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An ROV operated undersea hydraulic hose repair coupling

Alexander Slocum [a,*], Luis Gutierrez [b]

[a] Massachusetts Institute of Technology, Cambridge, MA, United States
[b] BP Corporation, Houston, TX, United States

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ABSTRACT

A hydraulic hose repair system is presented that was developed for use at the Deepwater Horizon accident site. The system can be deployed with a single ROV with two controllable arms. One arm holds the device and the other arm pushes a severed hose into the device. Hydraulic pressure is applied from the ROV to the device and a hydraulic coupling within the device is crimped into one end of the hose. The second hose end to be spliced to the first is pushed into the other side of the device and the second half of the coupling is crimped onto the second hose end. The device itself is left in place as part of the splice. The design, on-shore testing, and fabrication of multiple devices ready to deploy at the accident site took on the order of a week to complete. They stand ready to be deployed in the case of another deep-water accident.

1. Introduction

In the immediate aftermath of the blowout, it was clear something went wrong with the intended functioning of the Blow Out Preventer (BOP) on the Deepwater Horizon, and an initial underwater assessment concluded that there might be damage to the BOP's hydraulic control modules. Several hydraulic lines were damaged and it was determined that to establish Remotely Operated Vehicle (ROV) control of the BOP, several hydraulic hoses would have had to be cut and spliced to bypass the control modules and allow for direct actuation of the BOP shear ram. It was known that it could take an ROV operator up to half a day to use available splicing devices to repair a single hose, and thus a method/device was needed in a very short time to reduce the time to splice to an hour or less. The time to accomplish the design, testing, and deployment of a new device was "as fast as possible" while in parallel, alternate use of the systems that remained in place were tried as a means of toggling the BOP in an attempt to stop the flow of oil.

The authors were part of the emergency engineering response team put into place just after the accident, and this paper describes the design process the authors used in conjunction with a highly skilled and motivated machine shop to rapidly create a new undersea hydraulic hose repair system for the Deepwater Horizon BOP that could easily be used with ROVs. The total time from "Design and build it!" to a workable design was 3 days, and a full array of manufactured devices were ready to deploy less than a week later. In the end, the devices were not used on the Deepwater Horizon site because it was determined that the BOP rams did deploy, but that they failed to shear through the pipe as intended for some reason other than hydraulic system failure [1,2]. However, the hose repair devices created were very efficient and have been kept ready should deep-sea hydraulic hose repair ever be needed. It is the intent of this article to document the design process used and the resulting design of the hose repair devices so they could be scaled and realized for other hoses, or improved upon for other applications.

2. Background

A conventional hose-fitting has extending from the threaded base an inner tubular member with external circumferential barbs that engage the inner rubber core of a hydraulic hose. Also extending from the threaded base is a concentric external tubular member with internal circumferential barbs. The hose presses onto the inner member and loosely fits inside the outer member, and then a hydraulic crimping tool radially deforms the outer member. Standard crimping tools are typically 20 cm or more in diameter due to the massive structure required to generate the very large radial crimping forces.

For underwater repair of hydraulic hoses using an ROV, it would be desirable if all the ROV had to do was slip the repair fitting over the end of the hose, and then crimp the fitting onto the hose with the flip of a switch. The mechanism to accomplish this must be relatively lightweight and simple to use. The system should operate

* Corresponding author. Tel.: +1 617 253 0012; fax: +1 617 253 0012.
E-mail addresses: slocum@mit.edu (A. Slocum), luis.gutierrez@bp.com (L. Gutierrez).

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such that one ROV arm holds the hose, and the second ROV arm puts the fitting over the hose, and then triggers the engagement of the repair fitting. The ROV should be able to carry a holster with many fittings so it could repair many hoses on one trip to the site. Alternatively, the fittings could be deployed in a separate carrier at depth and the ROV could move to and from the carrier picking up one fitting at a time.

To begin the deterministic design process [3,4], an assessment was made of the design challenge by considering known at the time functional requirements, design parameters, analysis, references, risks, and countermeasures. The authors based themselves at Industrial Machine Corp. in Houston for ready access to skilled machinists used to rapidly producing precision custom parts for the oil industry. With laptops loaded with CAD and analysis software and high speed Internet access, the team set out to get the job done.

2.1. Functional requirements

The design process started with BP and the ROV operator stating the functional requirements for the Hose Splicer. Overall, the hose splicing system needed to be relatively lightweight and be powered via the ROV's existing hydraulic system while being manipulated with the ROV arms. Ideally the ROV only has to slip the repair fitting over the severed end of the hose, and then engage the fitting with the flip of a switch, and then the process is repeated with the second severed hose end inserted into the fitting. The ROV should be able to carry a holster with many fittings so it could repair many hoses on one trip. When repairing multiple hoses, the ROV could also pick up additional fittings from a receptacle located near the location where the repairs were being performed. Other functional requirements include[1]:

1. Water depth rating: 1525 m (5000 ft) below Mean Sea Level (MSL) (minimum).
   a. Nice to have: 3050 m (10,000 ft) below MSL.
   b. Temperature rating: 1–60 °C (34–140 °F).
2. System to work with three different hydraulic hose sizes: 1/2″ (12.7 mm), 1″ (25.4 mm) and 1 1/2″ (38.1 mm), highest pressure applied to hose after splicing is 31 MPa (4500 psig).
3. Power Sources:
   a. ROV manipulator wrist:
      i. Non-regulated torque range: 109 to 163 N-m (80 to 120 ft-lb).
      ii. The ROV pilot cannot dynamically modify the torque being output by the ROV manipulator wrist.
      iii. Modifying the hydraulic power supplied to the wrist in order to change the wrist torque is not desirable as it will affect all other manipulator functions.
   b. Hydraulic, 2.2 kW (3 HP):
      i. The nominal hydraulic pressure readily available for powering ROV tooling is 21 MPa (3000 psig).
      ii. Greater pressure can be supplied with modest system additions: 35 up to 70 MPa (5000 psi up to 10,000 psi).
4. ROV Manipulator use:
   a. Strong preference for operation by a single ROV manipulator arm holding the device and second arm holding the hose.
   b. Two-ROV manipulator operation of the device is acceptable (One ROV using both its manipulators), but discouraged as only one of the two manipulators can be equipped with a fine control interface.
5. Weight limits:
   a. For retrievable systems: 68 kg (150 lb) max, for the ROV to carry, operate, and return with the device.
   b. For sacrificial components: 14 kg (30 lb) max, to avoid damaging spliced hoses by being pulled down by a heavy object.

[1] Both SI and imperial units are used here as appropriate as many in the oil industry still use the latter.

2.2. Design parameters

Conventional hydraulic hose-fittings were considered a starting point for the design; after all they work quite well and are readily available. Parameters associated with their use include:

- Hose: Rubber core for sealing with layers of rubber and braided metal to resist pressure forces, and for gripping by the fitting (by radial deformation).
- Fittings: Extending from the threaded base an inner tubular member with external barbs engages the inner rubber core of a hydraulic hose to form a seal. A concentric external tubular member with internal barbs loosely fits over the hose and then is crimped in place to resist pressure induced axial forces.
- Crimping tool: A fitting's outer member is radially deformed by a hydraulic crimping tool that is typically 30 cm or more in diameter and 20 cm long due to the massive structure required to generate the very large crimping forces. Such tools also typically completely encircle the hose, requiring the hose to be withdrawn from the crimping tool, meaning there must always be a free end of the hose.
  - o It was not considered viable to crimp threaded fittings onto the end of hose ends and then expect the ROV to connect the ends.

As stated in the functional requirements, hydraulic power from the ROV is readily available. Connecting to an electric power source was not an option, and a mechanical linkage (e.g., a screw or lever) activated by a ROV's manipulator had previously been found to be too time consuming and bulky, and in fact took typically two ROVs working together.

2.3. Analysis:

The hose core is rubber and the hose has layers of steel braid and rubber to give it strength. Conventional hose-fittings form a seal with the hose by creating uniform radial pressure on the hose to engage circumferential barbs on the fitting's inner tubular member over which the hose has been placed. This is accomplished by radially crimping the outer cylindrical sleeve onto the hose. The amount of radial deformation might be analytically determined and verified with testing, or more appropriately to rapidly achieve an acceptable workable design, the same amount of deformation as is currently attained with conventional fittings could be specified for a new fitting.

2.4. References

A literature review on existing technology did not reveal any existing splicing tools designed specifically to be used by ROVs in deep water. While high pressure quick connect tools have been used for hydraulic systems across a wide range of industries such as agricultural machinery and construction equipment, none have been designed with the given power requirement restrictions of a standard ROV. High-pressure couplings usually have a connector interface that is secured to the hose prior to installation. Therefore, during a splicing operation, where the existing damaged hose has to be severed, securing interface connectors adds complexity to the system. Quick connect couplings are more representative of the tool required for splicing; however, standard quick connect couplings would fail under the high pressures required to activate the shear rams in a BOP.

Published articles on ROV operable hose splicing tools were not found, but several patents were identified [5–7]. Some devices were created, for example, where the fitting's outer cylinder was replaced with a clamshell device that was closed by the ROV turning a T-handle bolt. A significant problem encountered by the ROV operators is that it was difficult for the ROV to align and push the hose onto the inner barb, but this could be addressed by placing a capture cone in front of the barb. The second problem is that it took too much time for the ROV's manipulator to turn the T handle multiple times to squeeze closed the clamshell, but this could be remedied by replacing the threaded clamp with an over center linkage. The third, and most difficult issue was the clamping deformation was not uniformly radial and it was reported that leakage occurred and the connection was unreliable. The team concluded that the resulting radial pressure on the hose must be relatively uniform as is the case with a standard hydraulic fitting crimped in a shop onshore. Given the tight timeline, this finalized the conviction that the design must be based on a standard hydraulic fitting, and an in-situ crimping tool designed around it.

2.5. *Risks and countermeasures*

One possible failure mode of the system is the disengaging of the splicing unit during operation. Therefore, any mechanism designed must be fail-safe, which means it must be self-locking once engaged. Any screw threads in the unit must not be back drivable which can be achieved with a fine pitch or using spring loaded shot pins to lock linkages in place. Locking features must be passive and must not require the use of fine manipulation motions by the ROV.

Previous couplings had suffered from the fact that it was difficult for the ROV to push the hose onto a barbed central element, such as in a conventional hose-fitting. A countermeasure would be for any new design to use a capture cone into which the hose end would be pushed that would then guide it into/onto the fitting.

3. Design development

A coarse-to-fine approach was used, starting first with considering different strategies (overall approach) and then once a strategy was selected based on first order analysis and manufacturing considerations to be the most expeditious and effective, detailed concepts could be developed. Simple bench level tests could be used to confirm the design resulting from first order analysis and workability of a concept and then detailed designs could be undertaken. A key was the team individually sketched ideas and then each member reviewed each other's ideas followed by brainstorming, and this helped convergence to be efficient and rapid [4].

3.1. *Strategies*

The first and most simple strategy considered was to use a conventional fitting and create a mechanism to crimp it onto a hose. Other strategies included finding an adhesive solution or other mechanical locking means that only engaged the outside of the hose. Using an adhesive would require surface preparation and operation of the adhesive in an environment never before encountered. In the end, it was decided because the system must work, and other companies had already tried and failed to use "novel" systems that did not employ a simple conventional coupling, and there was no time for an **R&D** development process. Hence it was felt that the best strategy would be to create a system based on a conventional hydraulic fitting.

Table 1
Estimate of radial forces for a conventional fitting crimp.

Fitting OD (in, mm)	1.75	44.45
Fitting ID (in, mm)	1.40	35.56
% wall thickness for barbs	50	
Fitting wall thickness through barbs (in, mm)	0.175	4.45
Nominal fitting wall thickness (in, mm)	0.088	2.22
Metal yield strength (psi, MPa)	40,000	276
Outer pressure to yield barbed region (psi, MPa)	8000	55.2
Outer pressure to yield unbarbed region (psi, MPa)	4,000	27.6
Percent of length barbed	50	
Crimped length (in, mm)	2.5	63.5
Total effective radial force to crimp (lbf, kN)	82,467	367

3.2. *Concepts*

The simplest concept would be to use a conventional crimping tool, one per splice and just leave the tool in place; however, commercial crimping tools weighed about a hundred pounds and were too big and unwieldy for the ROV. The ROV operator and BP had considered this option and vetoed it, which was why the team had been assembled. However, the operating principle was straightforward: radially crimp the fitting's outer tubular member to deform the hose. Was it possible that the industrial crimping tool was just over designed and for the intended one-shot use maybe it could be much smaller? This called for an estimate of the forces required to crimp, so a first order analysis based on yielding a tube was created to measure the forces required. This took less than an hour, whereas tests would have taken over a day. As shown in Table 1, the forces predicted are very large, commensurate with the size of a commercial tool, and hence there was little hope of miniaturizing the commercial tool.

Considering the mechanics of a hydraulic hose-fitting, as shown in Fig. 1, the function of the outer sleeve is to deform the hose structure and thereby engage the steel braiding to form a mechanical lock that resists the hydraulic axial forces that try to push the fitting off the hose. The forces applied to deform (crimp) the outer sleeve of the fitting do nothing to actually hold the hose, although once crimped the reduced diameter maintains the fitting's grip on the hose. Thus by applying the principals of Reciprocity (try the opposite) and Maudslay's Maxims (get rid of anything that is not really doing any good) [8,9], the team arrived at the conclusion that the force needed to deform the outer sleeve to engage the hose could be lowered by axially slitting the fitting's outer tubular member.

To determine if the axial slitting strategy was feasible, a number of fittings were measured that were not crimped as well as others crimped to hoses that had been provided as examples, to determine the amount of radial compression needed, and then the number and

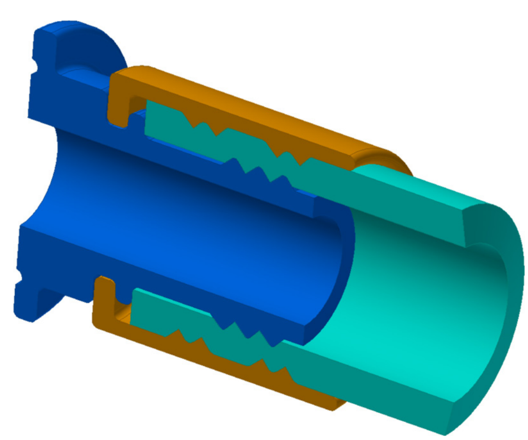

Fig. 1. Outer sleeve of a hose fitting deforming a hydraulic hose so barbs engage, seal, and hold hose in place.

Table 2
Hose and fitting geometry to determine axial slit width.

	Hose size					
	0.5		1		1.5	
Hose OD (in, mm)	0.84	21.3	1.4	35.6	2.25	57.2
Crimped OD of hose fitting (in, mm)	0.97	24.6	1.54	39.1	2.45	62.2
Uncrimped OD of hose fitting (in, mm)	1.13	28.6	1.80	45.7	2.90	73.7
Diametral compression (in, mm)	0.16	3.9	0.26	6.6	0.45	11.4
Hose fitting outer tube						
Post compress, effective arc angle of segments (deg)	44		44		44	
Required initial segment arc angle (deg)	37.9		37.6		37.2	
Taper angle (deg)	13		14		20	
Axial travel (in, mm)	0.75	19.1	1.00	25.4	1.25	31.8
Diametral compression (in, mm)	0.17	4.4	0.25	6.3	0.45	11.6
Number slits	8		8		12	
Minimum slit width (in, mm)	0.06	1.55	0.10	2.59	0.12	2.99
Mill diameter to use to make slits (in, mm)	0.094	2.38	0.125	3.18	0.125	3.18

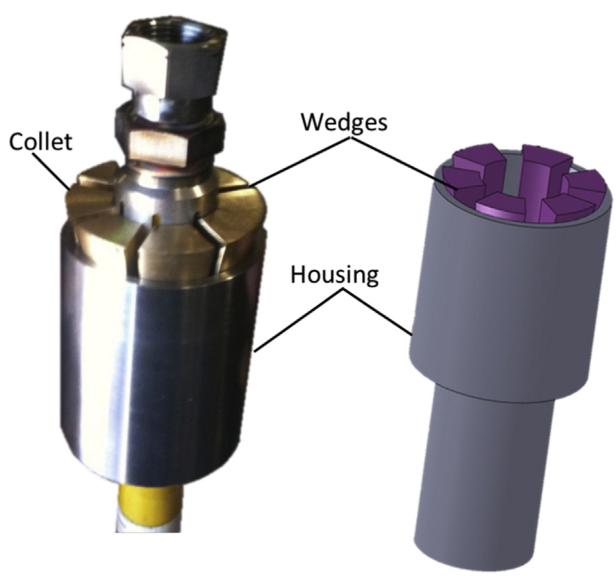

Fig. 2. Solid model of Wedges crimper concept with proof-of-concept unit.

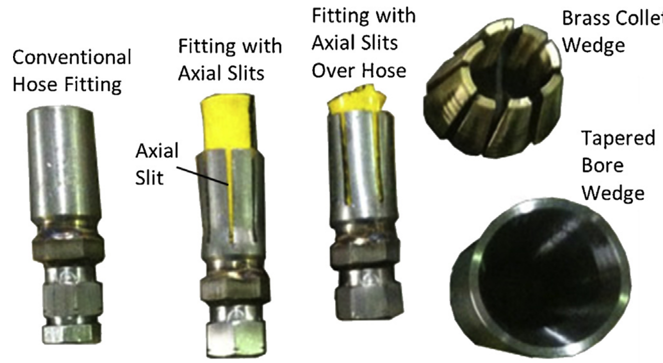

Fig. 4. (L to R) A conventional hose-fitting, a fitting with axial slits and members compressed about a hose, a fitting with axial slits over a hose, brass collet wedges with ID equal to fitting OD, Tapered bore wedge receiver.

width of slits required for the different hose sizes was determined. It was envisioned that the segments would be compressed by the action of a tapered wedge. Table 2 shows the geometry parameters for the hose coupling system, where it was found that it was indeed feasible to create axial slits with a standard milling cutter which would allow the outer sleeve to be compressed around the hose while causing the slits to just close.

3.2.1. *Proof-of-concept experiments*

Once the realization was made that any device to compress a full cylinder would be too big, but that segments might be sufficient, the machinist was asked about the feasibility of slicing a conventional hose-fitting's outer member and then radially compressing the segments using a collet type system. The machinist said the slices in the fitting could be made, but a conventional collet system from a machine tool spindle could not provide the several mm+ radial compression believed to be required. A quick test with the compression that could be achieved via a standard collet and a hose segment pressurized by a hand pump showed it leaked badly. Hence it was determined that a new type of collet would have to be designed with enough radial travel by creating individual brass collet wedges and a tapered bore wedge receiver. Fig. 2 shows the simple solid model made to illustrate the concept, which was shown to the machinist for design review that afternoon. Manufacturability and sanity of the design were confirmed and Fig. 3 shows part drawings rapidly created so the parts could be made that evening. The parts were ready the next morning.

Fig. 4 shows the parts made for the proof-of-concept test, and Fig. 5 shows the system being tested in a hydraulic press that axially loaded the wedges to radially compress the axially slit coupling onto the hose. A cap was put on the coupling's threaded end and the other end of the hose, with a conventionally crimped coupling, was

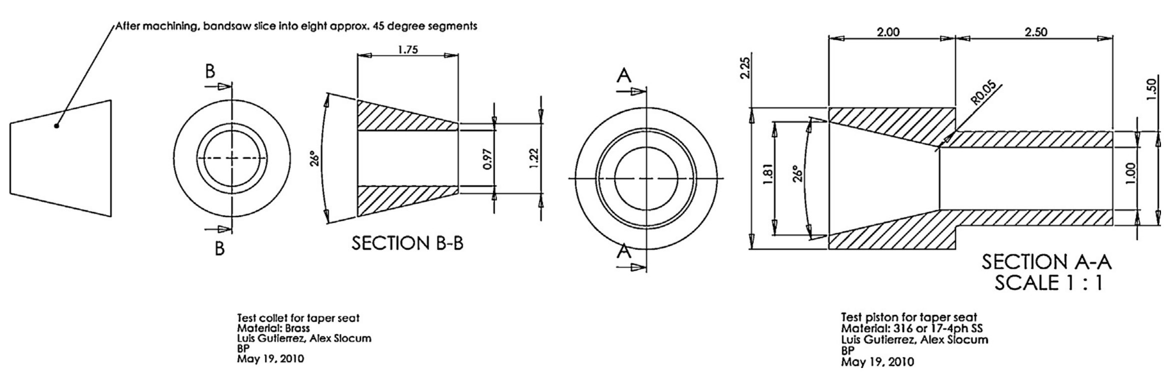

Fig. 3. Part drawings for the parts to be made that evening so bench level experiments could be done the following day.

Fig. 5. Testing the concept wedges to determine axial force required to obtain equivalent radial compression of fitting and to check for leaks.

attached to a hand operated hydraulic pump. To check for leaks, a white sheet of paper was put below the system. The hydraulic press pressure required to achieve the desired radial motion of the segments was measured and the resulting calculated force became the specification for the system to be designed.

4. Detailed design of the Hose Splicer

The overall "Hose Splicer" design is shown in Fig. 6. Guide funnels direct the hose to be spliced over the inner barbed tube and inside the axially slit outer sleeve of a conventional hydraulic fitting which is threaded into the central region. Hydraulic fluid is supplied to the coupling port which actuates the tapered bore wedge piston that moves forward and causes the brass collet elements to radially compress the slit outer sleeve onto the hose and inner barbed tube. Fig. 6 shows a detailed numbered cross section and Table 4 lists the elements in the cross section (Fig. 7).

Prior to a splicing operation, the brass collet wedges have a shape contoured to loosely fit that of the pistons in their initial nominal starting position, with portions of the wedges fitting inside the pistons, and the remaining wider portions extending out of the pistons, as shown in Fig. 8. The wedges are manufactured by slitting a part with cylindrical inside diameter to match the initial outside diameter of the hose-fitting and an outside conical shape to match the inner conical surface of the piston. The wedges' ID initially conform to the hose-fitting's OD and their outside radii of curvature is smaller than that of the piston's inside conical surface and thus line contact is initially made along the length of the wedge with the piston. In the final position, surface contact is made with the conical surface and surface contact is made with the then deformed hose-fitting segments that are deforming and gripping the hose:

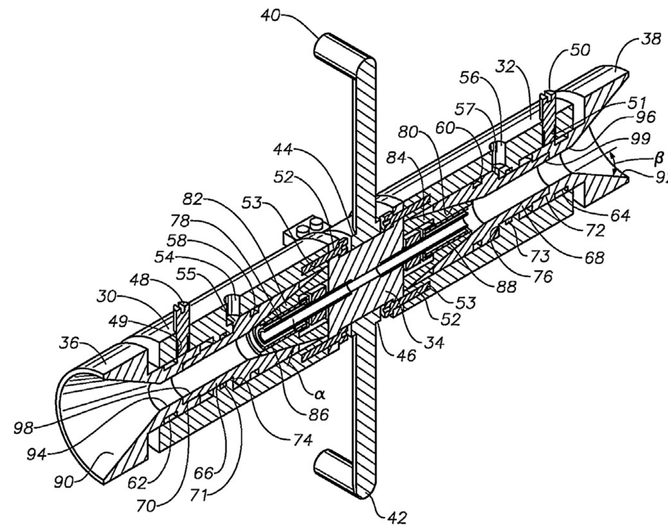

Fig. 7. Cross section of final design (elements listed in Table 3).

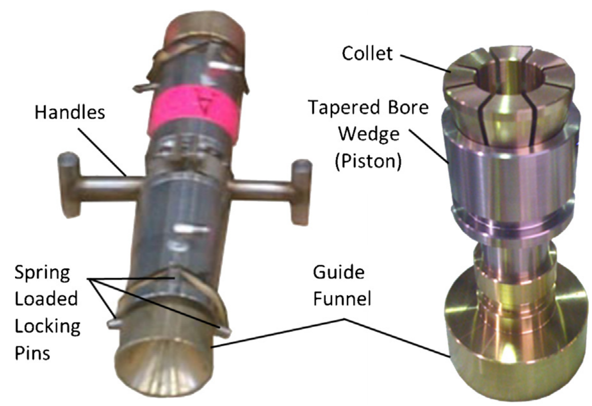

Fig. 8. Manufactured parts and assembly.

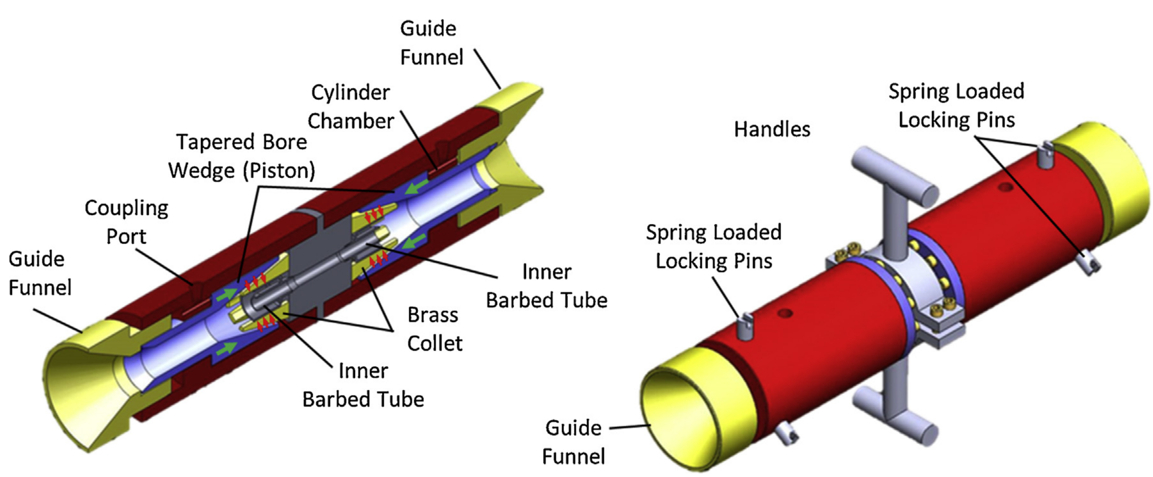

Fig. 6. Solid model of final design for the "Hose Splicer" an ROV operated hydraulic hose-fitting crimper. The brass guide funnel is attached to the piston that pushed on the collet segments, and when it moves fully forward, a spring loaded locking pin maintains its position even if hydraulic pressure is lost. On the right the central region has been lengthened to provide a region for grab handles for the ROV or top surface technicians.

Table 3
Hose Splicer elements.

30, 32	Tubular body
34	Central mandrel
52	Bolts to connect left and right half tubular bodies to central mandrel
53	Thread holes for bolts 52
36, 38	Guide funnels for hydraulic hoses to be spliced
40, 42	ROV handles
44, 46	Alternate ROV grab points
48, 50	Spring loaded locking pins
49, 51	Ports for locking pins
54, 56	Hydraulic “hot stab” ports for receiving high pressure hydraulic fluid
55, 57	Hydraulic cylinder chambers
66, 68	Pistons
58, 60	Seal grooves
62, 54	Grooves for engaging locking pins
70, 72	Threaded connections between guide funnels and pistons
74, 76	Circumferential shoulders on pistons
78, 80	Conical surfaces inside pistons for engaging wedges
82, 84	Brass wedges
86, 88	Hose-end fittings with slit outer barbed tubular members
90, 92	Funnel regions for receiving hydraulic hoses
94, 96	End of funnels slightly larger than hydraulic hose diameter
98, 99	Passages for hydraulic hoses to enter splicing region

Table 4
System parameter development and analysis based on thin walled pressure vessel analysis.

	Hose size					
Actuation piston	0.5		1		1.5	
Modulus of elasticity, E (psi, GPa)	2.9E + 07	200	2.9E + 07	200	2.9E + 07	200
Supply pressure Ps (psi, MPa)	3000	21	3000	21	3000	21
Piston rod OD (in, mm)	1.50	38.1	2.25	57.15	3.0	76.2
Piston rod ID (in, mm)	1.00	25.4	1.63	41.28	2.6	66.7
Diametrical clearance to hose (in, mm)	0.16	4.1	0.23	5.72	0.4	9.5
Housing OD (in, mm)	3.25	82.6	4.00	101.60	5.0	127.0
Piston OD (in, mm)	2.50	63.5	3.50	88.90	4.5	114.3
Axial force from piston, Fp (lbf, kN)	9425	42	16,935	75	26,507	118
Wall thickness (in, mm)	0.375	9.53	0.250	6.35	0.250	6.35
Hoop stress, sighoop_head (psi, MPa)	11,500	79	22,500	155	28,500	197
Diametrical compression head, delta_head (in, mm)	0.0004	0.009	0.0005	0.012	0.0006	0.015
Wedges						
Taper angle, phi (degrees)	13		14		20	
Assumed efficiency	50%		50%		50%	
Combined radial force on wedges, Fr (lb, kN)	20,412	91	33,962	151	36,414	162
Taper engagement length, Ltaper (in, mm)	1.25	31.75	1.5	38.10	1.5	38.10
Approx. surface area, Ataper (in2̂, mm2̂)	5.89	3800	10.60	6841	14.14	9121
Pressure on piston inner tapered surface (psi, MPa)	3465	24	3203	22	2576	18

The axial slits in the hose-fitting allow the brass wedges to cause the modified fitting to radial deform the hose, thereby locking the hose in place on the hose-fitting's inner barbed tube. This creates the same type of crimp as obtained with a commercial crimping system (Table 3).

The sizing of the elements was enabled by using the axial force measurements from the proof of concept tests, which provided the forces on the wedges needed to compress the slit hose-fitting, as input to a design spreadsheet. The spreadsheet was used to drive creation of a solid model from which part drawings were made. Table 4 shows the calculations made to arrive at system dimensions. 316 stainless steel was specified for the body as it performs well in salt water and was readily available in the sizes required. Brass was specified for the wedges and the capture funnels which also serve as a rear linear bearing to help guide the piston. With the exception of the brass parts, all parts should be made of the same metal to avoid galvanic corrosion issues.

The brass wedges reduce the chance of galling and high friction, but other non-galling metals could be used as long as the Anodic Index between the metals comprising the wedges, pistons, body portions, and guide funnels is 0.15 or less for permanent subsea installations. A larger Anodic Index may be tolerated, up to 0.45, for temporary or emergency subsea operations [10].

4.1. Seals

Conventional Parker PolyPak™ piston and rod seals were chosen as brand name seals for which generic replacement sizes were also readily available, as they had a proven performance record. In particular, they allowed for relaxed tolerances; however, the smaller the seal the more compact the design potentially, but the less accommodating of radial clearance error. As part of the tolerance analysis, the hydraulic cylinder member deformations due to pressure were also included in the spreadsheet calculations; because in the quest to minimize size, wall thickness had to be kept to a minimum. Even with highly stressed components, radial deformations were much less than acceptable machining tolerances (but it was important to check!) as shown in Table 4.

5. Production

Fig. 8 shows an assembled Hose Splicer and Fig. 9 shows proof testing. The decision was made to manufacture 16 Hose Splicers for a 1/2″ hose size, Fig. 10, and they were to be ready within a week to be deployed to the Deepwater Horizon site to complete hydraulic hose repairs at the BOP.

6. Operation of the Hose Splicer and verification of functional requirements

In a splicing operation, an ROV grabs a hose and stabs its end into the guide funnel (36) and moves it forward until it is pushed over the hose-fitting's inner barbed tube. The ROV then can let go of the hose and then use its now free arm to insert a conventional hot-stab into the coupling's port (54) to provide hydraulic fluid to the cylinder chamber (55) which moves the piston forward against the brass wedges and thus compresses the slit hose-fitting. The sequence of events is as follows:

1. The final Hose Splicer is already pre-plumbed to a dual port API 17H hot-stab (Fig. 11). Elbow fittings are used to connect the hydraulic hose to the hot-stab.
2. ROV gets one Hose Splicer from the basket and connects it via the hot-stab so the Hose Splicer can be powered hydraulically.

Fig. 9. Production Hose Splicer unit under pressure testing.

Fig. 10. Assembled Hose Splicer systems readied for final assembly (handle and spring pin attach).

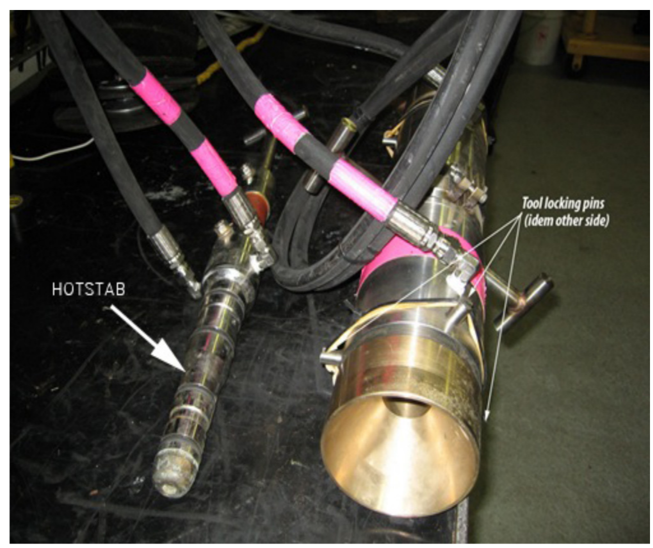

Fig. 11. Hose Splicer and Hot-stab hydraulic fittings used by the ROV.

3. After making a clean cut on the hose end using a standard subsea cutting tool (grinder), the ROV inserts the end of hose into the capture cone (funnel) on the Hose Splicer and continues pushing it in until the hose engages the modified fitting inside.
4. The ROV energizes the Hose Splicer's piston by providing hydraulic power through one of the two ports in the hot-stab. The piston drives the wedges forward compressing the fitting's slit outer sleeve to radially compress and engage the hose. A spring pin falls into place locking the piston in position so the wedges cannot relax after the hydraulic pressure is released.
5. The process is repeated using the other end of the Hose Splicer to engage a second hose end.

If the wedges are kept in place after the deformation, the hose will also remain locked in place on the barbed fitting and a tight hydraulic connection without leaks will be obtained even under high pressure (e.g., 10,000 psi, or whatever the hose and fittings are normally rated at). Hence after the initial splicing operation, even if the wedge angle is not sufficiently self-locking, the pistons have moved far enough for locking pins to snap into place in the piston grooves (62) so the hot-stab's hydraulic fluid pressure can be removed. With this method the only subsea operations required to be performed by an ROV operator are the severing of hoses to produce clean cut ends, the stabbing and connecting of hose ends into the splicing device and the hot-stabbing of hydraulic connections. All the stabbing operations utilize wide capture funnels and thus are easily done by ROV operators.

In summary, the first functional requirement for ability to operate at depth and temperature were not tested, and although no unusual elements or materials were used that are not typically used in deep water hydraulic systems, deep water testing should be before deployment to an emergency site. The second and third functional requirements were met by testing on land with ROV hydraulic systems, and the balanced design is such that the loads on the ROV wrist do not come close to the load limits. The fourth functional requirement was cleanly met with the design. The fifth functional requirement for device weight was mostly met as shown in Table 5. The assessment by the ROV operators was the design was easy enough to manipulate and that the larger size hoses could

Table 5
Hose Splicer weights for the as-built systems.

Hose size	In air	In air w/2 × HS	In water	In water w/2 × HS
1/2″				
lb	39	63	33.9	54.8
kg	17.7	28.6	15.4	24.9
1″				
lb	72.6	96.6	63.2	84
kg	33.0	43.9	28.7	38.1
1.5″				
lb	98	122	85.3	106.1
kg	44.5	55.4	38.7	48.2

support the weight, so stainless steel and brass would be used for a limited production run. Longer term more testing would be needed to determine if a titanium based design is called for which could realize a 50% weight reduction. Furthermore, if a larger production design was to be pursued, because there was a significant safety factor in the design, it is likely component sizes could be reduced potentially by about 90%, but this would have to be verified with more extensive analysis and testing.

7. Conclusions and recommendations

During the week it took to develop and manufacture the Hose Splicers, it was determined by the response team that the Deepwater Horizon rams did indeed deploy before the hoses were severed, but the rams were not able to shear the drill pipe, most likely because a joint section was at the point of ram deployment. Hence the Hose Splicers were not deployed. However, they remain ready for use, and the design herein documented enables them to be scaled for other hose sizes should the need arise [11].

Accordingly, it is recommended that the units be extensively tested using an ROV in an underwater training environment, and then production quantities (several dozen) units for various hose sizes be made and kept ready should the need arise for their use.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precisioneng.2015.06.010

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