FIG. 1—VIEW OF PART OF DEVASTATION CAUSED BY EXPLOSION

CORROSION-FATIGUE CRACKING IN STEAM ACCUMULATORS

There has recently been a report from the Brazilian Naval Authorities of a fracture in the water drum of a boiler in Minas Gerais (*ex H.M.S.* Vengeance) *apparently resulting from the seal welding of a riveted circumferential joint.*

The following article is abstracted from Technical Report *Volume* IV, *March* 1962, *of the British Engine Boiler and Electrical Insurance Company, Limited, Manchester, and is reproduced by courtesy of the Company. It explains the mechanism of failure arising from seal welding a riveted joint and emphasizes the possible serious consequences of effecting such a repair to a pressure vessel of riveted construction, a number of which are still in service.*

On the 5th October, 1958, a disastrous explosion occurred in Norway, involving a large steam accumulator working in conjunction with the boilers supplying steam to a paper mill. The disaster occurred shortly after the mill had re-started after a week-end shut-down and the explosion was extremely violent, wrecking the vessel and causing serious damage to surrounding property. Unfortunately, one person was killed and, having regard to the extent of the devastation, (some idea of which is conveyed by FIG. 1) it is miraculous that the casulaties were not more numerous. The Company is greatly indebted to the owners of the accumulator, and to the authorities and others in Norway concerned with the investigation of the cause of the failure, for facilities for inspecting the remains of the vessel and the provision of samples of the defective seams for examination in the Company's laboratory.

The accumulator was built in Norway in 1920. It was approximately 13-ft diameter, 52 ft 6 in. long, and was of riveted construction, the cylindrical part comprising five rings of $\frac{7}{8}$ in. thick plate with two longitudinal treble-riveted double butt-straps, $\frac{5}{8}$-in. thick, per ring ; the hemispherical ends were built-up from $\frac{5}{8}$-in. thick petal plates with double-riveted single butt-straps located internally. The vessel was designed for a working pressure of 100 lb/sq. in., and its purpose was to act as a reservoir in the steam supply to the paper mill and reduce fluctuations in the steam demand on the boilers. It was positioned horizontally and supported from two pairs of brackets riveted to it, these being located approximately 26 ft apart, and it was normally kept filled with water to a height of approximately three-quarters of its diameter, incoming steam being fed into the water through a perforated distribution manifold. The steam flow from the vessel was taken via a dome at the top, situated at approximately mid-length.

It appears that trouble was experienced due to leakage from the riveted seams of the vessel shortly after it was installed and, as caulking proved ineffective, it was decided to seal-weld the edges of some of the butt-straps, laps, and internal rivet heads. This welding was carried out by means of the metal-arc process, using bare wire electrodes as was the then current practice. So far as was known, this initial welding was confined to those parts of the inner laps of the longitudinal and circumferential shell seams that were located below the water-level, the seams in the hemispherical ends and above the water-level not being welded. It appears that the seal-welding was effective in remedying the leakages and it was not until some time during the last war that leakages again took place in localties where the seams had not been welded. The records available were not complete but there is reason to believe that the further welding that was carried out was done with covered electrodes, which were available by then. Towards the end of, or immediately after, the war there appears to have been a third application of welding, in the course of which any lap edges or internal rivet heads not previously welded were dealt with in this manner. The vessel had been inspected internally at five-yearly intervals since it was installed, each inspection being followed by a hydraulic test to a pressure of 1·5 times the designed working pressure, the last such examination and test having been carried out in 1955.

By 1954 the internal steam distribution system had corroded to an extent necessitating replacement. The arrangement installed originally consisted of a pipe, running longitudinally on the horizontal axis of the vessel, with 10 equi-spaced nozzles directed downwards and discharging into lengths of vertical open-ended pipes to form primitive injectors to assist water circulation. The new distribution system comprised a longitudinal pipe located about 3 ft from the bottom of the vessel, the bottom quadrant of this pipe being perforated with a large number of holes. No information was available as to why the design of the distribution system had been changed.

The initial point of rupture at the time of the explosion was located in the first shell ring at the end of the vessel nearest to the boiler house. This ring fractured along the lower lap to the inner butt-strap of the lower longitudinal seam, which was located about 45 degrees below the horizontal centre line. The rupture extended round both adjacent circumferential seams and a section of the ring was more or less flattened out, torn clear and blown upwards, alighting about 300 yards away from the vessel ; the adjacent hemispherical end also

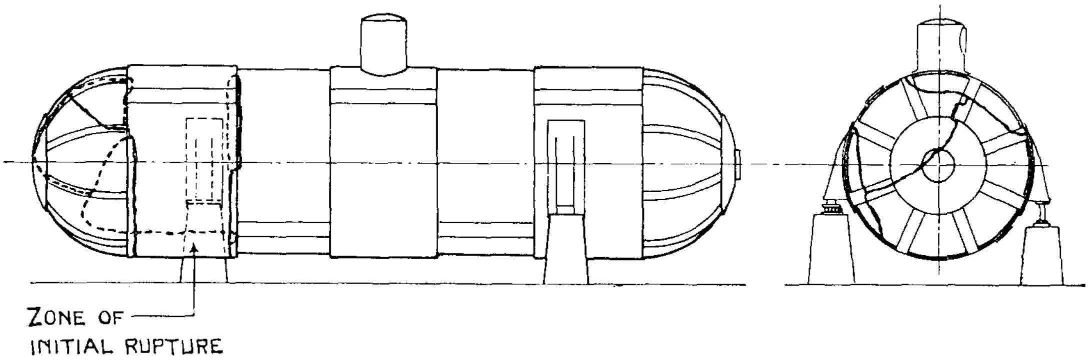

Fig. 2—Sketch showing paths of ruptures

ruptured extensively. The paths of the various ruptures are indicated in Fig. 2 The virtual removal of one end of the vessel enabled the steam and water contents to discharge violently and the reaction thus set up projected the remains of the vessel, in the manner of a rocket, through a considerable part of the factory premises until it finally came to rest in the evaporation plant.

The cause of the rupture that initiated the explosion was found to be the presence of a corrosion-fatigue fissure that had extended practically through the shell plate over almost the full length of the seam at which it occurred The fissure had developed at the toe of the seal-weld at the lap edge of the butt-strap, and examination of a number of specimens showed that it was a typical example of corrosion-fatigue.

As its name implies, corrosion-fatigue arises from the simultaneous action of corrosion and fluctuations of tensile stress. The corrodent need only be very mild—ordinary tap water will suffice—and the fluctuations in tensile stress need not be of a very high order ; it is the simultaneous action of corrosion and fluctuating stress that gives rise to this form of deterioration. It is well known by the name of ' grooving ' in this country and is often found in shell type boilers in such localities as the junctions of furnace rings and front end plates.

In addition to the fissure that initiated the rupture in the vessel, similar fissures of slightly less depth were present adjacent to other longitudinal seams and also in places at the circumferential seams. At the time the remains of the vessel were inspected by one of the Company's officials it had been largely cut up prior to removal from site, but enough was observed to indicate that practically all the seams located below the water level had developed corrosion-fatigue fissures at the toes of the seal-welds to an appreciable degree. Numerous fissures, almost in the form of cracks, had also developed around many of the welded rivet heads some extending radially.

Judging from the many cut-up pieces that were inspected, the internal surfaces of the vessel were singularly free from corrosion, having regard to its age Below the water level there were isolated, widely separated small corrosion scabs of the type associated with differential aeration corrosion, but over most of the surfaces the original mill scale was still visible beneath a patina of friable rust. In those parts of the vessel where the corrosion-fatigue fissures at the weld toes had not been appreciably disturbed as a result of the explosion, it was noted that they were practically filled with corrosion products that appeared to consist largely of magnetite (Fe_3O_4). Bearing in mind that the interior of the vessel would be covered with a thin layer of rusty sludge after it had been emptied for examination purposes, the existence of the fissures could easily be overlooked unless their presence was suspected and steps taken to dig away the corrosion products that filled them. A typical example of the fissuring at the toes of the seal-welds is shown in Fig. 3 ; it should be noted that this fissure had been opened up and the corrosion product broken away as a result of the deforma-

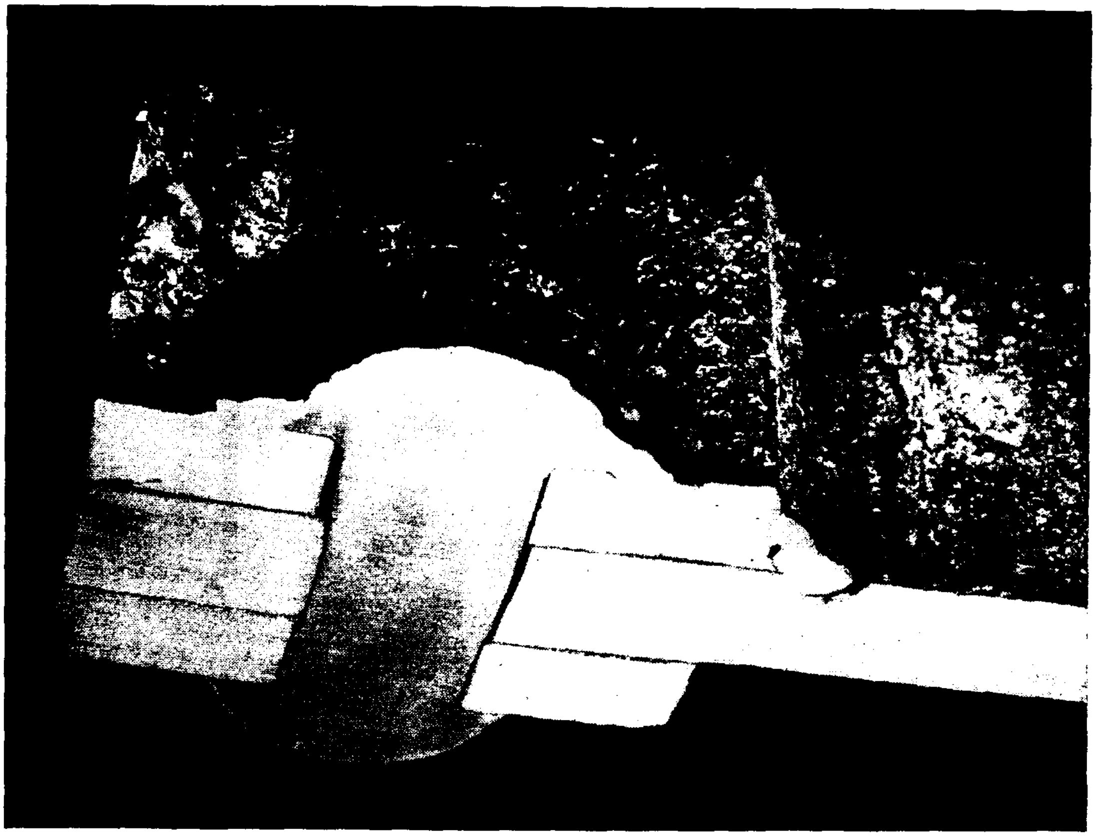

FIG. 3—TYPICAL EXAMPLE OF FISSURE AT TOE OF SEAL WELDING SHOWING WELDING OF RIVET HEAD AND INCOMPLETE FILLING OF HOLE BY RIVET

tion that occurred at the time of the explosion. Further examples of the fissuring are shown in FIG. 4, (*a*) and (*c*) depicting bare-wire welds and (*b*) a weld made with a covered electrode.

As the failure of the vessel resulted from corrosion-fatigue it is pertinent to consider the nature of the water with which it was partly filled and the stress fluctuations that occurred in service. The water supplied to the vessel was not treated, being tapped off before the point at which the boiler feed water was conditioned by the addition of trisodium phosphate and sodium hydroxide. For the first 10 years of the vessel's life the water was taken from a local river, but was subsequently obtained from a lake. Judging from the general condition of the plates, the water could not be said to be corrosive but its potentialities in this direction would, of course, suffice for the development of corrosion-fatigue-fissures in those parts of the vessel that were subjected to fluctuating tensile stresses of the requisite magnitude. According to information, the lake water had a mean pH value of the order of 7·4, that of the water in the vessel being about 9·5, which is on the low side, as a figure of 10·5 would be desirable if corrosion was to be minimized. So far as is known, no steps were ever taken to decrease the oxygen content of the water and this is consistent with the presence of some scab corrosion on the plates. It is also understood that examination of the corrosion products revealed strong indications of the presence of chlorides. Sodium chloride is, of course, a very undesirable constituent in a boiler or accumulator water, particularly if the water contains organic matter as did that taken from the lake. Whatever may be deduced from the meagre data available regarding the chemical composition of the water in the accumulator, the fact remains that, after 38 years of service, the general condition of the vessel was remarkably good from the corrosion point of view. It may be assumed, therefore, that the water conditions within the accumulator had been on the corrosion border-line, at least for much of the service life.

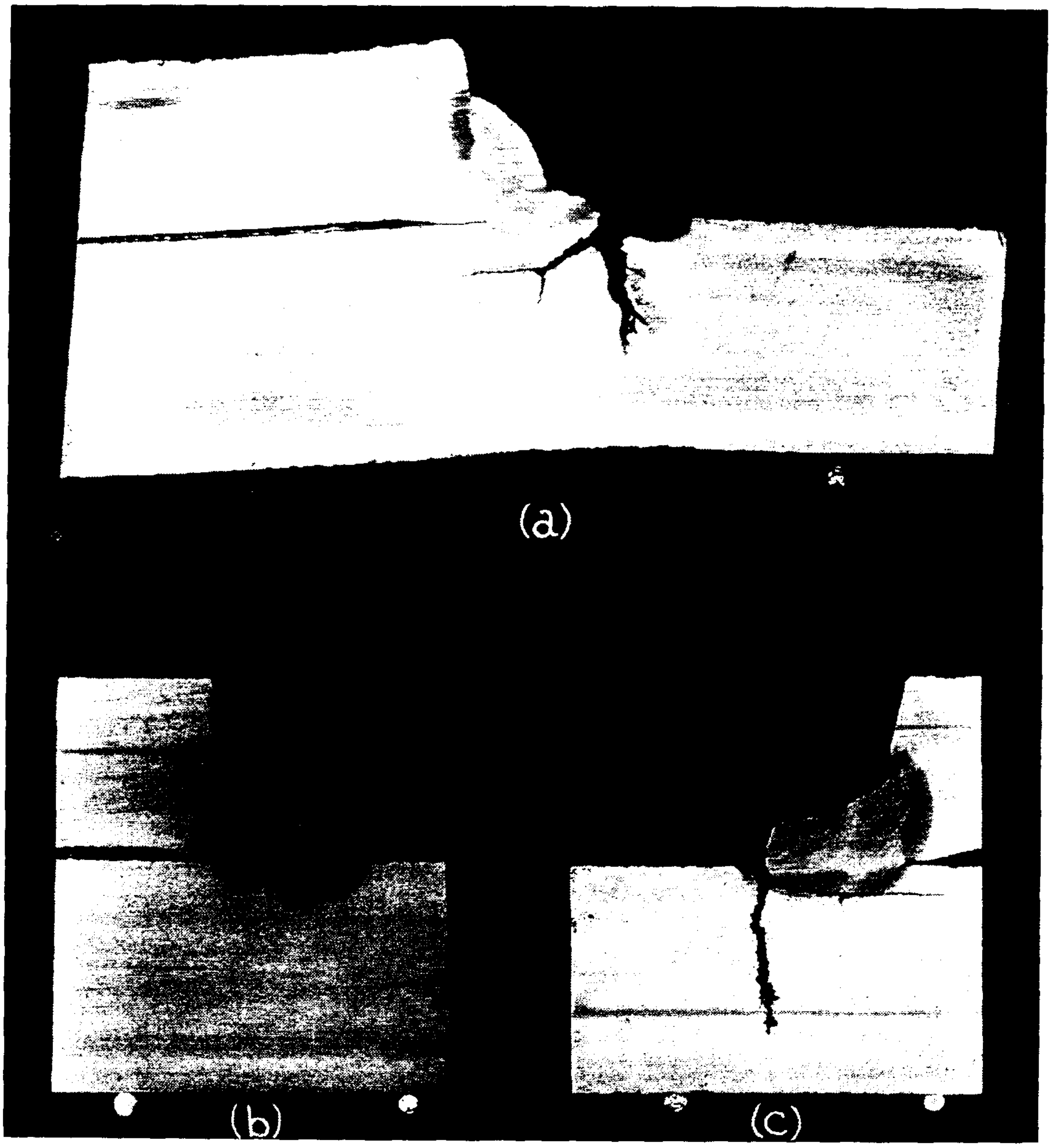

FIG. 4—TYPICAL EXAMPLES OF FISSURES—(A) AND (C) BARE WIRE (B) COVERED ELECTRODES

As it is extremely unlikely that any corrosion-fatigue trouble would have been experienced in the absence of seal-welding of the vessel seams, it is of interest to consider the question as to why such seal-welding was necessary. It will be noted from the transverse section shown in FIG. 3 that the rivet depicted did not fill the hole properly. As the fit of the rivets could have been disturbed in a circumferential direction by the working stresses, and in particular at the time of the explosion, an adjacent section to that depicted in FIG. 3 was cut through longitudinally and this is shown in FIG. 5, from which it will be observed that the fit of the rivets was not substantially different from that shown in FIG. 3. It is evident, therefore, that the rivets did not fill the holes properly when the seam was riveted. This being the case, slight relative movement of the shell and butt-strap plates would be bound to occur when the vessel was pressurized and this would disturb the caulking at the lap edges of the butt-straps and so lead to the development of leakage. There is no reason to doubt that the original leakage from the vessel seams was due primarily to the unsatisfactory fit of the rivets, but a contributory factor was that the pitch of the outermost row of rivets was 7½ in., which would render adequate caulking

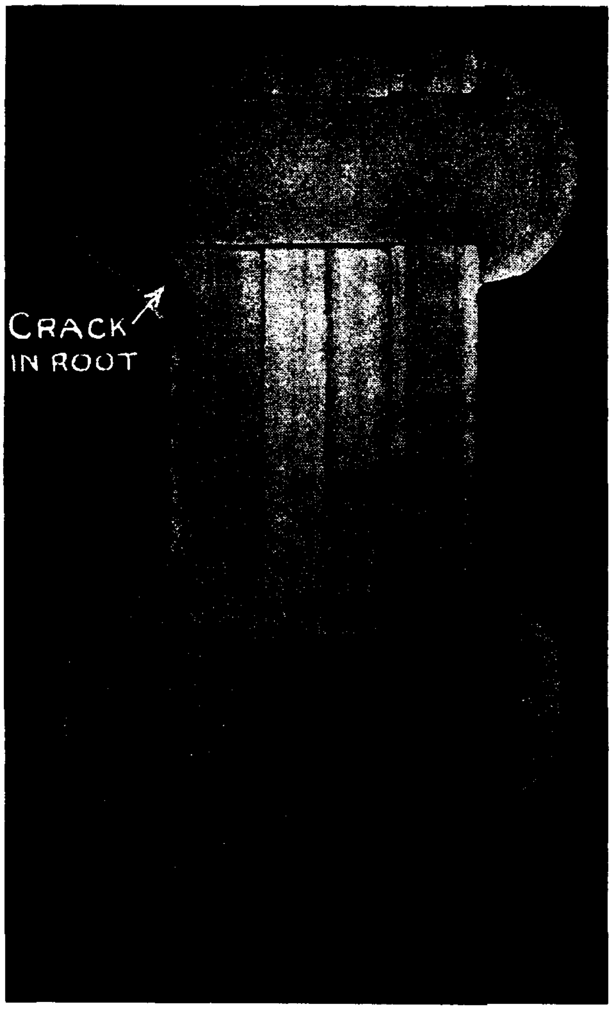

FIG. 5—LONGITUDINAL SECTION THROUGH SEAM ADJACENT TO PART SHOWN IN FIG. 3

difficult owing to springing of the butt-straps at the spaces between the rivets.

The application of seal-welding to the lap edges of riveted seams is a most undesirable practice because it gives rise to a severe concentration of stress at the toe of the weld. In the sketch, FIG. 6, is shown a section through part of a longitudinal seam in the vessel under consideration. At the time seal-welding was applied the vessel would not, of course, be under pressure, and owing to the slight relaxation that would invariably take place on removal of the pressure, the holes in the plates would not necessarily be in contact with the shanks of the rivets. It follows, therefore, that after the deposition of a seal-weld along the lap edge of a butt-strap there would exist, or be brought about by contraction of the weld-metal, a slight gap between the hole in the butt-strap and the rivet shank, designated X in FIG. 6. When the vessel was subsequently pressurized the shell plate would no longer be free to move relative to the butt-straps so as to take up any gap between the holes and rivet shanks; consequently, the hoop stress arising from the pressure would be imposed largely and in some places probably wholly, on the seal-weld. The effect of this would be to introduce a bending stress at the weld junction between the shell plate and the inner butt-strap, largely concentrated in the shell plate at the toe of the weld; as the neutral axes of the shell plate and butt-strap lie in different planes, the application of a hoop load, T, would produce a couple, Y, and the bending moment thus set up would produce a tensile stress at the toe of the weld in the locality designated Z. A simple calculation shows that at the designed working pressure of 100 lb/sq in. the maximum nominal skin stress thus developed would be in the region of 10·0 tons/sq in. To arrive at an approximation of the true stress

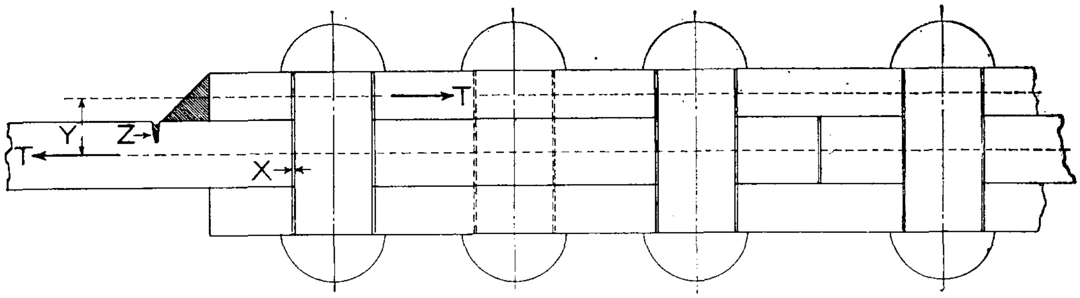

FIG. 6—TRANSVERSE SECTION THROUGH LONGITUDINAL SEAM

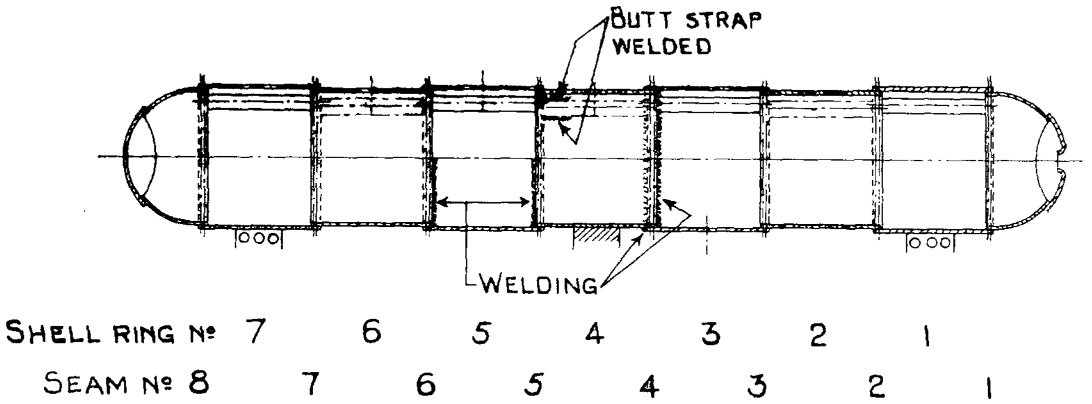

FIG. 7—DISTRIBUTION OF WELDING IN FIRST ACCUMULATOR

it is necessary to apply a stress concentration factor to take into account the abrupt change of section at the weld toe and the undercutting that was present in the vicinity. Assuming a modest factor of 1·5, the maximum skin stress would be in the region of 15·0 tons/sq in., i.e. in excess of the yield point of the material. It is known that the vessel was tested hydraulically to 1·5 times the working pressure on several occasions and this would cause the formation of a wedge of plastically deformed metal in the locality indicated by Z, the depth of the wedge depending largely on the extent to which the shell plate moved relative to the butt-strap before the rivet shanks began to take up the load. There is every reason to believe, therefore, that the plate material at the toes of the seal-welds at the longitudinal seams was strained plastically to an appreciable degree when the vessel was put back into service after the welding had been applied.

The formation of a wedge of plastically deformed metal in the manner described would rupture the oxide film on the surface, thus exposing bare metal. As the latter is anodic with respect to the oxide film, which would cover most, if not all, of the remainder of the plate surface, there would exist the dangerous state of affairs arising from the presence of a small anode and a large cathode, which would lead to preferential corrosion of the plastically deformed metal. This susceptibility to corrosion would be enhanced by the plastically deformed metal, which is itself anodic with respect to undeformed metal and therefore liable to corrode preferentially. It is thus to be expected that corrosion would be initiated along the toes of the welds under conditions that might not suffice to give rise to it elsewhere.

With regard to the question of stress fluctuations, it is understood that the pressure within the vessel varied between 45—100 lb/sq in., and severe thermal fluctuations are bound to have occurred depending upon whether the accumulator was absorbing or supplying steam. The consequent stress fluctuations would be ample to bring about the development of corrosion-fatigue fissures. It is probable that the development of these was rapid at first and that the attack was then slowed down by the stifling action of the corrosion products that would accumulate within the fissures.

The cause of this disastrous explosion is attributable to the application of seal-welding to initially faulty riveted seams, there being no evidence to suggest that any fissuring would have occurred in the absence of seal-welding. Such fissuring does sometimes occur in line with the lap edges of lapped seams*, but the Company is not aware of a case where it has occurred in a double butt-strap riveted seam that was free from seal-welding.

Another similar case of corrosion-fatigue cracking, which developed at the lap edges of the riveted seams of vessels which had been sealed by fillet

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* An example is reported on p.9 of Vol. III of this series of reports.

FIG. 8—LOCATION OF PROBE WHEN ULTRASONICALLY TESTING FOR FISSURES AT TOE OF SEAL WELD

welds, involved two identical horizontal accumulators which were situated in this country. They were manufactured in 1928 and had been in continuous operation at a pressure of 250 lb/sq in. Both vessels had a long history of seam leakage, which repeated caulking had failed to rectify, and in 1943 welding of certain of the seams was resorted to, this expedient probably being dictated by circumstances imposed by the war.

Each vessel was 9 ft in diameter, 60 ft in length, and consisted of seven shell rings of $1\frac{5}{32}$ in. thick plate, with treble-riveted, double butt-strap longitudinal seams located above the water line, which was approximately at half diameter. The circumferential seams were lapped and double riveted, the fourth one being hand riveted as the vessels had been transported to site in two portions. The end plates were of hemispherical form.

In the case of the first accumulator the welding had been applied along the full length of the lap edges, both internally and externally, at the (hand riveted) No. 4 circumferential seam and, internally, over only the bottom halves of Nos. 5 and 7 seams, as indicated in FIG. 7. The butt-straps of the No. 4 shell ring longitudinal seam had also been welded, internally and externally, at the top and bottom edges for approximately 18 in. extending from the No. 5 seam.

During a visual examination of the vessel, what appeared to be undercutting was revealed along the toes of the fillet welds. Closer examination, however, showed this to be more suggestive of corrosion-fatigue fissuring, and careful probing adjacent to the toes of the welds confirmed the presence of fissures filled with hard corrosion products. Attrition marks approximately $\frac{1}{16}$ in. wide could also be seen at the lap edges of some of the unwelded seams, indicating appreciable relative movement of the plates.

The only seam in the second accumulator that had been welded was the fourth (hand riveted) circumferential and, since the surface of the weld had been heavily peened, it was not possible to ascertain visually whether or not there was a fissure at the toe of the weld.

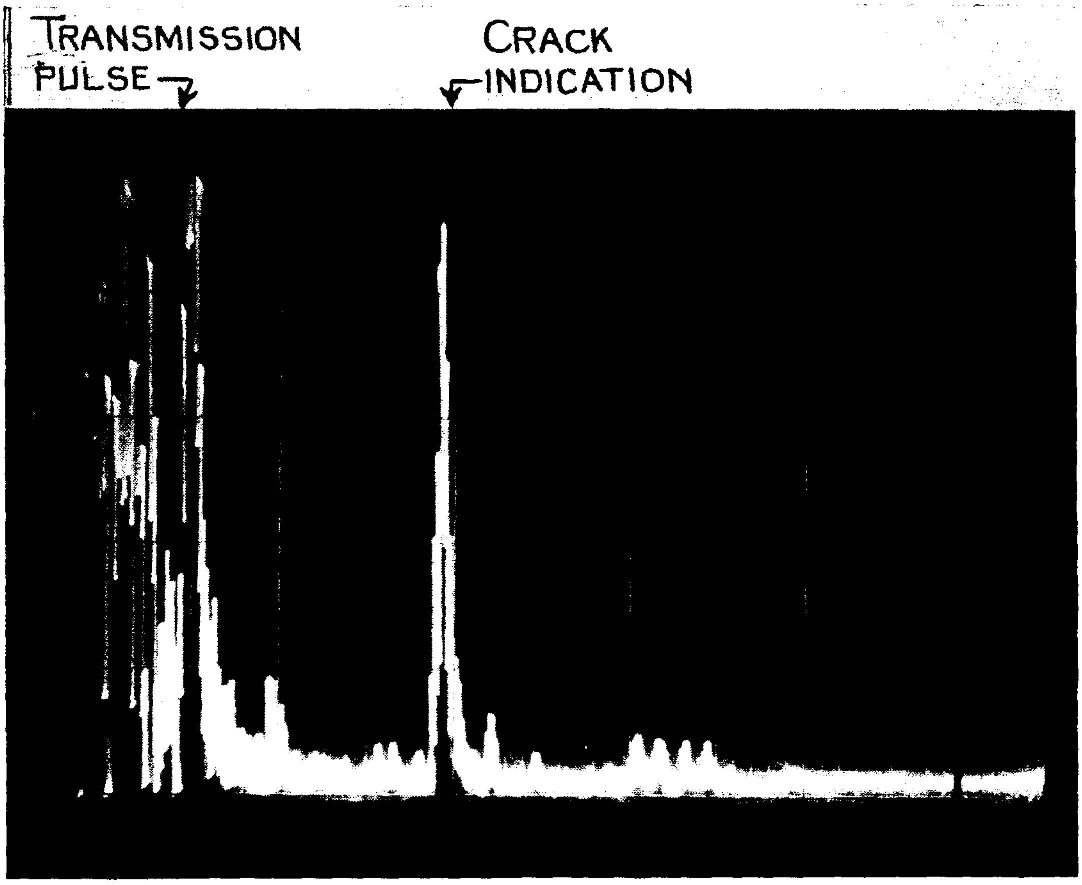

FIG. 9—TRACE ON CATHODE RAY TUBE OF ULTRASONIC TEST INSTRUMENT

In order to determine the extent of the afore-mentioned defects it was decided to examine the vessels ultrasonically. The examination was carried out by means of Kräutkramer Type U.S.I.P. 9 Ultrasonic Flaw Detectors, employing 2 Mc/s 70 degrees and 45 degrees barium titanate angle probes and medium grade machine oil as the couplant. When the angle probes were placed in a position similar to that shown in FIG. 8, the screen indication obtained was as is depicted in FIG. 9 and this confirmed the presence of a crack at the toe of the fillet weld. The length of a crack was traceable by moving the probe parallel to the seam until the crack indication disappeared from the screen. In places, the cracks were found to extend into the plate material to a depth sufficient to prevent any ultrasonic waves passing through to the rivets, and subsequent sectioning of such localities showed that the cracks were approximately 1 in. deep and slightly angled to the place surface. At every location where welding had been resorted to, cracks had developed along the toes of the welds for their full length, and, in most cases, they extended past the ends of the welds for approximately 2 in. During the examination of the fillet welds there were some indications of small cracks radiating from a number of rivet holes.

Due to the extent and severity of the defects revealed by the ultrasonic examination it was decided that the first accumulator should be taken out of service permanently and replaced, and that the ultrasonic examination of the other vessel, which was not affected so seriously, should be extended to ascertain if it was in a condition that would justify repair.

The results obtained from this examination indicated that the circumferential seams of Nos. 1, 2 and 6 shell rings, as well as one end plate, were seriously cracked at nearly every rivet hole. Confirmation of the ultrasonic indications was obtained by removing several rivets and then magnetically testing the holes ; in each case several cracks were detected, radiating in all directions. Further ultrasonic testing was carried out over localised areas in other seams and

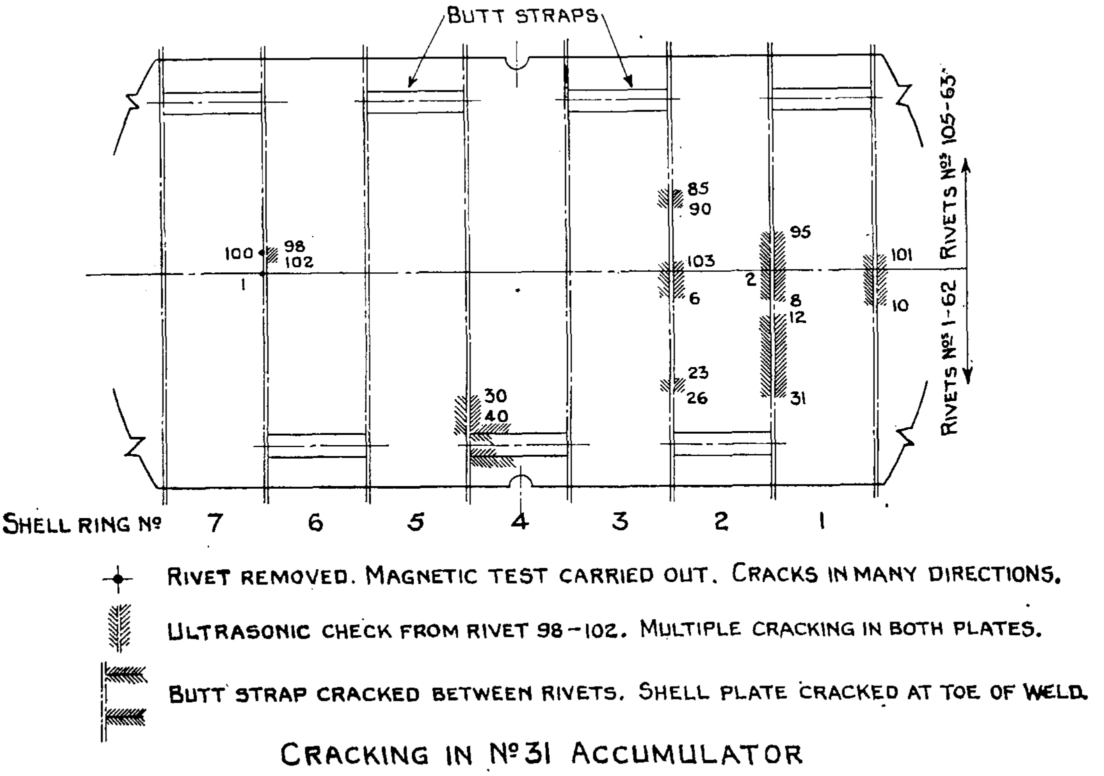

FIG. 10—DEVELOPED PLAN OF SECOND ACCUMULATOR SHOWING NON-DESTRUCTIVE TESTS APPLIED

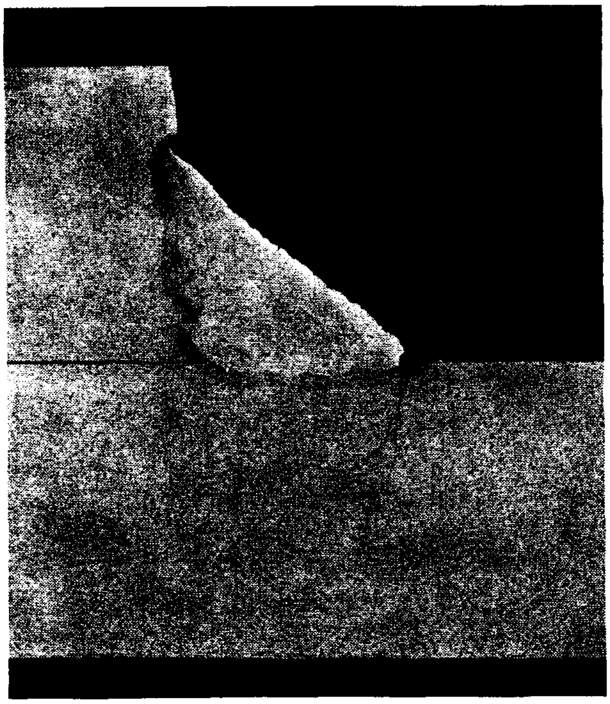

FIG. 11—SECTION AT 6TH CIRCULAR SEAM OF FIRST ACCUMULATOR SHOWING SEAL WELD AND FISSURES

similar results were obtained, which were also confirmed by the removal of rivets and magnetic testing on the holes. The areas tested are delineated on the accompanying sketch, FIG. 10, which is a developed plan of the accumulator as if opened up longitudinally along the top of the vessel. The severity and extent of the defects revealed at the rivet holes was such that it was decided that repair of this accumulator was impracticable and it was taken out of service and replaced. When the two vessels were cut up prior to removal from site, samples became available for laboratory examination, the more interesting features revealed being as follows :—

FIG. 11 shows an axial section cut from the bottom of the sixth circular seam from the manhole end of the first vessel, and the development of a duplex crack system from the slight undercut present at the toe of the fillet weld to the outer plate will be noted. A similar section farther round the same seam is illustrated in FIG. 12, this intersecting the excavation made at the toe of the weld at the time of the visual examination in order to facilitate magnetic crack detection. At this location the crack had a developed depth of $\frac{5}{8}$-in. and extended to $\frac{7}{8}$ in. below the plate surface.

Microscopical examination of several specimens cut to intersect the crack showed it to be typical of corrosion-fatigue ; it was in the form of a broad fissure, contained oxide deposits, and the termination was blunt-ended, as shown in FIG. 13. The crack origin at the junction of the weld metal with the plate material showed a modified plate structure resulting from the heat input during welding, depicted in FIG. 14. At this location two separate cracks were present, most likely due to the fact that the section intersected two separate cracks which had broken out at different locations round the seam and during their subsequent development in the circumferential direction overlapped at their ends by a small amount.

The plate material showed a normal structure and its Brinell hardness of 143 is indicative of a tensile strength of approximately 32 tons per sq in.

A macroscopical examination was also made of a sample from the second vessel, cut so as to include a crack at a rivet hole, this being taken from the lower portion of the second circumferential seam from the manhole end. Magnetic crack detection showed several radial cracks up to $\frac{3}{8}$ in. long to be present. A specimen embracing a typical crack was subsequently prepared for microscopical examination, which revealed it to be of the corrosion-fatigue type, the blunt-ended termination of the oxide-filled fissure being shown in FIG. 15. No structural abnormalities were observed in the plate material, which had a Brinell hardness of 170, equivalent to a tensile strength of 37 tons/sq in.

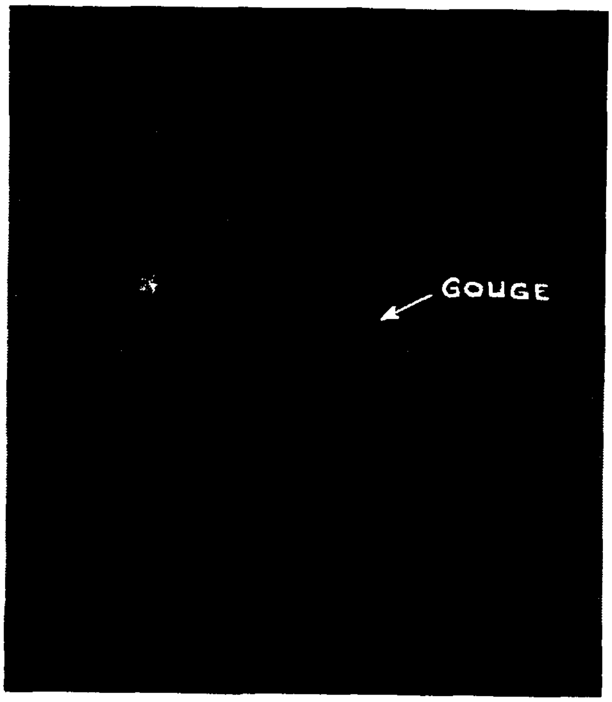

FIG. 12—AS FIG. 11 BUT FURTHER ROUND THE SEAM

FIG. 13—TERMINATION OF FISSURE IN FIRST ACCUMULATOR

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The mode of cracking in the case of both these accumulators follows closely that found in the vessel which exploded in Norway and the several causes discussed earlier are also applicable to this case. In this latter instance, the vessels were carried at their mid-lengths on fixed supports and by roller supports situated near to the ends and it is significant that the most seriously affected seams in each vessel were situated in the region of the centre supports, which would be zones of contraflexure. The fact that the centre seams were hand-riveted doubtless played a contributory part. Another factor which probably

FIG. 14—ORIGIN OF FISSURE SHOWN IN FIG. 13

FIG. 15—TERMINATION OF FISSURE IN SECOND ACCUMULATOR

had a bearing on the seam leakage trouble as well as the subsequent cracking was vibration from nearby forging hammers, which would tend to disturb the caukling of the seams and give rise to stress fluctuations at the toes of the fillet welds. The cracking in the latter locality, however, is attributable primarily to the presence of the welds. As can be seen from FIGS. 11 and 12, these consisted of substantial fillets, greatly in excess of the light runs which are sometimes applied for seam sealing purposes, and their stress-raising proclivities would be enhanced in consequence.

The cracking at the rivet holes was also found to be of the corrosion-fatigue type, the factors responsible being the variable stresses arising from the frequent pressure and thermal fluctuations to which vessels of this type are subjected in service, and the corrosive action of the water that entered the seams at localities where the caulking was disturbed due to relative movement of the plates.

If the fissures in the first vessel had passed undetected and continued to develop, it is probable that, ultimately, a disastrous explosion, similar to that of the Norwegian vessel, would have occurred. The two cases described not only serve to illustrate the danger of applying fillet welds to seal the lap edges of riveted seams, but point to the inadvisability of employing riveted construction for vessels intended for service under conditions involving frequent pressure and thermal fluctuations, as it is extremely difficult to maintain the tightness of riveted seams under these conditions. Such vessels are now almost exclusively of all-welded construction.