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EXAMINATION OF FAILED COPPER ALLOY FLEXIBLE METAL STEAM HOSE ASSEMBLIES

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

Two flexible metal joints, which had exploded at the new Union Station, Ottawa, were examined.

Analysis and examination of the bellows and braid wires showed these to be normal in composition and structure.

It is suggested from the layout of the assemblies and damage to the piping that Joint No. 1 failed first, this causing the subsequent failure of Joint No. 2.

It was found that, in Joint No. 1 (Figure 13), 60 braid wires out of 432 were not bonded to the flange by the brazing operation. These unbonded wires were concentrated in one portion of the circumference so that in one 2-1/4-inch arc, only 35% of the wires were bonded. Although it is considered that this defect is significant, it is not known exactly what reduction in the bursting pressure of the joint it would cause.

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INTRODUCTION

On October 14th a letter was received from Mr. J.W. Noonan, Group Leader, Aircraft Hydraulics, Structures and Materials Laboratory, National Research Council, providing information concerning the failure of two flexible metal hose assemblies from the steam installation at the new Ottawa Union Station. This was in confirmation of a telephone request for assistance in determining the cause of this failure which had killed two persons and seriously scalded another.

Two similar but longer joints which were received by National Research Council for comparative testing are shown in Figure 1. The recovered components of one of the other two failed joints are shown in Figure 2 to illustrate the extent of deformation and general mode of failure.

METALLURGY AND CONSTRUCTION OF THE JOINTS

The construction and metallurgy of both joints appeared identical. The steel flanges, etc., were not examined since failure occurred in the copper parts.

The joints consist essentially of an inner closely corrugated thin pipe of bronze (approximately 98.5% Cu, 1.5% Sn and 0.06% P) which is overlaid by a braided sleeve of brass wire (approximately 90% Cu and 9.5% Zn). These have been butted against the steel flanges, surrounded by a brass collar, and brazed to form a joint. A cross section of the joint, with the brass collar torn away to facilitate visual inspection, is shown in Figure 3.

Metallographic examination, hardness and tensile tests show the wire material to have a normal structure and grain size (0.006 to 0.010 mm) and to be in the half hard temper. Similar wire from the joint tested at National Research Council had mechanical properties of 50 kpsi UTS, 35 kpsi YS and 20-25% El, wire diameter 0.027 in. approximately.

Similarly the corrugated tube material also appeared to have normal structure and grain size (0.015 mm). The deformation in manufacture and in failure rendered mechanical testing impractical, but hardness tests suggested that the material was probably in the half hard temper with mechanical properties of 54 kpsi UTS, 52 kpsi YS and 13% El. It was noted that these tubes had been made by welding. Some superficial staining could be seen particularly on the inner surface of the corrugated tubes, but there was no evidence in the microstructures of any corrosion damage.

Metallography suggested that the brazing material was of the common type containing say 45% Zn and 55% Cu.

The brass collar was not examined since it did not appear to be involved in the original failure.

EXAMINATION OF FRACTURES

The many fractured surfaces of the two failed joints were examined carefully in an attempt to determine the mode of failure.

(a) Joint No. 1. The joint which is shown in Figure 4 is seen to be in two pieces, and the way in which the corrugated tube has split and forced the braided sleeve down towards one flange and other factors suggest that the progression of failure was as follows:

(1) failure of the braid wires at or near the brazed joint,

(2) extension of the inner corrugated tube,

(3) failure of the inner tube near one end,

(4) longitudinal splitting and opening of the inner tube from this end pushing the braided sleeve ahead of it towards the other end.

On the premise that the failure occurred in the above manner, the broken ends of the braid wires were carefully examined since it was thought these were the first to fail. The wires are arranged in 48 braids of nine strands each around the circumference, giving 432 wires, or approximately 30 wires per inch of circumference. The broken ends of the wires showed a characteristic "necking down" at the fracture, and the fracture itself is rough and crystalline in appearance. These two features are shown in Figures 5 and 6. However about 60 of the wires did not show these fracture characteristics. Instead the wire ends were smooth (although sometimes blackened by the heat of brazing) and showed no necking. This is illustrated in Figures 7 and 8. Of this total of 60 wires, 42 were in one area extending over about 2-1/4 in. of the circumference, and the others were close to this area.

By relating discoloured "water level" marks on the inner surface of the corrugated tube with those on part of the tube remaining on the flange, it was possible to orient the wires showing non-tensile fractures with the approximate section of the brazed joint approximately where they were located. Figure 9 shows a view of this area in the fracture after the outer brass collar had been removed, and for comparison, an area showing the full component of fractured wires bonded in the brazing metal is shown in Figure 10. It would appear therefore that over about 2-1/4 in. of the circumference of one end of Joint No. 1, 42 out of an expected total of 67 braid wires were not bonded to the brazing metal.

The probable progression of failure for this joint has already been outlined. The lack of registry of the fracture surfaces between the sections of corrugated inner tube attached to the two flanges, and a count of corrugations shows that a relatively large piece of the inner tube is missing (only 26 of an expected 42 corrugations remain). However, examination of the fractured surfaces and the general deformation of the remaining material suggest tensile failure of the corrugated inner tube in the region of the unbonded wires (as shown by the "necking down" of the inner tube), the other fractured edges showing tear or tensile fractures depending on the mode of crack propagation in the particular area.

(b) Joint No. 2. As shown in Figure 2, three components were recovered, although examination of the fractures indicate that smaller lens-shaped pieces (say 2" x 4") are missing from each end of the corrugated inner tube. The appearance suggests that initial failure occurred in the braid at the brazed joint on the right hand side of Figure 2, and that the inner corrugated tube had then extended under the steam pressure. It is proposed that failure of the inner tube then occurred at the left hand brazed joint of Figure 2, and, in pulling the corrugated tube through the braided sleeve, the necking down of this sleeve occurred. It would be expected that once the inner tube was separated from the sleeve, steam would escape, and no further fracture would occur. Hence it is proposed that the fracture of the inner tube at the right hand flange of Figure 2 was probably initiated by some bending or shear movement of the inner tube on the flange. Once this fracture was initiated, the inner tube, completely unsupported by the braid was torn and split upwards towards the already broken end, but the tear stopped before it reached this end. This can be seen in Figure 2 where the lens-shaped fractured end of the tube can be seen just behind the right hand flange. In fact this fracture came from the left hand flange so that the whole corrugated tube should be displaced end to end.

Examination of the broken braid wires showed that, in this case, only three could be found which did not appear to have been bonded to the braze metal, and these were not all in the same area.

It was noted that the fractures of the failed inner tube on the free flanges of both Joints 1 and 2 were very similar (Figure 11). Both contained what appeared to be an original tensile failure close to the braze, both ends of which tore upwards, and the extensive damage to the inner tube and collar at the opposite side of the fracture appears to have been caused largely by bending. Figure 10 shows the tensile portion of the fracture on the free flange of Joint 2.

In one area of Joint 2, about 18 braid wires had been melted, presumably by the careless application of a brazing or welding torch, as can be seen in Figure 12. (It is not known whether these melted wires had been displaced before, during or after the explosion). Careful registration and examination of the corrugated inner tube in the area which would have been behind this heated zone suggested that the fracture passed a little away from this area, and that in any case, the fracture in this region was of secondary tearing origin, not that of primary failure.

Both joints showed some mechanical damage as is to be expected and it could not be determined if any of this was present before the explosion. However, there appeared to be no obvious relationship between mechanical damage and initial failure.

FAILURE OF THE JOINTS RELATED TO THE WHOLE PIPING SYSTEM

A plan of the critical section of the piping system is given in Figure 13 which also shows the location and direction from which the following four photographs of the failure site were taken (Figures 14-17). It is most unfortunate that the failed expansion joints were stripped from the pipes before the photographs were taken. This makes it much more difficult to determine the mode of failure since the fractured surfaces can no longer be positively related to the movement of the steam pipe during the explosive failure.

Considering the location of the pipes, and the damage to the piping system shown in Figures 14-17, this must now be explained in terms of a sequence of failure.

If it is assumed that Joint No. 2 failed first, then it would be expected as shown in Figure 17 that the arm of the pipe would be blown off the pipe supports. An axial load would be applied to the other side of the joint, but, as shown in Figure 16, this is fixed to the wall with a pipe clamp. Thus, unless this pipe clamp is sheared off the wall it would be expected that little load would be transmitted to Joint No. 1 by the failure of Joint No. 2. Since the pipe clamp although bent, still remains attached to the wall (Figure 16) the double failure cannot be readily explained on this basis. (See also Figure 18).

On the other hand, if Joint No. 1 failed first, this would blow the other unclamped arm off the pipe support bracket as shown in Figure 15, and this long unsupported arm of pipe would then exert a bending tearing movement on the pipe clamp and would cause the deformation to the pipe and to the clamp shown in Figure 16. This motion in turn would impart a severe side shear to Joint No. 2 which would probably be quite sufficient to initiate failure in this joint. It will be appreciated that although the boiler may only be connected to one end of the pipe,the system has enough capacity that in the event of failure there is a relatively large amount of stored energy on either side of the fracture. Thus there is probably enough stored energy in the system even on the side remote from the boiler to explosively propagate a second fracture.

Thus it would appear that initial failure in Joint No. 1 explains all the observed damage in the photographs.

TESTS ON UNBROKEN FLEXIBLE JOINTS

Tests were conducted by the Structures and Materials Laboratory, National Research Council on an unbroken 4 in. joint 16 in. long of the same general construction as the failed joints. Hot oil was used as the pressurizing medium and an offset was given to the joint to simulate the service conditions. It was found that this joint extended about 3/4 in. then braid failure in the brazed joint caused the test to be stopped at a pressure of about 400 psi (as compared to 150 psi at which pressure the other joints were said to have failed after 6 days).

This joint was then sectioned and examined as before. It was found that approximately 250 wires had broken and that all except four of these showed typical tensile failures. It is perhaps significant that these four unbonded wires were in one group at the centre of the fractured area (i.e., approximately 125 wires on each side of the group) suggesting that fracture initiated in this unbonded area. It should be noted that the mode of failure was fracture of the braid wires before rupture of the corrugated inner tube (which did not occur in this case as the test was stopped). It is not known whether the inner tube extended and, unsupported by the braid, would burst at a higher or lower pressure than that necessary to cause initial failure of the braid. However, the manufacturer's literature suggests a reduction factor of about 20:1 comparing the maximum allowable working pressure of braided joints with similar unbraided unrestrained joints.

DISCUSSION

It is assumed that the joints used were nominally the correct ones for the application and that the failure was due to some mechanical or metallurgical inadequacy of the joints or to some unusual service conditions.

Examination of the materials of the joint construction suggests that they are of normal commercial quality, and contain no defects liable to cause premature failure. However, an extensive defect in the brazing of Joint No. 1 was discovered which left 65% of the braid wires loose and unbonded over about 2-1/4 in. of the circumference. It is not known to what extent this would lower the bursting pressure but the National Research Council tests showed that initial failure occurred in the wire rather than the corrugated inner tube, and indicated that failure started in an area containing a small group (4) of unbonded wires. In the introductory comments concerning metal hose, the manufacturer states "Whenever internal pressure is applied to a corrugated metal hose it will elongate unless restrained. Generally this restraint is provided by a wire braid sheath ---- the strength of the braid sheath determines the maximum working pressure of the hose".

It would appear therefore that these unbonded braid wires on the 2-1/4 in. length could markedly reduce the ability of the joint to withstand the applied pressure, and the general damage and progression of failure analysis is consistent with the view that initial failure occurred in Joint No. 1.

Little comment can be made with regard to service conditions since these are not subject to examination in the same manner as the joint materials. However, it was stated that the steam line had been under pressure for six days before failure occurred. If this were the case, it would appear that by coincidence the operating pressures were such that the joint was progressively moving towards final failure over that period or that some sudden load increase caused catastrophic failure of the joint (which, because of the unbonded wires is presumed to be already overloaded). It was thought that, as the joint expanded slowly during failure, an increasing resistance to further movement would be offered by the constraint of the piping system itself. However approximate calculations indicate that the resistance to movement imparted by the piping system is only about 150 lb per half inch of extension of the joint. When it is considered that the load available from the steam pressure is about 1900 lb it will be seen that the constraint imposed by the piping system is nominal and is probably not a factor in explaining the slow failure. Again, this points out the importance of a sound braid and the fact that the restraint on joint movement is generally provided by the wire braid sheath as noted by the manufacturers.

CONCLUSIONS

(a) The alloys from which the wire braid and corrugated inner tube of the both failed joints were made were a low zinc brass, and a low tin bronze respectively. These were of of normal commercial quality.

(b) Examination showed that in one area of the brazed joints on flexible Joint No. 1, over a length of about 2-1/4 in. only 35% of the braid wires were bonded to the brazing metal.

(c) Pressure tests on a similar flexible joint and the manufacturers literature suggest that failure starts by rupture of the braid wires at the brazed joint, and emphasize the influence of the strength of the braid on the permissible working pressure of the flexible joint. However, it is not known to what extent the lack of bond on the 60 braid wires would influence the rupture pressure of the joint.

(d) The damage to the piping and other factors are consistent with initial failure of Joint No. 1, and subsequent failure of Joint No. 2 under the stresses imposed by this initial failure.

(e) The statement that the joints had been in service for six days at the same nominal pressure can only be explained on the basis of one of the following

(i) by coincidence the pressure was such, that slow failure took place until after six days the joint was so weakened that it failed catastrophically.

(ii) unrecorded overload condition in system took place, causing the weakest member (Joint No. 1) to fail catastrophically. Again, the magnitude of this possible overload cannot be estimated without some prior knowledge of the extent to which Joint No. 1 was weakened by the lack of bond on the 60 braid wires.

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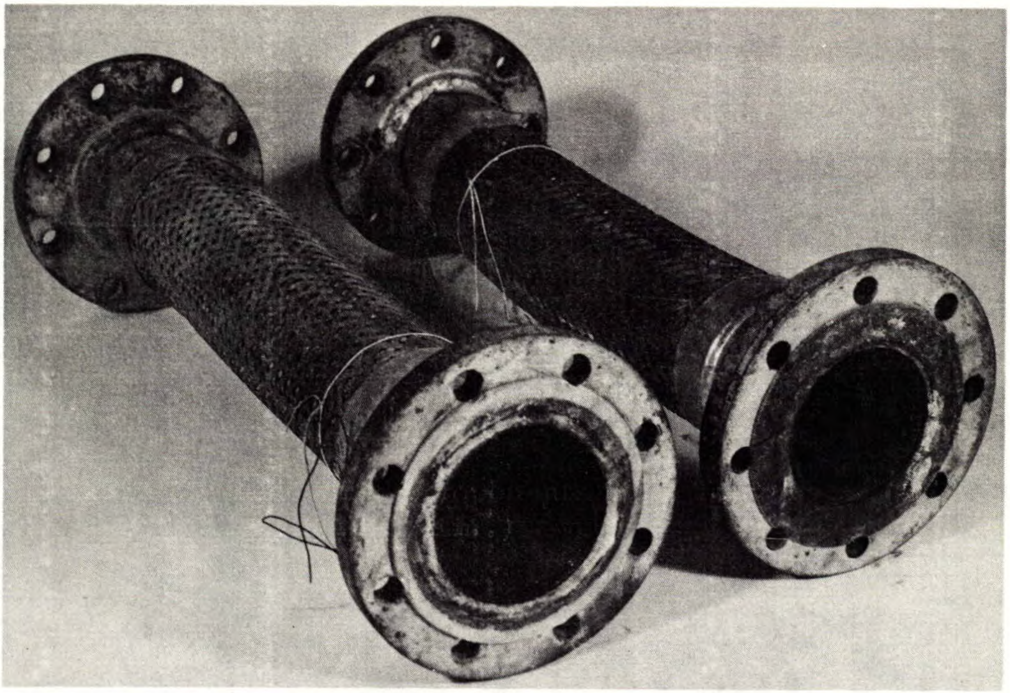


Figure 1. Flexible metal hose assemblies (live length 16-1/2 in.)

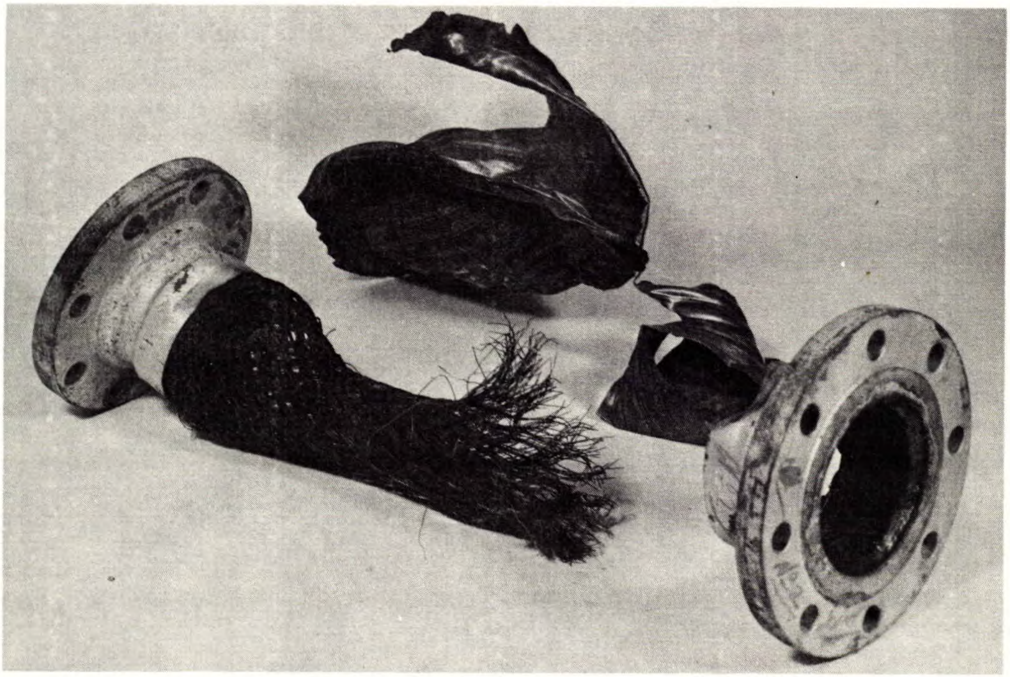
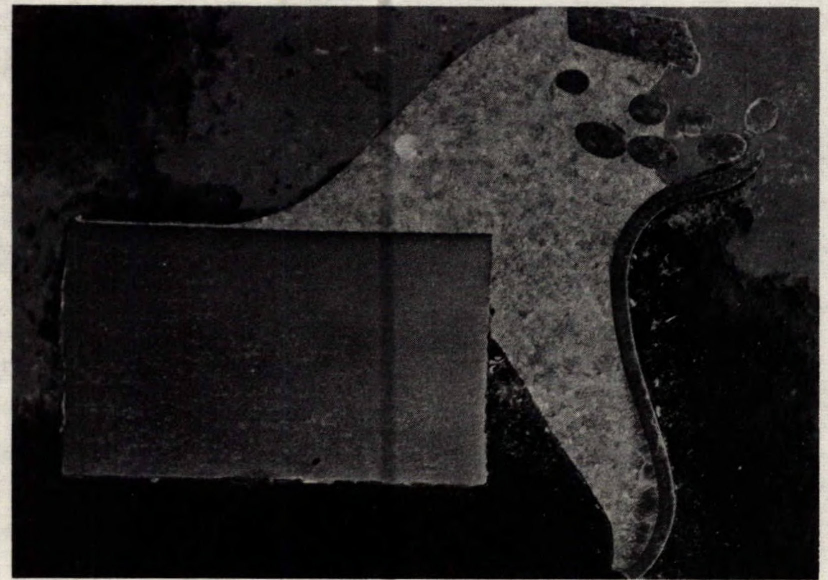


Figure 2. Recovered components from Joint No. 2 (live length 10-3/4 in.)



X5.5

Figure 3. Cross section of brazed joint showing steel flange, inner corrugated tube, wire braid, brazing metal and part of binding collar.

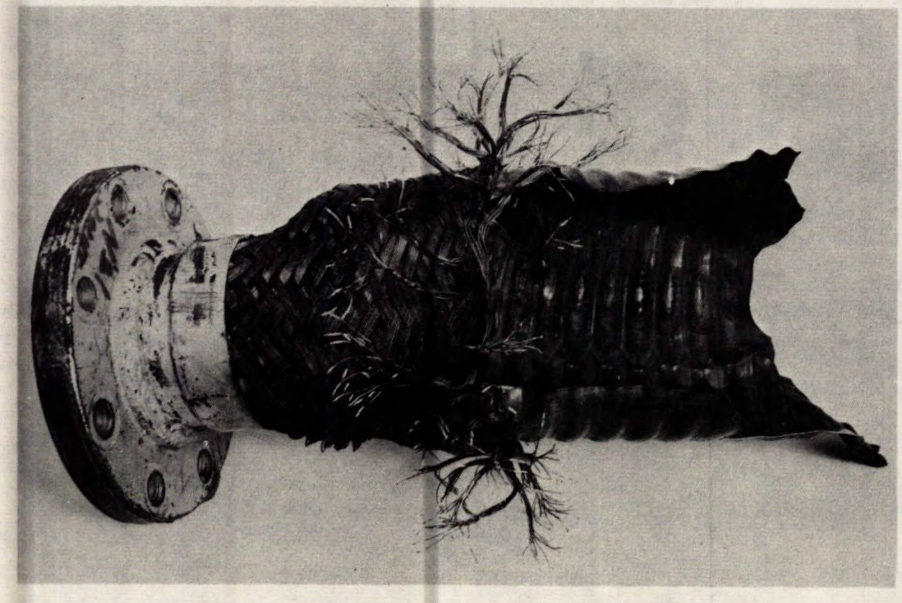
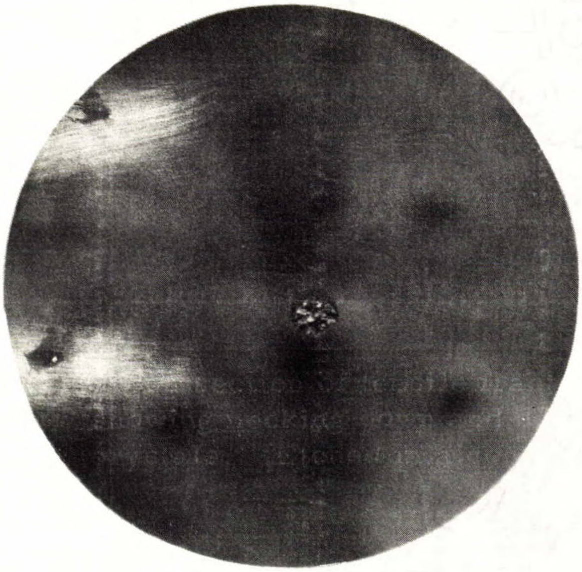
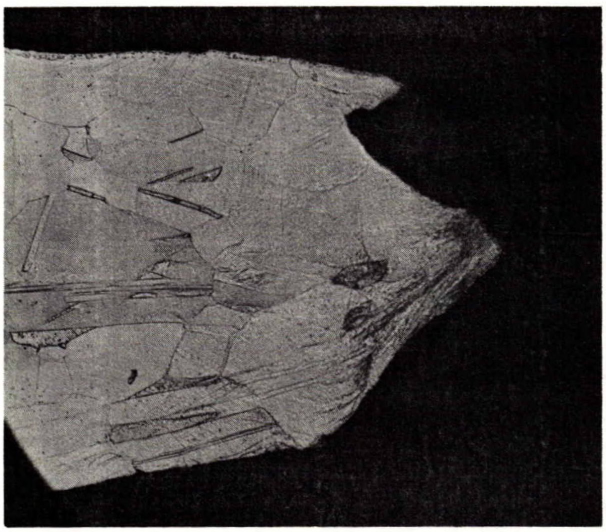


Figure 4. Joint No. 1 - photographed after preliminary examination of broken wire ends etc.



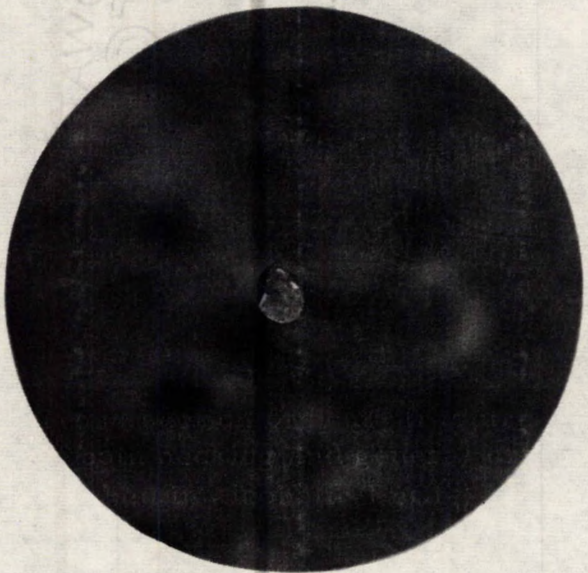
X10 approx.

Figure 5. Fractured end of braid wire broken in tension.



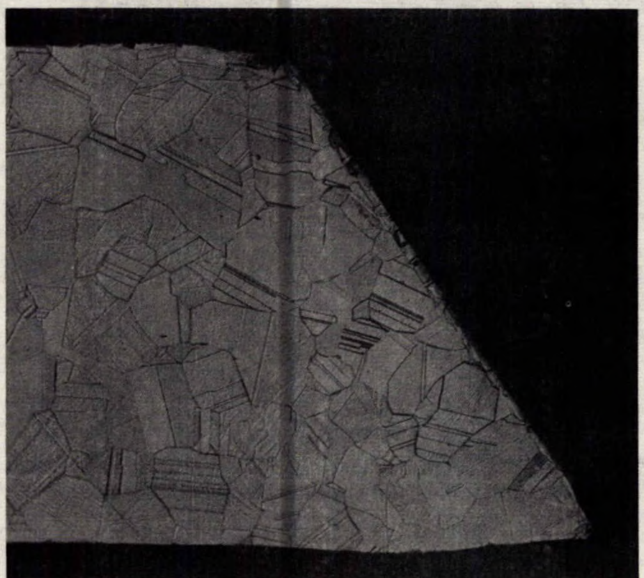
X100

Figure 6. Cross section of tensile fracture of braid wire showing necking down and deformation of crystals. (Etched in alcoholic $FeCl_3$).



X10 approx.

Figure 7. End of braid wire from Joint No. 1 showing cut marks rather than tension failure.



X100

Figure 8. Cross section of "cut" fracture showing absence of both necking and general crystals elongation. (Etched in alcoholic $FeCl_3$).

X2.5

Figure 9. Top inside view of brazed joint from area showing "cut" wires after removal of outer brass collar. Note general absence of wires bonded into brazing metal.

X2.5

Figure 10. Area of brazed joint showing fractured wires securely bonded and embedded in brazing metal.

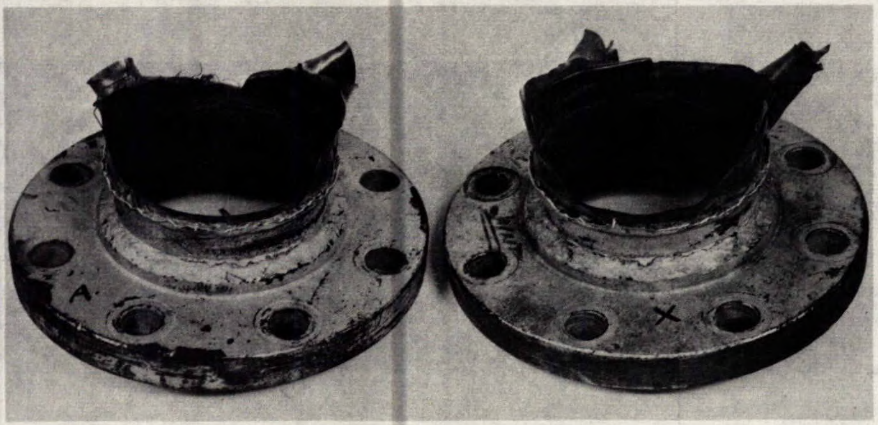


Figure 11. Two free flanges from No. 1 and No. 2 joints. Similarity of inner tube fractures suggests that fracture mechanisms were essentially similar. Outer brass collar has been peeled back to facilitate examination.

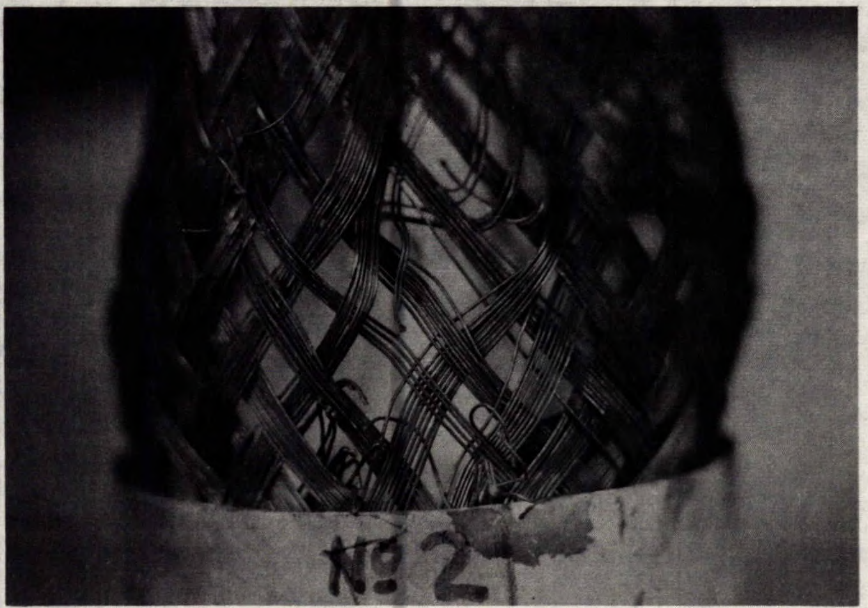


Figure 12. Braid wires damaged by melting above the collar of Joint No. 2.

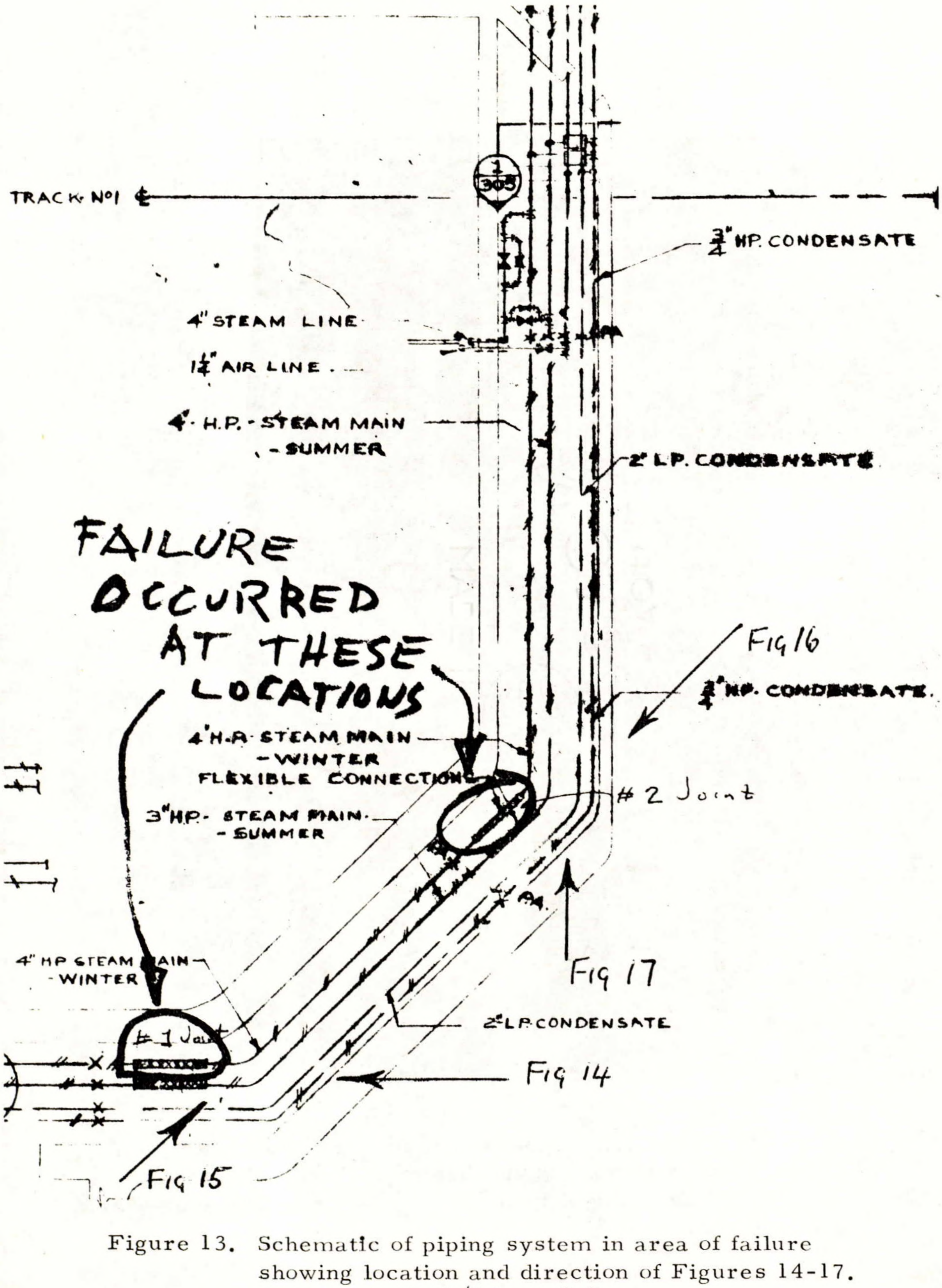


Figure 13. Schematic of piping system in area of failure showing location and direction of Figures 14-17. Approx. scale 1/8 in. = 1 ft.

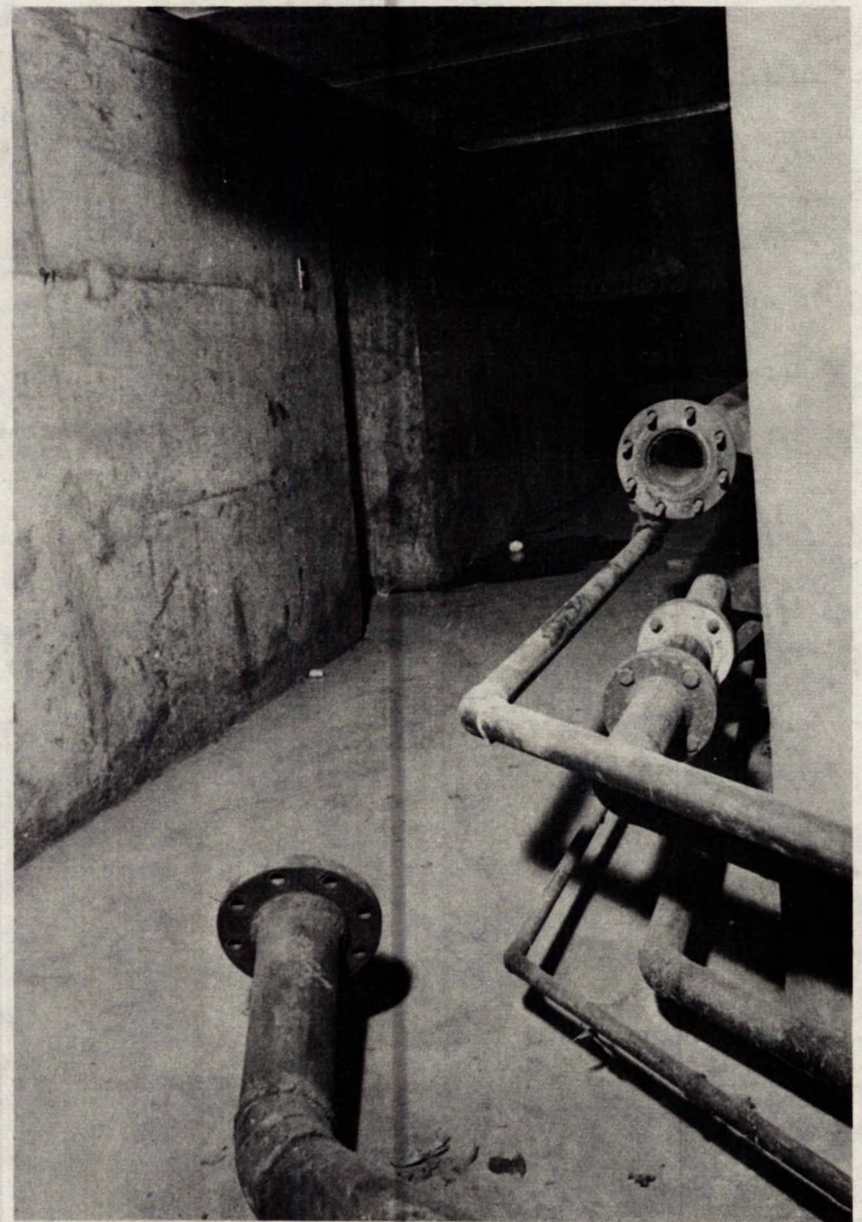


Figure 14. Joint No. 1 showing one arm held to the wall with a pipe bracket just behind the joint, the other arm being blown outward and away from the joint. (See Figure 13).

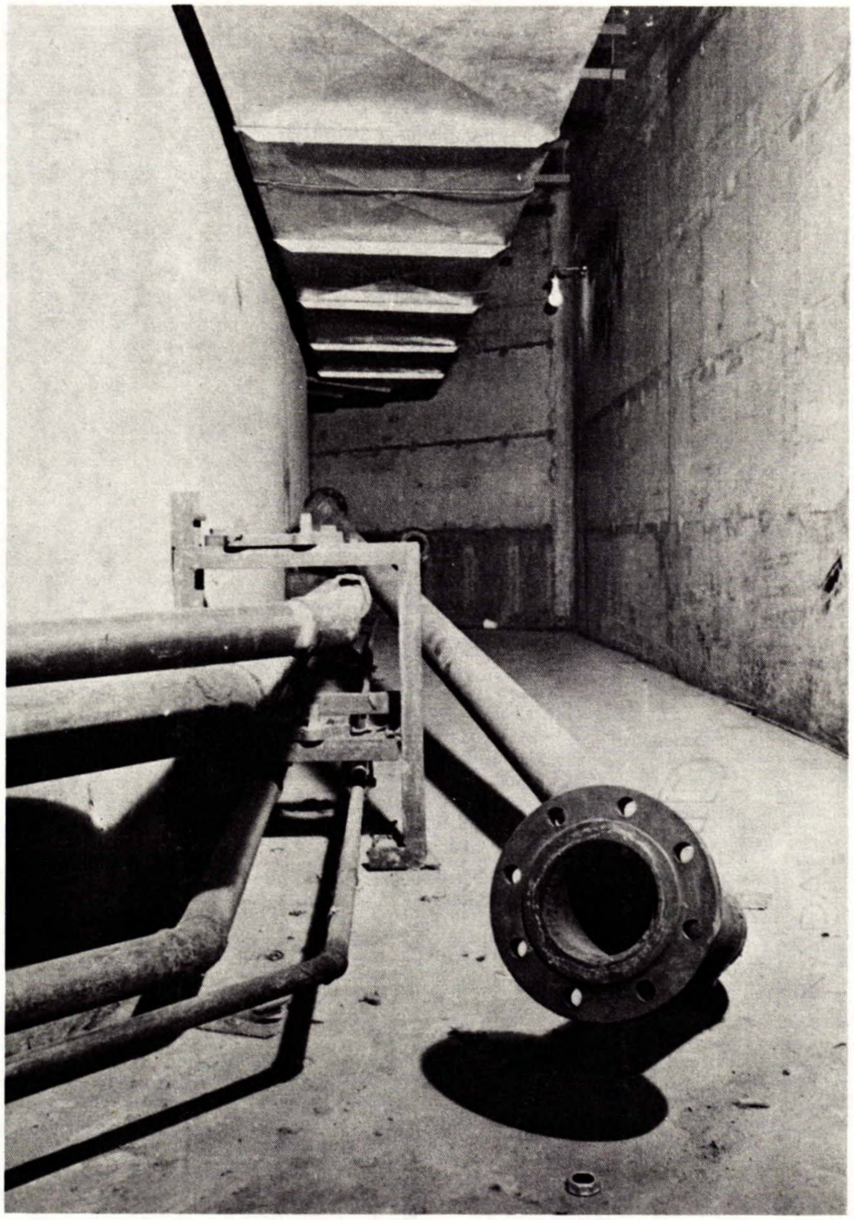


Figure 15. Joint No. 1 showing longer arm blown off pipe support, and the displacement of the ends of Joint No. 2. (See Figure 13).

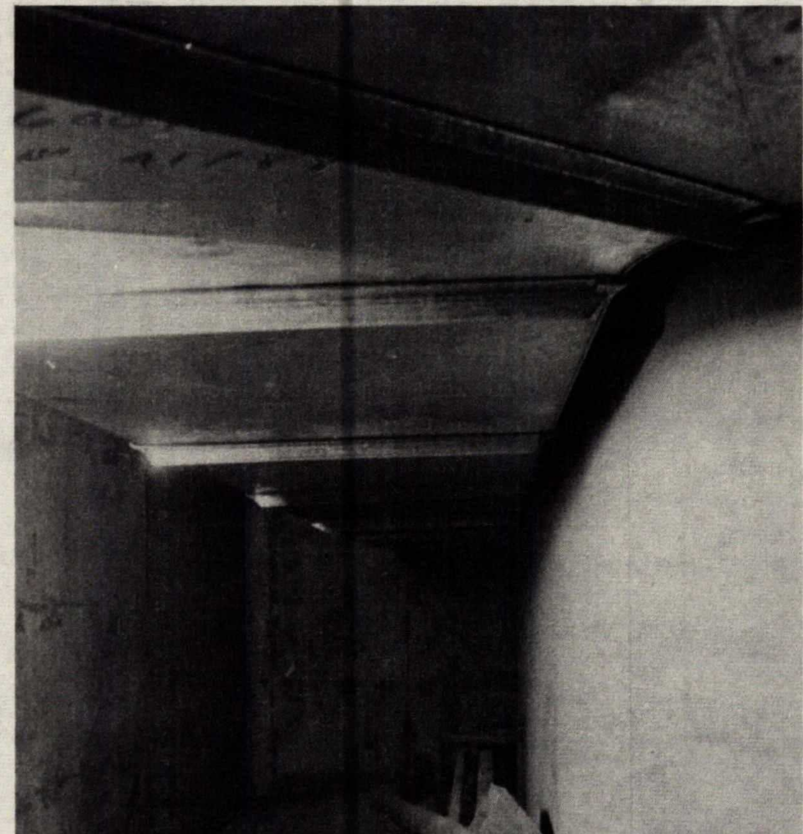


Figure 16. One end of Joint No. 2. Note particularly the deformation in the pipe in the region of the pipe bracket bolted to the wall, the deformation of the pipe bracket itself and the displacement of the end of the joint towards the wall. (See Figure 13).

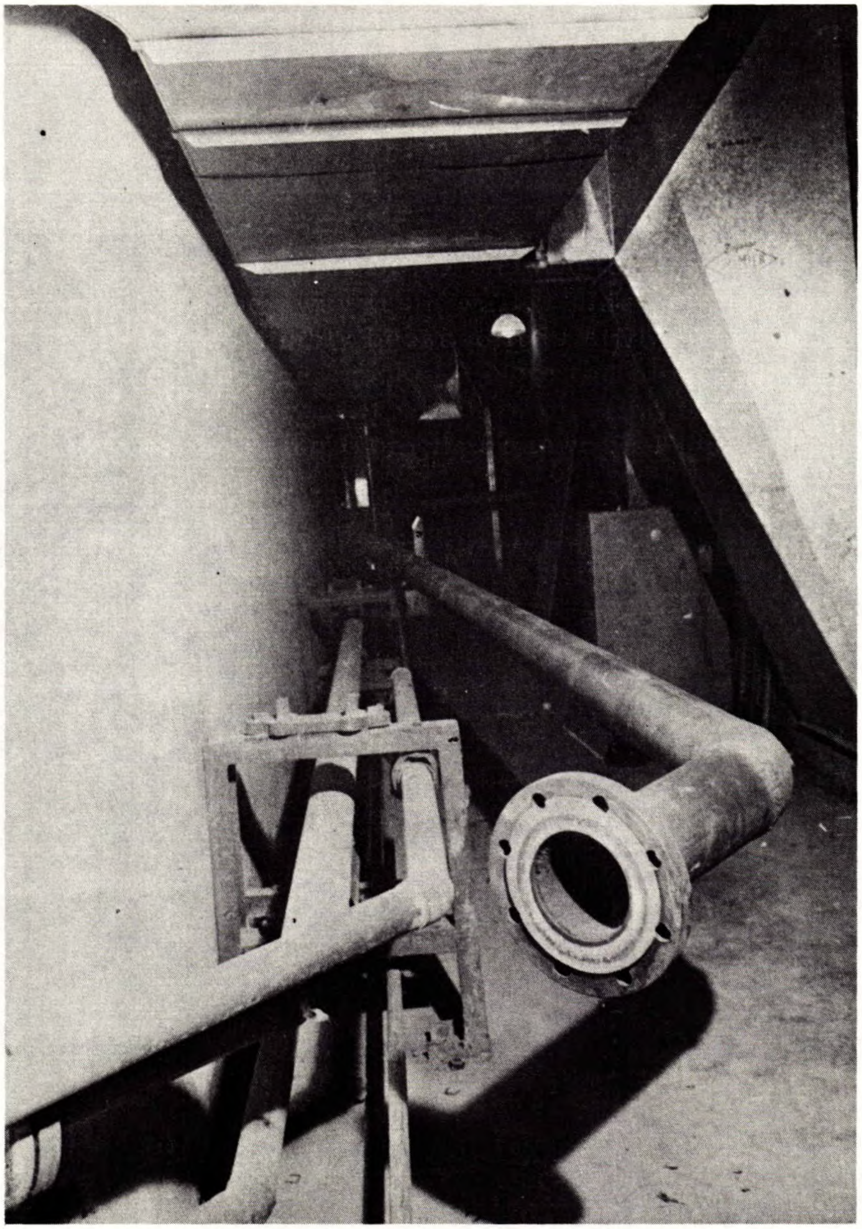


Figure 17. Other end of Joint No. 2 showing outward displacement of pipe away from wall. This pipe has not fallen presumably because it is still supported by the second pipe bracket. Note the pipe roller support on this bracket which is missing from the front bracket and also from that shown in Figure 15. (See Figure 13).

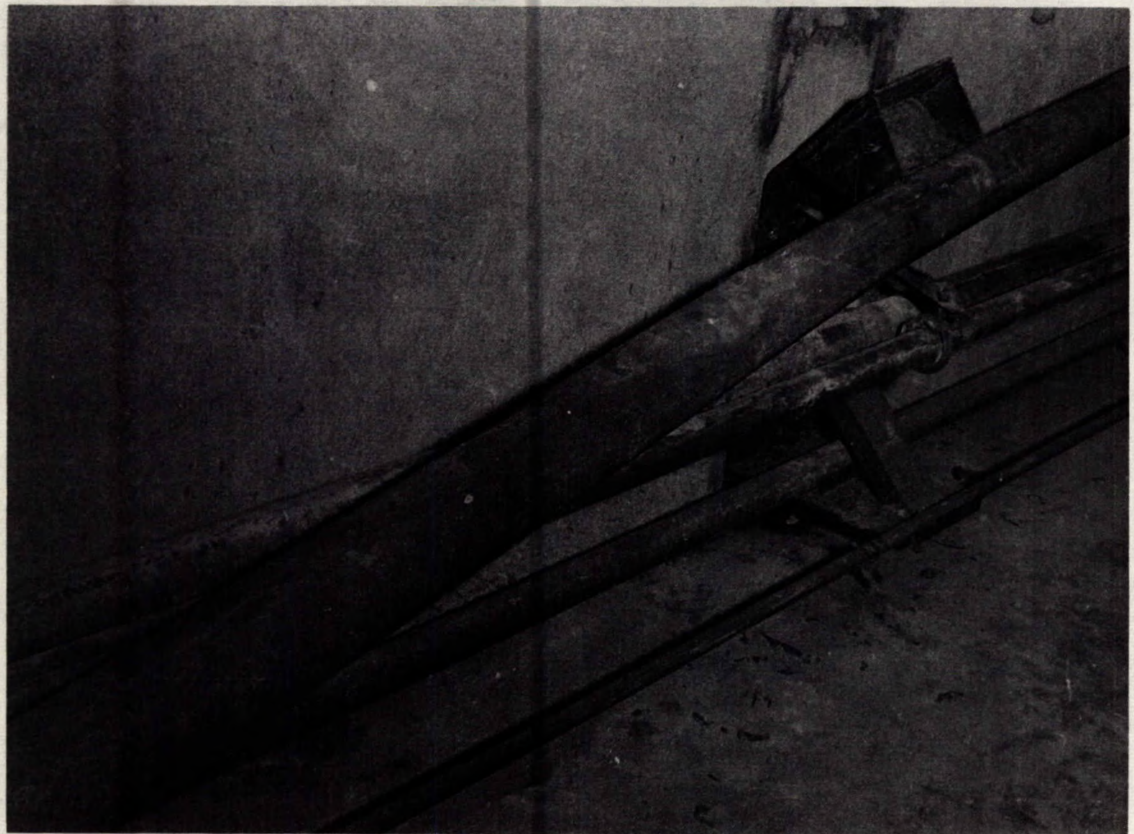


Figure 18. Detail of pipe wall clamp shown in Figure 16.