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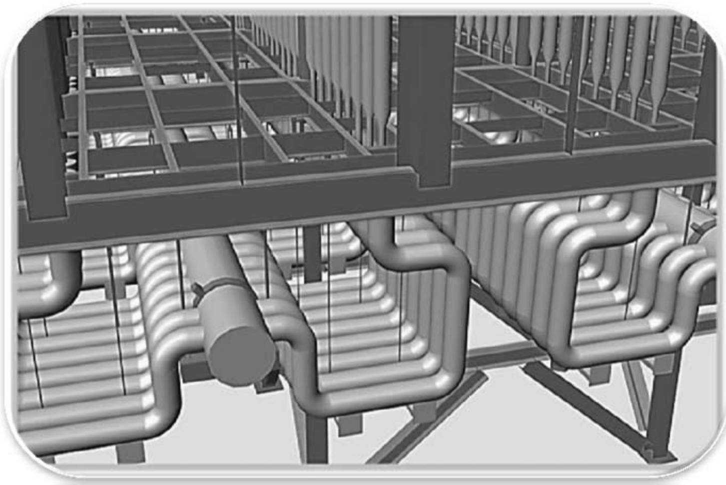

Reformer Furnace Outlet Systems

Design Considerations, Emergency Repair, and Enhanced Reliability

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Executive Summary

Reformer furnace outlet collection systems operate under severe service conditions that push the metalurgical limits of the materials used. For that reason, reliable long-term performance depends strongly on the operational control and maintenance practices applied by the owners as well as the design margins and inherent robustness of the mechanical design. Reformer outlet system components are also subject to service-induced embrittlement due to the formation of carbides and other compounds which results in loss of repair weldability in the outlet system components and complicates any need for repair over the life of the system. This paper presents the significant operational and maintenance factors that influence reformer outlet system reliability, discusses the adequacy of design margins typically applied, the failures and the repair methods that have been successfully applied when outlet system failures occur, and design features that can be applied to make the outlet system more robust and therefore more reliable.

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Background - The Issue

Steam-methane reformer furnaces, or SMRs, are used in a number of common synthesis gas production applications. These may support the production of Ammonia, Methanol, Gas-to-Liquids, Hydrogen, or Reducing Gas. The operating conditions of each process differ and there is also a range of conditions within each of these production applications depending on the specific technology used in the plant. However, almost all applications result in outlet system conditions that challenge the design limits of the materials of construction. In general, ammonia plant reformer furnaces have lower operating temperatures but significantly higher pressures when compared to methanol and hydrogen applications while reducing gas applications have lower pressure but even higher temperatures than methanol and hydrogen applications. The table below shows the typical range of operating conditions for the reformer furnace outlet system for each of these applications. Note that for the purposes of this comparison we are examining *conventional* designs therefore, we are not including ammonia plant applications that incorporate the use of enriched air or excess air to the secondary reformer, nor are we including methanol plant applications that incorporate the use of an oxygen-fed secondary reformer.

Table 1

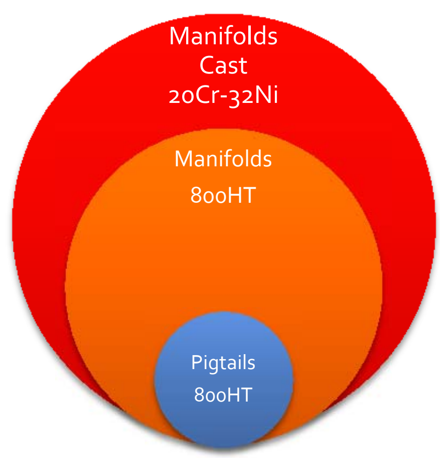
Typical Operating Conditions @ Reformer Furnace Outlet

Process Application	Temperature Range (^{o}F)		Pressure Range (psig)		% Methane Slip %CH_4	
Conventional NH_3	1525	1450	450	600	10	16
Conventional MeOH	1625	1550	250	350	3	7
Hydrogen / GTL	1650	1550	150	300	2	5
Reducing Gas	1750	1650	30	100	0.8	1.0

Temperature / Pressure Limits of Outlet System Materials

The material of choice for outlet pigtails is a wrought 800HT material due to its high strength and relatively high ductility. Mechanically, the pigtail is relied upon to provide the required flexibility within the system to avoid overstress of the end connections of the pigtail to the manifold and to the bottom of the catalyst tube. It also is sometimes pinched as a means to isolate a tube leak. The use of 800HT material with relatively small diameter of 1 ¼-1 ½- NPS is typically used. Outlet pigtail designs often push up to a thickness/diameter ratio in the range of 0.15-0.20

The material of choice for outlet manifolds varies somewhat among the reformer designers based on application. Some lower temperature designs having a design temperature in a range below 1525^{o}F can use either 800HT material or the cast equivalent 20Cr-32Ni alloy while those designs in a temperature range above 1525^{o}F tend to use the cast equivalent 20Cr-32Ni alloy. Outlet manifold designs typically have thickness/diameter ratio closer to 0.10-0.12 in order to limit thermal stresses through the thickness of the manifold during temperature cycles.



The Issue Quantified

Since all reformer applications tend to push the temperature/pressure limitations of the materials, good control of the operating conditions is extremely important. The graphs provided below show the typical design conditions for Conventional Ammonia, Conventional Methanol, and Hydrogen superimposed on the graph of temperature/pressure limitations of each of the material/component cases outlined above.

Figure 1

Outlet Pigtail Temperature/Pressure Limitations

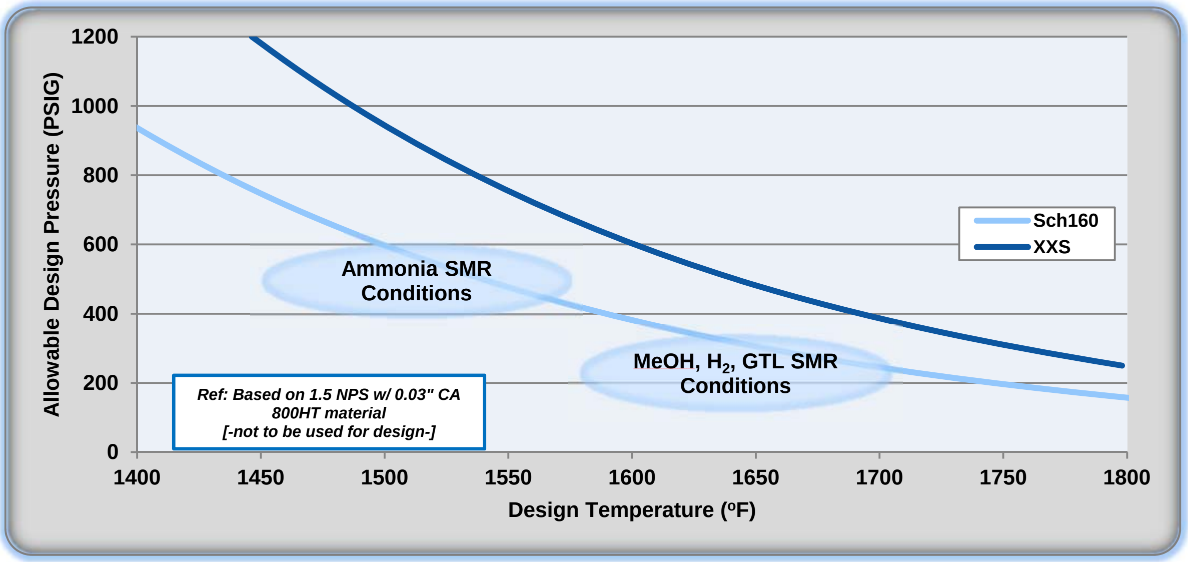
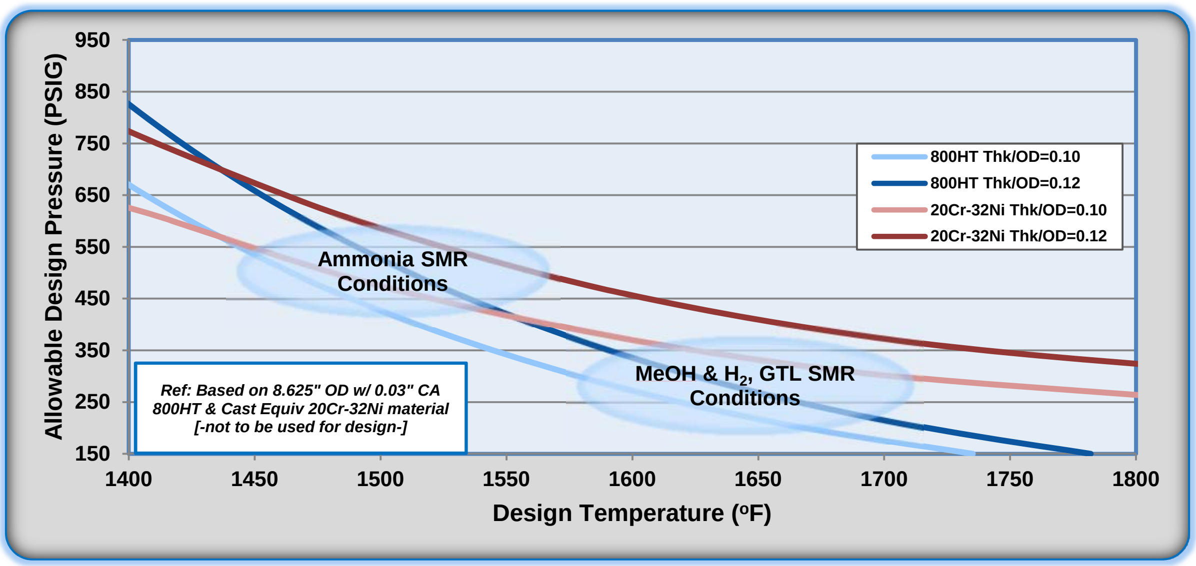


Figure 2

Outlet Manifold Temperature/Pressure Limitations



Discussion of Design Margin Adequacy

Design margins are applied to the operating temperature and pressure to allow for operating flexibility and survival of operating upsets that may result in short-term conditions that deviate from normal. For long-term operations, design margins also allow tolerance for imperfect flow distribution and heat input among the total population of catalyst tubes.

Uniformity of process flow to all catalyst tubes is confirmed with pressure drop checks carried out at the time of catalyst loading. These checks confirm pressure drop uniformity within about +/-5% which translates to a flow uniformity tolerance of +/-2.5% when catalyst is loaded using modern catalyst loading methods. However, as the reformer is put through start-up/operation/shut-down temperature cycles the expansion/contraction of the catalyst tube length and diameter results in some amount of settling and breakage of the catalyst. The greater the number of cycles, the more catalyst settling and breakage is experienced. Over time this produces additional pressure drop through the catalyst which is not uniform among all of the tubes. This creates greater deviation in flow uniformity over the life of the catalyst.

Likewise, uniformity of heat input to all of the catalyst tubes is considered to be within +/-5% when the burners and the flue gas collection tunnels (or coffins) are new. With operation however, the burner tip orifices can become restricted with pipe scale or with coke accumulation due to the presence of heavier hydrocarbons and in some cases fuel gas orifices can become enlarged due to oxidation and erosion. In addition, the dimensional consistency of the flue gas collection tunnels can deviate over time which can open new flow paths for flue gas into the tunnel from the firebox, causing an imbalance of flue gas flow in local areas. These factors can lead to a deterioration of heat input uniformity as the reformer ages without proper attention to the importance of maintenance.

Overall combined heat input and flow uniformity tolerance may therefore start out at +/-7.5% when the reformer and catalyst is new but can easily deteriorate to +/-15% or worse as the catalyst condition and heat input factors deteriorate.

When setting design margins it is important to understand that the temperature margin applied should consider the reformer furnace application. The significance of this statement is clearly illustrated in the figure below. With reference to Figure 3, a design temperature allowance of 50°F for conventional Ammonia reforming conditions allows a combined flow uniformity and heat input uniformity tolerance of +/-12-14%. Historical operations have proven this allowance to be generally acceptable for reliable performance in conventional ammonia service. To achieve a similar level of flow and heat input uniformity tolerance for conventional methanol or hydrogen operating conditions requires a design temperature allowance of 100°F or more. The reason for this difference relates to the proportion of incremental heat that is consumed by additional reforming reaction versus that which goes directly to sensible heat. As previously noted in Table 1, there is a greater percentage of unreacted methane remaining at the outlet of the catalyst tube (or methane slip) for the conventional ammonia plant reformer conditions when compared to the unreacted methane remaining for the conventional methanol and hydrogen conditions. As the remaining unreacted methane approaches zero, a greater portion of the incremental heat input becomes sensible heat increasing temperature.

It should be noted that most conventional methanol and hydrogen plant reformer furnaces do not have a design temperature allowance as high as 100°F; therefore, in order to achieve reliable performance they require tighter control of operating conditions and greater attention to maintaining the condition of the burners and other factors that influence heat input uniformity.

If we consider that the outlet system, no matter the application, should be designed to provide a relative heat input and flow uniformity tolerance of +/-13% then we arrive at a design margin approach as presented in Figure 4. With reference to Figure 4, Conventional Ammonia reformer conditions with catalyst tube outlet methane slip in the 14-16% range should have an outlet system design margin of 50°F, Conventional Methanol reformer conditions with catalyst tube outlet methane slip in the 5-6% range should have an outlet system design margin of at least 75°F, and Hydrogen reformer catalyst tube outlet methane slip in the 3-4% range should have an outlet system design margin of at least 100°F in order to provide the same level of heat input tolerance and reliability.

Figure 3
Relative Heat/Flow Uniformity vs. Outlet Temperature Deviation

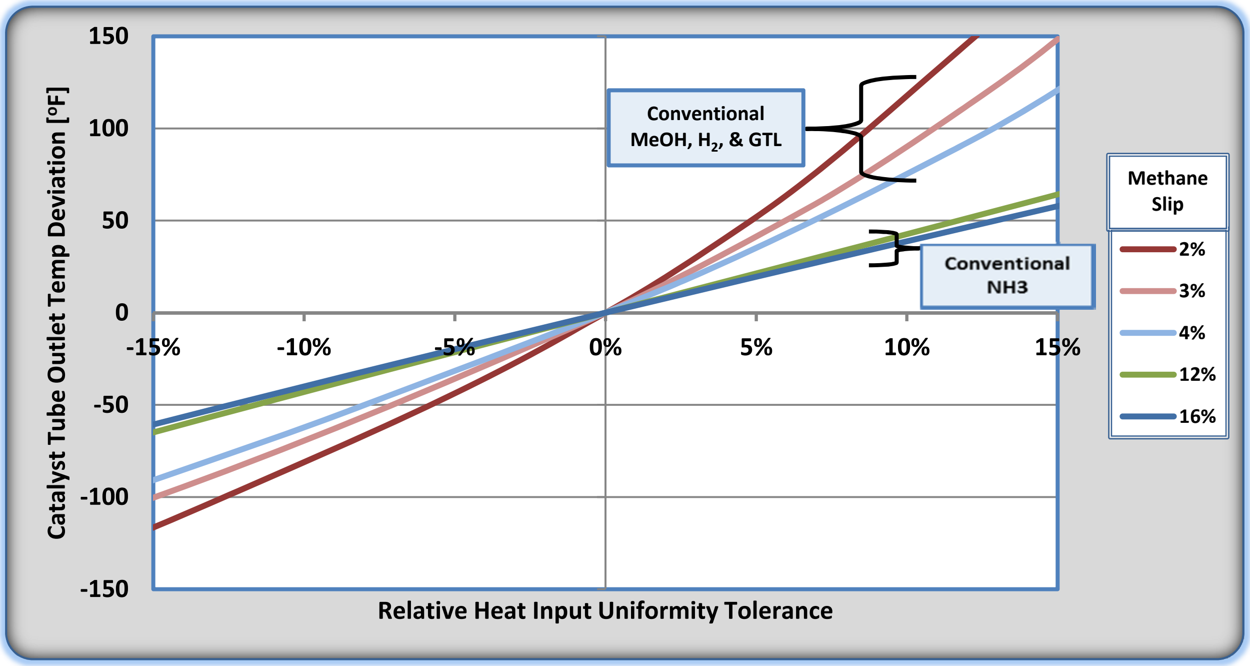
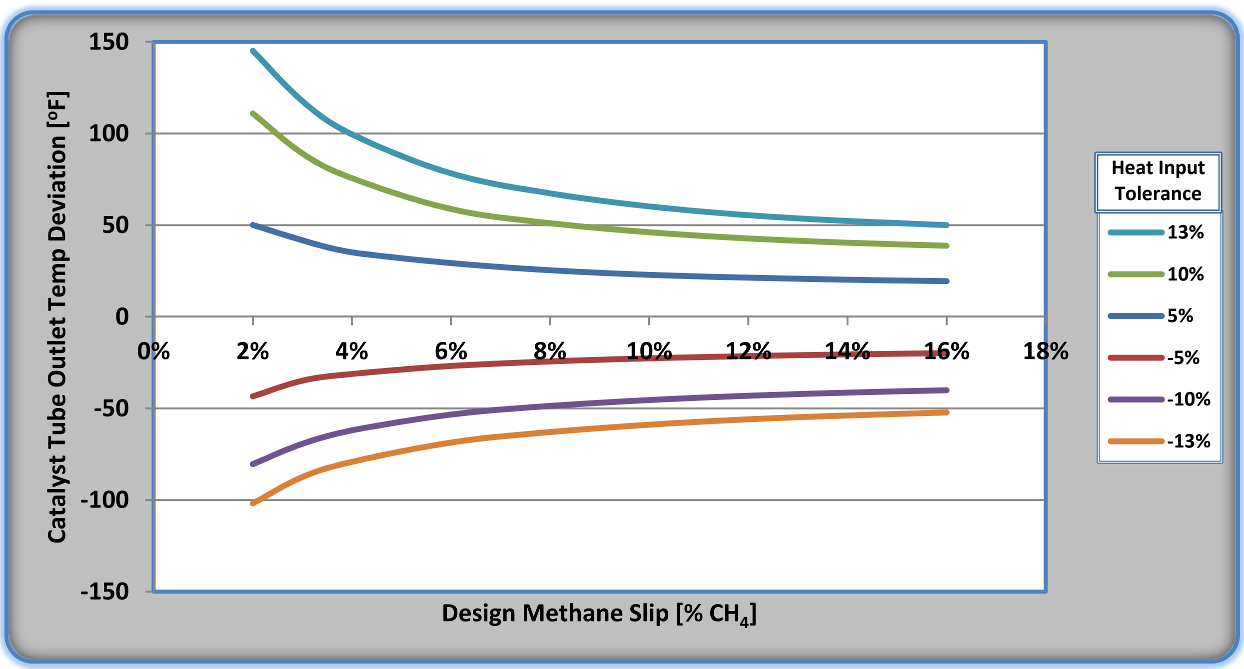


Figure 4
Relative Heat/Flow Uniformity vs. Outlet Temperature Deviation



The Problems

With long-term operation of a reformer furnace, various pressure containing components [outlet reducer cones, pigtails, collector manifolds, tees, transfer line connection transitions] of the outlet system are subjected to high stresses and creep damage due to exposure to the temperature and pressure conditions as well as the effects of mechanical support system deficiencies and deterioration of these supports over time. The design intent of any reformer outlet support system is to maintain the stresses of all components of the system within their limits as the furnace cycles up in temperature to operating conditions and back down to ambient conditions during shutdown. To achieve this design intent, the pigtails must first be designed with sufficient flexibility to keep the stresses at the end connections within the allowable limits, and the spring supports, fixed and/or sliding supports, and hangers must be designed to carry a consistent load while allowing unrestricted thermal expansion as the system transitions from ambient conditions up to operating conditions. It is very important that the support system provide consistent long-term support of the loads over the life of the furnace. When the support system fails to provide proper support of loads, any unsupported load is transmitted through the outlet system to the fixed support points which often results in over-stress and failure at locations where these stresses are concentrated.

In addition, as explained previously, reformer furnaces designed for Methanol and Hydrogen conditions may not have sufficient design margin to maintain all components of the system within their design limitations when relative heat input tolerances are considered. Therefore, some components may operate at elevated temperature conditions that will result in premature aging of those components relative to the total population of components which may in turn result in premature failure of those components.

Common Failures

Failures within the reformer furnace outlet system commonly fall into one or more of the categories listed below:

Outlet Pigtail Failures

- Cracks and possible through-wall failures at pigtail end connections to manifold branch fitting or to the cone at the bottom of the catalyst tube
    - Can be the result of weld detail used for connection [socket weld used?]
    - Can be the result of under-support of pigtail weight
    - Can be the result of high temperature excursions
- Excessive bulging and possible "fish mouth" fissuring due to high temperature at individual catalyst tube outlets
    - Individual outlets can see high temperature due to flow reduction caused by catalyst crushing
    - Individual outlets can see high temperature due to locally higher than average heat input due to burner issues or flue gas flow distribution issues
    - Individual outlets can see high temperature due to a combination of reduced flow and higher than average heat input

Outlet Manifold Failures

- Cracks and possible through-wall failures along the length of the manifold [most common at welds]
- Bowing or deformation of the manifold along the length [see Figure 5 photo]
    - Can be the result of water coming into the manifold from pigtail low points or accumulating in a sagged manifold following a shutdown
    - Can be caused by long-term under-support or over-support along the length of the manifold
    - Can be caused by restriction of thermal movement at one or more support points

Manifold to Tee or Tee to Cone Failure

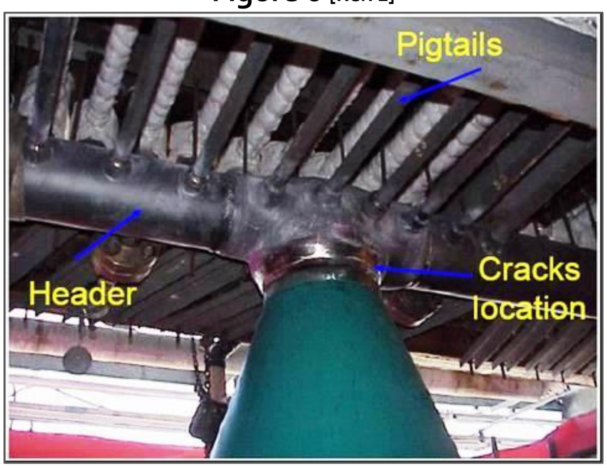
- Cracks at the welds between the manifold and the tee or between the tee and the cone [see Figures 5&6 photos]
    - Can be caused by under-support or over-support of the manifold weight causing high stress at the weld connection to the tee
    - Cracks in the weld to the cone can be caused by asymmetrical under or over-support of the connecting manifolds to the tee
    - Above can be the result of restricted thermal movement at one or more of the support points

Cone to Transfer Line Pressure Shell Failure

- Cracks at the welds between the cone and the transfer line pressure shell
    - Can be caused by failure or deficiency of the internal refractory lining of the cone causing overheating of the connection between the high alloy cone and the lower grade alloy transfer line pressure shell
    - Can be caused by improper insulation of the outside of the cone which reduces heat loss from the cone, concentrates the thermal gradient, and increases the thermal stresses at the connection to the transfer line pressure shell

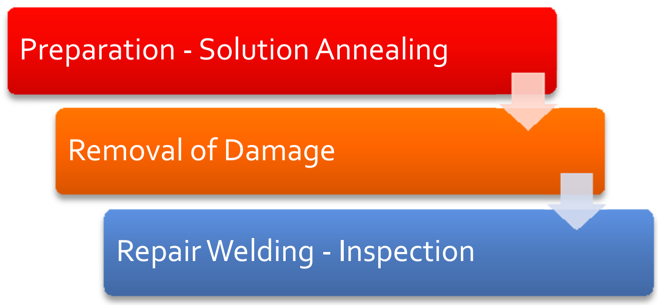
Figure 5

Figure 6 **[Ref: 2]**



Discussion of Common Repair Techniques

There are varied opinions regarding best practices for successful repair of reformer outlet systems. From the success stories found, it is apparent that the best practice depends strongly on the specific set of circumstances. Breaking the activities down to three basic steps is helpful when attempting to plan the best repair approach for each individual situation.



The potential benefits of solution annealing relate to addressing the issue of carbide precipitation and embrittlement of either 800HT or the cast equivalent 20Cr-32Ni material. It is well-established that service-exposed 800HT and cast equivalent 20Cr-32Ni materials are subject to severe loss of repairability due to susceptibility to heat affected zone cracking upon repair attempts. There are numerous references which conclude that high temperature solution annealing and relatively rapid cooling is necessary in order to redistribute carbides and other precipitates into the material and restore repairability. A number of reputable references [1, 2, 3] recommend that solution annealing be carried out at a temperature of 2100-2150°F for up to 6 hours (minimum 1 hour per inch of thickness) followed by rapid air cooling. This practice has been found to sufficiently disperse precipitated carbides and and other precipitates back into the material allowing subsequent removal of damage and repair welding to be done with proper care. Rapid cooling with fan driven air prevents excessive re-precipitation of these compounds.

Removal of cracks and adjacent damaged areas in preparation for repair welding is done following solution annealing. The removal of through-wall cracks around a segment of a weld circumference may be best carried out using grinding and cutting methods that put relatively low heat into the adjacent area. Excessive heating of the material during this step can lead to propagation of cracks around the circumference or into adjacent material in a manner sometimes referred to as "spider cracking". If the cracks do not extend through the entire thickness of a thick-walled manifold or tee, it is sometimes possible to use a small diameter electrode to arc-gouge into the material to get below the root of the crack for removal. The use of a small diameter electrode again limits the amount of heat input and the amount of material removed.

Repair welding is done after confirmation that all cracks are removed. In some cases, "buttering" of the repair area using small diameter weld consumables is often beneficial as a means to begin the fill of large or thick-wall repairs. Buttering can also help to put some distance between the main portion of the weld and the base material that may remain subject to liquation cracking problems. Again, low heat input is beneficial.

Learned Techniques

Construction contractors experienced with the repair of reformer furnaces have many learned techniques for each of the steps involved in repair of reformer outlet systems. Some of these techniques, on the surface, may appear to be minor details. However, combined, they can mean the difference between a successful repair on the first try versus multiple attempts to achieve the desired repair quality. A few examples are provided below:

- When solution annealing with heating pads, use "booster" heating pads on adjacent branches and internal air flow dams on adjacent branches if possible [access through the transfer line ID] to avoid excessive heat losses through the branches.
- Use of x-ray to see extent of cracking to assure that the entire crack is removed and that material removed is minimized.
- Removal of damage using burring tools and pencil grinders puts less heat into the material than use of an arc gouge. Arc gouge can be used in some cases; small diameter electrode can be effective to reduce heat input to material.
- Successful repair welding may also require altered techniques in order to achieve best results.
- Use of small diameter weld rod in order to put less heat into the material, use of 332 stick if crack is not through-wall, and use 332 TIG rod with back purge if through-wall.
- Low-temperature pre-heat ~200°F or no preheat to reduce possible liquation cracking.
- Weld examination in steps to assure quality [RT root pass, RT at 50% thickness, RT final].

Potential Solutions

Steps that can be taken to improve the reliability of reformer furnace outlet systems include those directed toward improved control of flow and heat input uniformity, improved attention to maintenance and inspection, and improved preparation to respond to problems or failures when they do occur. In addition, when it is time to replace the outlet system there are basic changes that can be implemented to increase the design allowances and to improve the support system to achieve a more forgiving and more robust design.

Operation and Maintenance Improvements

Improvements in operation and maintenance practices should concentrate on:

- Maintaining stable control of critical operating parameters
- Avoidance of unnecessary shutdowns
- Monitoring of catalyst tube temperature uniformity
- Proper maintenance of burners using a quantifiable method
- Monitoring and adjustment of outlet system support springs to maintain proper support
- Targeted turnaround inspections

Review of operating controls and emergency shutdown systems should be considered with a focus on maintaining the high temperature components of the reformer within their limits while also avoiding severe thermal cycling and unnecessary shutdown as much as practical. Critical control parameters such as feed flow, process steam flow, fuel firing, firebox draft, and combustion air flow should be measured using 2 out of 3 sensing elements/transmitters to assure that the controlled variable is reliably measured, alarmed, and protected within the ESD system.

Avoidance of unnecessary shutdowns and reduction in the total number of shutdowns will help to extend the useful life of reforming catalysts by subjecting the catalyst to less severe crushing conditions. Less catalyst crushing should result in less deterioration of flow uniformity among the tubes as the catalyst ages. If possible, a check of catalyst tube pressure drop during a plant turnaround can provide useful information to judge the significance of any catalyst crushing experienced after service and whether flow uniformity has been adversely impacted.

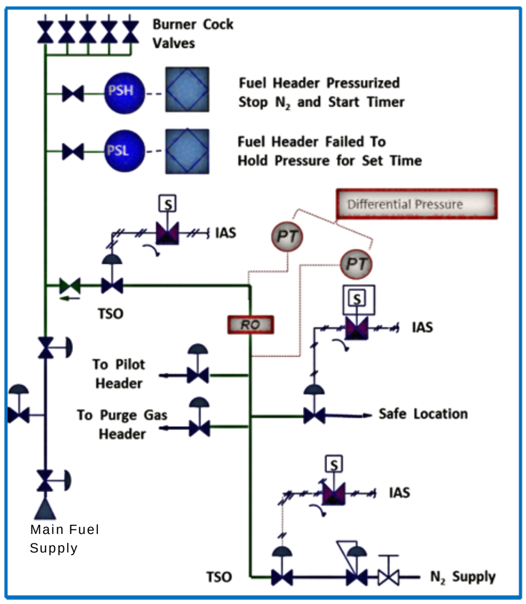
Burner firing uniformity is generally tuned by experienced operators based primarily on the visual appearance of the burner throat and flame. Operators will generally attempt to achieve more uniform heating of the tubes by adjusting manually positioned dampers in the combustion air ducting and burner wind-boxes. Some reformers also have provisions to adjust fuel flow to each burner but most rely upon the burner tip as a flow orifice to maintain uniform fuel flow to each burner. In addition to these normal practices applied to assure reasonable burner firing uniformity, it is possible to carry out a fuel flow uniformity test for each burner to assist operators in the identification of burners that require maintenance cleaning or replacement. An outline for such a burner fuel flow uniformity test is provided below and further defined in Figure 7. This system is a relatively minor adaptation of a commonly applied nitrogen pressurizing system used as part of burner light-off permissive systems to confirm that all manual burner valves are closed prior to opening the main fuel supply. The change involves the addition of a restriction orifice in the nitrogen supply line and two pressure transmitters, one upstream and one downstream of the restriction orifice. This system allows operations staff to carry out a flow uniformity check for each of the burners very quickly as outlined.

Burner fuel flow uniformity check

- **With all burner manual valves closed, main fuel gas supply isolated, and header pressurized with nitrogen**
  - ***Open one burner valve***
  - ***Measure and record RO differential pressure***
  - ***Close burner manual valve and open another***
  - ***Measure and record RO differential pressure***
  - ***Repeat for all burners***
- ***Differential Pressure <95% of average indicates burner tips restricted***
  - ***Tips should be cleaned or replaced as required***
- ***Differential Pressure >105% of average indicates orifices eroded/enlarged***
  - ***Tips should be replaced as required***

Figure 7

Diagram for Burner Fuel Flow Uniformity Check Method



Monitoring of outlet system spring and/or sliding supports on a periodic basis can provide needed information to assure that spring supports remain within their working range and that the outlet system loads are properly supported during long-term operation.

Improved Preparation

Inspection during turnarounds is the best way to prepare for and detect potential problems with reformer furnace outlet systems. Plans should be made for removal of external insulation or the opening of outlet system enclosure boxes as appropriate for access to and inspection of some percentage of pigtails and manifold critical areas. This would include as a minimum the following areas:

- Pigtail end connections
- Check pigtail OD to determine if bulging is a problem
- Check end connection welds using PT
- PT check of welds between manifolds and tee, tee and cone, and between manifold segments

Maintain some number of spare pigtails, reinforcing fittings, manifold segments, tees, and cones for use during turnarounds as a means to minimize time required for repairs and improve reliability of any repairs needed.

Long-Term Improvements

There are a number of long-term improvements that can be considered as a means to achieve higher reliability in the mechanical performance of the reformer furnace outlet system.

When it comes time to replace the outlet system;

- Consider the use of a higher design margin for the outlet system components.
- Consider the use of higher quality spring supports and hangers as a means to assure proper long-term support of outlet system loads. The use of constant spring supports rather than variable spring supports should also be considered as a means to assure proper long-term support.
- If the outlet system supports are primarily based on the use of spring supports, consider the modification of the support design to include sliding supports in strategic locations as a means to assure that over-stress is avoided as the spring supports relax with time.

Conclusions

Achieving the desired level of reliability from reformer furnace outlet systems requires first, an understanding of the factors that contribute to premature aging and failures. Second, it requires an understanding of the areas of the design that are most at-risk of failure and the issues with repair of these failures. Third, it requires an understanding of the actions that can be taken to improve the long-term performance and reliability of the system.

With adequate understanding and appropriate action, significant improvements in reliability can be achieved.

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