COMPREHENSIVE ANALYSIS OF HEAT EXCHANGER FAILURE

Miloslav Procházka

Tediko, s.r.o., Pražská 5487, 430 01 Chomutov

If a failure caused by rupture of the material occurs in the equipment or if a condition which may result in a failure is detected (for example by non-destructive testing), in many cases the ruptured component is repaired or replaced and no analysis why such a condition happened and how to avoid its repetion is done. However, failure analysis may lead to such remedial actions which will eliminate the failure or reduce the possobility of its repetion. Even though the failure analysis and remedial actions „cost some instant money", in fact they can save or reduce the costs in the future. Unfortunately, it quite often happens that little technical knowledge of those who make decisions and their short-term „business" plan result in underrating of these facts.

In case the owner of the equipment decides to have the failure analysis done, there can arise another significant problem because such an analysis is multidisciplinary. It means that it is not enough to perform a detailed non-destructive testing or laboratory analysis, but it is essential to launch both disciplines at the same time together with assessment of the operation, construction, development etc. There is a frequent problem that most parties involved in the project deal only with one and that is „their" discipline. The result of an investigation and analysis should be, in case of a more serious failure, the determination of causes (RCA – Root Cause Analysis), or respectively, a possibility of putting the equipment into the operation again after some basic remedial actions have been done with high probability that the failure will not any more.

The objective of this paper is to show a way of solution in case of one particular failure when a few NDT methods and laboratory analyses were launched in successive steps. It is necessary to point out that not always the result of investigation will specify the causes of the failure clearly but it is important to know whether out-of-service condition is basically accidental or the condition is affected systematically by an actual process. The elimination of a „failure" and control of possible critical locations can have a vital effect on extension of service life and cost reduction.

At the end of 2005 a leak was detected in heat exchanger – steam developer. The exchanger in question developed the steam in tubes by heat transfer from the residue of process product in the intertube space. The exchanger had been operated for more than 17 years and previous inspections did not indicate any fundamental problems. The owner performed a basic pressure test which revealed a leak in one of the tubes.

The horizontal bundle of tubes consists of 812 U-shaped Ø20 x 2.5 mm tubes made of carbon steel (magnetic). The tubes are about 6 m long in their straight sections and about 1 m in the bend which means cca 13 m of the total length.

With respect to the fact that there had been no plans to change the tube bundle and the situation occured at the end of the year, it was not possible to replace the bundle with a new one simply because the owner did not have a backup tube bundle at his disposal. The production cost of a new tube bundle would be extremely high and considering the delivery terms, there would be an extensive loss of break in capacity. Costs of cleaning and inspection of the bundle were estimated as well as the chance that after the necessary diagnostics had been done, it would be necessary to replace the exchanger anyway.

The first preliminary inspections performed after the bundle had been removed and cleaned did not indicate any serious and clear systematic damage of the bundle. The inspections performed were:

- on-site VT inspection of the budndle
- on-site RTG inspection

In view of the fact that the above mentioned inspections had not revealed any series and clear systematic damage of the bundle, we drew a conclusion that the risk of spending needless money on performing other inspections is acceptable provided we found that the exchanger was not capable of further operation. A decision was made to carry on step by step and evaluate whether the chance of putting the exchanger into operation will increase.

Procedure

The layout of work (decision layout) shows the way of procedure. In total we used the following examination/testing methods:

- Analysis of data supplied by the client
- On-site VT inspection of the bundle after the primary cleaning prior to RTG
- On-site RTG testing
- Removing four tubes for laboratory analyses
- Preparation of samples for laboratory analyses
- Visual examination of the samples including photographic documentation
- Verification of the material grade
- Metallographic analysis including photographic documentation
- Preparation of RFT standards
- RFT testing of the removed tubes and metallographic verification of the findings
- Visual examination of bends
- Visual examination of the bundle after the second cleaning)
- On-site non-destructive testing of bundle tubes with inner probes
- On-site visual examinations (direct, indirect – with endoscope)
- Removing a tube on the basis of tests mentioned in 5.12 and its detailed analysis
- Verification of tightness using method H_2

Analyses of data supplied by the owner

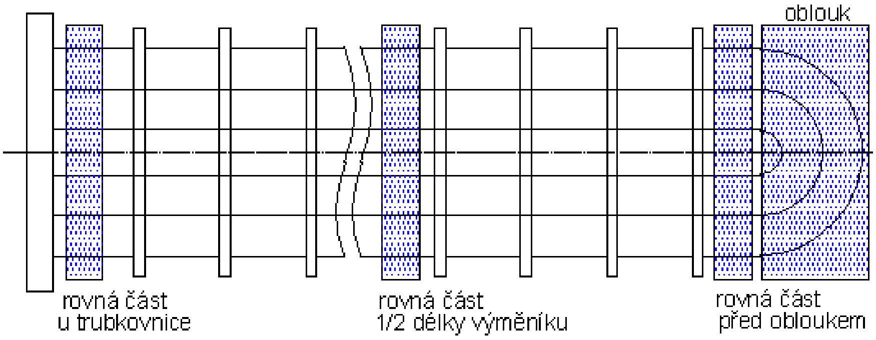
At first we analyzed the existing data in details. We assumed that the exchanger was not likely to be damaged globally and that performing other inspections with a chance of eliminating problem spots apperared effective.

Preliminary visual examination after the primary cleaning

The condition after the primary cleaning was from the point of visual inspection significantly worse than optimal. We drew a conclusion that no relevant non-destructive testing was possible under the given condition. However, we did not find any fundamental signs of damage. The only possible non-destructive testing was radiography. The following photo clearly defines the condition

On-site radiography

Radiography of randomly chosen spots – bends and straight sections was performed on-site after primary cleaning. The locations were chosen with regard to accessibility and representativeness (see the following picture). The radiographs did not show any signs indicating extensive corossion or erosion attack on the surfaces. The inspection did not find any systematic damage of the exchanger and the wall thickness did not show any anomalies.

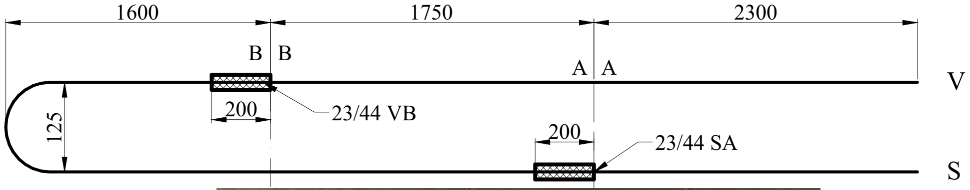


Removing four tubes for laboratory analyses

Four tubes were removed on the basis of radiography and visual examination results. Obviously, the tubes could be only removed from the outer layers but it was the only possibility which could be taken into consideration.

Prepration of samples for laboratory analyses

Samples each 200 mm long were cut out of the removed tubes. The picture below shows the layout of locations where the samples were cut out. This „cutting layout“ shows how the tube was cut after it had been removed from the exchanger. The following photo illustrates the cut-out samples.



Visual examination of samples including photographic documentation

The samples were cut longwise and both surfaces, inner and outer, visually examined.

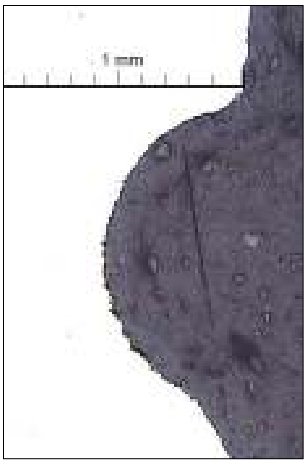
No signs of the process medium were detected on the inner surface of any of the samples. Chemical cleaning of the samples in Clark´s solution did not reveal any significant defects or corossion attacks. The outer surface shows a uniform corossion attack and the loss in wall thickness was estimated to be max. 0.1 mm. The inner surface was smooth with a lot of pittings with depth of mostly 0.20 mm, in once case even 0.60 mm (i.e. less than 25 % of nominal wall thickness). Regarding the distribution of smaller pittings on the inner surface we can say the pittings probably appear in tiny heterogeneities in the material which do not create conditions for further attack or they may appear during shut-downs. Bigger pittings may be caused by conditions on the side of environment, i.e. a product of oxygen corrosion or improper composition of the water (corrosion on the boundary between phases).

Samples for metallographic analysis were cut-out on the basis of visual examination findings – the worst looking locations (for example with corrosion pits). Typical appearance of the surfaces is shown below.

Verification of the material grade

Chemical analysis was performed using an automatic optical emission spectrometer ARC-MET 930SP. Chemical composition corresponds with steel grade A213 T5.

Metallographic analysis including photographic documentation



The samples were analyzed to determine the depth of corossion attack and type of steel structure. The structure is formed by ferrite matrix with precipitated carbides which corresponds with expected condition. Outer surface is attacked by corossion only to the depth of 0.2 mm, on inner surface the depth of corrosion is up to 0.55 mm (pitting) – see the picture.

The laboratory tests did not discover anything which wouldn´t correspond with the time of operation. Therefore we had to come up with further diagnostics examination..

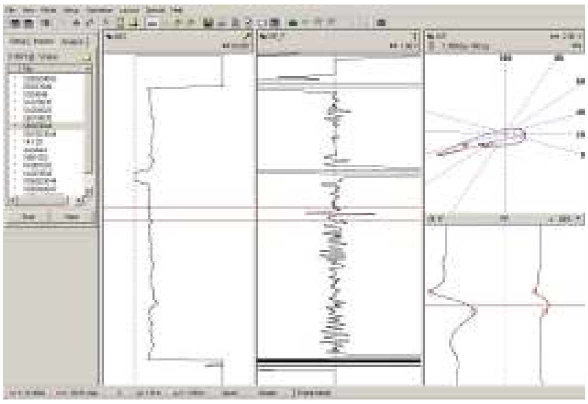
Preparation of RFT standards

One of the removewd tubes was used for making a standard for RFT examination according to draft no. 8 of ASTM Standard practice for In Situ Examination of Ferromagnetic Heat Exchanger Tubes Using Remote Field Testing (ASTM number not assigned) and a procedure of R/D-Tech. – Inspection Procedure of Ferrous Tubing .

RFT examination of removed tubes and metallographic verification of findings

When the standard had been made, we performed RFT inspection (Remote Field Testing) on the removed tubes using R/D Tech device (Eddy current testing is not possible since the permeability of the material is much higher than 1). This inspection did not reveal any significant indication of damage. Only two locations with distinctive signs of damage up to the depth of approx. 40% of wall thickness were identified – see recording of the measurement. These locations were cut out and visual examination was performed after the samples had been cut longwise. A sporadic defect 0.72 mm in deep (30% of wall thickness – original wall thickness in this place was 2.56 mm).was found.

Comparison of findings of non-destructive RFT measurement and metallographic verification shows quite good harmony within the range of expected accuracy 10-20 % of nominal wall thickness**.** In the case the depth of damage was a little overestimated when measured by non-destructive RFT examination. Probability of detection of defects such as pitting with diameter of 2 mm and bigger and deeper than half of the wall thickness is in diferential channel relatively good (apart from tube sheets where the probability of detection is very limited.)



Visual examination of bends

Since no other inspection was possible (RFT probes of R/D-Tech are not available for small tube diameters as flexible type, at the time of measuring there were no RFT flexible probes available for another technology used by Tediko - C-MEC), the tube bends had been cut longwise and visually examined before and after the corossion products and other impurities were cleared off.

The inner surface was covered with about 0.3-0.4 mm thick fine-grained non-magnetic layers. When the layers had been removed and the surfaces cleared off, it was visible that the outer surface was attacked by uniform corrosion in the form of tiny pits of negligible depth while inner surface showed neither corrosion nor manufacturing defects. An example of one of the tube bends is shown below.

Visual inspection after the second chemical cleaning

All inspections and examinations described in previous articles had been performed on tubes before the bundle was chemically cleared, i.e. only after the first cleaning by pressure water in the cleaning area. When the holes after the removed tubes had been plugged, the bundle was placed back into the casing and chemicaly cleaned with 80% kyrasol at approx. 80°C. Cleaning including the preparation took nearly two months. The result is commented and documented by photos below.

a) Direct visual examination (VTp) after re-cleaning (second cleaning):
Direct visual examination of the exchanger revealed that the bigger part intertube space was still filled with technological product mixed with corossion products. The surface of tubes that were accessible for visual examination showed a uniform general corossion attack with corossion products contaminated with oil and oil products coming off the basic material in form of up to 1 mm thick scales. Equivalent loss of material in wall thickness was estimated to be 0.1-0.2 mm.

b) Indirect vizual examination (VTn) after the second cleaning:
Two tubes were inspected by ViZaar videoendoscop. One of these tubes was after the pressure test considered to be leaking. This inspection showed that there were some free sediments and some which adhere firmly to the inner surface of the inspected tubes. Some sediments were were corrupted by corossion process. Water in tubes (approx. 1/5 of the cross section) made the inspection rather difficult, We failed to find a highly damaged location with a leak. The sediments that adhere firmly to the surface might have covered possible damage causing the perforation of the tube.

On-site electromagnetic testing (eddy current principle) of tubes in the bundle

There was water in the tubes after the second (chemical) cleaning. The water contained the residual products of cleaning and intertube space was not quite clean either. Despite the situation RFT inspection started together with direct visual examination. However, the inspection did not produce results that would be relevant enough. Therefore we recommended to clean some sections of the bundle again, especially tube no. č.14/12 which was leaking according to the pressure test performed by the owner. New special probes were ordered at the same time.

The sediments on the inner surface generally hamper the course of inspection, corossion products in the sediments induce the indications concealling the real defects which means that use using MFL method is rather limited.. The sediments filling up the intertube space and containing corossion products too, impose limitation to the use of RFT method due to field attenuation. Basically, everything was unfavourable for any non-destructive testing at the moment.

On-site non-destructive testing of the tubes in the bundle using internal probes

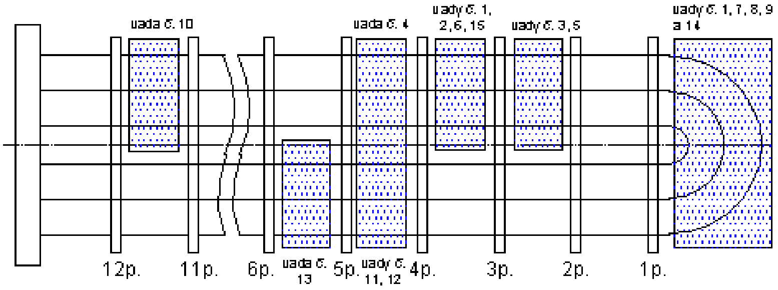
With respect to the above mentioned facts, the exchanger was pressure-cleaned for the third time and then 100% of tubes were inspected using electromagnetic methods on eddy current and scattered magnetic flow principles. The following methods were chosen for the inspections:

1. **RFT – Remote Field Testing – technology R/D-Tech :** primary method for testing using R/D-Tech technology. The method is time consuming and in the end only 33% of halves of the exchanger tubes instead of originally planned 100% were tested together with all tubes with indications or those which were suspected to have some indications after they had been tested by faster C-MEC method.
2. **RFT - C-MEC – technology T.M.T. :** secondary method using conventional voltage level of eddy current was chosen especially on account of possibility to use a flexible probe which had been developed and made for C-MEC technology. This probe enabled to inspect exchanger´s tube bends as well as the straight sections. The inspection with this technology does not require so much time to perform the testing and enables to move the probe faster while making a record of the tested tube. The problem of C-MEC technology is a different way of interpretation of the distant field and the evaluation is more demanding. Therefore the RFT technology R/D-Tech is much more suitable for testing even if it is slower than C-MEC technology because it enables better determinability and evaluation of defects and interpretation of the findings.
3. **MFL – Magnetic Flux Leakage – technology R/D-Tech:** this method is used especially for inspection of tubes which is supposed to have a leak detected by previous pressure test.

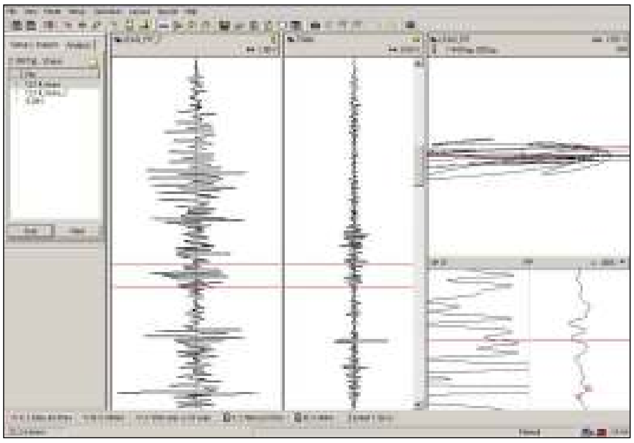
The testing of tubes using the above described methods concentrated at first on detection of a leak in a selected tube. The first testing by means of a binary RFT probe and one testing frequency failed to get any relevant results. Therefore we used testing with two frequencies at the same time. The signals from two channels were mixed in such a way that we eliminated the effect of the tubesheets. This method enables to look for defects located very close to the tubesheets (supporting metal sheets) and even under the tubesheets providing the situation is favourable. However, this modification did not determine the indication clearly, either. On the basis of this fact we drew a conclusion that the defect was probably located right under the supporting metal sheet or in a very close vicinity and moreover it might be hidden under the residue of the technological product or corossion products which were not removed by cleaning. The same conclusion was made after the testing using C-MEC method. In total 93 tubes were checked both ways. .

Therefore we chose MFL method which is primarily used to check tubes of air coolers with aluminium ribs. The advantage of this method as compared with RFT and C-MEC methods is insensibility to obstacles on the outer surface of the tested tube. On the contrary, the disadvantage is quite a loud noise if the tubes have not been cleared completely and some inaccuracy when evaluating indications. This inaccuracy is caused by the absence of the phase in the received signal. MFL method found an indication by means of so called guiding coil which records the residual magnetism but does not evaluate indications. A conventional differential coil failed to find the indication due to loud noise of the background caused by magnetic impurities. Using the record for guiding coil we specified the location of the indication into the vicinity of the fifth tubesheet from the end of the exchanger. This fact was proved by a simple test with pressured air because it was possible to hear the leakage clearly at the fifth tubesheet.

In total, we detected 15 tubes with indications of defects with extent of damage 40% and bigger. The following picture shows the location of defects along the exchanger longitudinal axis..



All in all nine tubes showed indications of defects in the range of 60 to 80 %, one defect exceeded 80 %. The following picture shows the MFL inspection record of a tube which was supposed to leak.

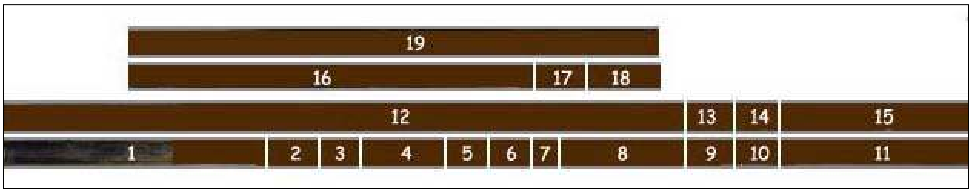


On-site direct and indirect visual examination with a videoendoscope

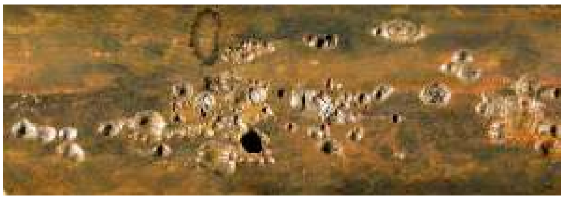
Visual indirect examination (VTn) of the inner surface was performed again together with testing by electromagnetic methods Leaking tube with indiciation of defect over 80% was checked again. We succeeded in finding the exact location of the damage thanks to detecting the approximate location of the leak. The following photos show the condition of the tube bundle after the last cleaning. Next photo from videoendoscope shows the discovered defect – leak in the tube.

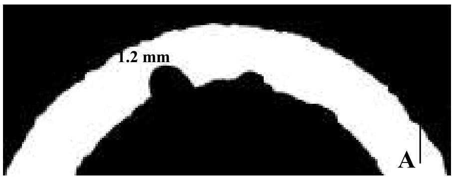
Removing a tube on the basis of tests mentioned above and its detailed analysis

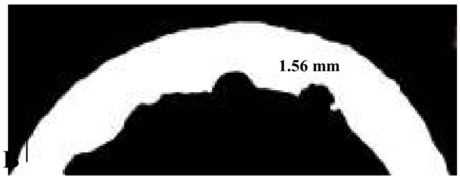
Sections of the tube showing defects were cut out and analyzed. This tube was chosen because it was located on the edge and easily accessible and there was defect to the indicated depth of 60-80% of wall thickness. The following picture shows the „cutting layout“.



The condition of both surfaces was examined in detail. The outer surface was covered with uninterrupted coat of rust and chemical cleaning revealed that the outer surface was attacked by corossion up the depth of approx. 0.10 to 0.15 mm. There was an uninterrupted thin layer of brown sediments on the inner surface together with scattered isolated pittings with diameter up to 3 mm but there were also clusters of pits. The depth of defects was 0.60 to 1.20 mm. The following photos illustrate corossion attack and sections through the wall showing the depth the damage in the given sections.







Verification of tightness using method H_2

With the tube bundle back in the casing in its position, we took the advantage of the situation when the exchanger was disconnected from the rest of technology and we performed the leakage test by means of the equipment Sensistor H2000. The leakage test uses the increased content of H_2 in the mixture of gas and leak is identified by leak location assembly (sniffer) which responds to the content of H_2 in the air.

A mixture of hydrogen was let through the side valve into the intertube space of the exchanger and a probe measured the concentration at the tubesheet. We found out that owing to the fact that the tubes are only rolled in, there was a distinctive background with all the tubes because the hydrogen diffuses between the tube and tubesheet as well. Since the tubes were free without temporary blinding during the testing, the background from more leaking tubes could superimpose. Therefore it is better to test the tubes one after another when only the tube that is being tested is not blinded while the other tubes are blinded by loose rubber plugs.

Nevertheless, the leaking tube 12/14 showed such a high increase of hydrogen content that it significantly exceeded the background and the leaking tube was identified without a fail.

Conclusion

All in all we used 16 separated steps for the diagnostics of the exchanger and we worked step by step. We can summarize that:

- defects which might have caused the leak of the exchanger were not identified. We only confirmed the leak in one tube.
- more significant defects such as pitting corossion were identified on the inner surface to max. depth of 1.2 mm, i.e. about 50% of nominal wall thickness in dependance on the local wall thickness
- distribution of pitting corossion on the inner surface of the tubes is very irregular
- no damaging mechanism causing the general degradation of tubes was found – i.e. general loss of material in wall thickness or frequent occurance of deep defects resulting in complete perforation of tubes, general damage of the tubes does not exceed usual level
- more serious damage on the outer surface, i.e. on the side of process medium was not identified
- indirect visual examination (videoendoscope) of the tube blinded on the basis of findings of leaking test and MFL method detected a location corresponding with indicated leak of medium
- despite the serious problems with cleaning of the tube bundle, non-destructive testing could be performed in required scope

On the basis of total condition in the given moment we arrived at the following conslusion:

- non-destructive testing found tubes with indications of defects both in straight parts and bend as well
- the leak was located at the the partition which affects the probability of identification of this defect
- the outer surface of the tubes showed only a mild attack of corossion of negligible depth, tiny pitting corrosion on inner surface mostly to depth of 0,3 mm, just a few deeper randomly distributed pits
- smaller pits on the inner surface probably develop in usual heterogeneities in the material, which do not set up conditions for further attack or possibly they can appear during shut-

downs, bigger pitting may be a result of conditions on the medium side, i.e. oxygen corossion, or improper water composition (corossion on boundary between phases)

- service life the tube bundle was estimated to be approx. 7 or more years, since we can´t rule out the formation of new individual deep pits or progressive corossion processes in the existing pits, we recommended to check the condition of the bundle no later than in four years´ time.

The comprehensive analysis resulted in putting the bundle back into operation. Despite a relatively extensive and time consuming diagnostics and laboratory analyses together with multiple cleaning, which weren´t cheap at all, the benefit and savings were quite evident. At the same time we verified the validity of comprehensive approach using all „portfolio“ of testing methods which complemented each other and filled up „deaf spots“ of individual methods.