# The Use of FEM in the Revamping of Existing Systems


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## ABSTRACT

Often the revamping of existing sulfur recovery systems requires replacing some of the equipment. At the same time, economic considerations can dictate re-using as much of the existing system as is possible and practical. This paper examines the process used to connect a new thermal reactor to an existing waste heat exchanger. Included are some of the design considerations necessary to ensure a safe and reliable final arrangement.

The complexity of the configuration - including the stresses developed in the existing equipment and the interconnection - required the use of Finite Element (FE) to assess the final design.


## INTRODUCTION

Typical Claus type Sulfur Recovery Units (SRU) operate at relativity low pressure in conjunction with high temperatures. Typical operating pressures are low. The operating temperatures, however, often are in the range of 1500 °C (2730 °F), which necessitates the use of refractory linings to protect the carbon steel pressure shells. The upgrading of an existing SRU typically requires detailed engineering investigation of the interface of new equipment to the retained existing equipment. The investigation described in this technical paper involved the connection of a new refractory lined thermal reactor vessel to the refractory lined inlet channel of an existing waste heat recovery exchanger for two similar SRU's. The new thermal reactors were designed and fabricated in accordance with the ASME Boiler and Pressure Vessel Code Section VIII [1]. The carbon steel shells were constructed of SA 516-70 with a design temperature of 343 °C (650 °F) with a multi-layer refractory lining designed for a 1500 °C process gas temperature.

The unit number one new thermal reactor was connected to an existing waste heat recovery utilizing the existing exchanger cylindrical channel nozzle arrangement as shown in Figure 1.

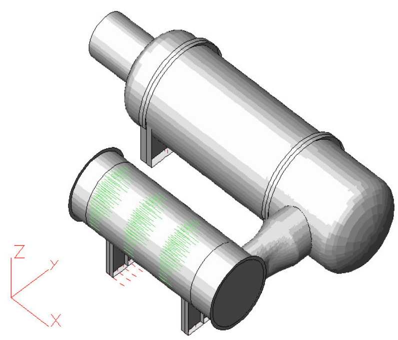


**Figure 1**

The Unit number two new thermal reactor was connected to an existing waste heat exchanger using the existing exchanger rectangular channel inlet nozzle arrangement, as shown in Figure 2.

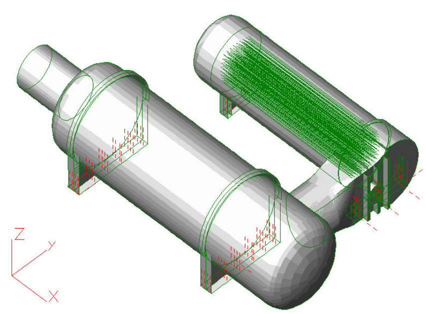


**FIGURE 2**

The actual configuration and condition of the existing exchangers' channel nozzles was critical to the engineering investigation. The available detailed drawings were compared to the actual items and were then updated to the current conditions, including remaining thickness of the nozzle walls and anchor locations. The rectangular nozzle utilized external reinforcement ribs. These were found to be altered from the original drawings and required considerable observation and measurements in order to confirm their current conditions.

The ASME Boiler and Pressure Vessel Code Section VIII Div. I paragraph UG-22 [1] requires the design engineer to complete an adequate design analysis for the loadings that effect the vessel. In this case, the complex geometry of the nozzles made the use of closed form calculations difficult and the use of procedures such as Welding Research Council Bulletin No. 107 [2] inappropriate. The design analysis had to include not only the pressure, but also the gravity and thermal growth-related forces that were imposed on these nozzles. Due to the complexity of the problem, FE analysis was used to investigate the loadings affecting the interconnecting nozzles.

## FINITE ELEMENT MODELING

The thermal reactor/heat exchanger system is a relatively complex system. Rigorously modeling all of the aspects of this system would require a substantial degree of effort, entailing a substantial amount of analysis time with its consequent cost. As is often the case, a trade-off between the rigorousness of the analysis and the degree of conservatism used in the modeling assumptions was used to hold the costs in line.

It was judged acceptable to use plate elements in the construction of the model as a means of reducing analysis time and effort. It was recognized that the reported stresses, especially in the sharp corners on the vessels, were likely to be under-reported with these elements. The reader is referred to technical papers by Porter et al 1997 [3], Porter et al 1998 [4] and Seipp 2001 [5] for additional discussion on modeling and stress evaluation methodologies for nozzles.

### Model Construction

The FE modeling of the two units followed the same general path:

- Construct a model of the portions of the existing heat exchanger that were to be reused
- Construct a model of the new thermal reactor
- Join the two models, apply loads, and compute displacements and stresses

The analysis of existing equipment differs from that of new equipment in several important ways. Perhaps the most important factor is that the geometry of existing equipment often differs from the design drawings. While "as built" drawings are the accepted practice, they are not always available at the time a modification is to be considered. Additionally, it is often necessary to evaluate the effect of corrosion during the life of the existing equipment before future design prediction can be developed.

The problems faced and addressed in these two units were similar. Since the severity of the problems was greater for Unit 2 (Figure 2), we will use this unit as the example for the paper.

The cross section of the inlet channel on the existing waste heat exchanger on Unit 2 was rectangular, as shown in Figure 3. This shape is somewhat atypical for pressure vessels. Additionally, no external (or internal) braces were indicated on the original drawings.

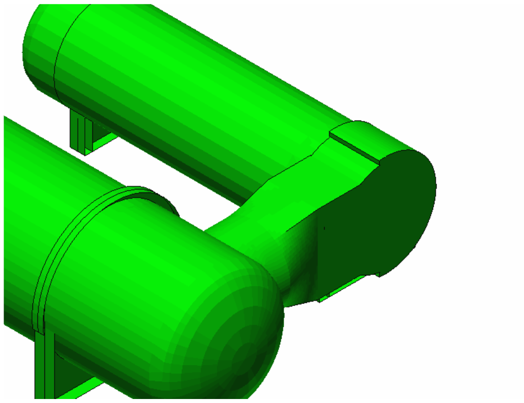

**Figure 3**

The initial analysis of this configuration indicated stresses in the channel that were much higher than would be allowed in such service. Subsequently, a field survey of the unit was conducted. This survey revealed both the existence of external bracing and the existence of a manhole in the channel.

The current "as built" geometry is illustrated in Figure 4.

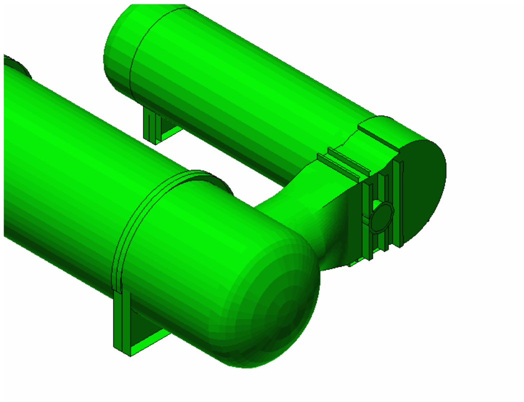

**Figure 4**

As may be seen in the comparison of Figures 3 and 4, the "as built" geometry differed significantly from the original drawings.

Subsequent investigation revealed that the manhole, but not the bracing, had been indicated on *one* of the original drawings.

## Restraint and loading

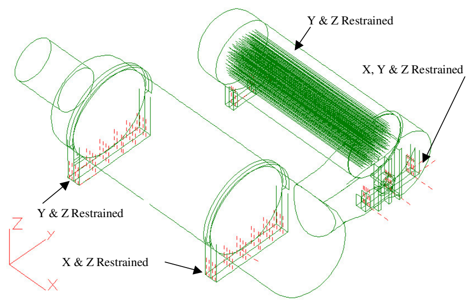


**Figure 5**

Figure 5 illustrates the initial restraint conditions imposed on the model. An initial run was conducted using the pressure and temperature loads. After determining the direction of the motion due to these loads, an opposing horizontal force (equal to the vertical load multiplied by 0.1) was applied to account for the frictional load.

## Displacements

Figure 6 illustrates the deflected shape (both X and Y) and a graphical scale of the displacement (IN) in the global X direction due to the thermal loads. The indicated displacements point out that it was necessary to allow for a displacement of approximately 1.41" in the X-direction.

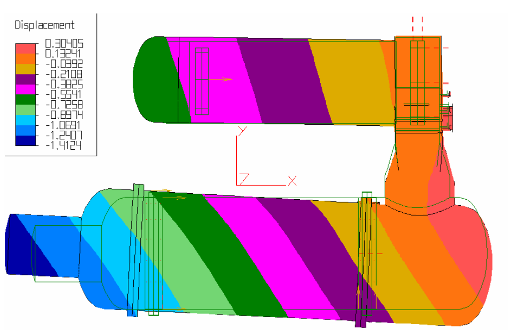


**Figure 6**

The addition of the pressure loading resulted in an insignificant change in the displaced shape.

## Stresses

Figure 7 illustrates the indicated stress (psi, averaged at the nodes) in the inlet channel due to both pressure and temperature loads. A convergence analysis was used to arrive at the mesh size employed. The highest stresses were indicated at the junction of the channel to the new reactor and at various points on the rectangular duct.

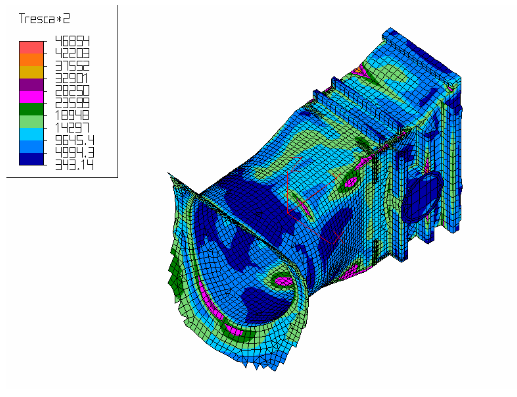


**Figure 7**

In general, the indicated stresses are below 1.5Sm for the SA-516-70 material (26,500 psi). However, stresses of nearly 47,000 psi are noted in several locations. Note that the current Code values are higher. This analysis was conducted prior to 1998.

In order to evaluate the compliance of this vessel with the ASME Code, it is necessary to separate the primary from the secondary loads. Figure 8 illustrates the indicated stresses in the channel due to pressure alone. In this figure, only those stresses which exceed the 26,500 psi stress limit are shown.

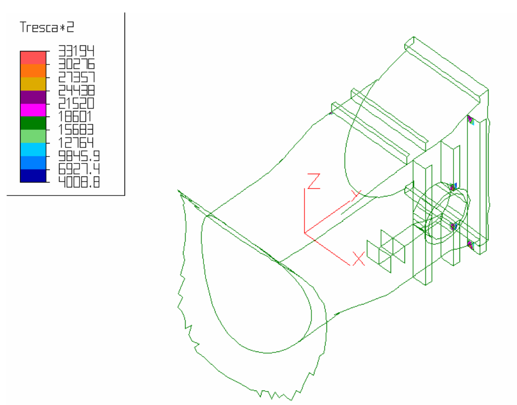


**Figure 8**

As can be seen, there are several isolated regions where the indicated stresses exceed the 26,500 psi limit. These areas are very limited, occurring mainly at local discontinuities. In general, we would conclude that the channel meets the primary stress limits.

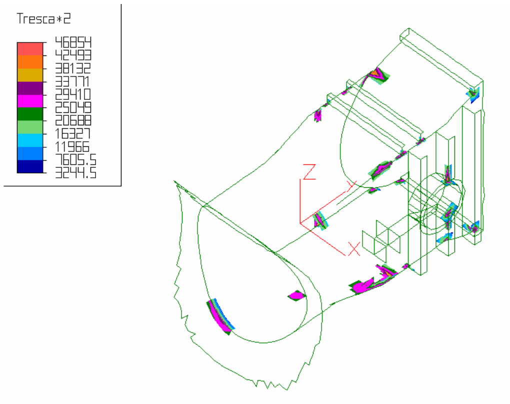


**Figure 9**

Figures 9 and 10 illustrate the indicated stresses in the channel due to both primary and secondary (pressure and thermal) loads.

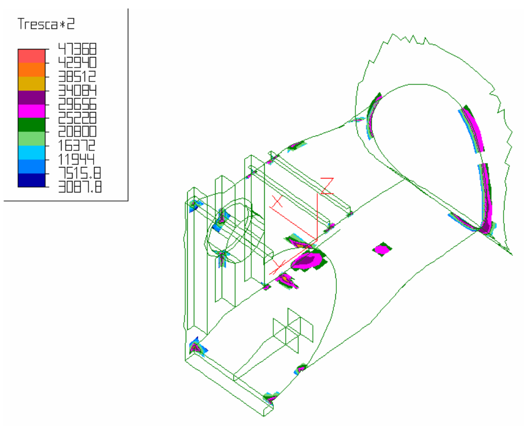


**Figure 10**

These figures show the channel from two opposite views. As with Figure 8, only those stresses which exceed 26,500 psi are shown. As can be seen, there are numerous regions where the indicated stresses exceed the 26,500 psi limit, but not 3Sm

3Sm is the ASME Code allowable for primary plus secondary loading. In the case of these existing vessels, however, the engineering decision was made to limit all stresses to 1.5Sm. The driving factor in this decision was the uncertainty about the condition of the existing components and the difficulty of assessing indicated stresses at local discontinuities. See Porter et al 1999 [4].

Looking closely at the stress due to primary and secondary loading (Figure 11), we can see that near the corners of the channel and near the manhole, the indicated stresses were well over the selected engineering allowable of 26,500 psi. For this reason, re-enforcement of the channel was recommended.

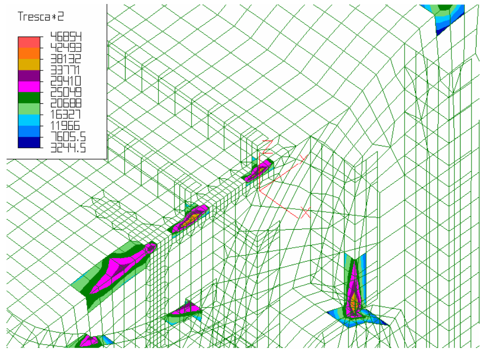


**Figure 11**

## Refractory Integrity

One of the primary concerns in this type of vessel, in addition to the component stress, is the deflection that is imposed on the refractory. Based on experience, the engineers had determined that a change in slope exceeding 0.75" per 100" of length would potentially cause degradation of the refractory material. A design value of 0.50" per 100" provides a desirable factor of safety.

Figure 12 illustrates the X-direction deflection for primary and secondary loadings in the duct between the thermal reactor and the existing heat exchanger as a function of the distance from the centerline of the combustor. "Interior" refers to the side of the duct on the left when viewed from the top as in Figure 10. "End" refers to the other side. The indicated deflections are at the vertical mid-point of the duct. The point where the rectangular-to-round transition begins is at approximately 120".

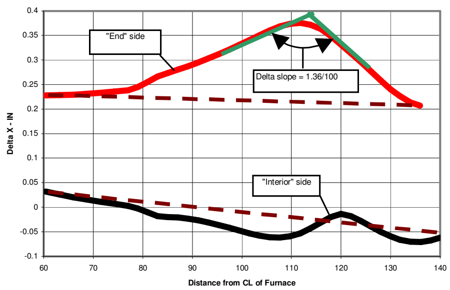


**Figure 12**

The two gray lines over the data curve at the top of Figure 12 approximate the slope before and after the deflection point. The change in slope at this point (indicated as 1.36" per 100") is considerably greater than the desirable 0.5" per 100". The dashed lines indicate the shape that the duct would take without bending. As can be seen, the differential is in excess of 0.15" on the Interior side. Given the greater than desirable change in slope and the magnitude of the deflection, cracking of the refractory in this region is likely.

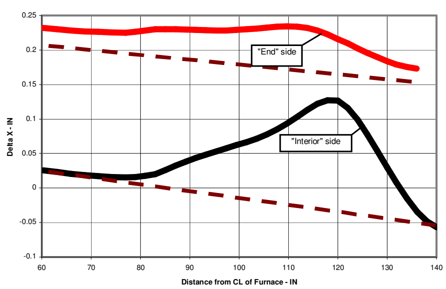


**Figure 13**

Figure 13 illustrates the deflection of the duct due to pressure loading only. As can be seen, the change in slope on the "Interior" side is significantly higher than the design value. Neither condition is desirable.

## RECOMMENDED MODIFICATIONS

Based on the analysis, the decision was made to reinforce the duct to reduce the indicated stresses and deflections. Rather than devote a significant effort to optimizing the added material, it was judged more efficient to simply double the section in regions where unacceptably high stresses had been indicated. The costs associated with this modification were less than would be required for a more detailed analysis. Again, it was a trade-off between the rigorousness of the analysis and construction costs and effort.

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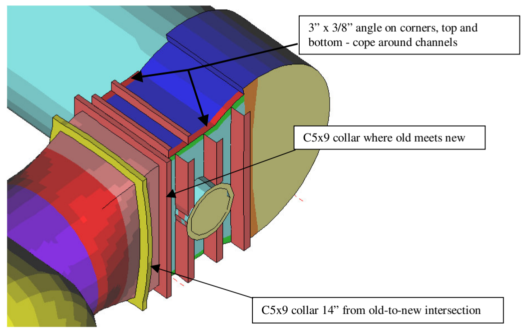


**Figure 14**

Figure 14 illustrates the recommended changes to the system. With the addition of these members, an additional finite element analysis was conducted. The results indicated that the added members reduced both the indicated stress and the refractory deflection to acceptable levels

## DISCUSSION

The described design project is typical of those that arise during maintenance and/or upgrading of existing facilities. As is the norm, economics is an important, if not controlling, factor in the design project. As the unknowns are often great (e.g. corroded material condition, as-built dimensions and even geometry), the required analysis effort is often more extensive than for a similar new design.

Nonetheless, it is the design engineers' responsibility to provide a design consistent with the criteria. This design project is an example of a situation where the application of "engineering judgment" is not only appropriate, but absolutely necessary, to achieve a suitable result without excessive analysis effort. The engineering judgements pertaining to this design project were:

- Reasonable verification of current "as built" conditions of existing equipment including:
  Metal thickness
  Additions and changes from original design drawings
  Location and condition of supports and anchors
- Decision to limit the indicated stresses to less than 1.5 Sm to:
  Reduce the engineering analysis effort that would be necessary to fully evaluate the local discontinuities and peak stresses
  Provide a reasonable allowance for unknowns of existing equipment
- Recommended Modifications
  Add reinforcement pad to the new thermal reactor vessel outlet nozzle to reduce deflections and discontinuity stresses

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Add angles on the corners of the existing rectangular nozzle to reduce discontinuity stresses
Add collars to the existing rectangular nozzle to reduce deflections to suitable values for refractory lining serviceability

The design engineer must provide a reasonable investigation of the loads that affect the vessel, as required by The ASME Boiler and Pressure Vessel Code Section VIII Div. I Paragraph UG 22 [1]. The engineer must establish the approximate balance of concise analysis and practical judgement to accomplish this charge. A parametric optimization FE study was deemed unwarranted in this case. Such investigations would require several reinforcement selection iterations and additional verification of analysis convergence. Structural reinforcement was selected based on the availability of material and ease of fabrication. That the system would then meet the code requirements was check by FEA. This approach is most often taken in fitness-for-use plant equipment updating and retrofitting. The additional reinforcement also reduced the deflection of the nozzle to values that were considered acceptable.

## REFERENCES


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