ULTRASONIC TESTING OF CRITICAL EQUIPMENT

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While all equipment is subject to failure under service conditions, the probability of failure for some items is greater because the function served in the production cycle subjects that equipment to physical phenomena that more readily produces failure. The physical phenomena, referred to in this instance, are those which initiate or accelerate fatigue cracking, such such as stress reversals, rapid stress loading, vibration or numerous stress cycles, and those which increase stress levels through thinning of metal, namely corrosion or erosion. Described herein are some service failures and the use of ultrasonic test equipment to locate service developed defects prior to component failure which is, accordingly, believed to have enhanced plant safety. By the term "critical equipment," one means those items of equipment which, based on experience, have proven more prone to fail because of the above described reasons. These are classified, for discussion, into three groups, namely:

(1) compressor components, (2) pressure vessels, and (3) pressure piping.

Periodic testing reduces failures

Operating experience over a number of years has shown that a program of periodic ultrasonic testing can measurably reduce the number of in-service failures of such equipment. Actually, the frequency of in-service failure of pressure vessels or pressure piping has historically been extremely low; however, the nature of such failures with the instantaneous release of the high energy content makes any failure virtually intolerable. On the other hand, while the frequency of failure of certain compressor elements has been somewhat higher, the attendant hazard to personnel is markedly less. Thus, the program of ultrasonic testing of compressors is based on air compressor failure experience, whereas, the testing of pressure vessels and piping is planned primarily to completely prevent failure.

Under each class of equipment a few typical failures or conditions leading to eventual failure are cited to demonstrate the hazards involved and, thus, the improved plant safety through elimination of failures. The economic advantage obtained from the ultrasonic testing program will also be evident from these examples.

Compressor failures

While the failure of a large compressor was said to be less hazardous than a high pressure vessel rupturing under gas pressure, it is nonetheless hazardous to personnel as well as a major economic loss in repair costs and production outages. Costs in excess of $25,000 are common for such failures. Also, anyone who has assisted in shutting down a booster-expander, which is handling 2 million cu. ft./hr. of 2200 lb./sq. in. air, because of a broken crankshaft, might even question the relative degree of hazard.

One compressor failure occurred when a connecting rod bolt broke and the nut, containing the threaded end of the bolt, wedged between the crankshaft and the frame on the high pressure air side of a 2500 hp steam-driven reciprocating air compressor. The sudden stop of the rotating elements, and adsorption of the inertia of these and other moving parts including a 1200 lb. counterweight, caused failure of the counterweight retainer bolts. Following this, the counterweight was forcibly ejected through the top of the frame and was stopped when it lodged against an intercooler, otherwise it would have traveled much farther. The counterweight hood was thrown 10 to 15 ft. from the machine. Major damage included: (1) the main frame was cracked for a length of over 400 in., (2) the throws on both ends of the crankshaft were rotated about 10°, (3) the trombone rod and crosshead pin were cracked, and (4) the intercooler was damaged. There was no injury of personnel even though two maintenance men had just arrived at the machine to investigate the unusual noise caused by the nut not yet wedged. The compressor was out of service for 17 days with a corresponding loss of production.

In Figure 1, a section of the main frame is seen in the center; the broken portion of it is shown above with arrows indicating where it was originally joined to the frame. Below is seen the broken counterweight. A main crosshead pin, connecting rod bolt, and trombone rod from this same accident are shown in Figure 2. All have typical cracks.

High pressure steam rod failure

In another compressor failure, the high pressure steam rod on a unit identical to that previously described, broke at its threaded junction with the

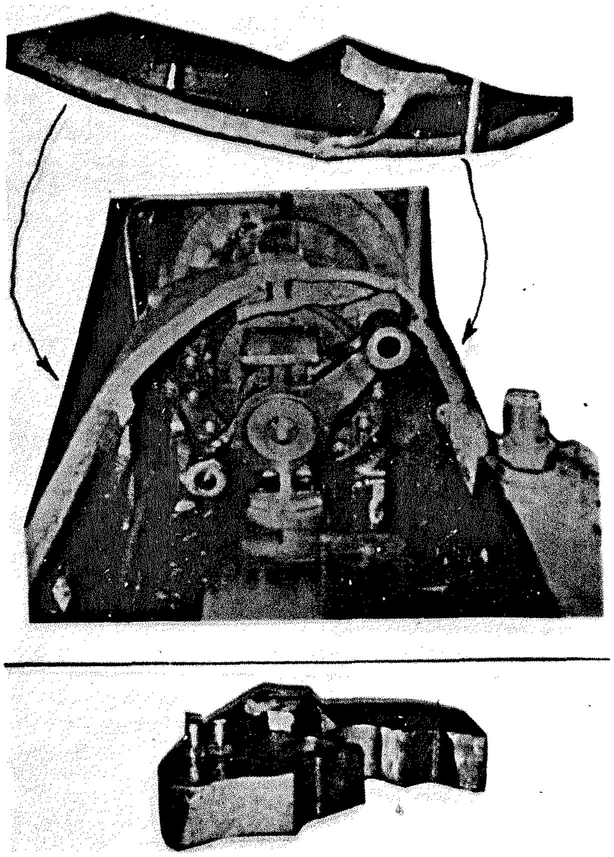

Figure 1. Section of the main frame (center): broken portion of main frame (top); broken counterweight (bottom).

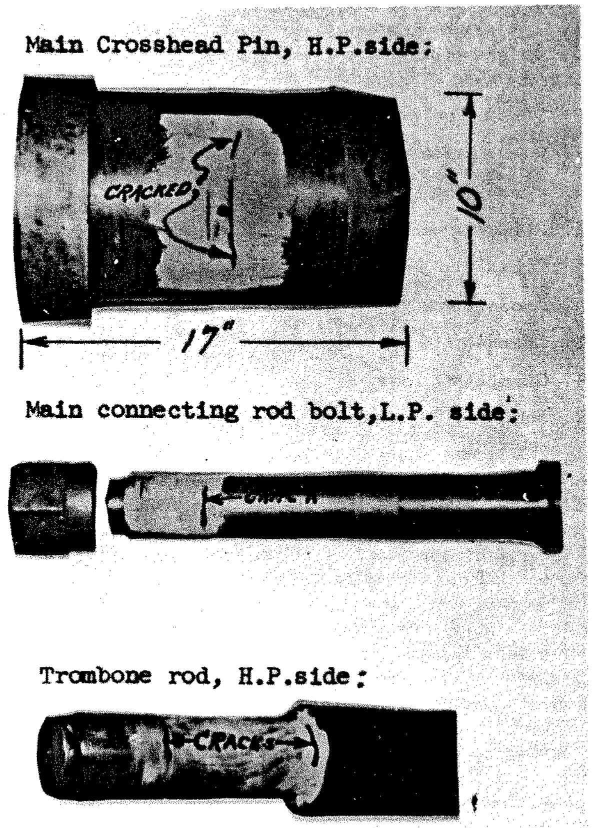

Figure 2. A main crosshead pin, connecting rod bolt, and trombone rod from the same accident as shown in Figure 1.

crosshead. On the next stroke, the inertia of the piston and rod had to be absorbed by the frame. As a result, the frame and tail rod pedestal broke. The tail rod pedestal cap, which weighed about 50 lb., was thrown 15 ft. where it struck and damaged a building column. Again there were no injuries. However, major repairs were required including a new frame, pedestal, piston rod, trombone rods, and attendant parts. Fortunately, the steam lines were not broken and so escaping high pressure steam was not a hazard. This compressor was out of service for 32 days with the resultant sizeable loss of production.

Another compressor failure involved a 4000 cu. ft./min. centrifugal oxygen compressor operating at 38 lb./sq. in. discharge pressure and driven at 10,000 rev./min. by an 800 hp turbine. In this case, the main shaft broke adjacent to the fifth-stage wheel because of a fatigue crack which initiated in a sharp notch caused by improper machining at a reduction in cross-section between the bearing area and wheel attachment area. As a result of the breakage, a fire occurred with ignition probably resulting from frictional heat generated between the two portions of the 5-in. diameter rod, rotating at high speed while in the presence of the 38 lb./sq. in. oxygen. The fire consumed part of the shaft and the fifth-stage wheel and case before the machine was stopped. Again, fortunately, there was no injury to personnel.

Pulse-echo type sonic device

Failures of this type, occurring even at infrequent intervals of years, certainly increase operating hazards and are also economically costly. In searching for some method of preventive maintenance, consideration was given to developing techniques for locating service-developed defects before failure occurred. It was found that the Sperry Rand Co. was marketing an ultrasonic testing device called a Reflectoscope. This is a pulse-echo type sonic device which reportedly would permit testing of steel shafts up to 30-ft. long, in-place, with accessibility from only one end and with detection of flaws of minute size. This sounded ideal for compressor testing. Extensive testing proved the instrument to be very effective in locating metal defects in either simple or complicated shapes. It was decided to try a program of preventive inspection by periodically testing those components which had a record of failure, to determine whether or not the number of actual in-service failures could be reduced.

The components which will most often develop fatigue cracks and eventually fail in service, will vary with different types of compressors. However, fatigue cracking normally occurs at stress concentrators in parts which are highly stressed and subjected to numerous stress cycles, especially stress reversals. In a reciprocating compressor there are a number of parts which are subjected to stress reversals during each revolution and the rapid stress loading during such reversals greatly intensifies stresses. These parts are subjected to 150,000,000 or more stress cycles per year.

Components developing fatigue cracks

Experience has shown that the following compressor components most frequently develop fatigue cracks and subsequently fracture in service. These were, therefore, given a periodic ultrasonic test. Frequency of testing was established from service experience.

1. Yoke bolts (cylinder to frame or spacer bolts)
2. Wedge bolts
3. Connecting rod bolts
4. Piston rods, air or steam
5. Crosshead pins
6. Crossheads
7. Crankshafts
8. Connecting rods
9. Main bearing studs

In one plant with twelve 2,500 hp steam driven high pressure air compressors, the frequency of failures and operating conditions has resulted in conducting the periodic test of the components listed above for each machine every 90 days when the unit is being thawed. Prior to using the periodic reflectoscopic inspection, several compressor wrecks were experienced. Since initiating the 90-day schedule no wrecks have been experienced. However, during a 4-yr. period of inspection a large number of cracked components were found by the 90-day inspection and were replaced before breaking. A list of the components found to be cracked and the number of each found during the 4-yr. period is given in Table 1. It will be noted that bolts account for a large number of the cracked components and since they can develop deep

TABLE 1. COMPONENTS FOUND TO BE CRACKED AND THE NUMBER OF EACH FOUND DURING THE 4-YR. PERIOD

Item	Number found to be cracked
Yoke bolts	124
Wedge bolts	32
Connecting rod bolts	19
Low pressure steam piston rod	2
Air piston rod	2
Crosshead pins	5
Total	184

cracks during the 90-day interval this test frequency has been continued. In another type horizontal-reciprocating compressor it was found that bolts begin to develop fatigue cracks after about three years service and so test frequency could be altered accordingly.

Since bolts are the most prevalent component found to crack, Figure 3 was included to show a typical crack in a stud bolt.

Cracked connecting rod

Figure 4 shows a steel connecting rod which failed from a flaw and severely damaged a high pressure pump. Incidentally, this points out the usual location of connecting rod failures, i.e., the inside of the large or small eye. Figure 5 shows another connecting rod which cracked in service, but which was de-

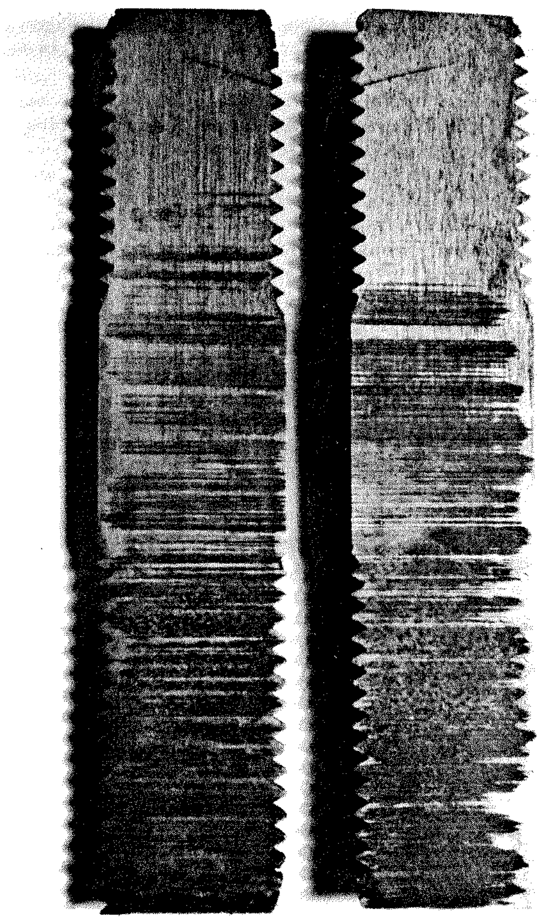

Figure 3. Typical crack found in a stud bolt.

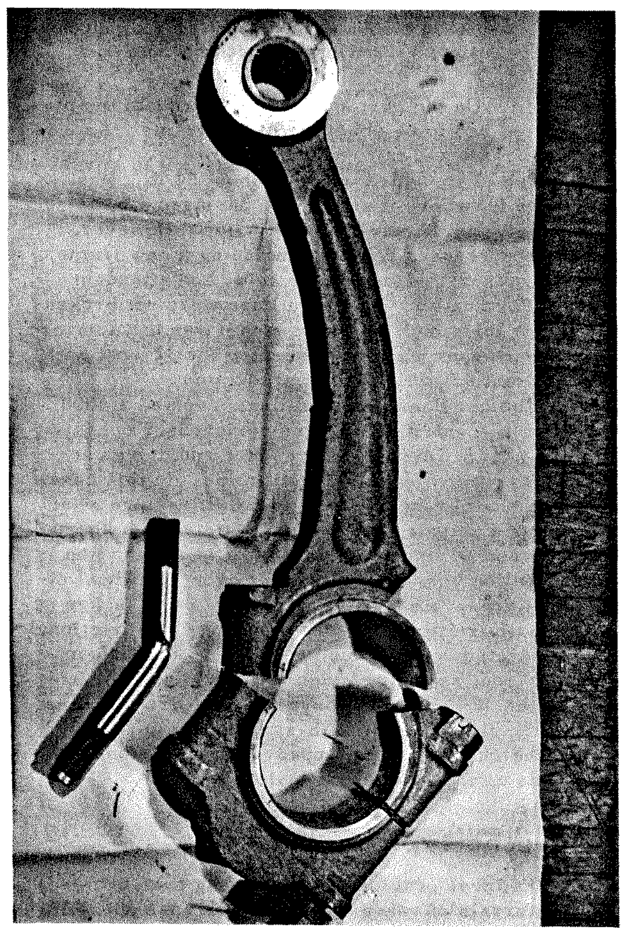

Figure 4. Steel connecting rod which failed from a flaw.

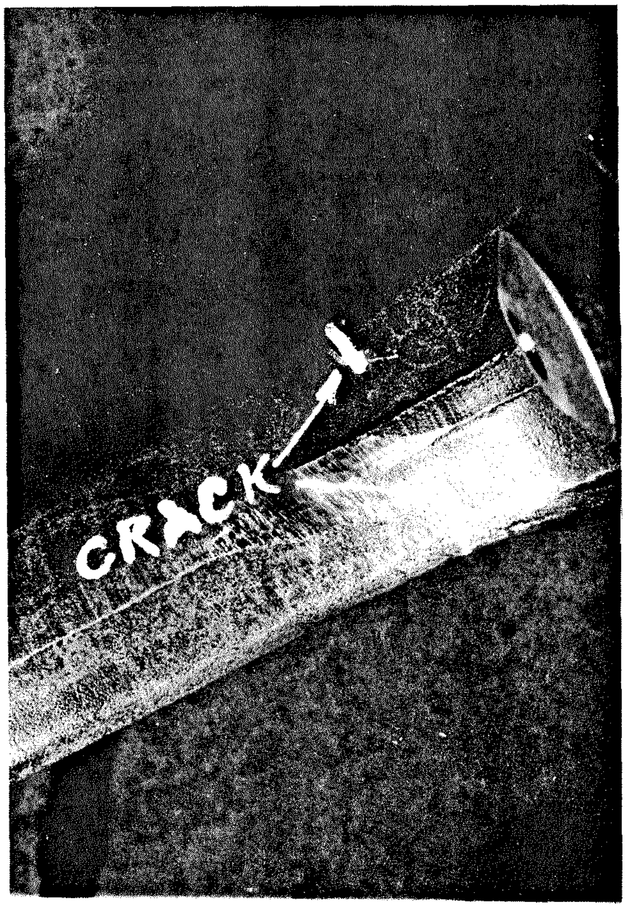

Figure 5. Connecting rod which cracked in service, but which was detected before fracture occurred.

Figure 6. Close-up of another crack in a connecting rod. The crack was found during periodic inspection.

tected before fracture occurred. Figure 6 shows a close-up of another crack in a connecting rod found during periodic inspection.

Enhanced plant safety

While it cannot be said that any one of these components, if allowed to continue in service until breakage occurred, would have results in a personal injury, it can be said without question that detection and replacement of these cracked parts has enhanced plant safety. Undoubtedly, at least one of those parts, if allowed to fracture in service, would have caused a compressor wreck. The repair cost of just one wreck would pay for the inspection and instrument several times over.

The information gained from routine ultrasonic testing has also had a beneficial side effect on new compressor construction. All major crankshafts and some other components for compressors over a critical size are reflectoscopically inspected prior to initial assembly. Many of our vendors now have equipment to inspect the new shafts for us. Inspection of new parts has resulted in better shaft design through (1) better control of heat treatment for grain size control since grain size directly affects fatigue failure limits and ultrasonic pulse transmission, (2) elimination of stress concentrators through improved forging, machine and design practice, and (3) improved metal quality through detection of the usual forged steel imperfections and rejection of shafts or parts which do not meet acceptance standards.

Pressure vessel rupture

The hazard to personnel and property as a consequence of a pressure vessel rupturing under gas pressure, when the energy content is of any degree of magnitude because of either vessel size or working pressure, needs no further explanation. In an air separation plant all of the ingredients may be present for loss of metal through corrosion or erosion; such as, high moisture content, high oxygen concentration, and high velocity with entrained moisture or dirt. Design engineering must take these factors into consideration, and experience has shown the effect of good design through a low incidence rate of vessel rupture or attrition of metal thickness. Nonetheless, there have been a few cases of rupture of a pressure vessel under gas pressure.

One example was a cyclonic moisture separator in a low pressure, high volume air line. This vessel, which handled up to 6,000,000 cu. ft./hr. of air at about 90 lb./sq. in., utilized cyclonic action as the initial moisture separator in the system. It was fed by a 24-in. pipeline of considerable length and was located out-of-doors in an L-shaped corner of a building. The vessel ruptured, separating more or less into two halves, as a result of erosion of a "path" that followed the cyclonic air flow. Failure occurred when the erosion, due to entrained moisture, scale, and dirt in the air stream, reduced the effective metal thickness below that required to withstand the applied stress. There was no personnel in the area at the time and so no injuries occurred; however, there was building damage, mainly shattered windows.

Ammonia storage vessels

Another example of improved safety in pressure vessel operation, through ultrasonic inspection, involved five ammonia storage vessels, 30-in. diameter × 12-ft. long, which operate at 175 lb./sq. in. water pressure. Three of the five vessels developed leaks after being in operation several years. It was feared that stress corrosion might be occurring and that the vessels would fail under pressure. The seriousness of releasing this quantity of ammonia is quite obvious. A reflectoscope was used to inspect the vessels while in service and without production outage. This inspection revealed that all of the leaks had occurred through weldments and were the result of poor welding practice at the time of manufacture. For example, a 6-in. long lack of fusion in a girth seam was the cause of one leak. On the basis of this information, the vessels were removed from service and repaired by welding with only four hours of production outage. All were satisfactorily repaired, tested and returned to service.

Inspection of the welding on an 84-in. O.D. steam exhaust line is another example of the use of ultrasonic inspection. During the erection of this line the quality of welding was questioned as a result of visual inspection, and a reflectoscopic inspection was decided upon. A total of 174 lineal feet of weld was examined and 34 ft. or 20% was found defective and required replacing. Replacement was necessary because of long areas of heavy interconnecting porosity, lack of fusion and penetration, and cracks.

Pressure piping

Ultrasonic inspection has also proven beneficial in examination of various sections of critical high pressure piping. The location of critical areas in piping will vary with many factors including corrosion conditions, gas velocity, working pressure, and operating cycle. While long lengths of piping have not ruptured in service with attendant hazards from whipping, energy release, or fragmentation, there have been many occasions of replacement of pipe because of known metal loss or pinhole leakage. Because of this experience a periodic inspection of various pipe has also been established.

During the routine ultrasonic inspection at one plant it was found that the elbows and pipe on all four precoolers had been thinned considerably through erosion. This was 4-in. diameter pipe operating at 2200 lb./sq. in. The precoolers are the final moisture removal equipment and are subject to erosion from entrained moisture in high velocity air. Even though the major thinning took place at the elbows, all interconnecting piping was replaced.

As another example of the use of ultrasonic inspection of pipe, the 24-in. pipeline that fed the cyclonic separator, mentioned previously, was inspected for corrosion and thinning, after the vessel ruptured, and found to be adequate for continued service.

In another case, a personal injury occurred when a precooler drain line ruptured, when a man opened the drain valve, resulting in a serious eye injury. It is thought that vibration caused fatigue cracking of the pipe in the threads adjacent to the valve. While ultrasonic inspection would detect such cracking, it was more economic to install heavy-walled pipe, which has eliminated the problem, rather than establish routine ultrasonic inspection for the numerous piping elements of this nature.

Replacement prior to failure

While such occurrences have been quite rare, personnel hazards are great and property damage is often extensive. In view of this combination, a routine ultrasonic inspection of critical high pressure vessels has been established. Frequency of inspection has been based on past experience and adjusted to fit any change in service conditions. For this inspection, a sonic thickness measuring device is used to determine remaining metal thickness at locations known or thought to be subject to corrosion or erosion. The remaining metal thickness must meet requirements determined by standard design formulae. This type of inspection has permitted replacement of vessels prior to failure, or alteration of operating conditions so as to eliminate the cause of corrosion or erosion.

Summary

In summary, a periodic ultrasonic test of certain critical air separation plant equipment was initiated, predicated on years of operating experience during which service failures occurred. The ultrasonic tests have detected service-developed defects and have reduced and nearly eliminated in-service failures. If the components with service-developed defects had been permitted to continue in service, failure would have occurred. Therefore, replacement of these defective components, before failure, has markedly improved plant safety.

In conclusion, it should be pointed out that a number of ultrasonic devices, which can be used for these purposes, are on the market; a complete inspection service can be purchased if others desire to initiate such a program.

DISCUSSION

TAYLOR—Northern Chemical Industries: I'd like to make a comment about this inspection service that you can purchase. Our vessel which had the hydrogen blister had been inspected. We had an actual inspection by these fellows from Boston; experts, since they were a full 50 miles from home. They gave us a complete O.K. During the turnaround, a week later, we went in to change the packing in the vessel and discovered a hydrogen blister.

I think this paper may offer an answer. I think what we may have to do is develop our own experts and start this type of preventive maintenance program. I think we'll train our own people as I wouldn't give you a nickel for purchased inspection. For example, we had about four years of this service—annual inspection—and in one case they were reporting to us that the vessel wall was building up instead of thinning.

TRIBOLET: We had to develop our own experts but the inspection service that I referred to is a service for people who can not economically justify all of the necessary equipment and personnel.

JONES—Canadian Industries Ltd.: I wonder if you'd be kind enough to indicate, with regard to the oxygen pump failure, whether the parts involved in the fire were in stainless steel.

TRIBOLET: They were not stainless steel.

JONES: We had a self-sustaining fire with a stainless steel oxygen pump. I just wanted to mention that this can happen. The second point is that there are many fatigue failures described, and many of these are threaded assemblies. We have seriously been considering specifying that all motion bolting have rolled threads. It appears in the illustrations that you have, that at least some of the components had machined threads. A substantial improvement in fatigue life is obtained, without any other design change, by simply changing to rolled threads. The major compressor manufacturers have already made this move on the larger parts, such as piston rods. I think it could be extended to all threaded parts subject to fatigue-type loading, irrespective of size, with a great advantage in safety to everybody.

TRIBOLET: I certainly agree with the comments on rolled thread. We have truncated the roots of the machined threads to provide less stress concentration. Rolled threads could be easily used on all these parts and we are now doing thread rolling in some cases.

MASON—Dow Chemical: What type stainless steel was this that had a sustained fire and can other stainless steels have a sustained fire?

JONES: The stainless steel pump material which fired was a shaft in Type 304 and a cast casing in Alloy Casting Institute Specification CF 8, the cast equivalent of Type 304. It is interesting to note that the stainless steel manufacturers inject oxygen into the melt in order to reduce carbon content, without encountering any very vigorous reaction.

We believe that it is necessary to superheat the stainless steel to a temperature above the melting point of the refractory oxide film before a self-sustaining oxygen fire results. This can be demonstrated reasonably well by lighting off a carbon steel nut, or similarly, in an oxygen stream, supported on a stainless plate. The intense heat generated by the oxidation of the carbon steel part will result in a molten pool of stainless steel, which becomes highly superheated. If the conditions are favorable, this molten pool will continue to burn in oxygen.

The readiness with which the various grades of stainless steel may be expected to burn in oxygen is probably a function of their iron content. One would expect greater difficulty with Type 310 than with Type 304, although this is largely conjecture. One air plant manufacturer, who had a Type 316 letdown valve light off in an oxygen stream, has, I believe, considered Monel as an alternate for the duty.

Anonymous: How long did it take you to train your own inspectors?

TRIBOLET: This, of course, depends on several items. If you're asking about the reflectoscopic inspection, it depends largely on the complexity of the parts you want to inspect. For the inspection of rods or bolts, which are quite easily inspected with a longitudinal wave, a relatively short training is necessary. For example, one week of intensive training is adequate for a well qualified trainee. However, the interpretation of results to insure that proper corrective action is recommended requires broad experience. For this, the supervisor should be trained and thoroughly understand both the inspection system techniques as well as the problems of metal failure. You also need to continue people in this work in order that they might keep their facility, once it is established.

Anonymous: I presume that the air plants of Linde have adapted this program or are about to. Do you have a traveling team of experts to make the rounds or does each plant facility have enough business to warrant training a man and keeping him trained, keeping him sharp in inspecting?

TRIBOLET: We have some plants with trained people at the plant where an incident rate of difficulty has indicated such was needed. We also have traveling experts who can visit any of the plants where they are needed. We do not have trained people nor the instruments at all of our locations by any means. There are a few plants in which we have had a higher incident rate of difficulty and these are being staffed with trained personnel and will have periodic visits to make certain that their capabilities are maintained. If experience indicates the necessity, other plants would be equipped. Again, let me emphasize that our experience has been developed over many years, 20 or more years of operation at some plants.

Anonymous: In general, how small an installation have you found it practical to staff with trained personnel?

TRIBOLET: Well, this has been dependent more on the occasion of component failure rather than the size of the plant. The trained people are not used full time on this work by any means. At one location with 15 large compressors, for example, the instrument men are also trained as ultrasonic inspectors. They perform this function as part of their job. There are two of them trained and they alternate on the ultrasonic inspection work so as to keep both at a high level of proficiency. Periodic inspection is made on all compressors. Where you have few compressors, say two or three, and have a limited number of men, we would tend to supply the service by a traveling expert.

HEPP—Sun Oil: We used some of these devices for measuring thicknesses of vessels. One limitation that we find is that the maximum operating temperature of the vessel is so high that you can not apply the sensing element. There have been occasions where we've had vessels up to 650°F and it would have been nice to measure their thickness while we were on-stream. Have you overcome that problem?

TRIBOLET: No and we haven't encountered temperatures of this level. This is one of the difficulties of conducting such tests. We use only contact testing in which the inspector must be able to place his hand on the item to be inspected. In immersion testing the ultrasonic pulse is transmitted through water or through a liquid stream. This system might overcome your difficulty. Since we have not used this type of inspection, I could not comment any further.

STOCKBRIDGE—Southern Nitrogen: Did you indicate that you found no cracks on your rolled threads?

TRIBOLET: I have no record at this time of any cracking with rolled threads, however, because of limited data, I do not say that this is an indication that such cannot occur. With rolled threads there is certainly less likelihood of fatigue failure because one source of stress risers has been eliminated.

STOCKBRIDGE: Can most of these or all these parts be inspected in-place or do you have to remove them from the machines to test.

TRIBOLET: All these parts mentioned can be and are inspected in-place. Removal of guards and covers is necessary to permit accessibility.

SIMMS—Phillips Petroleum: Have you ever tried to use a reflectoscope to measure cracks or imperfections in an intercooler that might be operating at 3,000 lb. pressure.

TRIBOLET: I personally tried that several years ago and this is one area where we have had very limited success with this type of ultrasonic testing.

SIMMS: Do you know of another test device that appears to offer some possibility in this type of testing?

TRIBOLET: Yes. It's called a Probolog.

Anonymous: We have a centrifugal compressor shaft that I would guess is about 8-ft. long. The temperature gradient along the shaft is something better than 250°. Would this technique be applied here?

TRIBOLET: To conduct a reflectoscopic inspection you must be able to get the crystal onto the work piece, in a place where a man can tolerate the temperature on his hand. If the end of this particular shaft is accessible and at a temperature the man can tolerate, the temperature gradient should make no difference in the ultrasonic inspections.

Anonymous: I was wondering about the temperature limitations?

TRIBOLET: I think the main limitation that we have considered so far is the comfort of the person, who must be able to lay his hand on the part when he is ready to do the inspection. He must be in contact with the part the way we perform this inspection.

GLASS—Monsanto: I was wondering if this equipment is capable of showing imperfections in forgings?

TRIBOLET: Yes, it is. In fact, the crankshafts discussed in the paper are forged.

GLASS: In addition to cracks, you also are able to have slag inclusions in something the size the order of a compressor crankshaft.

TRIBOLET: We can locate such things as flakes, hydrogen bursts, porosities, slag inclusions. A sonic reflection occurs at any interface where there is a change of density in the material under test.

BURNS—Diamond Alkali: I have one remark concerning the temperature limitations. We've used this on a high temperature exchanger of ours at 600° or 700° F, where they have a special adapter that's lubricated for use at high temperature.