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Hose Safety During High-Pressure Water-Jet Cutting

By C. D. Taylor, J. L. Thompson, H. J. Handewith, and E. D. Thimons

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Flexible hoses with rated working pressures up to 40,000 psi are used when high-pressure water jets are employed to cut rock or improve the performance of mining machines. Hose failures at such high pressures can result in serious injuries to workers. The Bureau of Mines used fatigue and burst tests to investigate the failure modes of high-pressure hoses at their rated working and burst pressures. Fatigue failure, at rated working pressures, occurred when the inner liner of the high-pressure hose broke, allowing water to seep through the wire wrapping, although the reinforcement wires did not break. At the burst pressure, all hoses failed catastrophically when the reinforcement wires broke. Low-pressure hoses placed over the high-pressure hoses for safety failed to contain water released by catastrophic failure.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

c/min	cycle per minute	pct	percent
in	inch	psi	pound per square inch
mm	millimeter		

HOSE SAFETY DURING HIGH-PRESSURE WATER-JET CUTTING

By C. D. Taylor,[1] J. L. Thompson,[2] H. J. Handewith,[3] and E. D. Thimons[4]

ABSTRACT

Flexible hoses with rated working pressures up to 40,000 psi are used when high-pressure water jets are employed to cut rock or improve the performance of mining machines. Hose failures at such high pressures can result in serious injuries to workers.

The Bureau of Mines used fatigue and burst tests to investigate the failure modes of high-pressure hoses at their rated working and burst pressures. Fatigue failure, at rated working pressures, occurred when the inner liner of the high-pressure hose broke, allowing water to seep through the wire wrapping, although the reinforcement wires did not break. At the burst pressure, all hoses failed catastrophically when the reinforcement wires broke. Low-pressure hoses placed over the high-pressure hoses for safety failed to contain water released by catastrophic failure.

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INTRODUCTION

The use of high-pressure water to cut rock or assist in the mechanical cutting of rock is being evaluated by the Bureau of Mines and others.[5] Water jet cutting uses solid or pulsed streams of high-pressure water which, upon impact with rock, have sufficient energy to cut and/ or fracture the material. For water-jet-assisted cutting, the high-pressure water is directed through spray nozzles located in front of each cutting bit on the miner drum. The spray nozzle produces a solid stream of water that impinges on the rock within 5 mm ahead of the cutting bit. The added energy supplied by the water improves rock cutting and bit wear and reduces dust generation and fines.

High water pressures for water-jet cutting are produced by a pressure-compensated piston pump or by an intensifier. Water is carried to the spray nozzles through hard piping or specially constructed flexible hose. In some cases, it is necessary to route the flexible hose through areas where miners must work, which could present a safety hazard if the hose ruptures.

The use of high-pressure water during mining shows considerable promise; however, the associated safety hazards have not been fully investigated. Many hose safety standards (e.g., for hydraulic oil hoses) are written for applications where the hose pressure does not exceed 10,000 psi. For water jet cutting, water pressures of 30,000 psi or greater may be required. Therefore, safety standards that apply to hoses for hydraulic fluids will not necessarily protect workers using high-pressure water hoses.

A jet of high-pressure water at 2,000 psi (0.006-in-diam orifice) can penetrate through 60 mm of human tissue.[6] Rupture of a high-pressure hose can result in a brief but potentially dangerous stream of high-pressure water that could cause serious injury to workers.

Adequate safety standards must be a primary consideration when using high-pressure-water underground, because water pressures up to 40,000 psi are required for some mining applications.

The operating characteristics of hoses are routinely evaluated by the manufacturers. However, the testing procedures used have not been published, and the testing procedures vary among the manufacturers. Hose testing procedures that have been published by several different organizations are written for specific types of hose and are not applicable for high-pressure water hose.

The objective of this study was to investigate the failure modes of typical high-pressure hoses and determine what safety hazards hose failures could present to a worker. Hose failure due to fatigue was studied by repeatedly cycling the water pressure up to the rated working pressure. For burst testing, the pressure was gradually increased until failure occurred. Protective sleeves consisting of sections of hose with lower pressure ratings were placed over the high-pressure hoses. Following failure of the inner hose, the sleeve was examined to determine if it had ruptured. A rupture in the sleeve would allow high-pressure water to escape from the annular area between the two hoses. Manufacturers' rated minimum burst pressures were compared with the actual burst pressures from the Bureau's tests.

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[5]Taylor, C.D., and R.J. Evans (comp.). Water-Jet-Assisted Cutting. Proceedings: Bureau of Mines Open Industry Meeting, Pittsburgh, PA, June 21, 1984. BuMines IC 9045, 1985, 86 pp.

[6]Ward, G. M. Safety Considerations Arising From Operational Experience With High Pressure Jet Cleaning. Paper F-1 in First International Symposium on Jet Cutting Technology (Proc. Symp. Univ. Warwick, United Kingdom, Apr. 5-7, 1972). BHRA Fluid Eng., Cranfield, Bedford, England 1972, pp. F1-F34.

HOSE SELECTION

Most available high-pressure hoses have a maximum inside diameter (ID) of 0.20 in and a rated working pressure of 30,000 to 35,000 psi. The manufacturers of the hose samples used established the rated working pressure at either 50 or 25 pct of the minimum rated burst pressure. Other manufacturers state that highly pressurized hoses can be safely used at 75 pct of the minimum rated burst pressure if a lower pressure rated sleeve is loosely fitted over the higher pressure hose.

Samples of high-pressure hose, 18 and 36 in long, from three manufacturers, were tested. Characteristics of each hose type are given in table 1. The minimum rated burst and working pressure values given were provided by the hose manufacturers. End fittings were provided and installed by the manufacturers.

TABLE 1. - High-pressure hoses tested

Hose type	Hose ID, in	Min rated pressure, psi	
		Burst	Working
A.........	0.20	72,500	36,250
B.........	.25	40,000	10,000
C.........	.20	62,600	31,300

Type A and B hoses had polymer inner liners, and type C had a rubber inner liner. Surrounding the inner liner were six layers of counterwound stainless steel wires (fig. 1). The wires were covered with either plastic or fabric. The hose used as the protective sleeve had a 3/4-in ID, a rated burst pressure of 5,000 psi, and a rated working pressure of 1,250 psi. The sleeve had a polymer inner liner reinforced with double-braided polyester cords covered with plastic.

TEST PROCEDURE

For each fatigue test, a 36-in length of either hose type A or B was connected to the test fixture. Thirty-six-inch lengths of type C hose were not available, and therefore this hose was not fatigue tested. Fatigue testing consisted of cycling the pressure in the hose from atmospheric pressure to the rated working pressure at 20 c/min for a minimum of 2,000 cycles unless failure occurred first. The fatigue tests were intended to simulate day-to-day usage. Hose samples that did not fail during fatigue testing were placed on the burst test apparatus to determine if the fatigue testing had weakened the hose causing it to burst at a lower pressure.

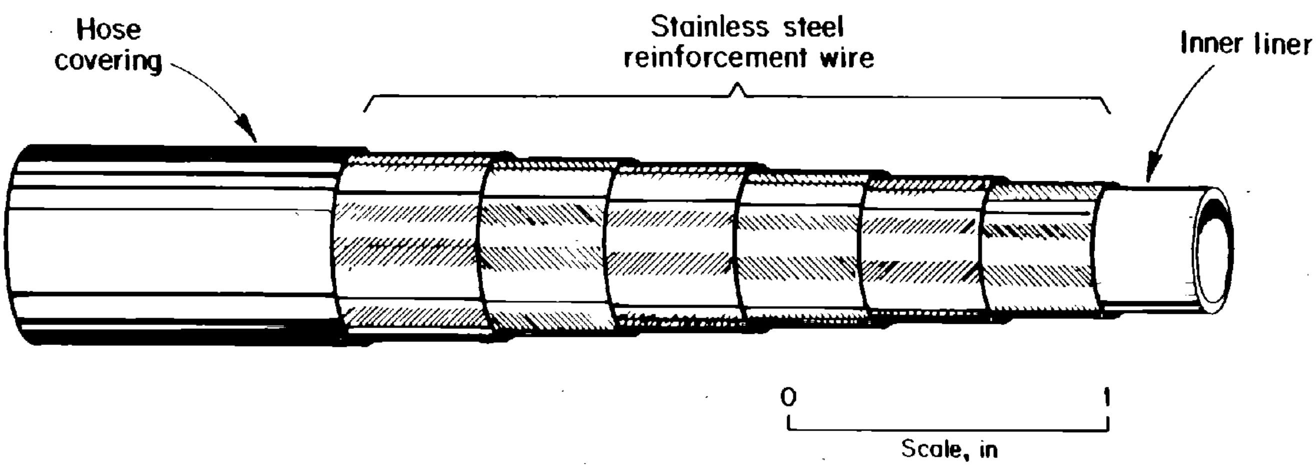

FIGURE 1.—High-pressure hose showing layers of reinforcement wires.

For burst testing, the Bureau used a hose burst test fixture that was designed and fabricated by a commercial firm for routine quality testing of high-pressure water hoses. The test unit consists of hinged steel channel sections locked together to create a safe pressure containment area for bursting hoses. An insert of clear rigid plastic in the top channel facilitates viewing (fig. 2). The high-pressure water is generated by an intensifier with a 47:1 water-to-oil pressure ratio (fig.3). For safety, the intensifier is located at the end of the test unit, inside a steel cylinder.

Fifteen new 18-in-long hose samples and seven 36-in-long samples that did not burst during fatigue testing were burst tested. For each burst test, the hose sample was placed in a test box and the coupling attached to the fitting leading to the pressure intensifier. The other end of the hose was connected to an elevated reservoir that displaced all air in the test sample and in the plumbing connected to the intensifier. When all air was eliminated from the system, the reservoir feed line was disconnected from the sample hose and replaced with an end cap. After the hydraulic system was pressurized, the intensifier cylinder raised the water pressure until the hose failed. Burst pressures were recorded on maximum-reading hydraulic gauges.

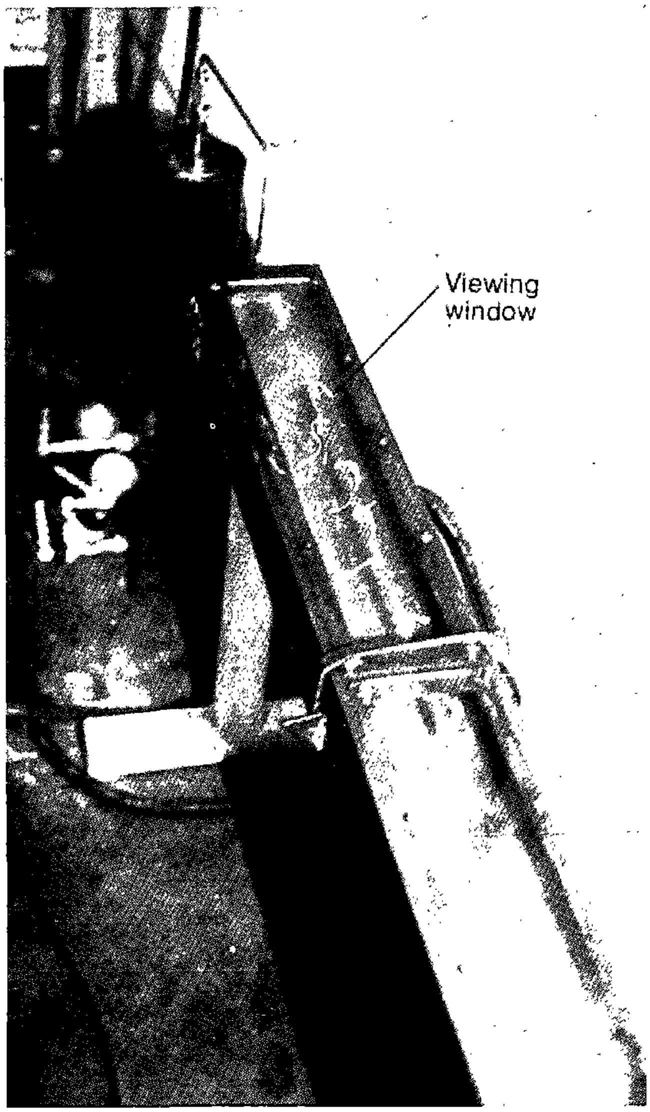

FIGURE 2.—Hose containment area.

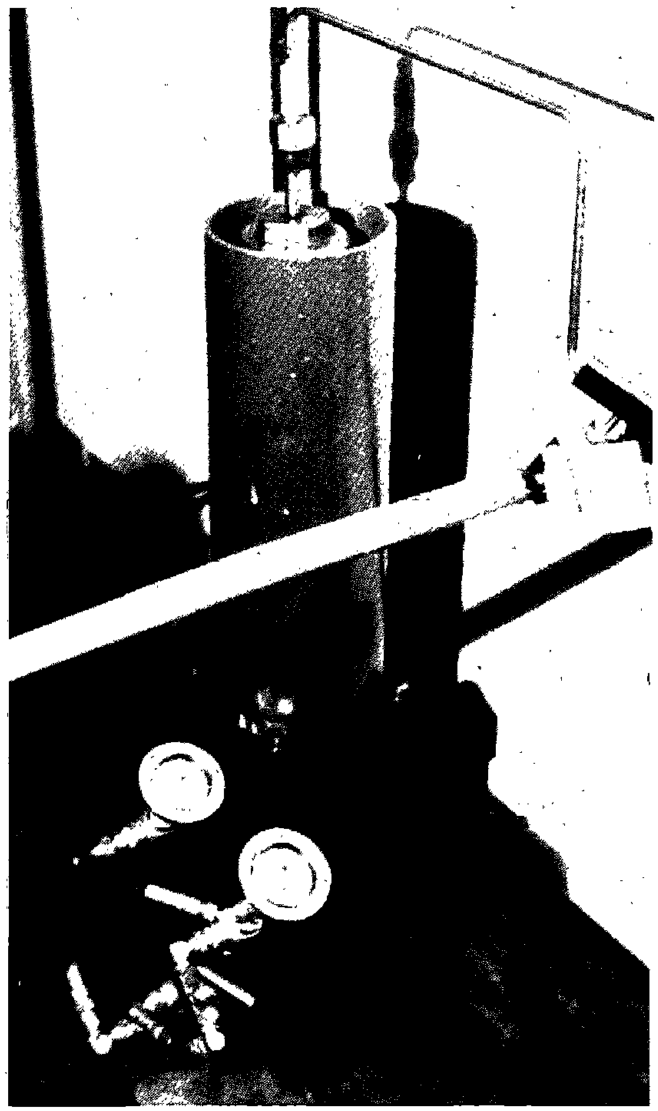

FIGURE 3.—Intensifier used for burst tests.

RESULTS

The fatigue test results are shown in table 2. The location where failure occurred in the hose is specified as "middle" or "end." "Middle" failures refers to failures that occurred at a distance greater than 2-1/2 times the hose outside diameter (OD) from the end fitting, while "end" failures occurred less than 2-1/2 times the hose OD from the end fitting. All failures during fatigue testing resulted in ballooning of the outer hose jacket (fig. 4) and were noncatastrophic (i.e., the water pressure was released slowly). In some cases, however, the ballooning was not localized, which made it difficult to locate the actual point of failure. None of the sleeves placed over the high-pressure hoses during the fatigue tests failed.

TABLE 2. - Fatigue test results

Fatigue test	Hose type	Cycles run	Failure location
1................	A	4,000	None.
2................	A	2,300	Do.
3................	A	2,500	Do.
4................	A	4,000	Do.
5................	B	2,000	Do.
6................	B	4,000	Do.
7................	B	6,000	Do.
8................	A	2,550	Middle.
9................	A	9,040	Do.
10..............	A	8,727	Do.
11..............	A	3,200	Do.
12..............	A	10,717	Do.
13..............	A	1,378	Do.
14..............	A	2,200	End.
15..............	A	3,198	Middle.

Results from the burst testing are given in table 3. For each test, the actual pressure at which the hose sample failed is given, and the burst pressure is also expressed as a percentage of the rated burst pressure. Table 3 also gives the number of fatigue cycles for the seven hose samples that did not fail during the fatigue tests and were subsequently burst tested.

In addition to middle and end failures, fitting failures also occurred during the burst tests (table 3). Fitting failures resulted in extrusion of material through the fitting weep holes or fracture of the fitting.

All failures during burst testing were catastrophic, producing a sudden and violent release of water preceded by breaking of the stainless steel reinforcement wires surrounding the inner lining (fig. 5). Two of the 22 catastrophic failures occurred at pressures significantly lower than the manufacturer's rated minimum burst pressure (tests 11 and 12).

For 11 of the burst tests, sleeves were placed over the high-pressure hose. The results in table 3 show that the sleeve failed in 7 of these 11 tests. Three of the sleeves were undamaged because the hose failure occurred in the fitting, beyond the sleeve length. Only one other sleeve did not fail (test 11); however, the inner hose broke catastrophically at

FIGURE 4.—Noncatastrophic hose failure.

TABLE 3. - Burst test results

Burst test	Hose type	Burst pressure		Fatigue test cycles run[1]	Failure location	Sleeve test failure[3]
		Actual, psi	Pct of rated[2]			
1.........	A	133,000	183	0	Fitting.	NAp.
2.........	A	128,000	177	0	..do....	NAp.
3.........	A	94,000	130	0	..do....	NAp.
4.........	A	94,000	130	0	..do....	NAp.
5.........	A	126,900	175	0	End.....	NAp.
6.........	A	82,250	113	0	Middle..	Yes.
7.........	A	89,300	123	0	..do....	Yes.
8.........	A	85,775	118	0	End.....	Yes.
9.........	A	84,600	117	0	Middle..	Yes.
10........	A	84,600	117	0	..do....	Yes.
11........	A	54,050	75	0	..do....	No.
12........	A	42,300	58	0	..do....	Yes.
13........	A	103,400	144	4,000	Fitting.	No.
14........	A	103,400	144	2,300	..do....	No.
15........	A	82,250	113	2,500	Middle..	NAp.
16........	A	82,250	113	4,000	..do....	Yes.
17........	B	75,200	188	2,000	End.....	NAp.
18........	B	75,200	188	4,000	Fitting.	NAp.
19........	B	63,450	159	6,000	..do....	No.
20........	C	63,450	101	0	..do....	NAp.
21........	C	74,025	118	0	End.....	NAp.
22........	C	75,200	120	0	Middle..	NAp.

[1]Number of fatigue test cycles prior to burst tests.
[2]From table 1.
[3]Yes = sleeve penetrated; No = sleeve not penetrated; NAp = not applicable, no sleeve test.

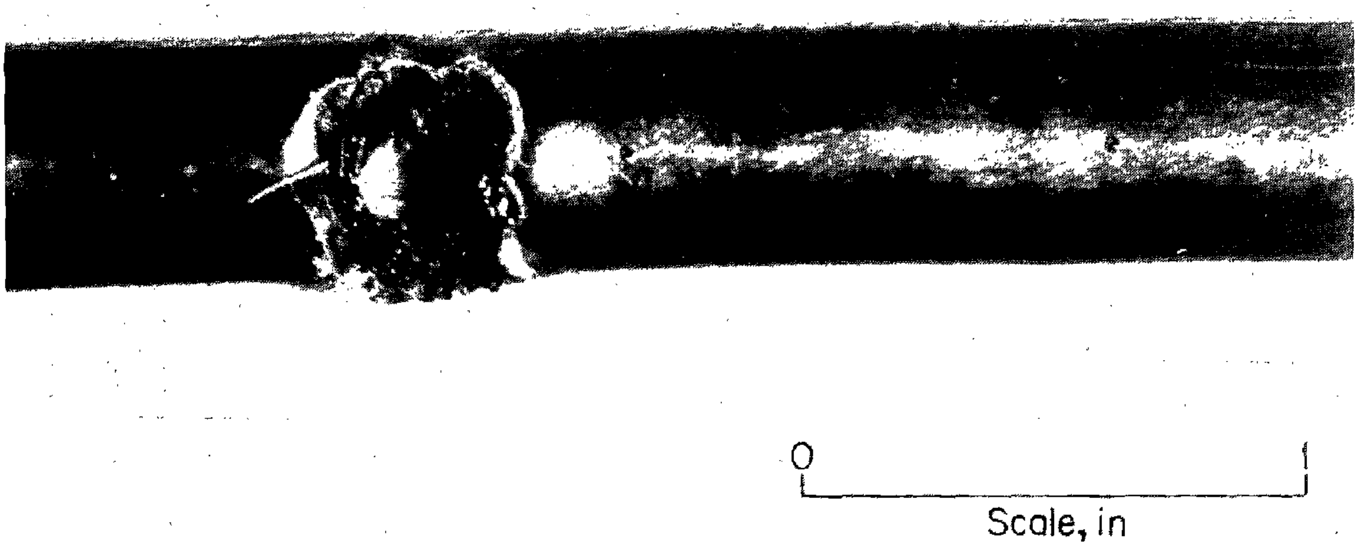

FIGURE 5.—Catastrophic hose failure.

a pressure lower than the actual burst pressure for most of the hoses tested, so a lower pressure spray was directed at the inner wall of the sleeve. Every sleeve subjected to a catastrophic failure at or above the rated burst pressure failed to contain the water.

DISCUSSION

USE OF OUTER SLEEVES

Following catastrophic failure of the high-pressure hose, the escaping water impinged on the inner surface of the sleeve. The sleeve did not fail due to the buildup of static fluid pressure in the annular space between the hoses, but because the sudden release of high-pressure water from the inner hose impinged on a small area of the sleeve with sufficient force to penetrate the sleeve material. During fatigue testing, the sleeves were not penetrated by any of the noncatastrophic failures. In all cases, the pressure of the water escaping from the high-pressure inner hose in the fatigue tests was lower than during catastrophic failure in the burst tests.

Further studies are needed to ascertain the feasibility of using a lower pressure outer hose to contain the catastrophic failure of a high-pressure hose. Only one type of hose was tested for use as an outer covering during these tests. Other types of hose (e.g., hoses having varying wall thickness and construction) should be tested to determine their ability to contain high-pressure water from a ruptured inner hose.

In this study it was not possible to determine the annular distance between the inner and outer hoses at the point of inner hose failure, or whether the two hoses were actually in contact. Even a short annular distance may be sufficient to allow the energy released from the inner hose to dissipate, resulting in less water pressure on the sleeve. Annular distance and other factors affecting outer sleeve performance should be studied further.

HOSE COUPLING CONSTRUCTION

The construction of the hose couplings is important when considering the safety of the high-pressure flexible hoses. The coupling may contribute to hose failure by weakening the reinforcement wires when the coupling is crimped in place (fig. 6). Coupling designs should be studied to determine hose integrity as a function of coupling type and installation technique.

In some tests the metal coupling split along the longitudinal axis (fig. 7). It is not known if this type of fitting failure was preceded by catastrophic failure of the hose inside the fitting. None of the couplings that failed by splitting had weep holes. When fittings with weep holes failed, failure occurred inside the coupling with sufficient force to extrude part of the liner through the weep hole. In these cases, release of pressure through the weep hole prevented rupture of the coupling or failure of the hose elsewhere.

LOCATION OF HOSES AND COUPLINGS

Obviously, the hazards associated with high-pressure water are much greater if high-pressure hoses are routed through areas where miners must work. In one test, a coupling broke away from the hose, but in no test was whipping of the hose material observed. All hose should be routed along equipment structures in such a way as to provide maximum protection of the operator and other workers.

NONCATASTROPHIC FAILURE

Noncatastrophic failure was the result of hose fatigue, which in these tests was induced by periodic cycling of the water pressure between atmospheric and working pressures. Noncatastrophic failures resulted in the slow release of water at pressures too low to cause rupture of the reinforcement wires or penetration of the outer hose. There was no indication from these tests that inducing hose fatigue failures resulted in a weakening of the

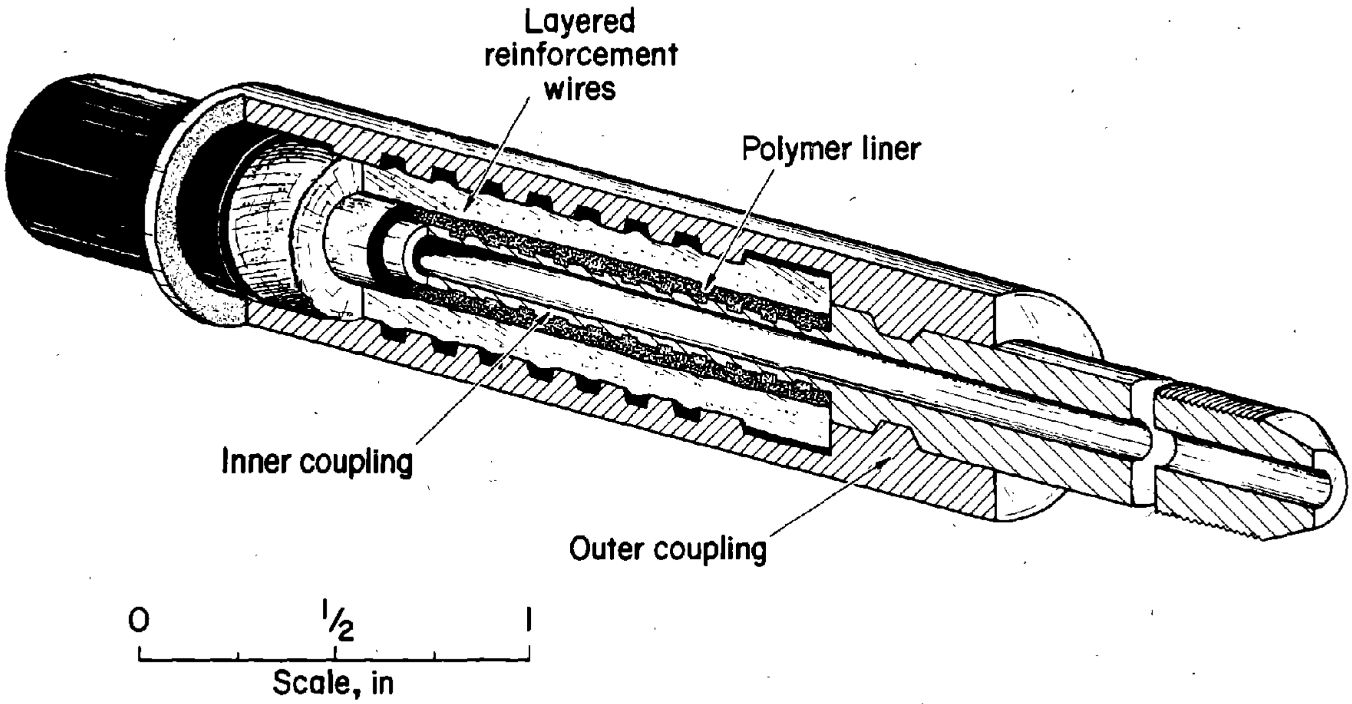

FIGURE 6.—Cross section of typical coupling construction.

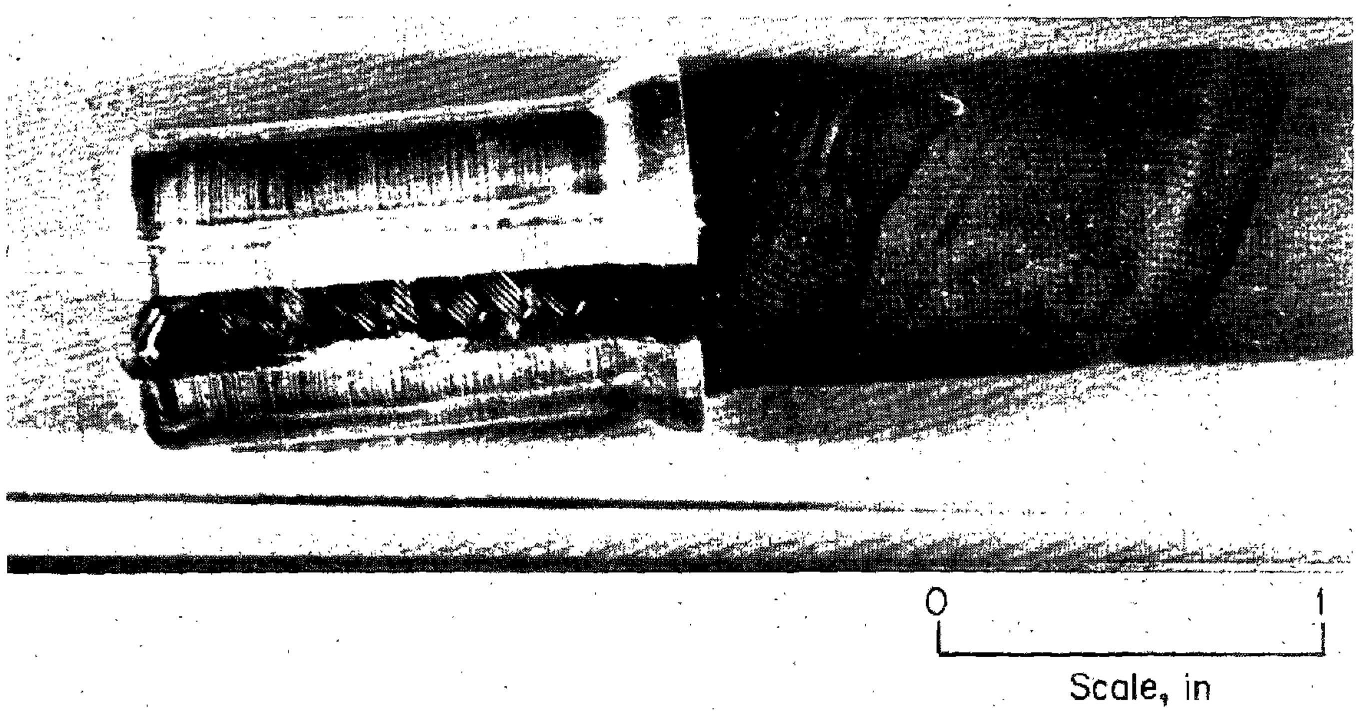

FIGURE 7.—Fitting failure (longitudinal split).

reinforcement wires. Because water is released at a lower pressure, the safety hazard to workers when noncatastrophic failure occurs is not great.

CATASTROPHIC FAILURE

The results of these tests indicate that catastrophic failure of high-pressure hose can occur if the pressure rises above the rated working pressure. The potential for dangerous failures is greatly reduced if pressures are maintained at or below the working pressure. During fatigue testing, the rated working pressure was not exceeded and no catastrophic failures occurred. Safeguards should be considered to prevent hoses from accidental or intentional pressurization above the rated working pressure. Pressure relief valves that release water in a safe location should be used.

ACTUAL AND RATED BURST AND WORKING PRESSURES

In most cases, the actual burst pressure exceeded the rated minimum burst pressure assigned by the hose manufacturer. The method of assigning the rated working pressure varied with the manufacturer. For the hoses tested, the rated working pressure was either 50 or 25 pct of the minimum burst pressure. While most of the catastrophic hose failures occurred at pressures much greater than the rated minimum burst pressure, two such failures occurred at 58 and 74 pct of the rated minimum burst pressure.

CONCLUSIONS AND RECOMMENDATIONS

All of the hoses that failed during the fatigue tests failed in a noncatastrophic manner; the inner liner broke, and water was forced slowly through the wire reinforcement, causing a bubble to form inside the plastic outer covering (fig. 4). Post-test inspections of these hoses showed that the wire reinforcement was not damaged, but that the inner liner had failed. Hoses that did not fail during fatigue testing were subsequently burst tested. These hose samples did not show significant reduction in actual burst pressures, suggesting that fatigue testing did not weaken the wire reinforcement.

All burst tests resulted in catastrophic hose failure, causing a sudden release of water and rupture of the hose reinforcement wires. Except for failures that occurred within the fitting, the broken wires formed a crater on the surface of the hose (fig. 5).

Variations exist in the methods employed by hose manufacturers to rate hose working pressures. A uniform method should be adopted for rating high-pressure hose used for water-jet and water-jet-assisted cutting applications. First, the method of establishing the rated minimum burst pressure should be standardized. Second, the same safety factor should be used for determining the working pressure of all hoses used to carry high-pressure water.

Evaluation of the sleeve containment tests indicates that a sleeve covering the high-pressure hose may not provide additional protection to a worker in the event of a catastrophic hose failure. The containment sleeve was penetrated by the high-pressure water stream in seven of eight burst pressure tests in which the inner hose failure occurred at a location covered by the sleeve. No sleeve failures resulted during fatigue testing when the inner hose failed noncatastrophically. Further testing is needed to determine if sleeve materials other than the one type tested will provide protection in the event of a catastrophic failure.

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