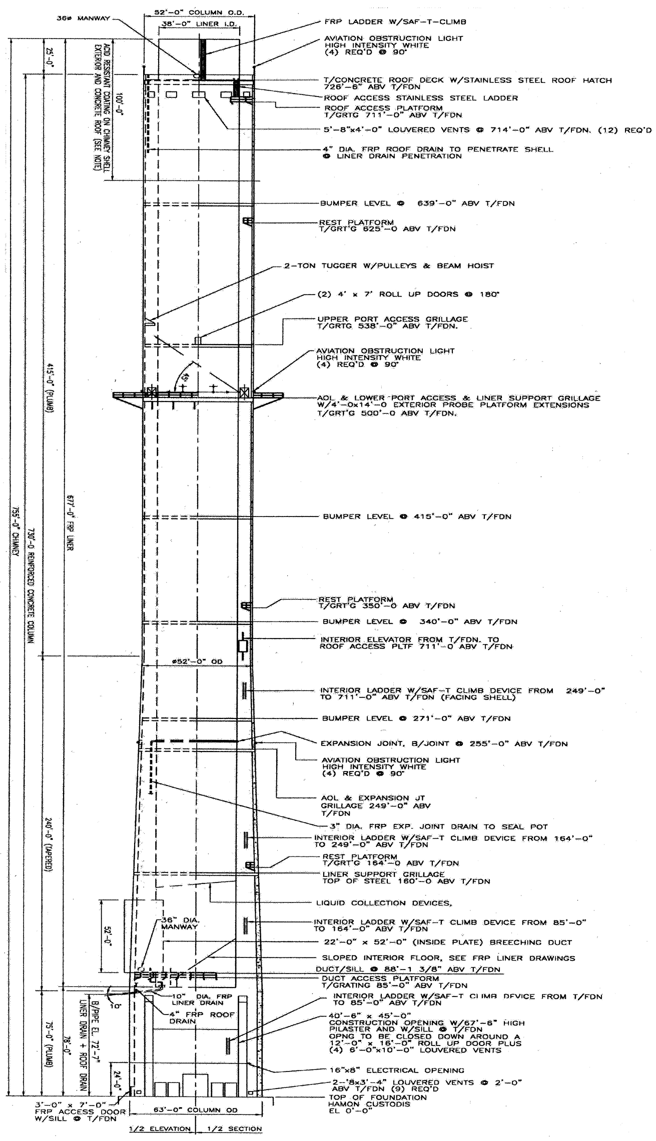



**Figure 1: Chimney General Arrangement**

The construction opening at the base of the chimney shell is sized to allow for the transportation of the GRP liner sections, which will be fabricated in a temporary facility at another location on the plant site. The opening is 40.5 ft. wide by 45.0 ft. high (12.3 m by 13.7 m), and is reinforced with 67.5 ft. (20.6 m) tall concrete pilasters on each side of the opening.

The chimney is equipped with the usual assortment of accessories, including access platforms for gas sampling and maintenance, an access ladder, a personnel hoist, aircraft obstruction lighting, a lightning protection system, a communication system, and an electrical system providing lighting and power to the various access levels.

The GRP liner is supported by two steel grillages, one supporting the upper 500 ft. (152.4 m), and the second supporting the remainder of the liner, the inlet breeching and liner floor. The liner is furnished with a system of liquid collection devises and drains to minimize stack liquid discharge, which were sized and located by use of a wet flow model study.

## Flue Gas Conditions

The two design flue gas conditions are shown in Table 1. The Normal gas case represents the design flue gas conditions with the WFGD in operation. The flue gas under normal operation with the WFGD is relatively low temperature, saturated, acidic flue gas, which is typical of coal-fired power plants with WFGD systems without reheat. The By-Pass gas case represents the design flue gas conditions with the FGD system by-passed. The flue gas temperature under bypass conditions ranges from 270 to 350 degrees F (132 to 177 degrees C).

| Design Data | Normal | By-Pass |
|---|---|---|
| $CO_2$, % by mass | 15 - 30 | 15 - 30 |
| $N_2$, % by mass | 60 - 88 | 60 - 88 |
| $O_2$, % by mass | 3 - 10 | 3 - 10 |
| $H_2O$, % by mass (Note: Under normal conditions, the gas stream will be saturated with water.) | 5 - 15 | 5 - 15 |
| $SO_2$, ppmv | 5 - 33 | 5 - 1300 |
| $SO_3$, ppmv | 2 - 50 | 2 - 50 |
| Other Acid Gases, % by mass | < 0.1% | < 0.1% |
| Entrained Mist, gr/acf | < 0.08 | < 0.08 |
| Inerts/Ash, % by mass | < 0.1% | < 0.1% |
| Max. Flow Rate (scfm,) (Note: Defined as wet gas flow at 68ºF) | 3,167,000 | 2,910,000 |
| Flow Velocity (ft/sec) | 49.7 | 64.0 |
| Normal Operating Temp (ºF) | 120-135 | 270-350 |
| Abnormal/Excursion Temp (ºF) | N/A | N/A |
| Pressure (in w.g.) | -3 | -5 |
| Ambient Temperature (ºF) | -10 to 100 | -10 to 100 |

**Table 1: Chimney Liner Design Data**

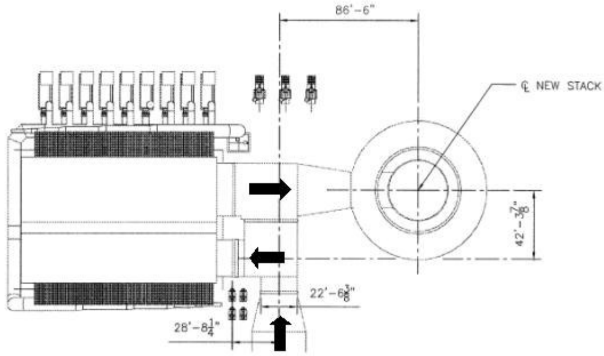
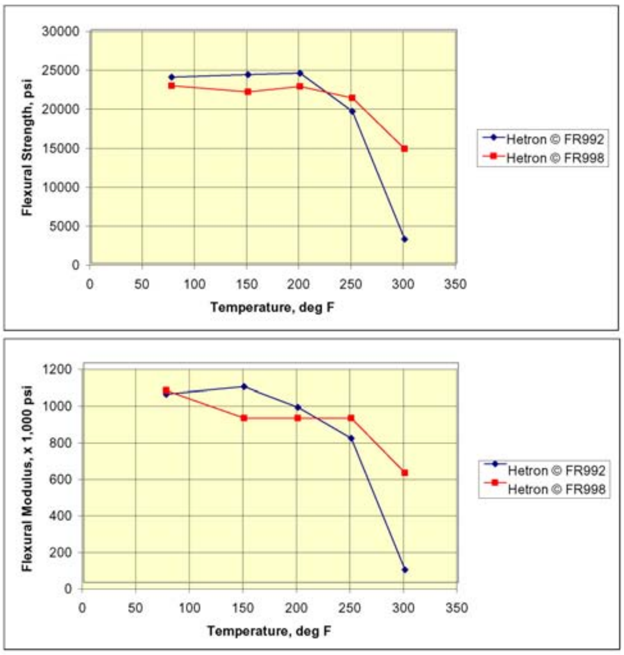



**Figure 2: FGD Duct Arrangement**

The operational requirements of the plant dictate that the By-Pass case be considered a continuous operating condition. This will allow maintenance work to be performed on the WFGD system without removing any of the three units from operation or needing separate bypass chimneys, and associated ductwork and dampers, for each unit. The arrangement of the WFGD ductwork is illustrated in Figure 2. The By-Pass gas flow enters the chimney liner by closing selective dampers and directing the gas flow directly into the chimney breeching duct.

## Liner Material Selection

A previous study of chimney liner materials for use in the owner's WFGD retrofit program led to the selection of GRP liners as the preferred material for the chimney liners for new chimneys serving wet scrubbers. Although this was the only plant to require a continuous by-pass operating condition, the owner wished to use GRP liners for this chimney also. The owner's consultant prepared a detailed specification for the design and fabrication of the GRP liners, ductwork and accessories. The specification called for a premium grade fire retardant epoxy vinyl ester resin. In selecting the resin to be used in the fabrication of this chimney liner it was recognized that the high temperature operation would dramatically affect the mechanical properties of the laminate. For the other chimneys in the owner's system Hetron © FR992 manufactured by Ashland was selected. This resin is not recommended for operation above 220 to 250 degrees F (104 to 121 degrees C). On consultation with Ashland, the GRP liner design and fabrication subcontractor and the owner's engineers and consultants it was decide to utilize Hetron © FR998, a high temperature, low styrene resin, specially formulated to provide increased mechanical properties at higher temperature, and which has a flame spread rating of less than 25 without the addition of additives such as antimony trioxide. A comparison of the flexural properties of FR992 and FR998 resins is shown in Figure 3 to illustrate the improved performance of FR998 resin at elevated temperature.




Reference: Ashland Inc. Resin Selection Guide, typical values of sample laminates, based on laboratory tests.

**Figure 3: Resin Flexural Properties**

## Annulus Ventilation and Liner thermal Design

The high By-Pass operating temperature and relatively high ambient temperature created concerns for not only the GRP liner material temperature but also for the annular space temperature. The major access provisions for the chimney, including the elevator, ladder, emission monitoring and aircraft warning light access platforms, are all located in the annular space. Although the use of external insulation could have reduced the annulus temperature, this would have increased the liner wall temperature by reducing the thermal gradient through the liner wall, making the use of GRP material impractical. It was concluded that a highly ventilated annulus would be desirable to provide a lower annulus temperature and to lower the temperature of the exterior surface of the GRP liner. A Chimney Thermal Analysis Spreadsheet was used to evaluate the temperature gradient through the GRP liner wall and the annular space temperature for various amounts of ventilation. The spreadsheet analysis method is based on a heat balance between the heat transfer through the liner wall, Figure 4, the heat transfer through the shell wall and the ventilation air flow in the annulus.

Classical heat transfer principals are used, representing convective heat transfer from the flue gas to the inner surface of the liner, conductive heat transfer through the two liner materials (the corrosion veil and the structural wall), and convection into the annulus. A similar heat transfer is established through the concrete shell wall, and radiation from the outer surface of the liner to the inner surface of the concrete shell is included.

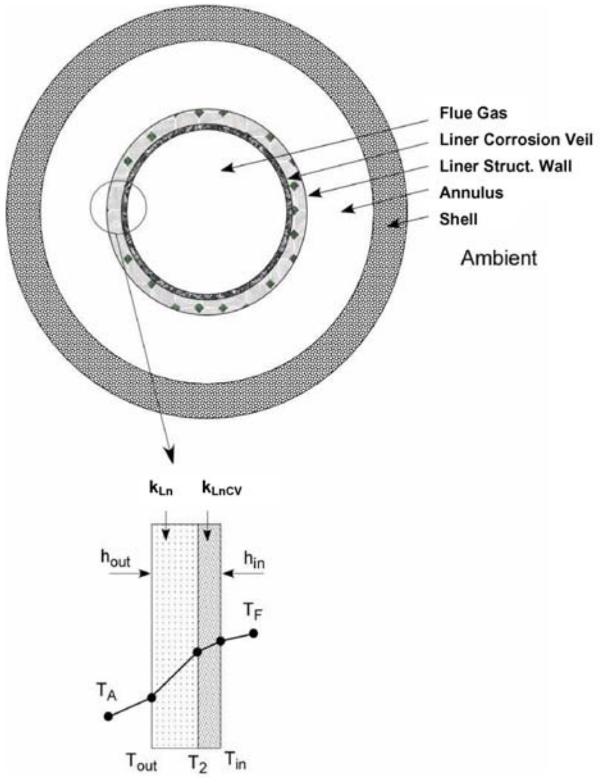



**Figure 4: Chimney Thermal Spreadsheet Analysis Method**

Ventilation flow in the annulus is determined using natural draft in the annular space including entry and exit losses. The spreadsheet iterates the calculation of the ventilation air flow at one-foot interval up the annulus based on an assumed temperature at the top of the annulus. The calculated temperature is compared to the assumed value. The result quickly converges to the final annulus temperature. Using the spreadsheet, the annulus temperature and average liner wall temperature was evaluated for varying amounts of ventilation area, Figure 5. A design annular space temperature criteria for the calculated annulus temperature at the sampling platform and at the top of the annulus was established with the owner. Based on this criteria, it was determined that 200 $ft^2$ (18.6 $m^2$) of ventilation

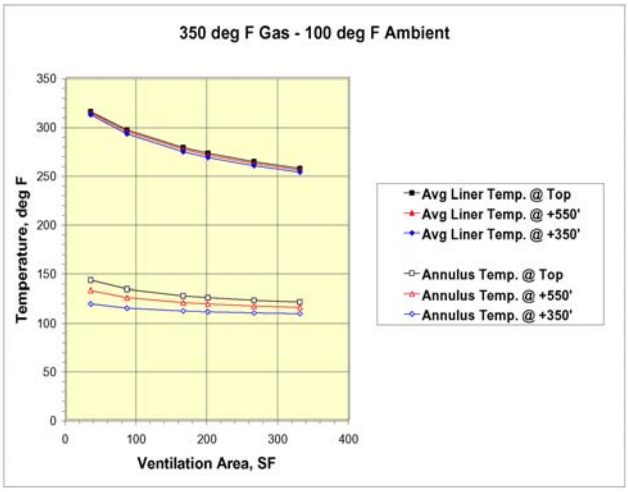



**Figure 5: Temperature Variation with Ventilation Area**

area would be provided. The variation in annulus and average liner temperature with height for 200 ft$^2$ of ventilation area is shown in Figure 6. This also established a design annular space temperature for use in the GRP liner thermal analysis.

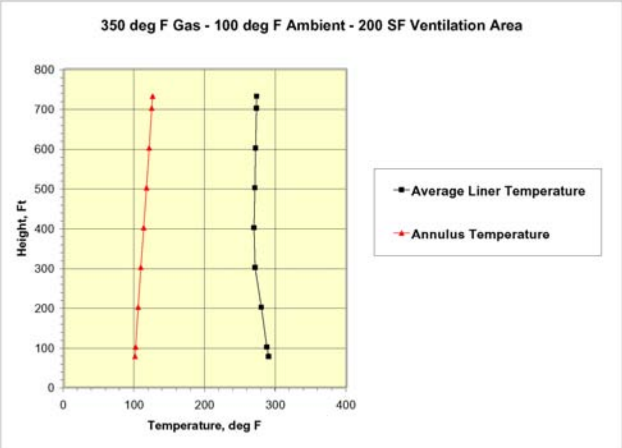



**Figure 6: Temperature Variation with Height**

The GRP liner is designed by the fabricator's consultant in accordance with *ASTM D5364, Standard Guide for Design, Fabrication, and Erection of Fiberglass Reinforced Plastic Chimney Liners with Coal-Fired Units*, and the owner's specification. Finite element analysis (FEA) used for both global and local detail design, using ANSYS, version 8.1. The program TRILAM is used for evaluation of laminate mechanical properties, stresses and strains. The thermal gradient through the liner wall is applied in the FEA. The mechanical properties are evaluated at 5 equally spaced regions through the laminate. These mechanical properties are used in the analysis to reflect the properties in each temperature region. In this manner both the effects of the thermal gradient and the non-linear material properties are taken into consideration. The typical liner wall thickness is comprised of a 0.656 in. (16.7 mm) structural wall and a 0.10 in. (2.5 mm) corrosion veil, with thickening of the structural wall at and near supports. The corrosion veil is not considered for structural resistance and is therefore modeled with zero stiffness in the FEA.

## Concrete Shell Structural Design

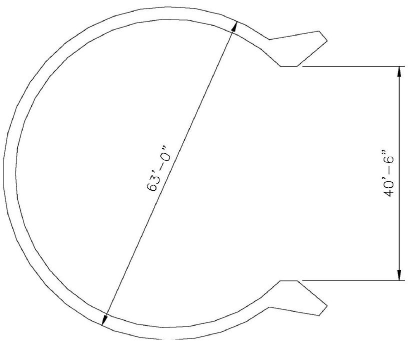



**Figure 7: Construction Opening Plan**

The concrete shell is designed in accordance with *ACI 307-98, Design and Construction of Reinforced Concrete Chimneys*, for a basic wind speed of 90 mph (40.2 m/s). A large construction opening is required

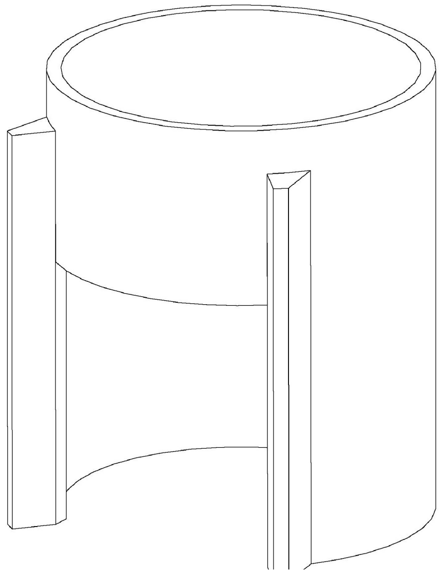


**Figure 8: Pilasters at Construction Opening**

in the base of the concrete shell for bringing in the GRP liner sections. The GRP liner sections will be fabricated by filament winding in a temporary facility on the plant site, and transported to the base of the chimney through the construction opening. To facilitate the size of the liner sections and the transport trailer a construction opening 40.5 ft. wide by 45 ft high (12.3 m wide by 13.7 m high) is planned. ACI 307 limits the one-half opening angle in chimney shells to 30 degrees. (The CICIND Model Code allows a slightly larger opening to use the Virtual Opening method, equivalent to a half angle of about 32 degrees, depending on the wall thickness.) If applied to this opening, an outside diameter of 83 ft. (25.3 m) would be required, a much larger diameter than would be needed to resist the design loading for this height chimney. In order to reduce the diameter, it was proposed that a larger opening be used with a one-half opening angle of 42 degrees, and pilasters be used at the sides of the openings, effectively replacing a

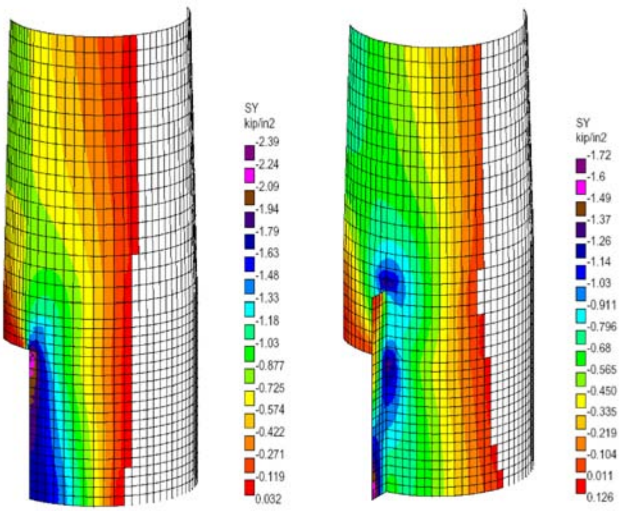



**Figure 9: Shell Opening Finite Element Analysis Results**

portion of the concrete removed in the opening and forming a non-circular cross-section. The general shape of the pilasters and opening is shown in Figure 7. The pilasters extend to a height of 1.5 times the height of the opening, Figure 8.

The opening limitation in the strength calculation procedure in ACI 307 serves to address two simplifying assumptions in the Standard. First, the reinforcing steel is considered uniformly distributed around the circumference and it is assumed that replacing the reinforcing interrupted by the opening at the sides of the opening results in a capacity within the accuracy of the procedure. Second, linear strains are assumed across the diameter of the shell. It is well known that the introduction of an opening in the shell results in a deviation from this assumption, and that the larger the opening the more significant the deviation. In order to address these issues in the design of the chimney, the following criteria was developed:

1. The chimney shell at the opening is designed, without the pilasters, using the ACI 307 methodology, with the actual location of the reinforcing steel at the sides of the opening included in the analysis

2. Pilasters are included at the sides of the opening and analyzed by FEA and compared to a FEA of an opening with a one-half angle of 30 degrees. The pilaster is sized and reinforced to result in lower stresses than the 30 degree FEA model results.

3. Shear transfer between the chimney wall and the pilasters is designed using the shear-friction method of *ACI 318-02, Building Code Requirements for Structural Concrete*.

The lower 150 ft. (45.7 m) of the chimney is analyzed by finite element analysis using shell elements. Two models were used, one with a 30 degree opening and no pilasters and one with a 42 degree opening with the pilasters. The unfactored wind loading was applied to the models. Figure 9 shows plots of the vertical stresses in the concrete for the two cases. The results of the 30 degree one-half opening angle model shows a high stress area near the top corner of the opening, while the results with the pilaster show a significantly lower stress level at the top of the opening and a transfer of the load from the wall to the pilaster. Figure 10 compares the stresses for the two cases at elevation 45 ft. (13.7m). Significantly lower stressed result with the pilaster. Figure 11 compares the stresses for the two cases at the base, where the maximum stresses are essentially the same. Finally, Figure 12 compares the moment capacity and moment demand for the various cross sections considered and illustrates the increased capacity of the section with the pilasters.

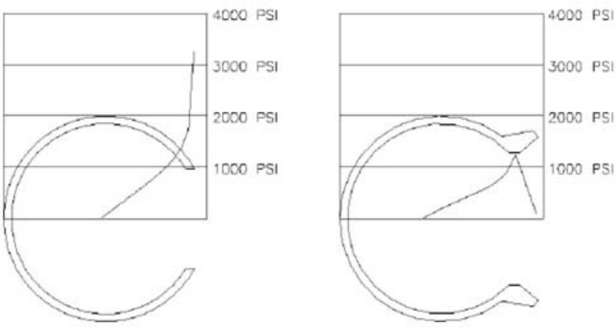



Figure 10: Stresses at Elevation 45 ft. (13.8 m)

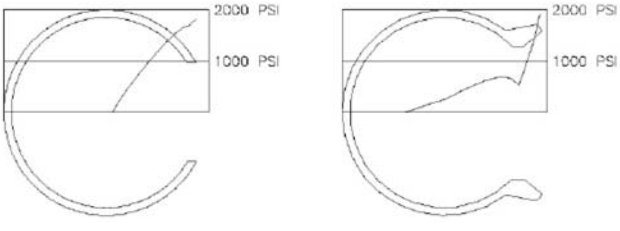



Figure 11: Stresses at Elevation 0 ft. (0 m)

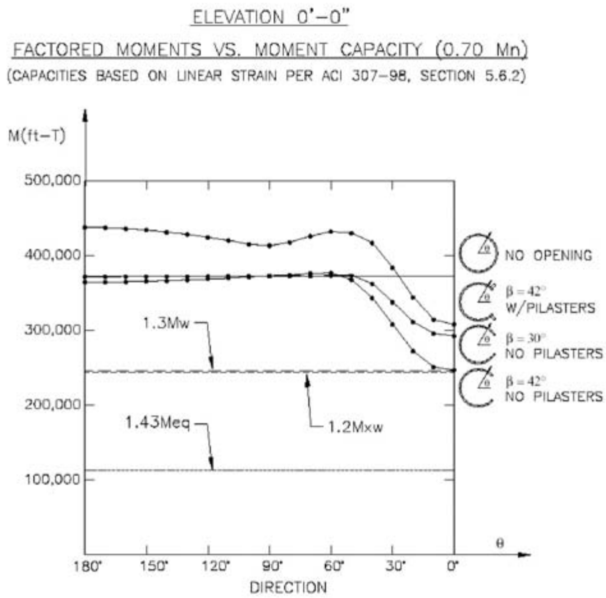



Figure 12: Moment Capacity and Demand

## Conclusions

The design of this chimney presented several interesting and challenging aspects related to the high temperature By-Pass operation. The use of a highly ventilated annulus aided in addressing concerns regarding access into the annular space and in the thermal design of the GRP liner. A large construction opening, reinforced by pilasters, provided structural performance equivalent to that of a similar chimney with a normal sized opening, at a significant cost savings.

The construction of the chimney is beginning in the fall of 2005. I would welcome the opportunity to report on the construction and operation of the chimney at a future meeting.