High Pressure Reformer Tube Operating Problems

A summary of useful data that has been developed in the five-year-old Reformer Information Network shows major problems encountered and how they are being handled.

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Useful operating information has been developed from the high-pressure reformer data developed in the 16-company Reformer Information Network. (*1*) Now in its fifth year, this group of 16 member firms, covering 21 ammonia plant reformers, has provided much of the data for this article.

To shutdown a large, high-pressure, single-train, ammonia plant has always been costly in terms of production losses, fuel consumption, and equipment damage. Today's expanding ammonia market, declining fuel supplies, and aging plants are magnifying these problems. Nowhere is this more evident than in the primary reformer where the most fuel is consumed, the most severe shutdown/startup transients prevail, and pressure-containing components operate in the creep-range with limited life even under the best of conditions.

When a large primary reformer is shutdown, the entire plant goes down, and total dollar losses commonly reach into the 6-figure range.

By their sheer numbers, a small percentage of the many catalyst tubes in a large reformer can cause frequent shutdowns. Complete tube replacement can take several weeks. In self-defense, after several premature tube failures, a group of operating companies formed the Reformer Information Network. (*1*)

A 1971 survey (*2*), and a 1972 update, (*3*) left unanswered questions on the performance to be expected of reformer tubes. Some are answered here by pure hindsight, while others will be debated for years to come. The 1971 survey, covering a wide variety of steam-methane reformers, established that high-pressures correlated with relatively poor tube performance. The 1972 update, concentrating on high-pressure reformers, established that plots on arithmetic vs. normal probability coordinates were effective tools for evaluating tube performance.

Newer trends revealed by latest experience

This article uses the same graphical method of evaluation plus more recent HK-40 tube performance data on the 21 oldest, top-fired, high-pressure, steam-methane reformers, all with tubes having approximately the same inside diameter. It covers all 13 first-generation reformers, each over seven years old, and the eight oldest second-generation reformers, each over five years old. It will show the following trends that were not apparent in previous investigations:

1. Tube life improvements have been accomplished in most of these reformers without complete tube replacement.
2. The projected-average tube life of the group has increased substantially since 1972.
3. For the same projected-average life at comparable stresses, creep-rupture specimens must be heated far above the original design temperatures of the tubes in these reformers.
4. Failure scatter bands for both tubes and creep-rupture specimens have roughly the same width on the time scale.
5. Slight increases in tube wall thickness, above that provided in the first-generation reformers, no longer appears detrimental. However, an optimum thickness may nevertheless exist.
6. Replacement tube specifications adopted for these reformers cover a variety of changes in thickness, materials, and other requirements.
7. These reformers are being completely retubed when most of their tubes still have many years remaining life.

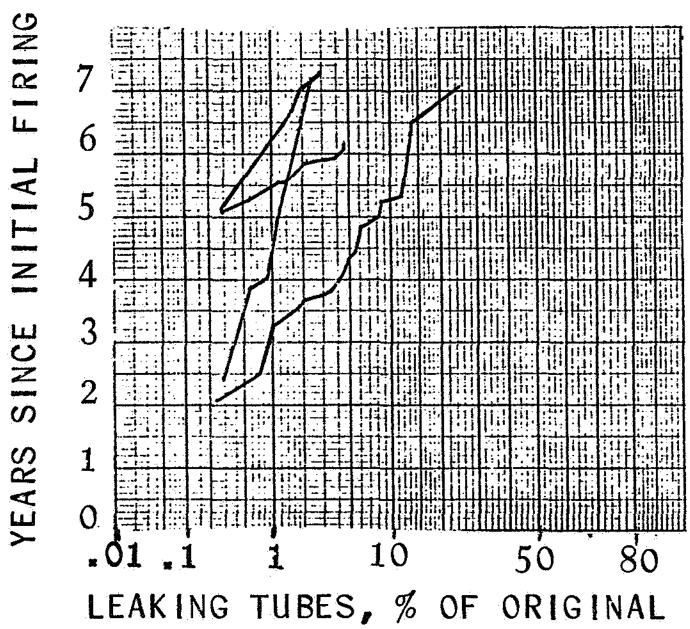

Figure 1. Normal probability tube performance—four reformers.

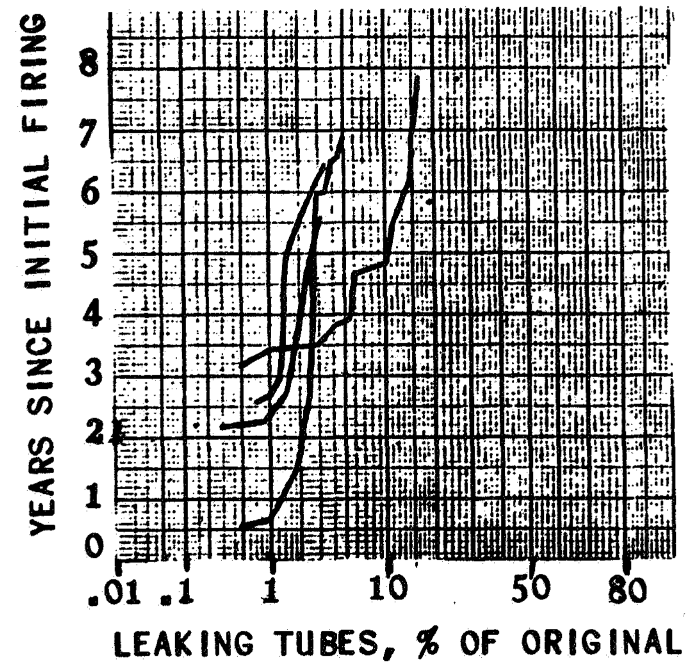

Figure 2. Improved tube performance—four first-generation reformers.

Tube life shows good improvement

When time vs. tube failure percentage plots as a reasonably straight line on arithmetic vs. normal probability coordinates, the failures are following normal probability. Examples for several top-fired, high-pressure reformers are shown in Figure 1. These lines may be extrapolated to predict future failures under the same operating conditions. The higher and steeper lines denote better performance than the lower and flatter lines. Differences in individual tube metal heats have practically no overall effect because each line represents more than 100 heats. It is assumed that tubes removed before they fail would have failed in proportion to the tubes left in service.

Unlike Figure 1, a majority of the tube performance lines plotted have a definite upward bend. Examples are shown in Figure 2. The upward changes in slope document distinct improvements in performance, most of which can be traced directly to closer control of tube metal temperatures or more effective inspection programs.

The cases in Figure 2 involved the following real problems and remedies:

1. One reformer experienced upsets which backed up catalyst into the inlet header. This restricted flow through some inlet pigtails, which caused severe overheating and premature failure of several tubes. Removing the catalyst from the inlet header and pigtails, and avoiding the backflow condition sharply reduced the tube failure rate. Perforated shields are incorporated in some replacement tubes to prevent catalyst blowback.

2. A second reformer was operated too long without changing damaged catalyst. A massive catalyst change followed by conservative operation produced a drastic improvement in tube performance.

3. A third reformer suffered early failures because many of its tubes were susceptible to catastrophic oxidation. An eddy current inspection instrument was developed to identify and monitor affected areas. Many damaged tubes were thereby removed before they failed, thus upturning the tube performance line.

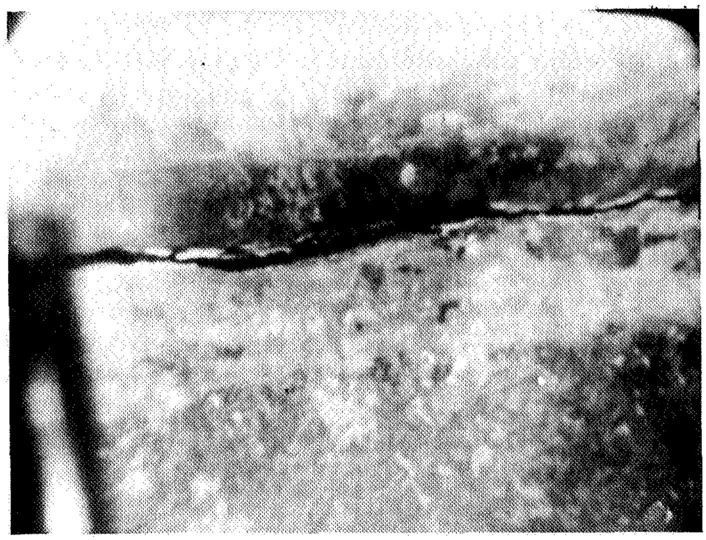

Figure 3. TV view of non-leaking weld root crack.

4. Another reformer proved susceptible to weld leaks. Using a borescope and later television inspection of the weld roots, many severely cracked tubes were removed before they failed. As in the above cases, results were clearly beneficial. Figure 3 shows a wide, non-leaking weld root crack, as depicted on the television screen during field inspection. It led to removal of the tube, as did many other similarly detected cracks in this reformer. One obvious protective measure being used in a few reformers is to insulate the vulnerable welds.

Consider the 13 first-generation reformers. Their 3,906 original tubes were all as-cast HK-40, designed to the same nominal inside diameter and minimum sound wall thickness. As of April, 1974, a total of 174 of them, including at least one in every reformer, had leaked. In addition, 2,099 of them, including at least one in every reformer, had been replaced before leakage.

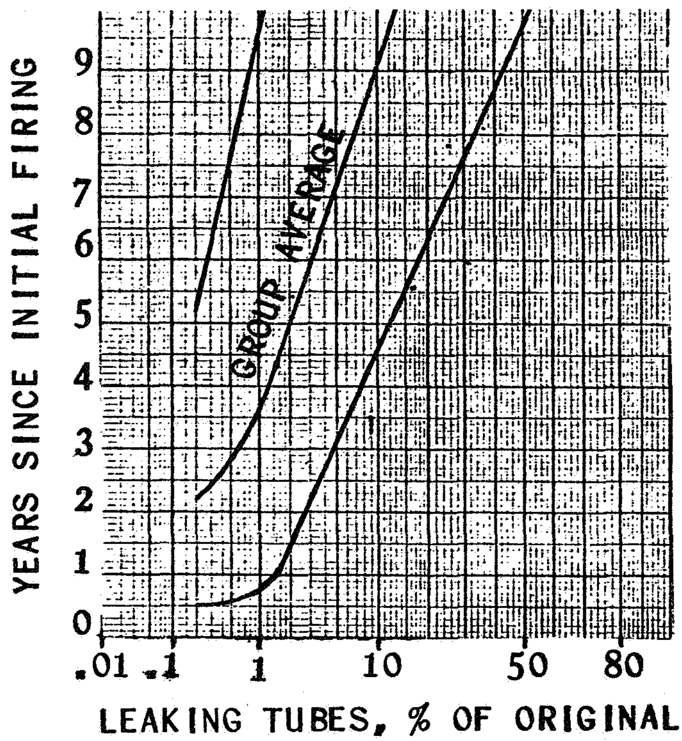

Figure 4. First-generation group average tube performance and scatter band.

The data, plotted individually for the 13 reformers, fall entirely within the scatter band in Figure 4. Plotting them as a whole, the same data result in the group-average performance line shown approximately bisecting that scatter band. Note that the scatter band spans slightly more than an order of magnitude on the time scale; for example, one percent of the tubes may leak in anywhere from 0.8 to 9.7 yr.

Data are useful for comparisons

Because Figure 4 is based on a 100% sample of almost 2,000 HK-40 heats operated under nominally identical conditions, it provides a fairly accurate basis for extrapolations and comparisons. For example, extrapolating the group-average tube performance line to 50% failure suggests an average tube life of 16 yr. could be realized if the tubes were left in service. Previous estimates were much lower because they did not recognize that many early tube performances were improving over the first four years.

Another interesting exercise is to use Figure 4 to compare tube performance with comparably stressed HK-40 creep-rupture specimens on which there are well-documented, long-time data covering hundreds of heats. (*4*) Reformer tube designs are based on such data. The scatter band width on the time scale for creep-rupture specimens is not much less than for the tubes covered by Figure 4.

Creep-rupture tests establish relationships among rupture time, constant stress, and constant temperature. A creep-rupture test of an average HK-40 heat can be designed to fail in the same 16-yr. average time as the tubes in Figure 4 while at the mean diameter stress in those tubes. The metal temperature required to accomplish this is approximately 120°F above the calculated mean diameter temperature of the tubes. On this basis, the tubes are performing as if they are creep-rupture specimens overheated by 120°F.

Under these circumstances, Figure 4 shows that 98% of the tubes are capable of lasting five years or more without failure. If the tube design temperature had been 120°F higher, creep-rupture data suggests that tube life would have been close to an order of magnitude longer. However, the mean sound wall would have to be about two-thirds thicker to take the extra 120°F.

Effects of tube wall thickness

Injudicious increases in tube wall thickness have long been questioned because of higher thermal stresses for a given heat flux.

Early performance of the 13 first-generation reformers even suggested that the thinner tubes were superior. (*2*) The thickness of the 2,058 tubes in seven of these reformers consisted of the minimum sound wall plus a 3/32-in. allowance for unsoundness. The other 1,848 tubes in six reformers were thicker by reason of a 9/64-in. allowance for unsoundness. Figure 5 shows how the seeming superiority of the thinner tubes gradually disappeared. The difference in allowance for unsoundness apparently was not significant. The improvement in performance of the thicker wall tubes is explained by Figure 2, which covers four of the six reformers involved.

Second-generation reformers incorporated changes in design criteria which resulted in a minimum sound wall thickness increase of 17%. The eight oldest of them are all more than five years old, with 2,620 original tubes having a group average tube performance as also shown in Figure 5. Their increased tube wall thickness has proved to be an improvement, although so far not as much as creep-rupture data would predict. It may still be too early to reliably extrapolate to their group-average life.

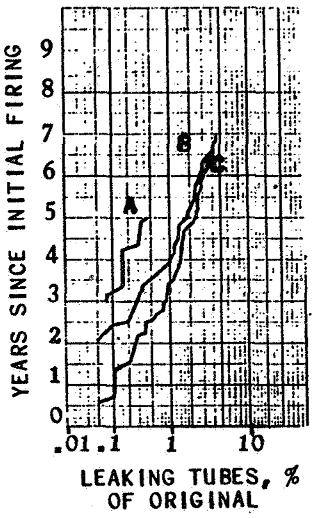

Figure 5. Wall thickness effects on tube performance.

This 21-reformer review would not be complete without looking into the status of tube replacements. Of the original 6,526 tubes, 2,639 in 19 reformers have been replaced or removed for later replacement.

Large quantity replacements have been made in or planned for 17 of these reformers. Only minor changes, such as in minimum carbon content and maximum lead content, have been incorporated in the replacement tube specifications for three of the 17 reformers.

More costly changes in replacement tube alloy, manufacture and/or thickness for the other 14 reformers suggests that disappointment with the original tubes is widespread. However, Table 1 shows there is no general agreement on the best remedy. It may take several more years to establish a clear consensus.

Points on Figure 6 show the time and percentage leakers at which each of the 13 first-generation reformers has been

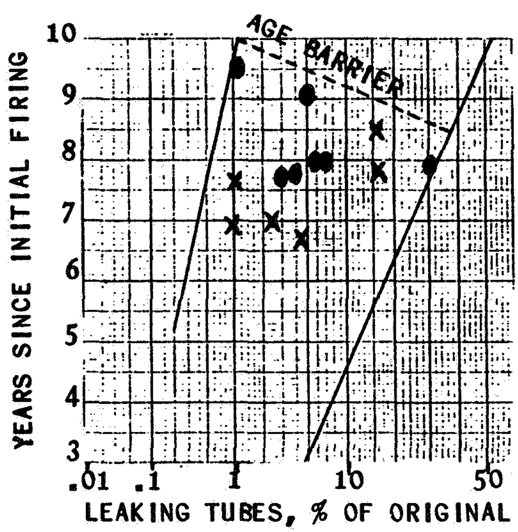

Figure 6. First-generation tube replacement age.

Table 1. Replacement Tube Specifications

Number of reformers	Alloy	Changes from original tube spec. Manufacture	I.D.	Wall
3	No major change			
1	–	–	–	up 17%
7	–	Bored	–	up 17%
1	–	Bored	up 6%	up 17%
1	–	Bored	–	up 43%
1	–	MWT*	up 4%	up 17%
1	HP	–	–	down 4%
1	36X*	Bored	up	down
1	36X*	Bored	up 14%	down 31%
4	Undecided			

*Proprietary designations

or is expected to be completely retubed. It is as if a wall were preventing tube operation beyond the dotted line in Figure 6. That wall is essentially a cost barrier, built up by an increasing reformer failure frequency or fear of same. Where reformer failure costs are high, early retubing may be economically necessary.

What makes failure costs so high in these particular reformers where 13 tubes are replaced for every one that leaks and where tubes which should have a 16 year average life may all be replaced in less than 10 years?

At least three factors are apparent:

1. There is considerable scatter in the performance of tubes made to the same specification.

2. One out of every four leaking tubes is the direct cause of a complete plant shutdown (*2*) with possible dollar losses in the 6-figure range. A majority of these leakers were at least contributing causes of such shutdowns.

3. The number of shutdowns caused by leakage at outlet manifolds and their associated welds has approached or exceeded those caused by tube leakage in some of these reformers. They have been a major consideration in decisions to retube. Obviously, tube improvements are wasted when outlet manifold failures require replacement tubes to be prematurely removed.

The cost of even a few plant shutdowns from these causes justifies much continuing effort to design around them.

Conclusions

High-pressure reformer data now clearly shows that:

1. Poor tube performance can be improved without complete retubing.

2. Tubes with the first-generation tube wall thickness have a projected average life of 16 years.

3. These tubes are performing as if they are creep-rupture specimens overheated by 120°F above the calculated mean wall temperature at the outlet end of the tubes.

4. The scatter bands for tubes and creep-rupture specimens are approximately the same.

5. The 17% thicker, second-generation tubes are performing better than first-generation tubes.

6. The variety of replacement tube specifications in use shows a desire to improve tube performance and a lack of agreement on how to.

7. Circumstances are forcing most tubes to be replaced early, with average remaining life of over six years.

Acknowledgment

The designer/constructor of the reformers covered in this paper has graciously agreed to release the following tube dimensions so that the observed tube performance can be better evaluated relative to various design criteria:

Nominal inside diameter of all tubes ...... 2.80-in.
Minimum sound wall thickness:
All first-generation tubes .... 0.52-in.
Most second-generation tubes .... 0.61-in.

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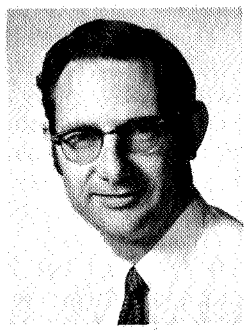

SALOT, W.J.

DISCUSSION

Q. Was there any correlation on the welding electrodes or the location of the failures?

SALOT: All of the tubes were welded with high-carbon Type 310 filler metal, although different manufacturers used different welding processes. Lines B and C of Figure 5 show that this difference between manufacturers was insignificant.

Most of the failures were either near the flame burst elevation or near the bottom where temperatures are expected to be highest. Weld cracking is usually near the flame burst where the temperature gradient through the tube wall is greatest.

BOB PRESCOTT, C. F. Braun Co.: How many of your leaking tubes were of the weld cracked variety? How widespread is this weld cracking and what causes it? Also, how do you arrive at 16 years as the projected life of these tubes? The design criteria, as I remember, promises at best no more than 11.2 years.

SALOT: Your first questions are on the weld cracking. Less than 10% of the leaks were through circumferential cracks in the welds, and most of them were in a single reformer that seems peculiarly susceptible to that type of failure. However, the finding of non-leaking cracked welds is commonplace, and many of them have never been replaced. These cracks, if they are tight, may hold for years without leaking, but the thing to watch out for is when they start getting wide. They are caused by thermal stresses, resulting from high temperature gradients through the wall thickness in the vicinity of maximum heat input, and acting on welds that have inherently lower creep-rupture strength than the parent metal.

Your other questions were on the 16-year life estimate. I obtained it by extrapolating the group average line in Figure 4 to the 50 percent failure point. That's a legitimate estimate for average life of tubes left in service until they fail in those particular reformers. Now concerning the design being for 100,000 hours or 11.4 years, there are not many designers that will not own up to such a statement. Certainly a lot of reformer tube designs are based on 100,000 hour creep-rupture data, but that doesn't mean designers are expecting the tubes to last as long as the creep rupture specimens did under steady-state conditions. If you calculate the life of these tubes based on any common pressure stress formula and using average creep-rupture data at maximum design metal temperature, you will find it greatly exceeds the 16-year average projected by Figure 4. Again, thermal stresses explain the difference.

Q. Have you any correlations between machined and non-machined tubes in Table 1?

SALOT: Not yet. I hope in a few years we will have because, as you saw in Table 1, 7 reformers have been retubed with bored HK-40 tubes, all of the same thickness. When we get some long term data on them, we can compare it to Line A of Figure 5 to get an idea of how much difference the boring made.

ELMARS BLUMENAUS, Heat Research Corp.: We at Heat Research are very interested in this type of feedback which can only improve the state of the art and the operational reliability of the reformer components. From your conclusions we are indeed glad to hear that our thicker wall HK40 reformer tubes bear out our original expectations for a longer life contrary to the school of thought that thicker tubes would fail faster due to thermal stresses. This is currently Heat Research design practice and it is good to see from the statistics of replacement tube specifications in your Table 1 that of the 17 decided replacements, over one half are taking this route and three are making no major changes from the original. We wish to comment therefore on the statement that "disappointment with the original tubes is widespread." What we believe is happening is the clients are generally taking the opportunity to obtain the latest design available, when the original harps finally have to be replaced. At this stage we do not believe there is sufficient evidence or service experience in materials other than HK40, to consider that any would be superior regarding reliability of time to rupture if designed on the same stress rupture criteria. We believe that to really consider a material superior it should have a reliably narrower stress rupture scatter band and be economically on par with HK40. The trend to bored tubes should be largely an economic decision, since surface notches in creep have been demonstrated not to have a detrimental effect on rupture life. Your Figure 1 showing the converging performance of the different unsound metal tubes seems to bear this out.

You mentioned the outlet manifold performance is a major consideration in when to retube. We certainly concur with this point, and we would like to expound on it a little further. Random feedback from our earlier reformers did indicate failures which could be broadly attributed to one of three causes.

1) The early use of Inco 182 weld material which is now known to exhibit weakness and cause cracking at elevated temperatures. The specification of this material was discontinued in '68 and owners were advised subsequently to remake failed header welds with Inco A or 82. We now use Inco 82 or Inco A for header welds.
2) The early designs employed a manifold with diameter changes and reducers which caused stress concentrations when subject to bending. This type of design, particularly with Inco 182 welds, had resulted in failures and this practice was also discontinued back in '67.
3) A couple of isolated failures have been reported due to eccentricity of the inner and outer diameters resulting in wall thickness below that specified, and we are now implementing ultrasonic thickness checks on the header material to detect such instances.

Realizing the critical nature of outlet manifold reliability, Heat Research did in July of this year, prepare, and with the help of yourself distribute the questionnaire to plant owners and operators to help us gather on a large consistent scale data on the performance of our reformer outlet manifolds. To date we have received 14 replies and initial analysis bears out three general causes for failure mentioned above. A detailed analysis of the results of the survey will be presented shortly.

Finally, a comment and a question on the statistical aspect. Figure 6 of your paper shows that one operator is considering replacing tubes after nine years when only one percent of the tubes have failed, while another after eight years with 50% tubes failed.

Could it be that further investigation in differences of operation or some other relevant cause could narrow this range down to a more average type of reformer?

SALOT: I think you're asking me for two comments: The first one is on the disappointment with the original first generation tubes. Table 1 shows that only 3 plants chose to stick with the first generation tube design, while 14 are spending extra money to get away from it. To me, that spells disappointment with first generation tubes, and Heat Research, by promoting thicker wall tubes, is sharing in that disappointment.

The other point you raise is whether we can narrow the range of tube performance in reformers.

BLUMENAUS: The point I'm trying to make here is that individual tubes have a very large scatter, whereas reformers should have a generally smaller scatter, and that maybe that one reformer is being operated different from another one when considering the survey.

SALOT: Certainly differences in operation can affect the scatter band width, but, if the scatter band width is reduced very much, it will be narrower than the HK-40 creep-rupture test scatter band. It seems to me we should not expect reformers to be run better than the creep-rupture tests on which their designs are based.

Q. Getting back to the welding, is the cracking in the root pass associated with an Inco type filler material?

SALOT: No, definitely not. The cracks are in HK-40 to HK-40 welds made with high-carbon Type 310 filler metal, and they probably do not initiate in the root pass.

Q. Was any failure analysis made to confirm that the high carbon 310 filler was used?

SALOT: I am sure in some cases it was. There have been so many of these tubes removed with weld cracks that most of them are not analyzed any more. I would think a low carbon weld would fail in very short order.

PRESCOTT: Does your overall statistical analysis include these cracked welds?

SALOT: Yes, those that leak.

PRESCOTT: Doesn't this present a somewhat misleading picture in an effort to evaluate tubes when we normally think of tube failures as being longitudinal stress rupture type failures? Perhaps you should have a statistical evaluation on weld cracks separate from creep rupture failures in tubes.

SALOT: That's a good point. I don't think it would make a lot of difference in this case.

PRESCOTT: It would make a lot of difference to me in interpreting your results.

SALOT: Let me point out that the statistics were based on leaks, not cracks, and that 12 of the weld leaks were in a single reformer whose tube performance line runs close to the "group average" line shown in Figure 4. If I eliminated the approximately 15 weld failures from the 174 total failures involved in Figure 4, I doubt that the picture would change significantly. This is because it is so heavily dominated by longitudinal type failures.

Q. You mentioned that the program to reduce the failure frequency included better operation and effective inspection, and you also mentioned eddy current and visual inspection internally. But if the majority of failures were due to creep rupture, did you effectively use OD measurements and were they helpful or not?

SALOT: I am sure O.D. monitoring is being tried in more than one of the reformers covered in this paper, but I have heard no success stories yet. Part of the problem is that the 2.8-in. I.D. tubes do not bulge much before they fail. The technique works better on larger diameter tubes, but even then some tubes will fail with less bulging than in neighboring unfailed tubes.

JAN BLANKEN, UKF Holland: In the reformer of the plant of Ammoniak Unie which we operate at Pernis, we found quite a large number of cracks in the top welds of the catalyst tubes after about five years of operation. To avoid this to happen also in the reformer of the IJmuiden plant, which is of the same design but younger, we decided to insulate all welds in the catalyst tubes.

Fiberfrax paper 1 mm thick and 10 cm wide dipped in a diluted solution of Rigidizer W was fastened by two rings of Kanthal wire 2 mm thick, one above and one beneath the weld. We operate furnaces with insulated welds now for three or four years and none of the insulation has come off.

And maybe I have to correct what I am going to say now in the future, but in the second, the younger furnace we found a certain small number of cracks in the top welds after one and a half year of operation without insulation.

After putting the insulation on and another one and a half year of operation there were about the same number of cracks found and statistically the propagation of cracks was negative. This could indicate, but I try to be as careful as possible that insulating welds has helped avoiding cracks in the weld.

SALOT: I agree. Perhaps I think even more strongly about it than you do. What impresses me is that at the edge of the insulation the tube is visibly darker and cooler. With a temperature-sensitive weld running cooler under that insulation, it's bound to have a lot better life.

IAN McFARLAND, Chemetics International, Montreal: I don't really know anything very much about this but I was fascinated by your paper, with this nice straight line, until I realized you had a linear scale on one side and a log scale on the other. And it therefore occurs to me that if, for example, you had one failure in your first year and had to stop your plant, after seven years you've got 49 and you're likely to stop it once a week. This is probably why you've got this age barrier up here because people say, just rebuild your reformer, and get back to square one.

SALOT: No, the horizontal scale is not logarithmic. It is a probability scale. Your description of the decision-making process is slightly oversimplified, but close to the point.

Q. In Table 1 you mentioned that some of the replacement tubes are being bored and the wall thickness has been increased by 17%. Do you refer to the total wall thickness or the sound wall thickness?

SALOT: The increase is in sound wall thickness.

LARRY ZEIS, *Kellogg Co.: I'd like to present comments* from John Lancaster of Kellogg International Corp. in London. Part of his comments, Bill. You have the whole thing in writing.

KIC recently compiled a survey of reformer tube behavior in ten European ammonia plants with an average service life of 7 years. The failure record of these tubes is qualitatively very similar to that reported in the Salot paper, although the performance curves indicate a somewhat lower failure rate. Referring to Figure 4, our scatter band lies between the curve marked "group average" and the lower limit curve which terminates at one percent cumulative failure. The form of our curves, however, is similar to those of Figure 4.

For a number of European plants the failure rate was very low and should be tolerable for a tube life of 15 years and perhaps longer. Thus, using more devious methods we arrive at the same conclusion as Bill Salot, namely, that tubes may still have a potentially useful life beyond ten years. It is hoped that the results of this and future surveys may encourage the use of HK-40 tubes beyond the ten year time barrier and enable the full economic value to be attained from this rather costly material. Thank you.

SALOT: I would like to follow up Mr. Lancaster's comments in the future since he's talking about 10 European reformers that supplement the American reformers I've shown here. I would like to have the raw data and the actual plots to make sure that we are talking on the same basis. He indicates that the tubes in Europe are doing better, but this is inconsistent with his statement as to where his scatter band lies with respect to Figure 4.

If the European reformers are performing better than Figure 4 suggests, it may be because they have thicker tube walls comparable to the younger reformers represented as Line A on Figure 5.

P. A. RUZISKA, Exxon Chemical Co.: I would think that variations in the tube metal temperatures would have a significant impact on failure rate. Have you got any numbers on what range of metal temperature these tubes experienced and whether any temperature differences could be correlated with tube failure rates?

SALOT: No, there are no reliable numbers on tube temperatures. They vary too widely from top to bottom, from side to side, from end to end, and even from minute to minute. It would be very hard to accurately compare tube temperatures in one reformer against another because of these variations. All I can say is that in general the operating temperatures were usually around the values that were intended by the designer.

RUZISKA: I suggest you could consider that when you remove tubes prior to failure, metallographic studies might indicate average temperature the tube has experienced, and you might correlate that with the degree of tube deterioration, or whatever you found that caused you to remove the tube.

SALOT: Yes, that's been done in many cases, and some of them indeed have shown severe overheating metallographically, like over 1800 degrees. It usually comes as a great surprise to the operator who never dreamed that he had ever operated a tube that hot. It may be that metallographic effects appear in a short time of upset. I doubt that any long term operation at such a high temperature is done without the operator knowing it.

Q. Do you have similar data for any other type of reformer?

SALOT: Not nearly so complete. The 1971 and '72 papers included other types of reformers. But I haven't updated them at all.