Anticipating Reformer Tube Life in Normal Service

Overheating, if severe enough, can override all other tube performance factors. Successful control depends on conscientous adjustment of burners for uniform tube metal temperature throughout the furnace.

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Former catalyst tubes, along with the other pressure-containing components of primary reformers, are most vulnerable to failure due to high operating temperatures and pressures *(1)*. When a failure does occur, the plant owner has no choice but to suffer the high repair costs and lost production associated with retubing a large unit. This article examines the various causes of tube failure in an effort to find ways to anticipate and prolong the lives of these components.

Reformer catalyst tubes are like human beings in that their individual life spans are not accurately predictable, and their loss entails costs that ought to be covered by some form protection. The human life insurance business is based largely on extensive actuarial statistics, most of which are readily available.

Until recently, data on reformer tube longevity have been practically non-existent. A Reformer Information Network *(2)* now facilitates development of such data.

Since the variables governing lifespan are fewer and more controllable for reformer tubes than they are for people, statistical data on reformer tubes need not be as extensive. This article is based on the premise that frequencies of occurrence will serve to adequately confirm or disprove theories on which some reformer tube decisions are made by research, design, manufacturing, and operations people. In many cases, the data will not be sufficient for rigorous statistical analysis.

To supplement data form the Reformer Information Network, nine companies who build reformers furnished at least a partial list of their customers. Questionnaires were sent to all those customers whose reformers have been operating at above 400 lb./sq. in. gauge, and to all owners of large single-train ammonia plants, 600 ton/day or more, in the United States. A few were also sent to operators of some lower pressure reformers. Approximately 90 questionnaires were distributed, of which 60 were filled in and returned. Fifty-five of them covered reformers in service at least two years. All exchanges of information were made on the stipulation that no company names would be divulged.

Table 1 updates information presented in the last 2 yr. Since the percentages given are not sensitive to causes and effects, they should not be extrapolated "to a grand conclusion" *(3)*. Such data are of little value except to show that the tubes do indeed have a finite remaining life, inexorably decreasing with operating time, and that most 4 year. old tubes still have some life in them.

Failure modes

Before breaking down the causes and effects of reformer tube failures, it is well to examine the three basic modes of failure shown in Table 2, which covers all of the reformers surveyed.

The survey results show that the first two modes are not normal in the industry as a whole, and should not be part of a statistical analysis of normal tube performance. They will therefore be discussed only briefly, to put them in perspective, before proceeding to a more intensive review of the most common failure mode.

Catastrophic oxidation

This popular term, as applied to reformer tubes, describes the corrosion mode of failure shown in Figure 1.

Table 1

Leaking tubes in reformers operating above 450 lb./sq. in. gauge.

Year	Source	No. of Reformers	Approx. Avg. Age	Total Tubes	Percent Leakers
1969	Zeis and Heinz (ref. 4)	32	2 yr.	8,966	0.27
1970	Salot (ref. 5)	16	3 yr.	5,082	0.67
1971	Salot	16*	4 yr.	5,082	1.28

*Same 16 reformers rechecked for comparison.

Table 2.

Relative frequency of three failure modes in reformer tubes

Failure Mode	Leaking Tubes	Reformers Involved
1. Rupture in areas thinned by corrosion (Figure 1)	11	2
2. Circumferential rupture through welds (Figures 2 and 3)	10	4
3. Longitudinal rupture through parent metal in absence of catastrophic oxidation (Figure 4)	352	29

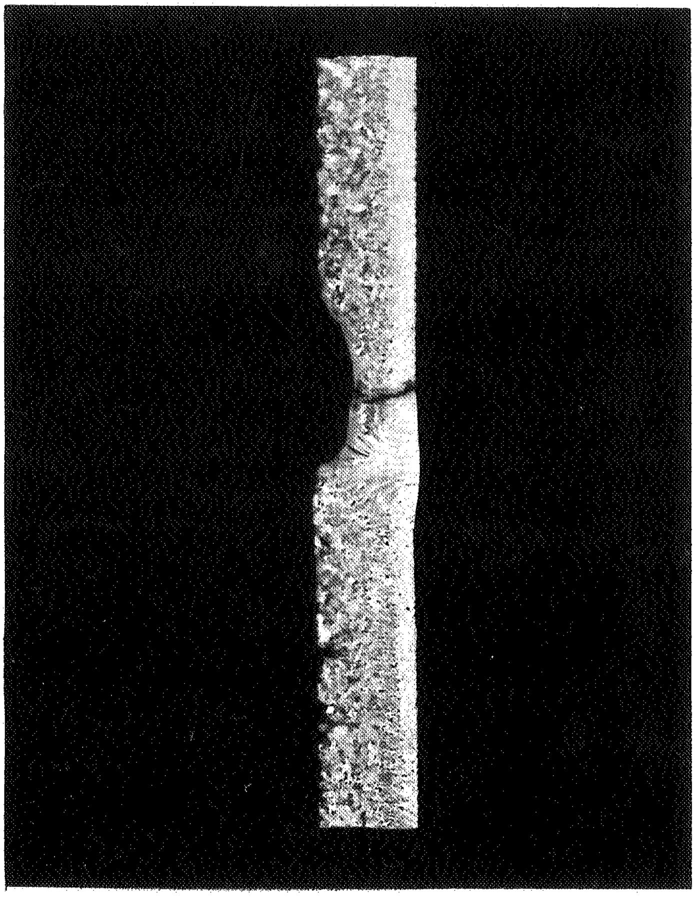


Figure 1. Rupture at Corroded Area

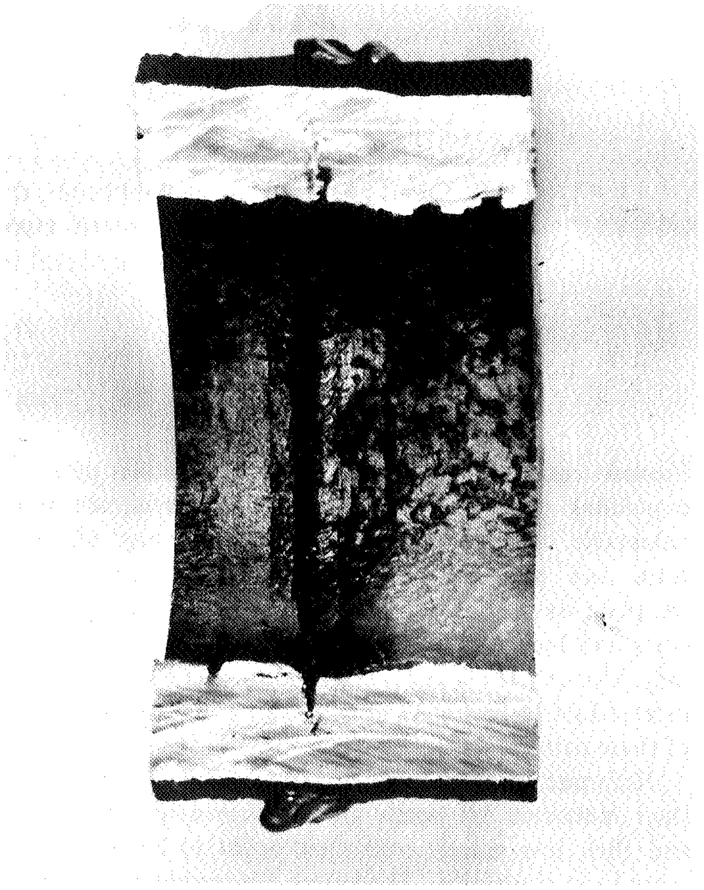


Figure 2. Circumferential Rupture Through Weld

It has been the subject of much published *(6)* and proprietary research during the past three years. Unfortunately, the results of this research cannot be reported here.

Although internal oxidation occurs to some extent in practically all reformer tubes, Table 2 indicates that catastrophic oxidation is a rare disease. Many believe that an abnormality in tube composition at the time of manufacture may have been the primary cause.

Since the oxidation product contains ferromagnetic material, eddy current methods of detecting large amounts of it have been used *(7)*. Such inspections are of little value until the malignancy has had time to grow. Even the most severe catastrophic oxidation required almost 2 yr. to progress to the point of failure.

External corrosion due to incomplete removal of welding slag, considered a problem in the early days of centrifugally cast reformer tubes *(8)*, seems to have been essentially eliminated by modern manufacturers. Only two of the thousands of tubes surveyed have been removed for this reason, and neither of them were leakers.

Weld cracking

Figure 2 shows the other rare mode of failure. Radiographic and borescope inspections during the past 2 yr. indicate that weld cracking is common near the flame in top-fired reformer tubes operating above 450 lb./sq. in. gauge. Table 3 shows these results:

Table 3

Weld cracking in top-fired reformers operating above 450 lb./sq. in. gauge.

Reformer	Approx.	%	% Tubes	%	Cracks in Service	
Age	Wall	Inspected	Cracked	Leaking	Number	*Time
2.0 yr.	1.07	20.6	38.5	0	18	4 mo.
2.7 yr.	1.00 in.	100	32.8	0	42	5 mo.
4-to 5 yr.	0.81 in.	–	–	1.02	–	–
3.8 yr.	0.80 in.	100	26.9	0	24	3 mo.
3.5 yr.	0.72 in.	100	19.3	0	46	12 mo.
4.2 yr.	0.64 in.	78.8	33.5	0.95	110	13 mo.
4.1 yr.	0.62 in.	80.8	12.1	0	36	12 mo.

*The cracks probably started long before they were observed.

It is remarkable that so many known cracks have existed so long without leakage. This very fact suggests that they tend to be self-relieving, as would be expected if they are caused by thermal stresses induced by temperature gradients through the wall thickness.

Such stresses increase with wall thickness, which seems to correlate well with the cracking percentages in Table 3. The lone exception is one of the reformers that experienced weld leaks. It is unique in two respects:

1. Alternate gas and oil firing has subjected it to many more thermal cycles than the average reformer.
2. The leaks were all in the area affected by a complete manifold separation which engulfed half a row of tubes in flames and starved one downstream row of its process flow.

Most side-wall fired and bottom-fired reformers have not been extensively inspected for weld cracking, although thermal stresses in them could be as severe as in top-fired reformers.

In top-supported tubes, tube weight also contributes to weld stresses, particularly in the very heavy wall tubes and when the weld must unintentionally carry part of the weight of an adjacent tube.

Figure 3 shows that the weld can rupture in the absence of significant bending stresses. This weld leaked for 10 days through less than 1/6 of its circumference, although over 90% of its cross-section had ruptured in almost perfectly symmetrical fashion.

Material deficiency is again a more contributing factor to such failures. The creep rupture strength of HK-40 welds has long been known to be inferior to that of equivalent parent metal. Weld metal with strength properties matching, or exceeding, those of the parent metal would be an obvious improvement, but the weld failure rate so far does not justify the experimental risk of adopting an untried weld metal.

Figure 3. Weld Fracture Without Significant Bending

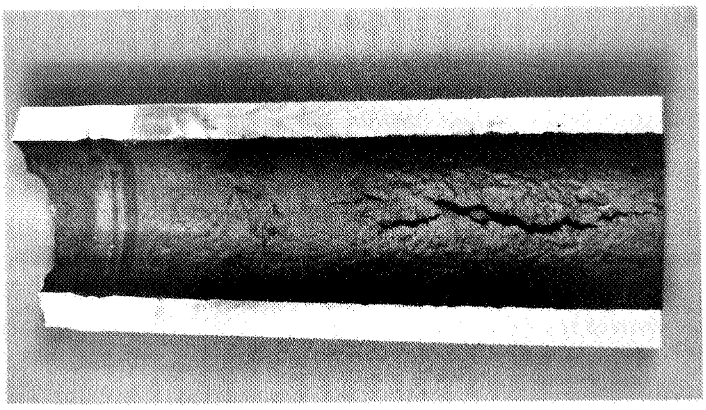


Figure 4. Longitudinal Rupture in Parent Metal Adjacent to Circumferential Weld Crack

Longitudinal splitting

Figure 4 shows the usual failure mode. The parent metal ruptured longitudinally and independent of a nearby circumferential weld crack, which may have been pre-existing.

A cross-section of the same rupture shows, in Figure 5, that families of subsurface cracks were concentrated in segments thinned by shrinkage voids on the inside surface. Where the cracks did not penetrate the inside surface they were not filled with oxide.

This type of failure is so common that several rough experiments can be run on the available statistics. The effects of many variables can be checked against the relative performance of many reformers.

First, a simple method of measuring reformer tube performance must be devised. It must be based on equivalent service time, but must not include abnormal failures, such as by catastrophic oxidation, weld cracking, casting defects, or extreme abuse. Table 4 shows that most of the reformers surveyed have been in service less than 5 yr., experienced very few leaks of a "normal" nature (Mode 3) during the first 2 yr. and seldom have had non-leaking tubes removed.

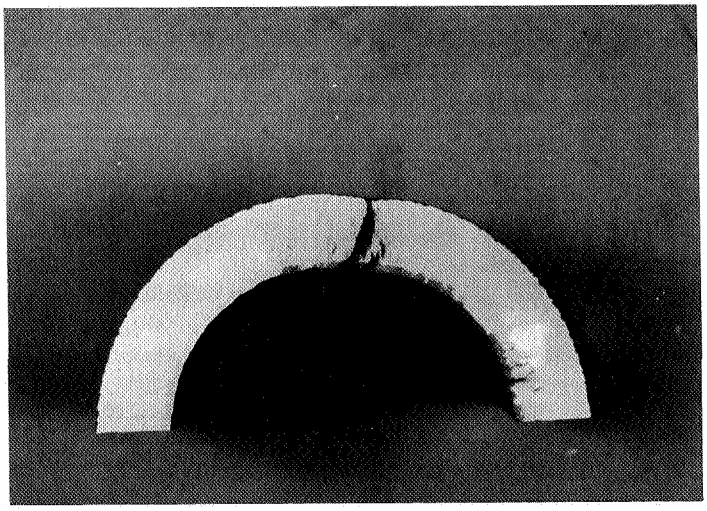


Figure 5. Cross-Section of Rupture in Figure 4

Table 4

Effects of service time

Reformers	After Years of Service 2	3	4	5	6+
Total surveyed	55	45	39	18	9
Percentage with leaks by Mode 3 failure*	14%	38%	51%	56%	78%
Percentage with non-leakers removed to prevent Mode 3 failure*	5%	16%	23%	0%	44%
Percentage completely retubed due to Mode 3 failure*	2%	4%	0%	0%	0%

*Longitudinal rupture through parent metal in the absence of catastrophic oxidation.

After soul-searching the data, the service time of 3-1/2 yr. was arbitrarily chosen as the standard of comparison because it resulted in a near equal sampling of different reformer designs. A longer or shorter time standard would produce similar conclusions, but are heavily influenced by one design or another.

A reasonable measure of the performance of a reformer is therefore the number of tube leaks it has suffered by Mode 3 during its first 3-1/2 yr. By means of "Lating Square" diagrams *(9)*, this performance may be checked for possible correlation with the variables surveyed. Table 5 is a statistically significant example.

The pressure variable

The fact that in Table 5, the sum of the numbers on one diagonal (12 + 16) far exceeds the sum on the other diagonal (11 + 2) indicates a good corelation between performance and pressure. This is no surprise to old timers who have long claimed that tube failures in their older, lower pressure reformers were less frequent than in newer, higher pressure ones. Table 4 also suggests lower failure rates in older reformers.

An interesting survey sidelight is that catalyst performance also correlates well with pressure, the average catalyst life being over 3 yr. in reformers operating in the 200- to 350 lb./sq. in. gauge, but less than 1-1/2 yr. in reformers operating above 400 lb./sq. in. gauge.

Table 5

Effects of pressure

Inlet Pressure, lb./sq. in. gauge	Number of Reformers *Superior Performance	**Inferior Performance
400-525	11	16
200-325	12	2

*No leaks by Mode 3 in the first 3-1/2 yr.
**One or more leaks by Mode 3 in first 3-1/2 yr.

It should be emphasized that high pressure in itself is not significantly harmful to either the tubes or the catalyst. Its most important effect is that it works against the reforming reaction. For successful reforming the laws of chemistry require pressure increase to be counterbalanced by one or more additional changes favoring the reaction. Such changes include increasing heat flux, increasing heat transfer area, decreasing space velocity, increasing steam/gas ratio, and increasing catalyst volume. The specifics are in the realm of proprietary design information and differ among the different designers, who are understandably sensitive about the possibility that such information might be used in unfair criticism.

The following observation is, therefore, particularly important. The correlations of both tube and catalyst performance with pressure was true for every design covered by both low and high pressure survey data. Inferior tube performance in high pressure reformers is a penalty, but it is not justification for avoiding the overwhelming advantages associated with high pressure reforming processes.

Assuming the generalization is true in spite of proprietary design differences, then either reformer designers and operators must have become much less conservative as a group during their advance to higher pressures, or there is another pressure-related variable affecting tube performance, or both. Leaving the question of conservatism open to conjecture, let us proceed to the most obvious pressure-related variable of all, wall thickness.

The wall thickness variable

As would be expected from its proportionality to pressure, heavy walls correlated with inferior performance. Wall thickness is proportional to diameter and inversely to design stress, the latter being especially sensitive to temperature, all of which similarly correlate with tube performance. Which of them is the chief culprit?

Temperature is the usual scapegoat because many leaks have developed in tubes known to be overheated, and because creep strength plummets in the face of excessive temperature. Wall thickness is also important because, along with the temperature gradient through the wall, it affects the severity of each thermal stress cycle. Thermal cycling is recognized as harmful because many leaks have been found during or immediately after a shutdown/start-up cycle, Table 9.

Overheating and thermal cycling are mutually contradictory insofar as one favors increasing wall thickness and the other favors decreasing it. This may explain why, of the three completely retubed reformers covered, two went to thicker and the other to thinner walls.

Available information on temperature histories is weak. Some operators consider it proprietary, while the records of others are frequently not in sufficient detail. The limited accuracy of tube temperature measuring techniques *(10)* is another shortcoming. Even if typical and maximum tube metal temperatures were accturately known, they would have to be related to proprietary design temperatures.

Despite these obstacles, one perhaps meaningful correlation was found as follows: one group of reformers, all over 4 yr. old and built to the same design, was found to have tubes manufactured to identical inside diameter and minimum sound wall specifications. They obviously were intended for operation at essentially the same temperature. Operator estimates of typical and maximum temperatures agreed. Survey data showed outside diameter variations of up to 1/8 in. from reformers within this group. These variations are believed to be real because they correlate with specific tube manufacturers, who may have differed on the thickness allowance necessary to account for shrinkage voids on the inside. Assuming they reflect real variations in sound wall thickness, they combined with minor reported pressure differences to produce hoop stress variations exceeding 200 lb./sq. in. gauge. If so, a full-scale, long-term test on the effects of pressure stress vs. wall thickness has already been run.

The results in Table 6 show that thickness variations correlated with tube performance better than did the hoop stress variations. If this is significant, then either:

1. The heavier wall was detrimental under the specific operating conditions of these reformers. (Table 3 has previously shown a similar trend with respect to weld cracking). or,
2. There was, in years past, a significant difference in tube quality between tube manufacturers. (No such correlation was found with tube performance in other reformers of various ages).

The evidence pointing to a thickness problem is only suggestive and by no means conclusive. By the time existing younger reformers with thicker tubes are old enough to compare with those in Table 6, experience with new techniques for analyzing cyclic thermal stresses may clear up some of the unknowns.

Like temperature histories, thermal cycle histories are also limited by proprietary restrictions and incomplete records. The sparse data did show a fair correlation with shutdown frequency, and an even better correlation with frequency of feed gas trip-outs at operating temperature, sometimes called "crashdowns", but it was not sufficient to show more than a faint thickness effect.

Table 6

Effects of thickness and pressure stress

Variable for a Specific Reformer Design	Number of Reformers *Superior Performance	**Inferior Performance
Total Thickness		
Above Average	2	5
Below Average	5	2
Pressure Stress***		
Above Average	4	4
Below Average	3	3

*No leaks by Mode 3 in first 4 yr.
**One or more leaks by Mode 3 in first 4 yr.
***Assumes equal depths of unsoundness

One reformer with a history of dozens of in-run fuel switching cycles, and another with a history of flame-outs were not among the better reformer performers, Figure 6.

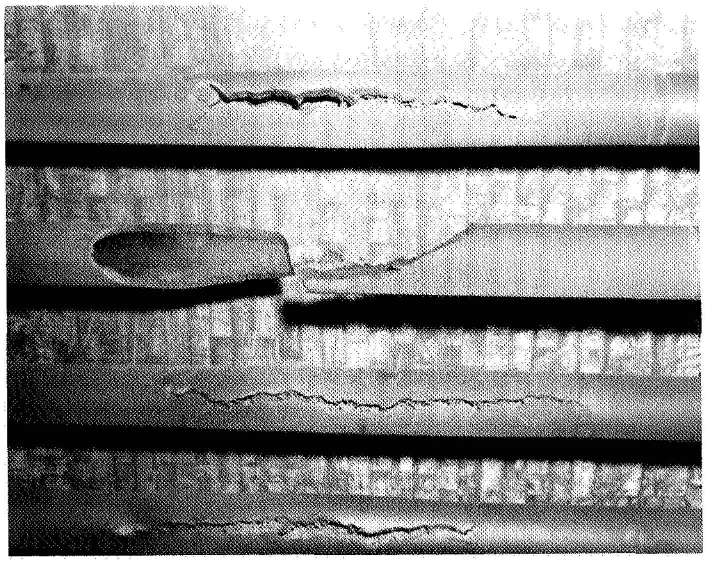


Figure 6. Reformer Tubes Shortly after a Series of Flame-outs

The temperature variable

Temperature is a pressure-related variable in those designs where increased pressures have been compensated by increased catalyst temperatures. It affects both the design point for the time-temperature parameter and the life of the catalyst. Even so, by itself, temperature does not provide a convincing explanation for the inferior tube performance of high-pressure reformers. There is no evidence to suggest that the time-temperature parameters used in design are significantly in error for the temperatures involved. Catalyst life for a given design should not affect the total time spent at any particular tube temperature. Although typical tube temperature and overtemperature limits reported by the operators varied widely, they did not correlate with tube performance at any given pressure.

Temperature becomes more significant in cases of maloperation where specified temperature limits are exceeded. Such overheating, like bad weather, is easy to discuss, but hard to control. If severe enough, as when process flow is stopped at full pressure, it can render all other tube performance factors insignificant. It has caused new tubes to fail in a few months, and entire reformers to be retubed after only a few years of service. The degree of control in startup and early operation, when tube metal temperatures may not have been adequately monitored, can influence overall tube performance considerably. Problems affecting temperature control include:

1. A phenomenon, apparently peculiar to some, but not all, high-pressure reformers, has been dubbed "hot bands". It involves the simultaneous development of hot areas in

many or all tubes, beginning sharply at a surprisingly uniform elevation near the top of the tubes involved and growing downward. They frequently begin three to six months after the catalyst is charged, and are only temporarily relieved by steaming. The cause is believed to be internal to the tubes, and much catalyst experimentation has resulted. While the survey did not cover this point in detail, it is clear that many reformer operators reporting extensive hot band experience have also been saddled with inferior tube performance, Table 8.

2. In multi-row reformers, where some tube rows are not close to a radiant wall, the rows may not be heated equally. Table 7 shows some clear-cut results.

Process variables

It was hoped that some process variables could be analyzed, but the survey data was not sufficint to establish any correlations. The reputedly more severe service conditions in hydrogen plant reformers was not ocnfirmed. Limited data suggests that they perform as well as ammonia plant reformers of comparable pressure.

Eight of the 12 reformers using naphtha experienced inferior tube performance. The ratio was lower for reformers using only natural gas, or refinery gas. No effect was noticeable for methane contents varying from 82- to 95% in the natural gas. For comparable pressures and tube dimensions, no correlation was found between tube life and tube manufacturer, reformer designer, reformer location, number of tubes, or type of firing.

Since reformer tubes are designed from creep data, they are designed for a finite life. The data suggest a likelihood that tube leaks will be by Mode 3, beginning after 2 yr. for high-pressure reformers, and after 4 yr. for medium-pressure reformers.

In the initial period before the first leak appears, it is important to minimize the severity of thermal cycles and high temperatures, keep records on each, and change catalyst when overtemperature limits are approached. After a reasonable time, an eddy current survey to check for possible catastrophic oxidation of the tubes may be justified.

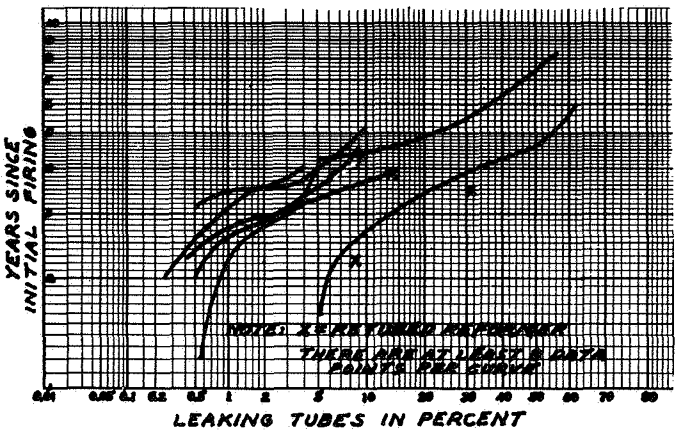


Table 7

Effects of radiant walls in 13 multi-row reformers*

Variable	Outer Rows	Inner Rows
No. of leaks by Mode 3	118	85
No. of tubes involved	987	2253
Leak percentage	12.0	3.8

*From 4 to 10 rows.

As the tubes get older, the importance of leak detection increases. Methods used include:

1. Frequent observation through peepholes during operation, occasionally facilitated by introduction of sodium carbonate or other powdery material at the burner air inlets.
2. Close-up visual inspection during shutdowns, occasionally facilitated by liquid penetrants or ultrasonic leak detectors.

The desired goal of reliably detecting serious tube damage prior to leakage may never be achieved. Methods

The desired goal of reliably detecting serious tube damage prior to leakage may never be achieved. Methods attempted include:

1. Determining suspicious areas by measuring outside diameters or circumferences, or by eddy current inspection, then radiographing the suspicious areas.
2. Borescoping during catalyst changes.

The biggest inspection problem involves time. Seldom is tube inspection permitted to increase the length of a shutdown. In large reformers, it must usually be concentrated in areas believed to have suffered most. Detailed operating temperature records, including periodic color photography, will sometimes narrow these areas.

The first leak, if well analyzed, will frequently tell more about the reformer than all of its pre-leak inspections did. The leak itself casts suspicion on firing, draft, and radiation patterns in that part of the firebox, and suggests potential trouble in nearby tubes, even among those not facing the initial leak. Its elevation and angular orientation, with respect to the burners and to radiant refractory, say much about the cause of failure. Failures in group patterns have been observed despite the wide scatter band of creep rupture times for material within specified composition limits. Table 8 shows an inconsistency of leakage elevations in top-fired reformers. A possible explanation is that leaks near the top were strongly influenced by thermal cycling or hot bands, while those near the bottom developed from high average metal temperatures independent of hot bands.

The survey data confirms that most leaking tubes are removed, rather than repaired. Various destructive tests can be made on the removed tube, but interpreting them commonly results in disagreement.

1. Short-time creep-rupture tests are frequently run on apparently sound used tube sections at locations far from

Table 8

Leakage elevations in 12 top-fired reformers.

Leaks by Mode 3 in Top 1/3	18 –	(15)
Leaks by Mode 3 in Middle 1/3	12 –	(4)
Leaks by Mode 3 in Bottom 1/3	16 –	(6)
Total Leaks	46 –	(25)

Note: Numbers in parentheses represent leaks in three reformers with extensive "hot band" experience.

any leak. It is common for them to fail in only about one-third the average time required by new material, thus prompting disconcerting predictions that two-thirds of the life in remaining tubes have been used up. At least three reformers have outlived such predictions. Possible explanations are long-time strengthening mechanisms in the material, decreasing frequency or severity of first stage creep cycles, and scatter in creep data.

2. Microstructural examination of used tubes frequently leads to temperature history estimates *(11)*. When they differ with operating records, it is usually with respect to the time factor. Such differences are hard to resolve.

3. Secondary creep cracks are a measure of tube material uniformity. Figure 4 shows such non-uniformity, although not as severe as is sometimes observed. It is not an accepted defect criterion.

Replacement

Inspection or failure analysis may suggest delaying tactics, but eventually the prospect of accelerating tube failures demands that a replacement program be given serious consideration. Even small reformers designed for convenient replacement of individual tubes are known to have required massive retubing to control runaway rates of tube failure.

So, perhaps the most important anticipatory action that can be taken is to plant a tube replacement program to cover the "when" and "how" details for all foreseeable circumstances. It should balance the benefits and risks of commiting too early, too late, too much, and too little.

Much depends on whether tube failures cause production losses. Table 9 relates tube failures and shutdowns in large reformers, where production losses are potentially greatest. Reformers which practice "pigtail nipping" *(12)* are not included.

It is clear that either many leaks are not discovered in service or there is a widespread willingness to temporarily operate with leaking tubes. In either case, production losses may not be as great as one might otherwise assume.

Table 9

Tube leaks and shutdowns in 11 large reformers having over 200 tubes each

Total tube leaks not blanked in service	96
Shutdowns involving tube removal	47
Shutdowns caused by tube leaks	26

Another important factor affecting tube replacement decisions is the failure history of the individual reformer involved. Figure 7 shows all individual reformer histories on which at least eight data points are available. They cover four different manufacturers, five differing pressures, and six different reformer sizes; yet the histories, plotted on logarithmic- probability coordinates show distinct similarities. An incubation period of varying length seems to precede the first leak. In six of the seven cases the first leak seemed premature relative to subsequent leaks. After a series of leaks, near parallel trends develop. The concave downward portions of the curves suggest that operating conditions may have improved with time. In none of these cases were many additional tubes replaced prior to leakage.

Among the reformers surveyed, failure histories of those that were completely retubed tended to fall below and to the right of the curves on Figure 7. Conversely, many of the longer-lived reformers are performing above and to the left of those curves.

Another key question is when to completely retube or replace all remaining original tubes. This has been done in two reformers before 15% of their tubes had leaked, but two reformers, covered by Figure 7 have replaced over 50% of their tubes on an individual basis with apparently no reason to change the practice in the future. Decisions on timing massive tube replacements are probably affected by several factors, including reformer size and design.

When tube replacement becomes necessary, should tube specifications be modified? The answer may vary, depending on tube availability and whether individual or massive replacements are contemplated. Some of the modifications being tried include increasing carbon content and boring the inside surface. Nine reformers with bored tubes were included in the survey, most of which were too young to establish any trend. Five of them, all in naphtha service, had tube leaks in less than 2 yr. One of the less recognized considerations involving tube specifications is tube weight. It can vary widely, within usual manufacturing limits, upsetting counterweight or spring support settings when tubes are replaced.

Conclusions

1. Although a rigorous statistical analysis for clearly defining significant factors was not possible, this survey supported a number of conclusions:

2. Longitudinal rupture through parent metal in the absence of catastrophic oxidation is by far the most common mode of failure, Table 2. Although weld cracks have been found in many reformers, they seldom propagate to the point of leakage, Table 3.

3. The superior lives of tubes, Table 5, and of catalyst in lower pressure reformers were confirmed by the data. The former may be partially explained by the influence of thickness, Table 6, on thermal stresses.

4. There was evidence that thermal cycling from various causes is extremely detrimental, Figure 6.

5. Overheating, if severe enough, can override all other

factors. Successful control depends on conscientious adjustment of burners for uniform tube metal temperatures throughout the furnace. It is seriously affected by a phenomenon called hot bands, and by radiant wall effects, both of which have contributed to numerous tube failures, Tables 7 and 8.

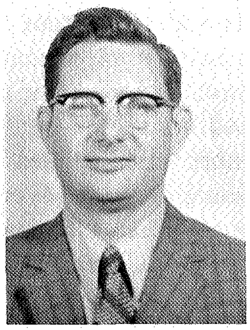
6. Limited data on process variables suggests that naphtha may cause more problems than natural gas.

7. Actions that are taken to anticipate tube failures include inspection and post-mortem failure analysis, by a variety of techniques, and development of replacement programs. Replacement programs are affected by shutdowns resulting from tube failures, Table 9, applicable tube failure histories, timing and procedural requirements, and replacement tube modifications. Tube failure histories, Figure 7 have some common characteristics, even under diverse conditions.

8. Continued cooperation among researchers, designers, tube manufacturers, and reformer operators is recommended.

Acknowledgement

Broadly speaking, one of the best actions possible to take on reformer tube problems is to fully use all technical lines of communication between researchs, designers, manufacturers, and operators, many of whom have anonymously contributed to this article. #



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DISCUSSION

S. ORSINI: Orsini, Montedison, Italia. I am very glad of this work. It's a very complete work about all the tube failures, a big part of furnace problems. I have just two questions. My plant is interested to know if there is another reason for the cracks in the welding, are they just in the root pass or not, from what you know? This is important. And the second point is as far as you know, when such plants have suffered parent metal cracks, and someone has thought to make x-ray checks on the welds, have they seen something of some initial crack in these welds or not?

SALOT: I understand the first question is, "Do they start in the root bead?" I think probably not. This is based on some information from one of the organizations covered by Table 3. They found many welds cracks by single wall radiography — a relatively sensitive method of inspection. When they removed and sectioned a number of tubes, they found that the cracks had not penetrated to either the outside or the inside surface. In other words, they were subsurface in origin. I imagine that is the way both weld cracking and parent metal cracking starts.

ORSINI: Well, but, it is very different if the crack begins from inside at the first pass of the welding, because it may be in the region of a defect when the tube was installed. I don't know if I am clear in what I am saying.

SALOT: Spot radiography of new tubes suggests that initial defects are rare.

ORSINI: Well, in the plants in which they have suffered longitudinal leaks in the parent metal, have there been some who have made radiography on the welds of the tube? If so, are there present some cracks on the welds or not? Do you know this point?

SALOT: I know of several reformers in which non-leaking weld cracks were found in tubes which had been removed because of parent metal leakage. Figure 4 shows one.

ORSINI: Now the point is this one: in the moment at which has been seen that there has been present also cracks in the welding itself, this could modify the statistical numbers you have shown.

SALOT: No, Table 2 included only leaks, and no tube leaked by more than one mode. The weld cracks reported in Table 3 were all found in the furnace and did not include weld cracks that may have been found in tubes that had previously, been removed.

L.A. ZEIS, M.W. Kellogg Co.: First we'd like to compliment Mr. Salot on the paper he has presented. The data will prove valuable to users and to designers of furnaces. With regard to the degree of conservatism in design of higher pressure reformers, our design was based on the experience with lower pressure minimum cast wall tubes. Our conservatism in design was to apply a 75% factor to the average stress for rupture in 100,000 hours. This factor allows for variations in castings and results in a design stress equal to the minimum stress for rupture in 100,000 hours. We feel this is more conservative than design for a stress equal to 100% of the average 100,000 hour rupture stress, which value is used in other designs.

Further, the design temperature was based on a mathematical model, and as design pressures were increased, the data from this model was verified by field measurements on six operating plants as well as on a pilot plant operation.

Although thermal stresses due to a given heat flux will be higher in thick walled tubes, there is no method to satisfactorily evaluate the effect on tube life of the increase in thermal stress.

In Table 8, there was no clear indication that the hot band effect has caused tube failures, although it is expected that higher temperatures will lower tube life.

In Table 7, the hot wall effects could have been eliminated by burner adjustment. This is one example of operator controlled variables which cannot be weighed in a statistical survey.

Finally, a question. In your survey of eleven identical furnaces in which one group had tubes 1/16" thick wall than the other you pointed out that superior performance corelates with the thinner wall. Since the thinner wall tubes were all from one manufacturer and the thicker wall tubes from another, could it not be said that the superior performance correlates with the manufacturer?

SALOT: There is no overall correlation with tube manufacturer. The manufacturer in the case of those reformers, who unfortunately chose the greater thickness got stuck with the wrong end of that particular correlation. But he also made tubes for many other reformers. Based on the larger numerical sample, there was no consistent difference in performance between tubes of different manufacturers at any given pressure level.

I'd also like to defend my Table 8. Table 8 is the one where you didn't see a clear indication of hot bands promoting tube failures. Table 8 covered 12 top-fired reformers on which leakage elevations were known. Included were 3 that had extensive hot band experience. These 3 accounted for most of the failures in the top 1/3 of the tube where hot bands are observed. That's why I think the hot bands were detrimental.

TONY TUCKER, African Explosives: I might answer one of Mr. Orsini's questions, that we are almost convinced our weld cracks start right at the edge of the root bead. That I think I showed in may paper yesterday.

SALOT: May I comment on that before I forget it, and then we'll come back to your next point. I remember the slides you showed yesterday. They showed some misalignments in at least some of the welds, which could cause the cracks to start there in the re-entrant angle at the edge of the root bead. Most of the welds that I've seen have been much better profiled than that, including the ones that have been found with subsurface cracks.

TUCKER: The one I passed around the audience yesterday had a very good profile.

SALOT: Yes, but that one had a very deep crack, and you could not say that it did not start subsurface and grow both ways.

E.E. OWEN, Humphreys and Glasgow Ltd., London: The previous speaker suggested the possibility of reducing firing on the outer rows of burners on a multi row furnace. We have conducted experiments early this year on a large ammonia unit in W. Germany which has demonstrated clearly that this is not the best approach. If firing to outer rows is reduced, and assuming that the furnace is operated at the same overall throughput, more heat must be applied through the inner rows of burners with the result that the tubes in the inner rows run hotter.

At the Design stage we arrange to increase the flow of reactants per tube to those tubes in outer rows. This extra flow absorbs more heat, thus applying additional cooling as opposed to reduced heating to these tubes. All burners are fired at the same heat duty. Extensive temperature measurements have shown that using this approach an extremely low tube temperature scatter is attained, which was not attainable when adjustments were made to individual burners.

RON MOORHEAD, Duraloy Co.: I have one question that stems from Tony Tucker's paper yesterday and yours today regarding the top weld cracking, the hot banding and the top firing of the furnaces. There seems to be a very definite correlation there. In your paper you said that there has not been very much work done on side or bottom fired furnaces, and I am wondering if this data might be picked up to determine if the first weld up in a bottom fired furnace cracks before the other welds, in a similar fashion as the top weld failed in top fired furnaces.

SALOT: I don't know of any side or bottom fired furnace that has been massively inspected for weld cracks in the tubes. I wish there were for comparison, but the fact that they haven't leads me to believe that you can't condemn top firing for the weld cracking until you prove that side firing or bottom firing avoids it.

MOORHEAD: That's what I was wondering. Also you mention in your paper that there were one or two other suppliers who had gone to a lower strength welding rod and I am curious to know which one it was. You did not say whether it was Inco 182 or A, or the HK-40 electrodes.

ESCHENBRENNER, M.W. Kellogg Co.: I believe that your paper refers to the fact that only recently, as a result of new research efforts, has it become apparent that normal welds in HK-40 material have a substantially lower strength than the base material. This comes as a kind of surprise since normally you assume that weld strength is or should be at least as strong as the base material. I believe there are developments underway to correct this deficiency.

SALOT: Yes. Obviously there is more than just the thermal stresses involved. But if we were to say it's only the pressure stresses, then that would only explain the failures at the bottom where the metal is generally hotter because of the gas being hotter, but what would explain the failures at the top and middle? I think there's a combination of the two forces working. Here are two examples: We know of a lot of tubes that have failed because of overheating, because they had a known history of high temperatures. Simple creep rupture from pressure stresses could explain them. On the other hand, there are a lot of other failures that have been found during or immediately after shutdown, and most probably were caused by the shutdown or startup cycle. They could best be explained by cyclic thermal stresses. Apparently neither mechanism predominates in all cases. I think each bit of information that I used to bring up the subject of thermal stresses, is vulnerable to some criticism. The only thing that leads me to believe that thermal stresses are perhaps more important than we thought before is that there are so many bits of information pointing to the same conclusion, but none of them is really rigorous.

MALCOLM CLARK, Lummus: May I address myself to this question? A number of people have been fooling around trying to definitively calculate the stress – time – temperature relationship at the high temperature conditions we have in these tubes. The analysis has indicated that the thermal gradient across the tubing as well as longitudinally in the tube should have more of an influence than it appears to exert. One can, by using figures on a paper or in a computer program, demonstrate that the differential thermal conditions that exist in these tubes are indeed in the position of putting a higher strain on the tube metallurgy and putting it more rapidly into a failure mode than the hoop stress which is calculated by the conventional hoop stress methods.

This information that Salot has turned up has been one of the first definite indications from the field that we may indeed be looking at this phenomenon. Now the problem is how do you plug this into a design calculation? This is the subject, of course, of another symposium. When you look at the thermal differentials, you find, as one gentlemen said, the top of the tube has the greater thermal differential, and therefore you would expect that the thermal stress would be greater. The stress, indeed, is greater at the top than it is down at the bottom of the tube. However, it really is not the stress per se that is going to do the damage, but it is the stress-strain relationship at the temperature of your metal. The further you get down in the tube, the less thermal stress or thermal differential can the tube metal take since it gets hotter as you go down the tube.

As far as the weld materials are concerned, surprise was expressed that we are in a situation where we are just developing weld materials that have the same strength as the cast materials because conventionally you use a weld material that is of the same strength as the parent material. I think that one has to look very carefully at what we are talking about as far as strength is concerned. Larry Zeis very quickly passed over the little comment that said we're using a certain percentage of the stress to produce rupture in 100,000 hours. Now this comment should not be taken lightly because this is an entirely different strength that we're talking about than the conventional short time strength which is normally what is considered when you are matching the weld material to the weldment. There's a lot that we don't actually know because some of these weldment tests have not been run out long enough to really get good correlation with the parent material.

JOHN LIVINGSTONE, ICI, Billingham, England: I would like to just comment now on this question of the hot band correlation. I mentioned this morning that we do not have hot bands, and have not had hot bands, but nevertheless most of our leaks in the tube have been in this top weld. In the vicinity of this hot weld we have, particularly on naptha fire – naptha feed stock, found evidence of disproportionation of hydrocarbons leading to restriction of flow in that tube, and that is obviously the really hot spot in that tube.

I would just like to ask if it's possible to break down a bit further some of the figures you've gotten there considering lower welds that have failed, whether or not these are in tubes that did actually have the hot band and whether or not some of the tubes that had failed at the bottom weld were perhaps hotter because of the operating people fired tunnel burners.

SALOT: I don't think that any of the lower HK-40 to HK-40 welds have failed to the point of leakage in top-fired reformers. Only two of the reformers covered in Table 3 had extensive hot bands. Both of them had relatively few welds cracks, percentagewise, and no weld leaks.