FABRICATION PROBLEMS WITH HEAVY PRESSURE EQUIPMENT FOR LARGE AMMONIA PLANTS

The trend to large, single-train plants has resulted in several serious problems involving fabrication; both construction schedules and plant reliability are affected.

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Although the new generation of large ammonia plants did not require any radically new or experimental materials and fabrication methods, the mere increase in size resulted in heavier, more complex pressure equipment. The development came at a time when the level of quality in the pressure equipment field generally appears to have deteriorated.

A recent British publication attributes 40 to 61% of the operational and startup difficulties experienced in recently completed ammonia plants to faulty equipment and components *(1)*. No reference is made to the proportion of equipment fabrication problems that caused serious delays in plant completion, but it may be assumed that the percentage would be even higher. An improved level of quality in the equipment therefore becomes a necessity to reduce delays in plant completion and to cut operational and startup difficulties—not to mention effects on plant safety and plant maintenance.

A few of our experiences with problems which occurred in the fabrication and testing stages of large, heavy wall pressure vessels and heat exchangers are described here. The corrective steps taken also are discussed, as well as what was learned from these problems which will benefit future pressure equipment.

All of these problems were solved by close cooperation among the fabricators, ultimate users, and members of the Kellogg Company. Credit is expressed to all the individuals who assisted in solving these problems.

Yielding during hydrostatic test

Several large ammonia converters were fabricated by a European vessel vendor, applying the German code as the design basis and using a German low-chrome alloy steel with high physical strength values. Major problems occurred in fabrication because of inability to obtain the required physical values with conventional heat treatment, due to the large size and mass of the vessel courses. Failure of two of the converters during final hydrostatic test resulted from yielding of several courses; the physical strength of the material of these courses had been reduced greatly below specification requirements during the final furnace stress relief.

Outline of the vessel is shown in Figure 1. No nozzle corrections or other major stress raisers were permitted in the cylindrical shell. In general, construction requirements approached or exceeded nuclear code level of quality. The basic design was based upon the German code which for pressure vessels below the creep range permits a design stress of:

(yield point at design temperature)/1.5.

Unlike the American codes, there is no requirement with respect to design factors from the ultimate tensile strength of the material provided that the ratio

$$\frac{\text{Yield point at room temperature}}{\text{Ultimate tensile strength at room temperature}} \leq 0.8.$$

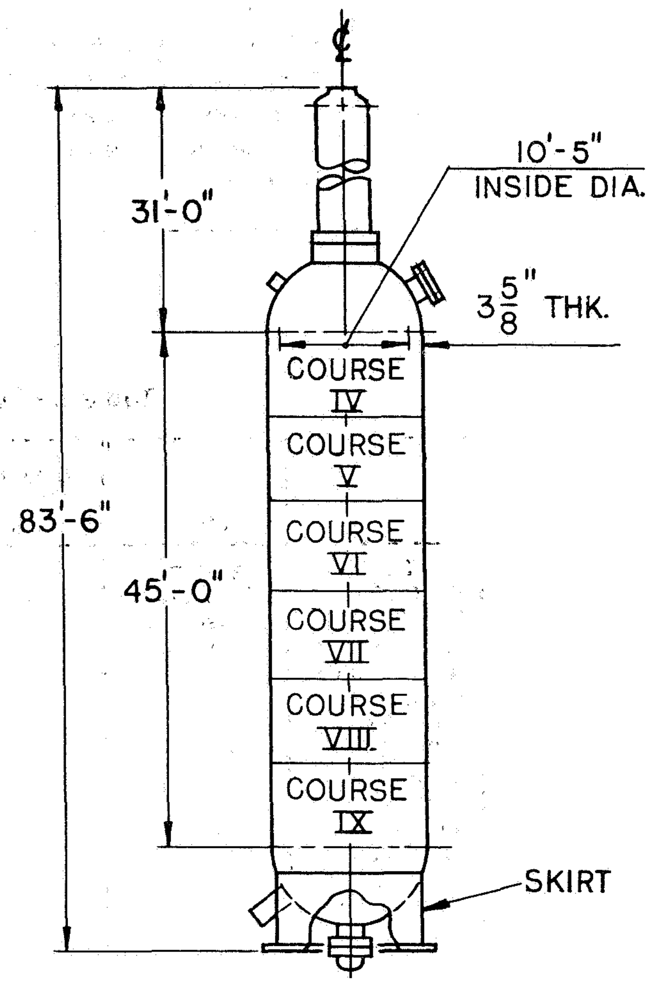


Figure 1. Elevation view of ammonia converter.

These requirements applied to the selected steel (described later) resulted in a total vessel weight that could be handled and shipped in Europe. The use of U.S. Codes (A.S.M.E. Section 3) and U.S. materials would have caused a weight increase of more than 50%.

The material selected by the fabricator for the shells and heads of the pressure vessel is essentially in accordance with standard German specification for hydrogen-resistant steel, and is similar to the A.S.T.M. Specification A387 Grade D. Table 1 shows a comparison between the chemistry of the A.S.T.M. steel and the German steel 24 Cr Mo 10. Column 3 shows the designer's special requirements for carbon level, which was to be kept low in order to minimize welding problems. Column 4 shows a typical actual composition.

Table 2 shows a comparison between significant physical requirements of the A.S.T.M. material, the standard German steel, contractor's minimum requirements, and requirements selected by the fabricator.

Fabrication sequence contemplated.

Based upon past successful experience with fabrication of pressure vessels of similar wall thickness but smaller diameters, the fabricator planned to have the plates for the shell supplied in the soft annealed condition. The proposed sequence was then to hot roll individual courses, weld longitudinal seams by the electroslag method, normalize completed courses, fog quench (blow wet air) against hot courses while courses are rerolled to obtain desired roundness, temper finished courses in the furnace, weld circumferential seams by submerged-arc method, and final stress relieve the completed shell and bottom head in the furnace. Several intermediate stress relieving operations were required because of the air-hardening characteristics of the steel, including high preheat for welding and maintenance of preheat until stress relieved.

The above description has been simplified and has been limited to the essential fabrication steps only. To verify the specified physical requirements the following major tests were to be conducted:

1. Mill test plates: The steel mill was to heat treat individual test plates in accordance with the heat treating procedures contemplated for the vessel.
2. Vessel test plates: Test plates were to be welded to the longitudinal seams of the individual vessel courses prior to the electroslag welding and removed prior to welding of circumferential seams.
3. Hardness tests were to be taken on the surface of the tempered vessel courses in order to verify that required tensile strength had been obtained during the normalizing-cooling-tempering heat treatment.

Table 1. Material chemistry

Composition	Column 1 ASTM-A-387 Gr. D	Comumn 2 24 Cr. Mo 10	Column 3 Contract-or's Req.	Column 4 Typical Actual
Carbon	0.15	0.20-0.28	0.16-0.24	0.23
Silicon	0.15-0.30	0.15-0.35		0.29
Manganese	0.30-0.60	0.50-0.80		0.64
Chromium	2.0-2.5	2.3-2.6		2.39
Molybdenum	0.9-1.1	0.20-0.30		0.30
Nickel (max)		0.80		Not Reported

Table 2. Physical requirements

	Units	Column 1 ASTM-A-387 Gr. D	Column 2 24 Cr Mo 10	Column 3 Contract-or's Req.	Column 4 Fabricat-or's Req.
Y.P. (20°C)	Kg./sq.mm.	21	45	-	48
Y.P. (200°C)	Kg./sq.mm.	18.5	39.2	-	42.8
UTS (20°C)	Kg./sq.mm.	42.5	65	-	65
Impact Stren. (DVM at 20°C)	Kgm./cm.sq.		5 (transv)	10	10 (transv)
Impact Stren. (Charpy V at 20°C)	ft.lb.	15	-	45	45
Circumf. Welds (S.R. only): Impact Stren. (DVM at 20°C)	Mk./sq.cm.	-	-	5	5
Impact Stren. (Charpy V at 20°C)	ft.lb.			35	35

Physical strength weaknesses

During the fabrication of the first vessel courses for three identical converters which were constructed simultaneously, it became apparent that the physical strength (yield and tensile) could not be obtained after tempering based upon results of hardness checks. The reasons for this were analysed as follows:

1. The furnace used for normalizing the vessel courses (3 at the same time) was relatively far removed from the rolls where the accelerated cooling was conducted. Therefore the heated courses went through a still-air cooling prior to fog quenching.

2. The large mass of steel, due to the large size of the individual courses, responded too slowly to the fog cooling. The result was that properties resembled those of annealed steel and did not meet specifications.

Several reheat treatment attempts failed to improve this situation and a laboratory program was initiated immediately by the fabricator to determine an improved heat treatment sequence. As a result of this program the heat treatment requirements were changed to the following:

1. Heating of vessel courses to approximately 940°C.
2. Immediate cooling by water sprays on inside and outside of course while being rerolled.
3. Tempering of vessel course at approximately 660-680 °C.
4. Intermediate stress relieving at 530-610 °C.
5. Final stress relieving at 670 °C.

The high tempering temperature, listed under 3, was required to obtain specified impact values for the completed vessel course, while the high stress relief temperature under 2 was necessary to obtain the specified impact values for the circumferential seams.

The above procedures were applied to all vessel courses, and based upon the hardness measurements and results of test plates, the required physical properties appeared to have been met. Unfortunately several courses had to be heat treated several times and records of actual heat treatment were not maintained.

The first vessel was then completed without any major difficulties. After all internals had been installed, the closing weld was made and locally stress relieved. The vessel then was hydrostatically tested. Except for drying, it was ready for shipment.

Yielding of courses during test

During the hydrostatic test several strain gages were installed to measure axial and circumferential strains of individual shell courses. Figure 2 shows measured strains against test pressure. The following conclusions can be reached:

1. Vessel Course 7 reached the yield point (.2% offset) at approximately 175 atmos. test pressure.
2. Vessel Course 6 reached the yield point at approximately 190 atmos. test pressure.
3. Vessel Course 5 approached yield point at the specified test pressure of 220 atmos.
4. Remaining courses showed no permanent yield after pressurization.

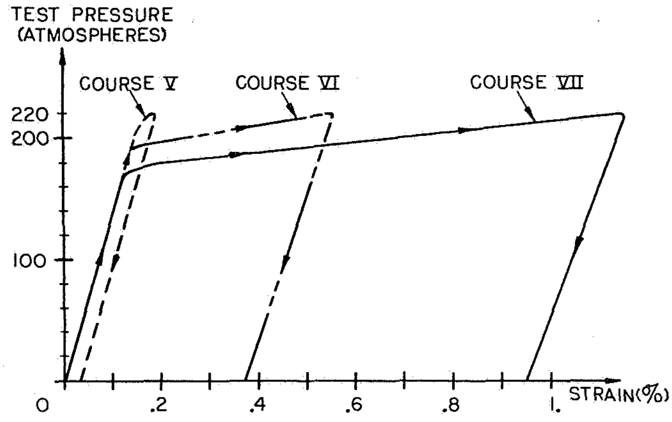


Figure 2. Vessel strain measurements.

actual vessel material properties, and (2) determination and correction of the causes of the failure.

These programs had to be conducted quickly, since vessel courses for four more converters had already been completed and the second converter was scheduled to be tested only a few months after the first converter failed. Actually, corrective measures for the second converter could not be applied effectively so that during the test of that converter one vessel course failed by yielding in a manner similar to the failure of converter No. 1 described above.

These programs were conducted by the vessel fabricator, the ultimate users and the contractor with frequent exchange of the results. The more important conclusions were the following:

1. The method of quenching used on the vessel courses resulted in material of varying strength with the higher strength values measured towards the plate surfaces due to faster cooling rates.
2. Hardness measurements at the surface gave unreliable values due to the non-uniformity near the surface caused by decarburization and surface quenching effects.
3. Values from test plates were higher because of the faster cooling rates of the test plates.
4. Recorded furnace temperatures did not represent actual metal temperature during tempering and stress relieving.

The main causes of the failure were determined to be: (a) The spread between tempering temperature and final stress relieving temperature was inadequate; and (b) Actual metal temperatures during final stress relief exceeded previously applied tempering temperatures for those vessel courses that failed due to inadequate yield strength.

Table 3. Converter shell data

	Specified		Test Plates		Actual Vessel		
Vessel Course	Y.S. Kg/ mm.sq.	UTS Kg/ mm.sq.	Y.S. Kg/ mm.sq.	UTS Kg/ mm.sq.	Y.S. Kg/ mm.sq.	Hardness (Mean) Brinell	UTS from Hardness
4						201	68.0
5						198	67.2
6	48.0	65.0	46.3	65.8	36.0	194	65.4
7			43.3	61.1	32.0	189	64.4
8			51.6	68.7	40.0	207	70.0
9						202	68.4

As a result of this failure all available test data were compared with calculated stress values. Significant data are shown in Table 3. The two major conclusions reached were: (1) The test plates did not represent actual vessel course material strength, and (2) the measured surface hardness resulted in optimistically high tensile strength values, but the courses which failed had significantly lower hardness values.

Goal of additional tests

Several programs were initiated immediately to achieve the following objectives: (1) More reliable test methods to verify

Corrective measures taken

Corrective measures to avoid recurrence of these failures were as follows. The extent to which they could be applied were dependent on the stages of fabrication of the individual vessel courses and assembled converters.

1. Improved methods of hardness determination were specified, with test points taken below the region of decarburization by grinding approximately 2-4 mm. below the surface.
2. Improved heat treatment furnace controls and recording of actual metal temperatures were specified for all heat treatment operations. Each heat treatment operation (normalizing, quenching, tempering, intermediate and final stress relief) had to be checked by recording thermocouples attached to the metal part during treatment.
3. The temperature of the final stress relief was required to be at least 20 °C below the minimum tempering temperature used on the individual vessel courses.
4. On each test plate attached to a longitudinal seam, a room temperature tensile test in the plate material and a hardness traverse were to be conducted immediately after quenching and tempering. The tensile bars were to be taken from the mid-thickness at a distance of at least two times the wall thickness from the edge.
5. The final hydrostatic test pressure was increased approximately 10%. Together with strain gage measurements this permitted final verification that the design factor of 1.5 from the yield point was closely approximated.

These improvements in the fabrication controls proved to be effective to the extent that no further yielding occurred during subsequent tests of converters. Adequate assurances were obtained that the actual vessel material met the specification requirements.

Cracking of Electroslag welds

Figure 1 shows an outline drawing of the ammonia converter pressure vessel for a single-train ammonia plant having a capacity of 1,000 tons/day. For the thick plates required for this type of vessel, electroslag welding is commonly used for the longitudinal seams. This welding process has been developed in recent years into a valuable technique capable of producing welds of high quality, rapidly and economically.

As with other welding processes, attaining high quality electroslag welds depends to a great extent on careful and continuing control of the many variables which enter into the welding procedure, and on thorough nondestructive examination. The fact that a fabricator has sucessfully performed this type of welding on several ammonia converters with little or no trouble, does not necessarily ensure that serious troubles will not develop on a subsequent converter. In fact, this is what actually happened in 1967 with an experienced fabricator who had previously employed electroslag welding in the construction of seven ammonia converters in the period of 1964 to 1966.

The material of all eight ammonia converters was the German steel 24 Cr Mo 10, as described before. This is a quenched and tempered low alloy steel, with chemical analysis as shown in Table 1. Physical properties are listed in Table 2. The thickness of the plate in this case was approximately 4.25 in. A typical example of the plate preparation for electroslag welding of the longitudinal seams is shown in Figure 3.

The electroslag welding on the first seven ammonia converters had proceeded in a satisfactory manner. However, on the eighth ammonia converter, ultrasonic examination revealed serious defects in the electroslag welds. The defects were of two types:

1. Fine shrinkage cracks in a herringbone pattern running along the axis of the weld near the mid-depth of the weld.
2. Longitudinal defects running along the fusion zone, approximately 1/16 in. wide and several inches long.

Causes of cracking

Subsequent investigation revealed the carbon content of both the plates and the welding wire was higher than it had been on previous work. There are a number of significant variables that affect electroslag welding, and carbon content is one of them.

A partial list of such variables is shown in Table 4. For some of these variables, it is not merely the absolute value which is important, but in many cases also the relationship between and amongst the variables. Successful welding therefore depends on careful control of these variables. This is particularly the case for thick plates of high strength low alloy steels.

In the case of this ammonia converter, it was concluded that the higher carbon content was the principal cause of the cracking. Plates and welding wire were reordered with reduced carbon content for subsequent electroslag welding on this vessel. Further corrective action included reducing the welding speed, preheating the plate to a higher temperature and, immediately after welding, placing the welded course into a hot stress relieving furnace without intermediate cooling. The objective of the latter requirements was to minimize any tendency toward cracking which might have been caused by thermal and shrinkage effects in the weld metal.

In addition to the steps involving the welding procedure and heat treatment of the material, the procedure for nondestructive examination of the welds was modified to provide greater assurance of detecting cracking in the event that the problem persisted or recurred. Previously, the ultrasonic examination of the welds was done by the normal beam technique only. The revised examination now includes shear wave searching at various angles and directions in addition to the normal beam technique.

The ammonia converter pressure vessel discussed here is currently in fabrication. The latest reports available at the time this technical paper is written indicate that the cracking problem has been overcome, and welding is proceeding in a normal manner.

The experience with this ammonia converter pressure vessel demonstrates that constant vigilance is required in controlling and checking welding procedures and techniques. The authors

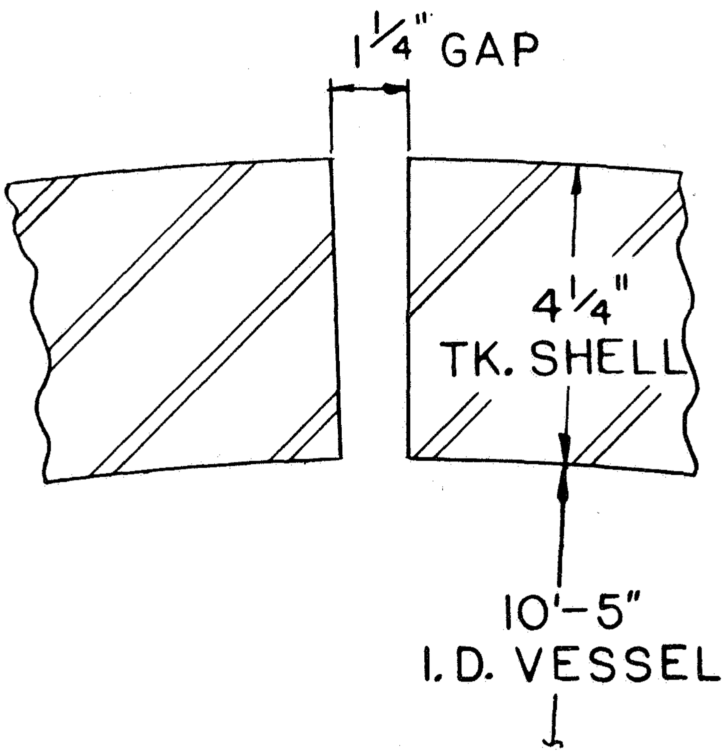


Figure 3. Plate preparation for electroslag weld of longitudinal joint of ammonia converter.

Table 4. Important variables in electroslag welding

TRANSVERSE ELECTRODE MOVEMENT RATE.	WIDTH OF GAP.
SPACE BETWEEN ELECTRODE AND SHOE.	WELDING SPEED.
ELECTRODE DWELL TIME AT SHOE.	WIRE DIAMETER.
DISTANCE BETWEEN ELECTRODES.	SLAG POOL DEPTH.
ELECTRODE WIRE PROPERTIES.	ELECTRODE CURRENT.
BASE MATERIAL PROPERTIES.	ELECTRODE VOLTAGE.
WELD POOL FORM FACTOR.	ELECTRODE STICK-OUT.

offer this example as a specific case where excessive variation from the original welding procedure occurred on a critical vessel, with serious consequences. The value of thorough nondestructive examination is also apparent here.

Cracking of nozzle attachment

Nozzle attachment welds in thick shells are potential areas of fabrication difficulties, particularly when the materials involved are low alloy steels. This can be illustrated by a case which occurred in late 1965 and early 1966 involving three shift converter pressure vessels for three ammonia plants, each plant having a design capacity of approximately 1,000 tons/day.

A contract for supplying the three identical vessels was placed with a single fabricator. An outline drawing is shown in Figure 4. Each vessel is actually two separate pressure compartments joined by an intermediate support skirt. The upper compartment was designed for a pressure of 485 lb./sq.in. and a temperature of 900 °F; the lower compartment was designed for a; pressure of 485 lb./sq.in. and a temperature of 700 °F.

The upper compartment was designed of carbon-molybdenum steel for resistance to hydrogen attack and for adequate allowable stresses at the elevated design metal temperature. For the lower compartment, carbon steel was the economic choice. No significant difficulties were encountered in fabricating the carbon steel lower compartments for the three vessels. On the other hand, serious problems arose in attaching nozzle "X" to the upper compartment of the first two vessels.

The general location of nozzle "X" is shown in Figure 4. Figure 5 is a plan view showing the nozzle and its attachment weld as originally designed. The nozzle is an 18 in. nominal size connection with a stub end for welding to the external pipe line in the field and an internal extension for attach-in an internal non-pressure pipe (not shown in Figure 5). The nozzle is slightly hillside in the shell, which is 14ft. inside diameter and 3.5 in. thick. Thickness of the nozzle forging wall where it passes through the vessel shell is 2.75 in.

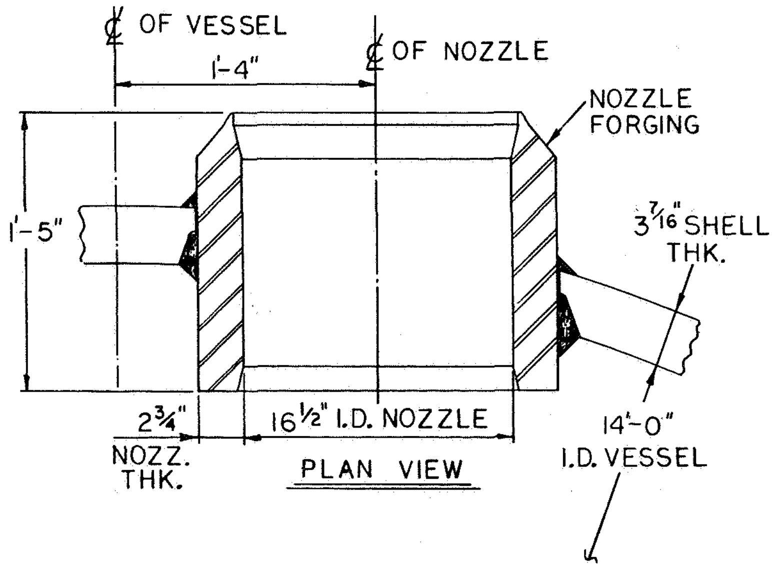


Figure 5. Original design of nozzle "X" for shift converter.

The engineering contractor specified that separate reinforcing pads were not permitted. The fabricator therefore elected to design the nozzle so that the required reinforcement was provided by excess metal in the nozzle neck inside and outside the shell. The fabricator's design for the attachment weld met all requirements of the A.S.M.E. Boiler and Pressure Vessel Code, Section VIII, Unfired Pressure Vessels, to which these vessels were designed and constructed. The shell material was SA-204 Grade B, fir box quality, and the nozzle material was SA-182 Grade F1.

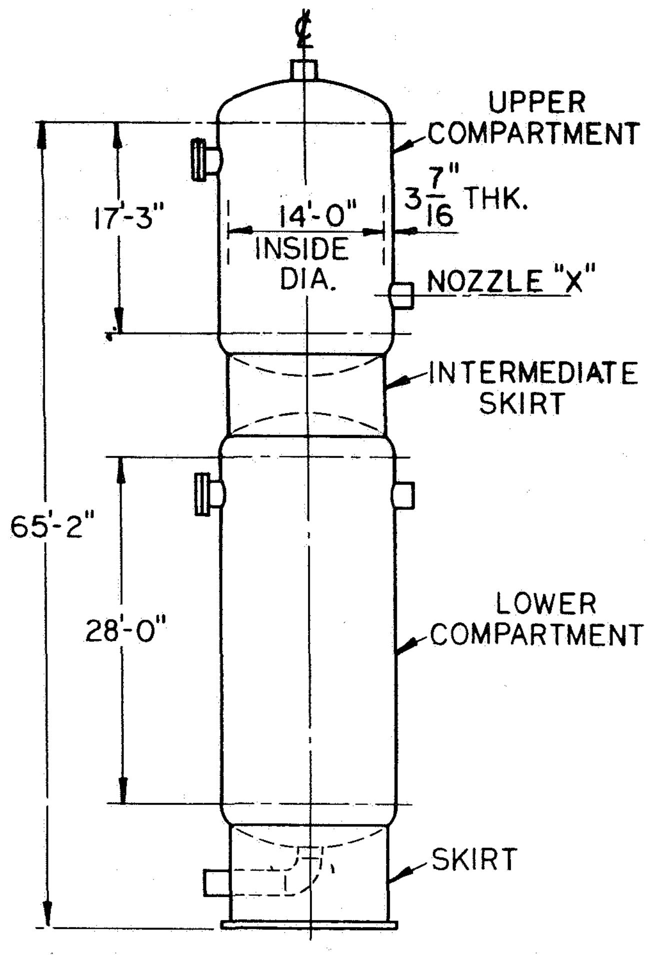


Figure 4. Elevation view of shift converter.

Fabrication experiences

Construction work on the three vessels proceeded sequentially in the fabricator's shop. On the first shift converter, some cracking of the attachment weld and nozzle forging occurred at nozzle "X". However, the difficulties were overcome by repairing and rewelding, with relatively minor delays in completion of the vessel. The original design of the nozzle attachment weld as shown in Figure 5 therefore was maintained in the welding and necessary repair work on the nozzle for the first vessel.

On the second shift converter, much more serious cracking was encountered at nozzle "X". The cracks were located as shown in Figure 6 and extended most of the way around the circumference of the nozzle. Repairs were unsuccessful, so the forging was cut out and scrapped, and a new forging obtained. The same type of cracking occurred when the new forging was welded into the vessel.

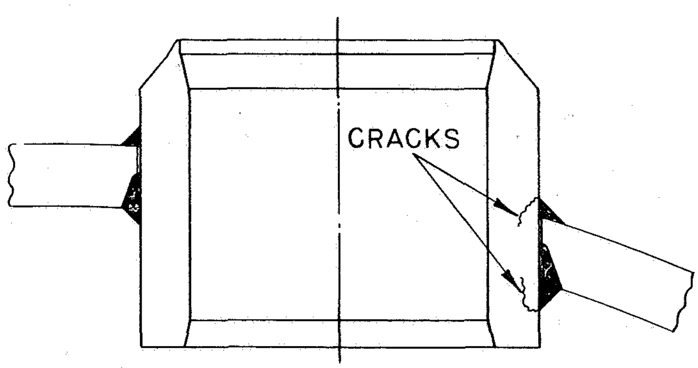


Figure 6. Cracking of original nozzle design for shift converter.

Careful repairs again were attempted, involving complete removal of the cracks by chipping and grinding, controlled preheat for welding, "buttering" the forging to replace metal chipped away, inspection for incipient cracks after each weld pass, local stress relieving before allowing the metal to cool from welding, etc. All this was to no avail, since the cracks repeatedly recurred.

The engineering contractor's design engineers, metallurgists, and inspection personnel then joined in a coordinated effort with the fabricator to determine the cause of the problem and evolve a successful procedure for this nozzle on the second and third shift converter vessels. Requirements for the new procedure were that the necessary high level of quality for these critical vessels be achieved and maintained, and that delays in delivery of the vessels be kept to a minimum.

The heat treatment of the forging and its physical and chemical properties were checked again and were found to be within specification limits. It was concluded that the principal cause of the cracking was thermal restraint between the thick shell and thick nozzle wall. Contributing factors were the unbalanced design of the attachment weld and the lack of full penetration of the weld through the vessel shell. Also, carbon-molybdenum steel on some previous occasions has shown tendencies toward sensitivity in welding, with cracking being a source of trouble. All of these factors apparently had combined in this case to cause the problem.

Design of new nozzles

The engineering contractor's vessel engineers proposed a new design for the nozzle attachment weld, which was developed into a final procedure through the joint efforts of the contractor's and fabricator's metallurgists, welding engineers, quality control experts, and inspectors. The new design is shown in Figures 7, 8 and 9.

A weld deposit was applied to the outside of the forging by submerged arc welding, after which the forging was normalized and the weld deposit machined as shown in Figure 7.

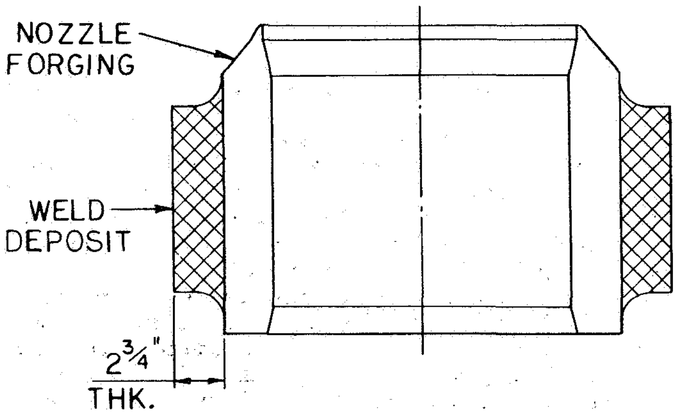


Figure 7. Weld deposit for revised design of shift converter nozzle "X".

A weld bevel for a full thickness double welded butt joint to the shell was machined into the weld despoit as shown in Figure 8. The final weld of the nozzle to the shell is shown in Figure 9.

The manual metal arc welding of the nozzle into the shell was performed by two welders working simultaneously at opposite points to obtain balanced thermal effects. The finished weld was then heat treated and examined by radiography and ultrasonics. Nondestructive examination, not described in detail here, was applied to the weldment at various intermediate stages of the work.

It should be noted that this design and procedure for the nozzle weld was directed toward counteracting to the maximum extent possible any tendencies toward sensitivity that the carbon-molybdenum forgings may have had. Furthermore, the design provided for complete assessment of quality of all welding

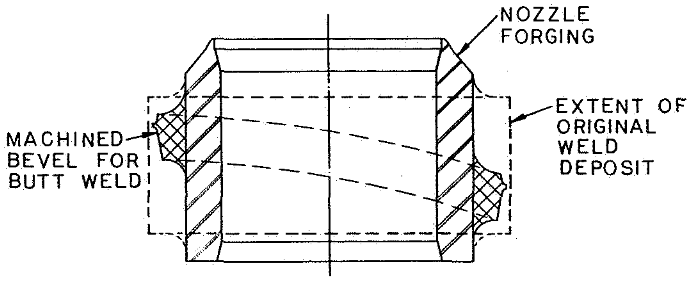


Figure 8. Revised design of nozzle "X", ready for welding to shell of shift converter.

by means of nondestructive examination. This type of nozzle attachment is permitted for nuclear reactor pressure vessels by the A.S.M.E. Boiler and Pressure Vessel Code, Section III, Nuclear Vessels, Figure N-462.4 (c) (2).

The planned procedure for attaching nozzle "X" as described above was applied to the second and third shift converter vessels. It proved to be completely successful on both these vessels. No problems were encountered and there was minimum disruption of delivery schedules for the vessels.

Leakage of Tubesheet joint

Tube-to-tubesheet joint integrity is an essential feature of a reliable shell and tube type heat exchanger. When the seal is made by expanding the tube into the tubesheet, its effectiveness depends upon the contact pressure between the tube and the tubesheet. The joint fails when this contact pressure is lost or greatly reduced for any reason.

Accordingly, it is reasonable to expect that a welded joint will be more reliable since it provides a metallurgical bond. Unfortunately, the art of welding relatively thin wall carbon steel tubes to thick, 70,000 lb./sq.in. tensile strength carbon steel tubesheets economically is not as well developed as the need for such joints.

The problem is aggravated by the fact there is no simple nondestructive test which will detect the presence of sub-surface flaws of the most serious nature. Figures 10 and 11 are examples of such defects. The usual practice is to develop a procedure which is capable of producing sound joints as demonstrated by leak tests and random sectioning of representative samples, and then to assume that all joints produced by such a procedure which are free of leaks and/or surface defects are sound.

In the current generation of ammonia plants there are a number of exchangers of the general type shown in Figure 12. The high pressure, somewhat above 2,000 lb./sq.in. gauge is on the tube side and the shell side design pressure is 150 lb./sq.in. gauge.

Considerable difficulty was experienced with the tube joints of one such unit at the plant of a leading American heat exchanger manufacturer early in 1965. The history of these joints will be reviewed in some detail here because unfortunately it was not an unique experience, but rather one that practically all heat exchanger manufacturers have gone through at one time or another. It is an experience that can be avoided, however, by

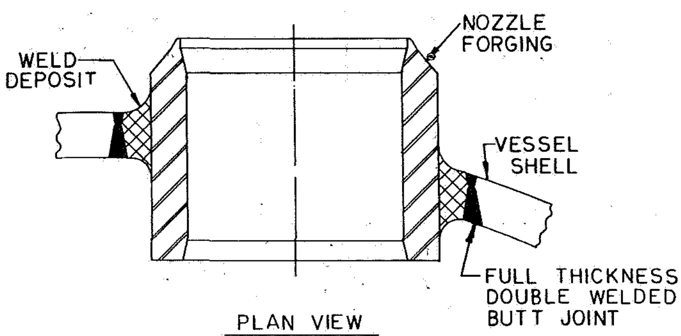


Figure 9. Weld of nozzle "X" to shift converter as successfully completed.

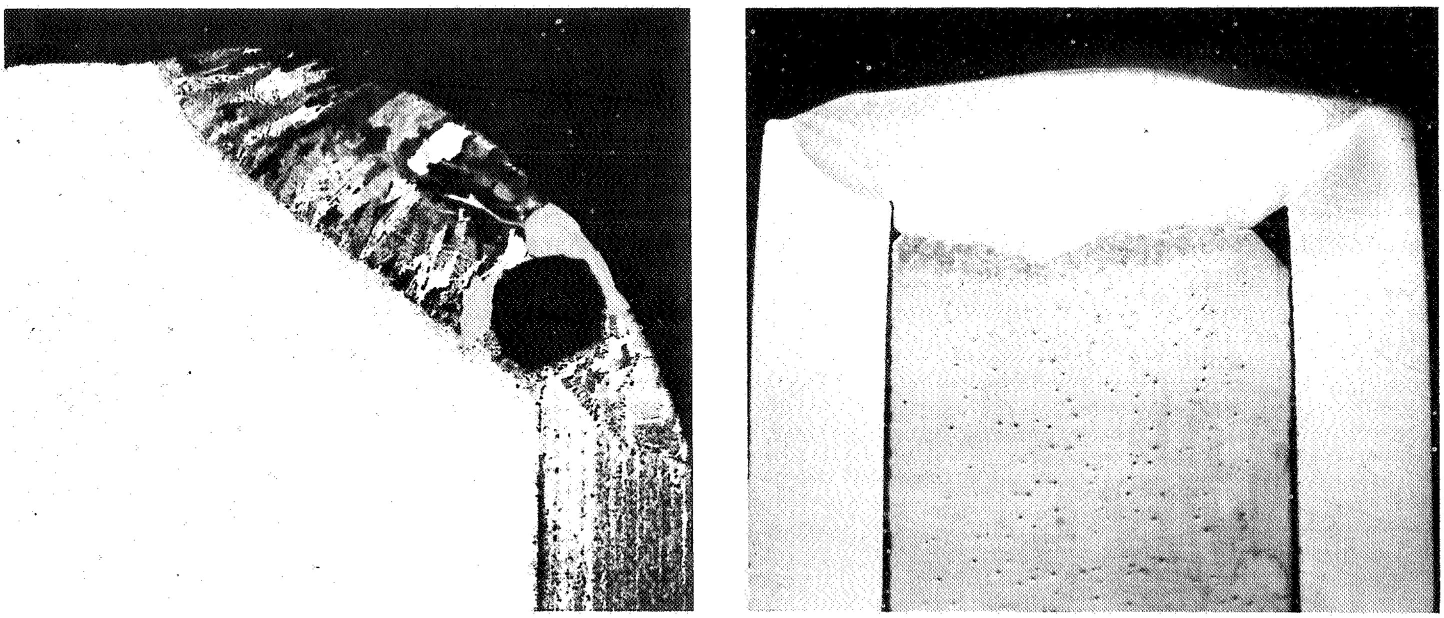


Figure 10 and 11. Welded tube joint samples with serious defects in subsurface.

proper procedures, and by a proper regard for cleanliness requirements.

Figure 13 shows the tube joint geometry. The welding was performed in two passes using the T.I.G. process with filler metal. The tube joints were welded before the welding of the pass partition plates and the reverse flange to the channel barrel.

Upon completion of the tube joint welding, a 15 lb./sq.in. gauge air test was applied to the shell side and a soap suds solution was brushed over the tube welds. Some one hundred leaking joints were found. Repairs were effected by removing all weld metal at these joints and re-welding.

On retesting, 15 leaks were found. The defective welds were again removed, and the joints re-welded. The number of leaks on the next air test was five, which were repaired in the same manner, and finally the unit was tight under 15 lb./sq.in. gauge air. It should be noted that the leaks discovered on retests were not necessarily at joints which had leaked on the preceeding test.

A Freon and air pressure test at 125 lb./sq.in.gauge was then applied to the shell, and a G-E type 2-H halogen leak detector disclosed three additional tube joint leaks. These were repaired and on the subsequent Freon test, a single fine leak was found after prolonged probing. This was repaired and no more leaks were found on retesting with 125 lb./sq.in. gauge air and Freon. A 225 lb./sq.in. gauge shell hydrostatic test was then applied, and it too disclosed no leaks.

The tube joints therefore were expanded, and the fabrication of the channel was completed. When the tube side hydrostatic test of 3,375 lb./sq.in. gauge was applied it became evident that some tubes were leaking. Accordingly, the tube side was drained, the channel cover was removed and a 125 lb./sq.in. gauge air pressure was applied to the shell side. Over two hundred joints leaked. Leakage was due to subsurface porosity which had cracked open during the hydrotest.

These were repaired and when tight under shell side pressure, another tube side hydrostatic test was applied. Again tube leakage was indicated. The channel cover was removed once more and surface examination again showed that leakage was due to subsurface porosity which had been cracked open by hydro testing.

Test procedure adopted

At this point, there was no longer any doubt regarding the fact that something was basically wrong with the tube joints.

A small test exchanger was fabricated, and it was demonstrated by a variety of tests. These included the cyclic application of 4,500 lb./sq.in. gauge hydrostatic pressure, and sectioning, that perfectly satisfactory joints could be produced using the same procedure and filler wire initially used in the exchanger. Equally satisfactory joints were also produced using the same prtcedure but substituting a filler metal having a larger amount of deoxidizing agent.

In view of these test results, the manufacturer decided to attempt to repair the exchanger by a complete rewelding of all the tubes. Accordingly the reverse flange was removed from the channel, and all tube joint welding was ground or machined away by regrooving the tubesheet around the O.D. of the tube. The tubesheet was preheated and allowed to soak for an 8 hr. period. All tubes were then rewelded using the filler wire with the larger content of deoxidizing agent.

This exercise proved futile, for on applying a 200 lb./sq.in. gauge air test to the shell and soap suds to the tubesheet face, more than a hundred leaks appeared. Surface grinding again disclosed the presence of subsurface porosity.

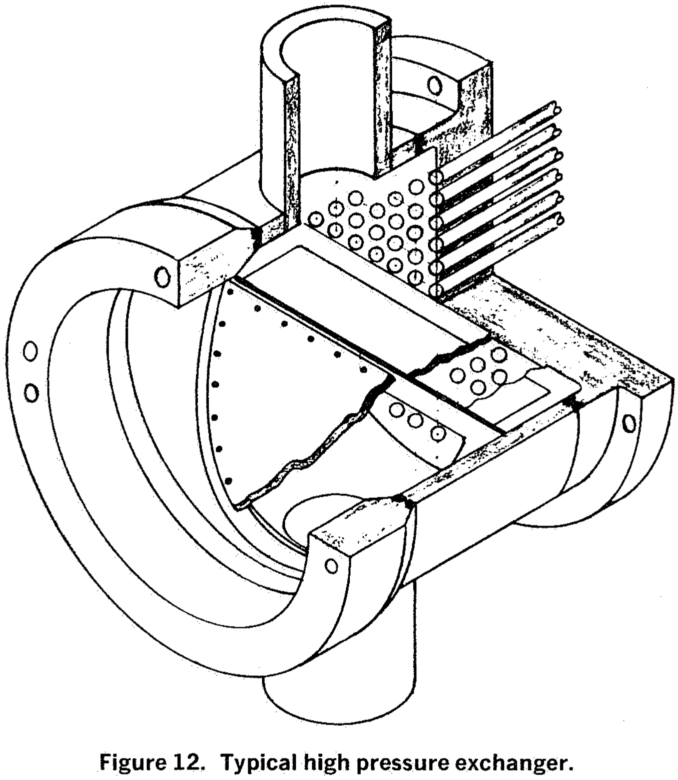


Figure 12. Typical high pressure exchanger.

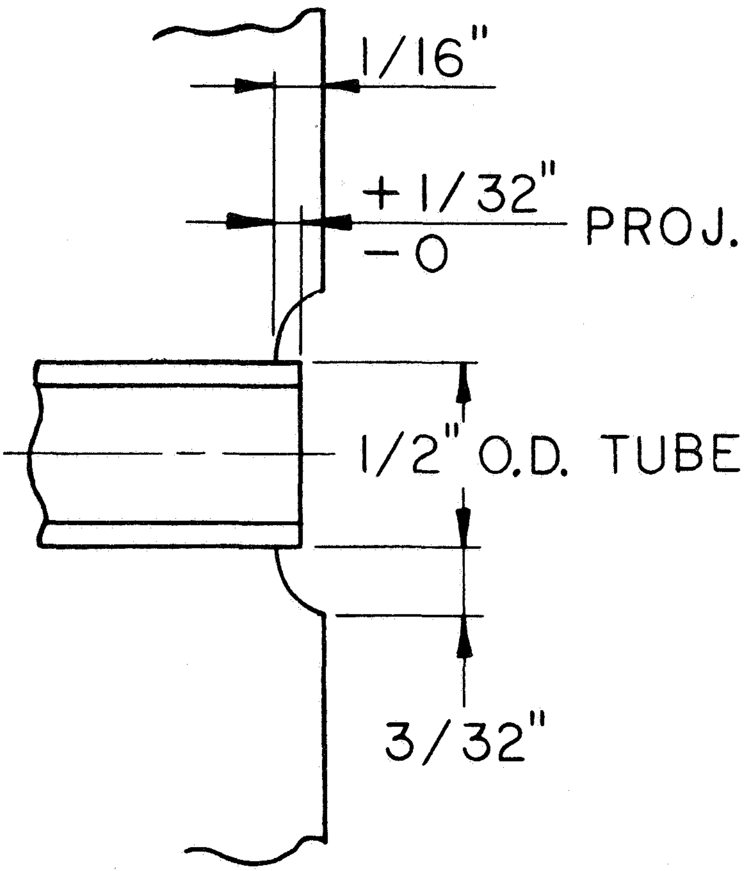


Figure 13. Tube joint preparation.

At this point, it was agreed by both the exchanger manufacturer and the engineering contractor that further attempts at repair would be useless. The tube joints were obviously contaminated to such an extent that welds free of porosity could not be produced without a fresh start. Contamination could have been caused by inadequate initial cleaning, by lubricants during the tube expanding process, by the numerous hydrostatic tests, and possibly simply from the cumulative effect of ordinary shop dirt during the long period the tube joints were being welded and repaired.

In order to minimize delay in delivery, it was decided to salvage the exchanger by cutting off that portion of the tubes which had been expanded into the tubesheet, and rebuilding the exchanger with the shortened tubes. This would reduce the effective tube length by about 2-1/4 in., a negligible amount. All welding on the tubesheet face was removed by end milling. This resulted in reducing the tubesheet thickness by 3/16 in. but fortunately there had been an excess and the remaining thickness was still adequate for the design conditions.

The rebuilding procedure emphasized the absolute necessity for completely cleaning all elements of the tube joint before welding and keeping them clean throughout the welding and preliminary testing operations. Cleaning was accomplished by steam jets, power brushing, swabbing with acetone, etc. Once clean, the channel and entire bundle assembly was kept covered to protect against contamination by shop dirt.

The salvage operation was quite successful and this exchanger has given trouble-free service now for nearly two years.

Conclusions about tube leaks

This and similar experiences in other shops suggest the following conclusions:

1. It is possible to produce sound tube joints with a variety of joint geometries and welding techniques. Given appropriate chemistries, sound joints can be produced with or without filler metals.
2. Regardless of chemistry, geometry or welding technique, it is *not* possible to produce consistently satisfactory joints between typical heat exchanger tubes and their tubesheet without first thoroughly cleaning all components, and then keeping them clean and dry throughout the welding, testing, and subsequent repair welding operations, if any. Among other things, this means that there must be no hydrotests until all joints have been proven tight by suitable pneumatic tests.
3. Expanding the tubes before welding cannot be tolerated. It is recognized that with some automatic and semi-automatic welding procedures, it is essential to obtain metallic contact prior to welding in order to insure uniform conditions around the entire circumference. Indeed this is desirable with any type of weld, but such line contact can, and must be produced without achieving a seal.

This can be done with a specially designed expander, or with a suitable "drift" pin which will produce essentially a line contact between the tube and tubesheet at the tubesheet face. The expander or other tool used to produce this line contact must be clean and dry. No lubricant of any kind should be used.

A detailed discussion of all aspects of welded tube joints is beyond the scope of this paper. Such discussions have appeared in the literature with increasing frequency in recent years.

We do wish to touch upon two other elements of importance in any welded joint. We feel that: (a) A minimum of two weld passes should be provided, and (b) after the weld has been proven tight by suitable pressure tests, the tube should be lightly expanded into the tubesheet. The latter step will prevent the imposition of cyclic bending stresses on the welded joint, and can serve also to minimize the danger of crevice corrosion when the environment provides such a threat.

Inadequacies of thick forgings

The channel forging for a feed and recycle gas third stage chiller was required to be in compliance with A.S.M.E. specification SA-350 LF-2 except that impact values of 13 ft. lb. average at -50°F on Vee notch specimens were specified. The forging was produced, rough machined and delivered to the heat exchanger manufacturer with test reports indicating Vee notch impact test results of 18, 17 and 15 ft. lb. on the three specimens tested and chemistry within specification limits. The rough machined forging is shown in Figure 14 and the complete exchanger channel is quite similar to that shown in Figure 12.

Since the exchanger manufacturer was required to make impact tests of weld and heat affected zone specimens, he made use of the nozzle cut-outs from the forging for this purpose. When he ran into very low impact values in the heat affected zone, he decided to make additional tests on the base material and obtained results of 3, 4 and 3 ft.lb. on three specimens, respectively.

These results were unacceptable to the engineering contractor and to the ultimate user. But the forging was not rejectable because it had been produced and test specimens had been taken in full accordance with the specifications. Since all requirements including impact properties had been met at the forge shop, there was no basis for rejection. Furthermore rejecting the channel forging was certain to delay the job.

It was established that the forging manufacturer had started with a billet smaller in diameter but longer than required by the final forging, and had worked this billet so as to produce a disk somewhat thicker than 30 in. The disk then was punched at the center of one of the flat sides so as to produce a relatively shallow recess with a correspondingly short peripheral prolongation from which the required test samples were taken after heat treatment. This meant that the test specimens were taken from a section of the forging which cooled rapidly compared to the balance of the piece. The required final shape was obtained by hogging out the forged disk.

It is clear of course that the test specimens in this case were not representative of the properties of the material in the rest of the forging. Nevertheless it is claimed that this practice is permitted by the wording of the specification and that it is commonly employed.

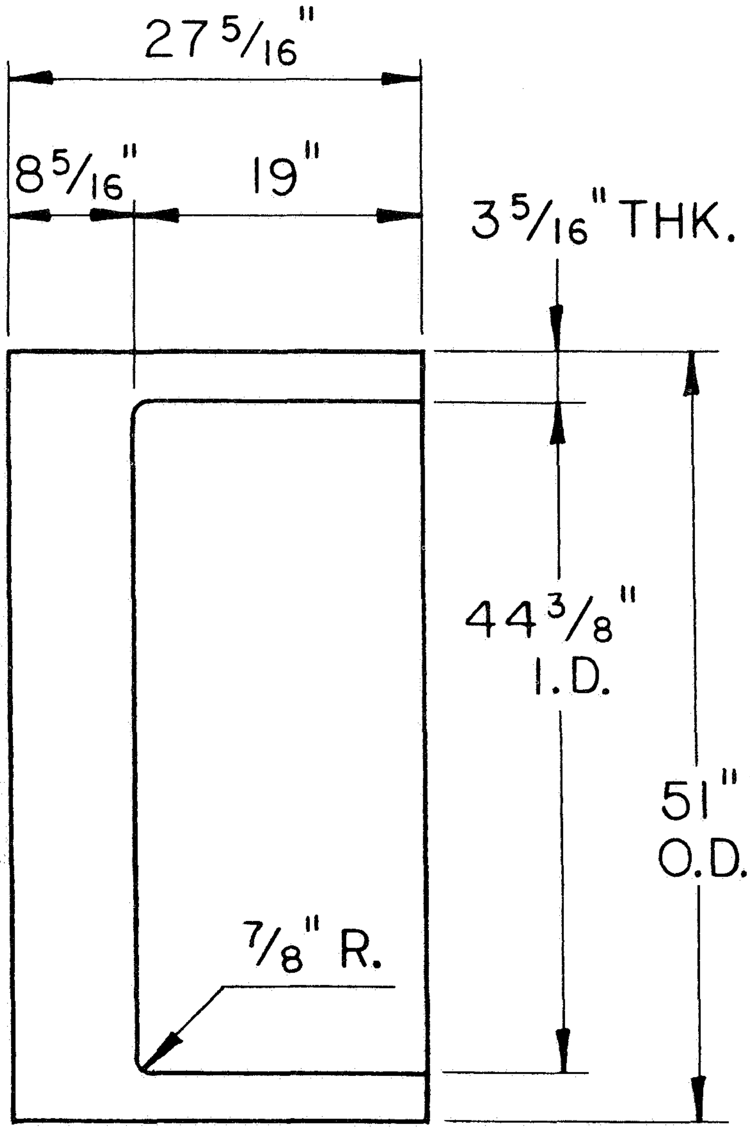


Figure 14. Heat Exchanger channel forging.

Heat treatment used

Since the prolongation of the forging was known to have satisfactory properties, it seemed reasonable to expect that an appropriate reheat treatment of the finished forging would improve its impact properties to a satisfactory level. This was shown to be the case by heat treatment of samples taken from the nozzle cut-outs. Since the forging was now machined to its final dimensions, reheat treatment involved the risk of loss due to warpage or excessive scaling, but the possibility of eliminating a serious delay made it easy to accept this risk.

In order to obtain as uniform properties as possible, about 150 undersize holes were drilled in the tubesheet properly located to fit the tube hole pattern. To minimize scaling, two layers of a protective coating were applied to the entire forging. Two closely fitting 2 in. thick diskswith appropriate cut-outs to permit flow of both heating and cooling media were braced together and tacked to the I.D. of the forging in order to minimize distortion. Test samples from the original nozzle cut-outs were attached to the inside face of one of the disks.

The following heat treatment was agreed upon by the interested parties:

1. Heat at a rate of 100°F or less per hour to 1,600°F and hold for 2 hr.
2. Quench into agitated water at 150°F with open end up. Raise and lower the forging in the water during the quench to facilitate water circulation through the tube holes to the inside of the channel. Continue the quench until the metal temperature reaches 300°F.
3. After the channel has been quenched to 300°F, place immediately into a furnace already at 550°F. Heat to 500°F and hold for 2 hr.; then heat to 1,175°F at the rate of 100°F or less per hour and hold for 2 hr.
4. Furnace cool to 400°F, and cool in still air to room temperature.

Subsequent to this heat treatment, impact and other physical properties obtained from test specimens cut from the samples heat treated with the forging were all found to be within specified requirements. The channel forging was grit blasted to remove the coating applied to minimize scaling. Thickness loss and distortion were found to be negligible. The channel was therefore salvaged for use in the heat exchanger.

Rupture during hydrostatic testing

In February, 1967, the installation of a synthesis gas compressor aftercooler in a brand new 1,000 ton ammonia plant was completed. It was in the process of being hydro-tested when massive failure of the channel occurred by brittle fracture. Hydrostatic pressure had reached 3,490 lb./sq.in.gauge in the channel when failure occurred in spite of the fact that the exchanger had previously successfully undergone hydrostatic testing in the manufacturer's plant at the full test pressure of 3,525 lb./sq.in.gauge.

During the shop testing, the channel nozzles were capped and the channel rested directly on timbers on the floor so there was no load on the permanent supports welded to the outside of the channel. In the field, the nozzles were welded to inter-connecting piping and the channel weight was taken by its permanent supports which were bolted to concrete piers. The temperature of the test water and surroundings was about 60°F in the shop and around 40°F in the field.

Details of the channel construction are shown in Figure 15. It consists of separate tubesheet, barrel, and flange forgings welded together. The nozzle forgings were welded into the channel assembly prior to stress relieving as were three strips of the horizontal pass partition, one to the tubesheet and one on each side of the channel interior.

The central part of the horizontal partition was welded to the strips, previously welded to the tubesheet and to the channel, after the tubes were welded to the tubesheet, tested and expanded. The ellipitical segment to which the pass cover plate is bolted was also welded to both the channel and to the horizontal partition after the tube joints were completed, and after final postweld heat treatment of the channel.

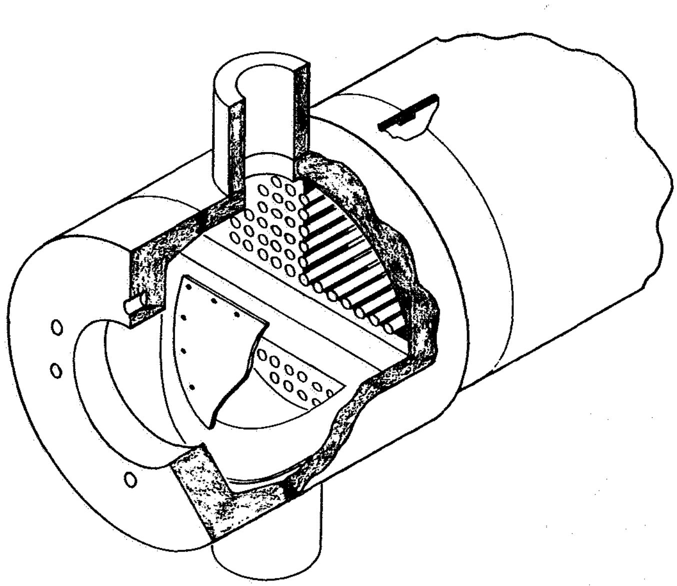


Figure 15. Synthesis gas compressor after cooler channel.

Nature of the failure

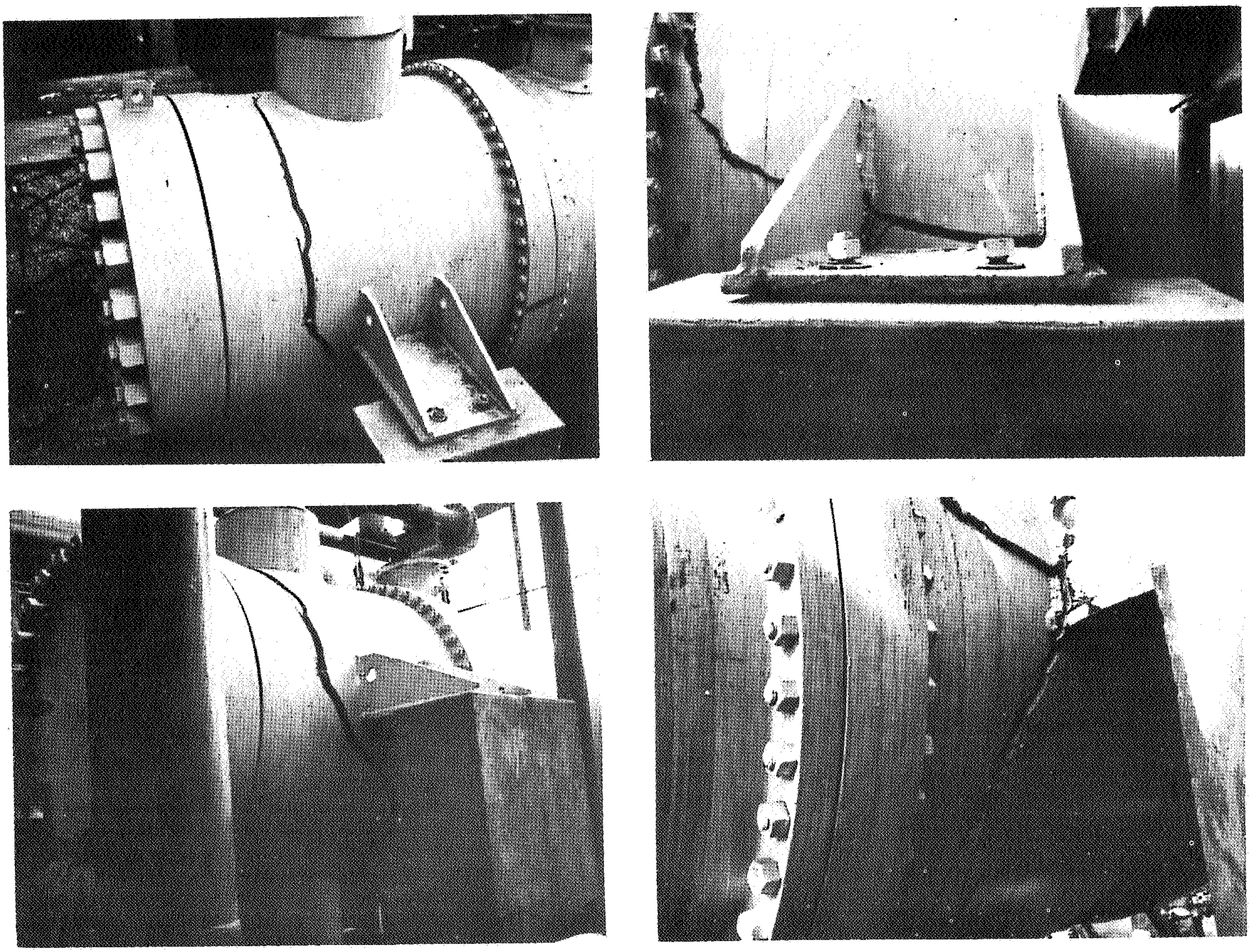
The extent and nature of the failure can be seen in Figures 16 to 19 inclusive. It is quite clearly a brittle failure. This is most unusual in view of the fact that the exchanger had previously been hydrotested without incident. In fact, the fabricating procedure employed required that the channel be tested twice; once to prove the tube joints after they were welded and before welding the internal partitions, and then again after all welding was completed. On this final test, the pressure was cycled from 0 to 3,225 lb./sq.in.gauge three times.

This failure casts considerable doubt on the validity of the widely held belief that brittle fracture is a danger only on initial pressurization; that once successfully tested subsequent pressurizations even at lower temperature (within code limits) will not result in failure.

The significant differences between the shop and field test conditions have already been enumerated. Water and ambient temperature was about 40°F in the field and around 60°F in the shop; exchanger nozzles were welded to inter-connecting piping in the field while they were capped in the shop; and in the field the channel weight was supported by concrete piers via the permanent support brackets welded to the channel while in the shop the channel had rested directly on timbers laid on the floor.

In order to learn as much as possible from this failure, an outside laboratory was engaged to conduct a thorough investigation. We are not yet in a position to discuss the results of their investigation in detail. But it confirms the preliminary findings of our own metallurgists that the brittle fracture resulted from the propagation through the channel barrel of a toe crack along the weld between the horizontal pass partition and the channel at the junction of this partition and the inclined pass cover plate holder, Figure 20.

The failure adds to the mounting evidence that there must be an upgrading of carbon and low alloy steel plates and forgings of heavy cross section. It also indicates that initial pressurization, both in the manufacturer's plant and in the field, should be made at a temperature higher than the probable transition temperature of the material. Further, it indicates internal pass partition attachment welds must be more carefully examined both for quality and strength. This is particularly true of welds subject to high residual stresses not relieved by post weld treatment. Better yet, such welds should be avoided.



Figures 16, 17, 18, and 19. External views of fractured exchanger channel.

Conclusions

The six fabrication problems described are typical of those faced by industries associated with large process plants. They were selected to demonstrate the broad area of equipment fabrication involved; material production, design, welding, fabrication procedures, heat treatment, and testing, all can cause serious problems.

There are some significant similarities among the problems described:

1. All occurred with equipment contracted with high quality, well-known fabricators in Europe and the United States.
2. All the equipment was specified to meet the requirments of recognized codes and specifications.
3. All failures occurred prior to start-up of the plant, and the

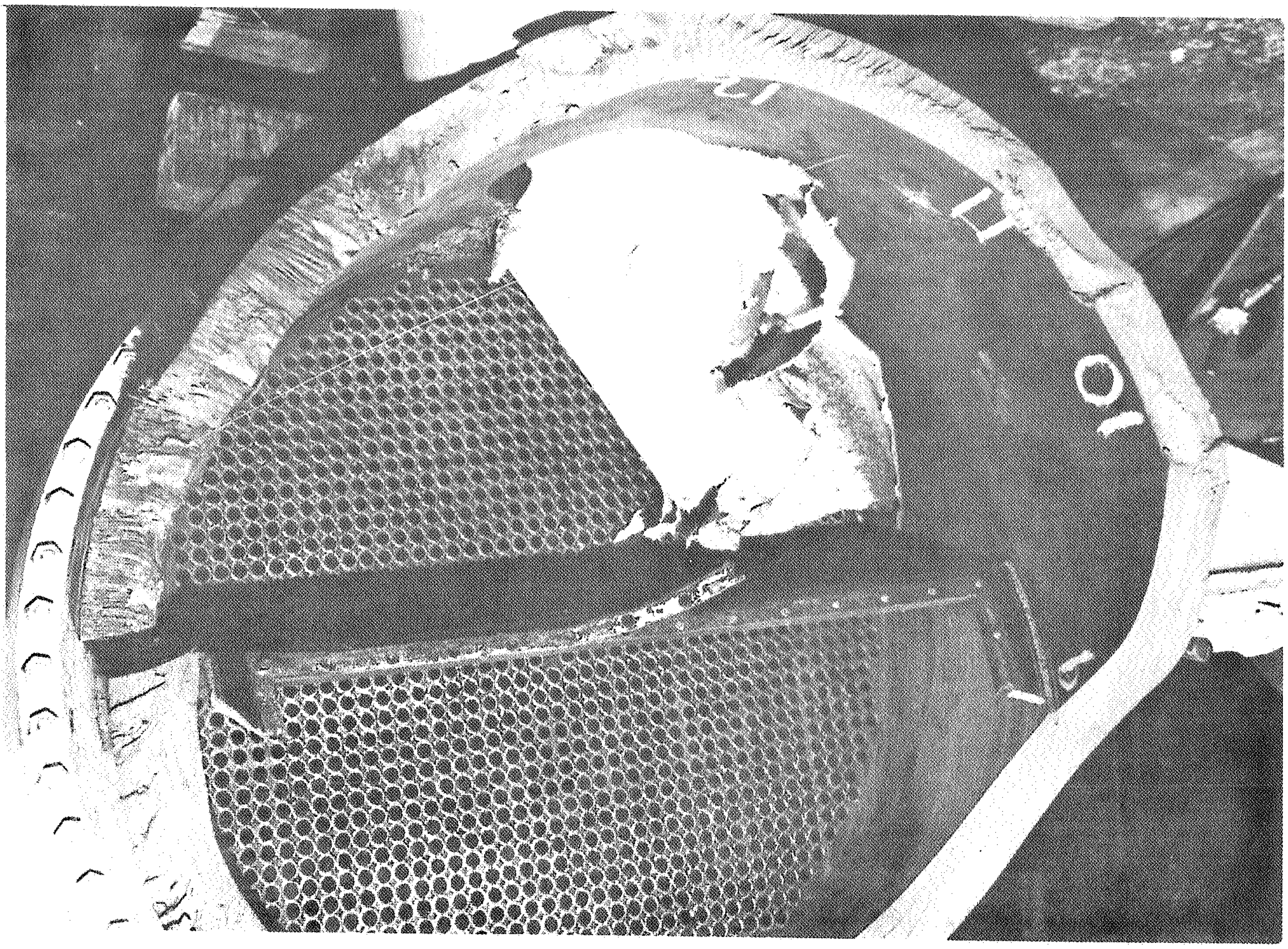


Figure 20. Internal view of fractured exchanger channel.

corrective measures resulted in a level of quality of the finished product which, to the authors' knowledge, has given no service difficulties.

4. The consequences of these failures were primarily serious delays in the delivery schedules, large financial expenditures by the parties involved and, in most cases, an extreme concentration of engineering effort by the fabricators, contractors, and users to find acceptable solutions.

The authors have concluded that only an industry-wide effort can reduce or prevent similar problems in the future. The nuclear power industry in the United States and abroad has recognized the need to demand a level of quality in its equipment commensurate with critical service requirements.

Similarly, the process industry must reappraise its requirements for design, materials, fabrication, and testing. With larger process plants to come, the current trend towards inadequate quality must be halted. The knowledge to bring about an improvement in reliability exists now. Proper application of this knowledge may well lead to a reduction in total plant costs despite possible increases in initial outlay for equipment, and will result in progress toward the vital objective of more reliable and safer plants.

Literature cited

"Ultra Large Single Stream Chemical Plants: Their Advantages and Disadvantages" by Sir Ronald Holroyd F.R.S. *Chemistry and Industry,* Aug. 4, 1967.

Discussion

Q. You made the statement on Carbon-Moly being sensitive material. I'd like some amplification of that. Also, is there a possibility of loss of ductility with tube sheet welds? Third, does the new code Division 2 of Section 8 meet the needs of the process industry in regard to improving the level of fabrication?

ESCHENBRENNER: To the first question, I believe you are referring to previous difficulties with Carbon-Moly. I know that on occasion this material has given difficulty with cracking during welding or in service. To my knowledge it is not a very frequent occurrence, but it has occurred more frequently than with carbon steel or the chrome alloys. I cannot state why. The best proof that the material is basically acceptable is that we experienced failures with complex geometries such as nozzle forgings while the rest of the vessel never had this problem.

On the tube joint problem, there are a number of things which can contribute to tube joint failures. In the cases I cited we pinpointed the problem to the lubricant used in rolling the tubes plus other shop dirt. Once it is present it cannot be removed easily. Explosion expanding has on occasion made it possible to correct the joint without extensive cleaning but then one has to rely on the expanded tube to maintain tightness.

I do not know whether the new code will do the job of meeting all needs. It will go a long way to improve over the present Section VIII for Critical Equipment. To what extent it will prevent some of the problems described here, I do not know. Division 2 has made an attempt to require more controls on materials and this may initiate the development of improved steels, this is as important as improvements to Codes, design and fabrication.

Q. *In the example described concerning the cracking of the* electric slag welding, did the weld pass the X-ray test before the ultrasonic test?

ESCHENBRENNER: No these cracks were found with ultrasonics prior to X-ray.

Q. What was the difference between the eighth one and the other seven?

ESCHENBRENNER: The other seven were successfully welded without cracking. For the eighth converter the fabricator chose to increase the carbon content of both the weld wire and the material. This was the only really significant difference we could find.

Q. What was the preheat temperature used for welding in the half-moly branch which cracked?

ESCHENBRENNER: The actual preheat temperatures were as follows: original 150°C., for rework raised to 200°C.

Q. Have you considered the prospects of carrying out a full program of radiography or other non-destructive testing before, rather than after stress relieving?

ESCHENBRENNER: This we have related to the material, the service, and the Code applied. If we consider high strength materials, low safety factor with use of foreign codes, we will require radiography after the final stress relief. Actually, if you specify this you pay for it twice since most fabricators will perform the radiographic examination also prior to the final stress relief.

Q. With the example of the heat exchanger which failed the hydrotest in the field after passing the shop test you indicated the temperature in the field was, roughly 20 degrees less: 40 degrees in the field, 60 degrees in the shop. You indicated this wasn't significant. At the Atlantic City Meeting (Volume 9) I believe considerable significance was attached to a converter which was hydrotested and I think the temperature was 50 degrees. Since that temperature is right in the range you've mentioned, I wonder if it could be possible that more significance should be attached to the temperature difference?

ESCHENBRENNER: I cannot go into too much detail of the causes of this failure but I think it significant that both 40 and 60°F. are below the transition temperature. The conclusion we reached is the desirability to stay above the transition temperature if at all possible.

Q. What temperature would you have in mind?

ESCHENBRENNER: With 2-4 in. thick exchangers and carbon steel of the improved ASTM 516 specification we are talking in the range of 70-100°F. as being safe.