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## Keyhole technology – finite element analyses

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Many gas companies build and operate gas distribution system in the city country and around the world. The traditional open-cut excavation requires the ground to be broken up by heavy equipment, the soil and asphalt need to be removed. Traditionally, a technician requires a minimum of 60 cm by 180 cm excavation to perform routine procedures. Often the trench must be temporarily supported using some type of shoring before a utility worker can enter the hole to perform the repairs to the utility pipe. This process is costly, time consuming, dangerous and is inconvenient to traffic patterns. We propose a new solution called keyhole technology which minimizes labor and restoration costs compared with conventional practices. In our design, the same construction and maintenance procedures can be accomplished through a 45 cm diameter circular holes above the utility pipe to be repaired. However, specially designed, long handled tools that operate remotely are necessary. This process is more cost-efficient, less dangerous and less disruptive to traffic patterns because there is no additional milling and overlaying of the road. The small hole requires little replacement materials to fill the hole. Because the concept is relatively new to the public utility sector, there is a lack of equipment/tools available that could perform the required services. The finite element analyses using commercial package Abaqus will be employed to obtain the force needed to close the pipe. As a final example, we will show the topology optimization of squeeze–off tool as the act of an iterative process. The correctness of the numerical calculations was verified by a pipe compression experiment on Instron 8850 testing machine.

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## 1. Keyhole technology

Because our devices are unique and are prototypes, there are no similar solutions in the literature. Therefore, we have omitted the part of work that refers to solutions given in the literature.

Keyhole technology is a new excavation procedure that reduce labor and restoration costs compared with traditional practices. Traditionally, a technician requires a minimum of 60 cm by 180 cm excavation hole to perform routine procedures [1–3]. The hole should be wide, long and deep enough to allow technician to be inside that hole and be able to use all his tooling necessary to perform the repair job. In keyhole technology, the construction and maintenance procedures can be accomplished through only a 46 cm diameter circular hole. However, specially designed, long handled tools that operate remotely are necessary. The operating personnel have identified different tools useful to this application. These include service cut-off as well as service connection tools. Service cut-off operations are often performed in high density of houses and commercial businesses in the city, where the benefits of keyhole technology are particularly apparent. Whenever an excavation is made in a public roadway, a sidewalk or a pavement, the restoration cost would be significantly lower if keyhole technology is used. Keyhole is the single excavation (opening) on the sidewalk or pavement of the road. The deepness, the width and length of the excavation should be below the pipe lines to allow performing necessary repair work. In some older gas connection from the sidewalks to the houses and buildings, the industry was using steel and cast iron pipelines with different sizes. Several tools (with pneumatic, hydraulic or electrical drives) are designed in the keyhole technology. These tools can be used for the purpose of disconnecting customers from the gas pipelines during construction, or during regular pipelines maintenance, or when there is an emergency, to prevent explosion, and further damage. For smaller inside diameter of pipelines 51 mm [2 inches], and wall thickness to maximum 4.8 mm, we are using squeeze-off tools and cut-off tools. In the case of pipelines made of plastic (ex. Polyurethane, Polyethylene) several technological methods and tools are used to connect or repair the pipes. We designed and developed some of these repair tools, but we don't intend to described all of these tools in this paper. Some of the tools can be utilized to repair or assemble plastic pipes: (i) Scraping tool. This device prepares two pipes for assembly. It reduces the diameter of plastic pipe. Those two pipes are then connected with the adaptor. (ii) Electrofusion fitting after scraping and assemble two plastic pipes with plastic adaptor. The pipes are joined by means of electrofusion (EF) fitting resulting in complete fusion of the pipe and electrofusion fitting. (iii) Gripper/squeeze-off tool. This tool is capable of squeezing pipelines before any repair operation of the plastic pipes. (iv) Cutting tool for plastic pipes. (v) Squeeze-off tool for plastic pipes. This is the universal tool which is capable of squeezing different diameter of plastic pipes 25.4 mm, 50.8 mm, 76.2 mm and 101.6 mm.

### 1.1. Mechanical development of squeeze-off tool version 1 for polyethylene pipelines. Conceptual design of main assembly

A first proposal of a similar device we presented in the form of our two-page paper at a conference in 2013 [4]. That paper concerned a device for clamping steel pipes which is no longer used in new solutions for gas transmission.

Before such a tool could be designed, the force necessary to positively squeeze-off any pipe within the required size and wall thickness range must be established. In order to find out the forces, we used a laboratory precision press with approximately 20 T capacity designed for material laboratory testing. This press has been used to experiment with squeezing different pipes with various forces as well as with different sizes and shapes of jaws. It has been found that when using the heaviest gauge pipes, only the maximum forces (about 20 T) provided approximately good squeeze quality (with very thin gap between two wall of the pipe).

It is known from literature that hydraulic actuators have the highest force to weight ratio, and a high-pressure hydraulic system must be used in order to provide high squeezing force and keep the weight of the tool reasonably low. The hydraulic actuator was selected and designed for a maximum working pressure of 690 bar [10000 PSI]. The actuator is capable of developing 20 T capacity. From a variety of hydraulic pumps offered by the company, a compact air-powered pump has been selected as most suitable for the application. Air-hydraulic pump has a built-in hydraulic cylinder of 600 cm<sup>3</sup> capacity, air motor assembly, relief valve assembly, and 3-way, 2 position valve that provides advance-retract cycle operation for the single acting cylinder.

In Figs. 1, 2 and 3 we see major parts that are necessary to build the squeeze-off tool. Item 1 (Fig. 2) is the selected hydraulic cylinder, which is capable of developing 20 T at the maximum rated pressure of 690 bars. This is a single acting

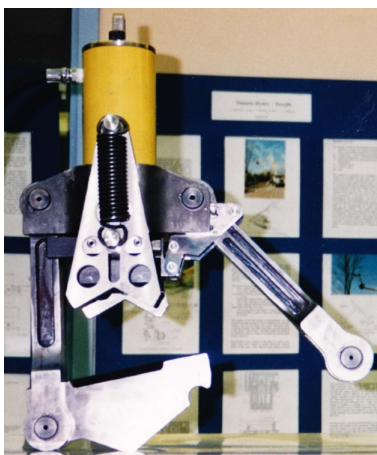


Fig. 1. Squeeze-off tool

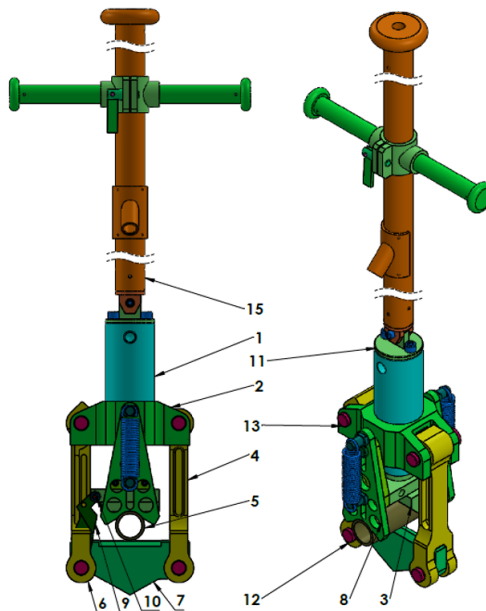


Fig. 2. Squeeze-off tool version 1 in close mode

spring return with the stroke of 101.6 mm (4 in). Air pressure at the input of the hydraulic pump is adjustable. Maximum squeezing force can, therefore, be reduced to any value lower than the nominal 20 tons, if desired.

Initially, the first concept of the tool structure in a form of an open C-shaped bracket has been designed. However, according to the preliminary mechanical design, the expected weight of the squeeze-off tool was greater than 40 kg. This was unacceptable to design it so as to meet the specification of our customers, and therefore the mechanical structure had to be redesigned. In the second approach to structure design, we implemented a closed-gate instead of an open-bracket concept that significantly reduced the weight, at the expense of increased design complexity. Since the tool should be operated remotely, an automatic gate opening and closing mechanism had to be added. The mechanism based on specially designed and developed dual-follower cam that uses first about 20 mm of the hydraulic actuator stroke to fully open or close the gate. It was necessary to keep the tool gate perpendicular to the pipeline at all times, so spring-loaded V-plates 8 were added at both sides of the hydraulic actuator. A hinged flange 11 between the tool and the lifting pole 15 has been provided to prevent the operator from forcing the tool out of alignment once it has been placed on the pipe with the help of the spring loaded V-plates.

High-quality heat-treated alloy steel (Atlas SPS) was used for all structural elements [5]. Stainless steel was used for less responsible components. Item 2 is the main support that is threaded to the cylinder, and the length of the thread is 49 mm. At both ends, this support has two tolerable holes of 25.4 mm diameter.

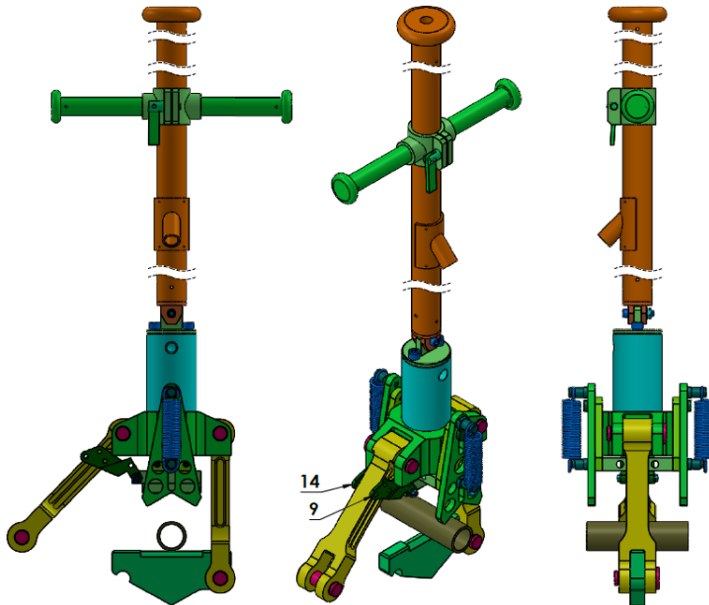


Fig. 3. Squeeze-off tool version 1 in open mode

Arms 4 and 6 are hinged with the item 2 by means of pins 13. The bottom beam 7 is also hinged with the arm 4 by means of pin 12. It has one degree of freedom of rotation only in one direction that allows the second end of this beam to rotate up to a certain angle. The cylinder plunger is mounted to the cylinder saddle 3 by means of the imperial thread. When the cylinder plunger with the cylinder saddle 3 is moving down, this will force arm 6 to rotate and eventually close the gate of the tool with the help of plate 9 and plate 14, with shaft 10 and cam followers that are mounted on the plate 9 and plate 14. The customer pipes 5 with different sizes can be used in the testing field.

The objective of this project was to develop appropriate concepts, and design and fabricate prototypes of two tools: squeeze-off and cutter/saw tool. The document herein gives an overview of the development process, discusses the results of laboratory and field tests. It also provides conclusions and recommendations. According to the design specifications, the tools should be capable of operating from above the ground to a depth of 180 cm below the ground level, and through a 460 mm diameter circular hole. The tools should work with polyethylene pipes with different sizes from 25.4 mm to 102 mm in diameter. The tools should be light-weight to permit handling by a single operator, and should use power sources typically available at the job site. It has been decided that compressed air is the most suitable power source for the task. Standard 100 PSI (0.689 MPa or 6.8 atm) airline is used to activate all functions of the tools. Compact power units carrying all necessary control equipment are connected to the air compressor on one side, and to their respective tools on the other side. Quick disconnect couplers are used

on all pneumatic and hydraulic lines. Power units and tools can therefore be carried and stored separately. Foot switches mounted on power units are used to control all tools functions. In operation, the power units are placed at the edge of the keyhole. The operator uses his hands to maneuver the tool in the keyhole and his foot to control the tool's actuators. The tools are attached to large diameter poles for easy handling. 50.8 mm outside diameter thin wall aluminum pipes have been used to fabricate the handling poles. Additionally, horizontal handles have been provided for better tool weight support. The handles are adjustable They can be attached to the pole at the height appropriate for the depth of the operation. All hydraulic and pneumatic lines connecting the tool to its power unit are routed inside the poles. Before this tool could be designed, the force necessary to positively squeeze off any pipe within the required size and wall thickness range had to be established. The finite element analyses using commercial packages Abaqus [6] are employed to obtain the force closing the pipe. Air pressure at the input of the hydraulic pump is adjustable. Maximum squeezing force can, therefore, be reduced to any value lower than the nominal 20 T, if desired.

#### 1.1.1. Control schematics of the squeeze-off tool

Air from the compressor goes through the service unit (filter with water separator, regulator, and lubricator) and activates a compact air-powered hydraulic pump that has been selected as most suitable for the application. Air-hydraulic pump provides advance-retract cycle operation for the single acting cylinder. When the foot pedal is pressed, the hydraulic cylinder of the air-hydraulic pump is activated and will act on the hydraulic actuator. The hydraulic pressure output of our air pump is controlled by the air pressure from the pump. If we increase the air inlet pressure, it will increase the hydraulic output pressure. If we decrease air inlet pressure this will decrease the hydraulic output pressure. To activate the pump, we need to depress the advance end of the treadle, so the air motor will be activated to pump hydraulic oil to the hydraulic actuator. The air motor will stop and hold load pressure when the treadle is in the free neutral position. To release load pressure or retract a cylinder, we need to depress the release of the pump treadle.

### 1.2. Mechanical development of squeeze-off tool – version 2 for polyethylene pipelines. Conceptual design of main assembly

The conceptual design of the squeeze-off tool – version 2 is shown in Fig. 4. Item 1 is the hydraulic cylinder mounting flange. To this flange, there is mounted hydraulic cylinder 2, with high flow hydraulic coupler 20. This cylinder is capable of developing 15 T at the maximum rated pressure of 690 bars. This is a single acting spring return with the stroke of 152 mm (6 in). Air pressure at the input of the hydraulic pump is adjustable. Maximum squeezing force can, therefore, be reduced to any value lower than the nominal 15 tons, if desired. Hydraulic cylinder

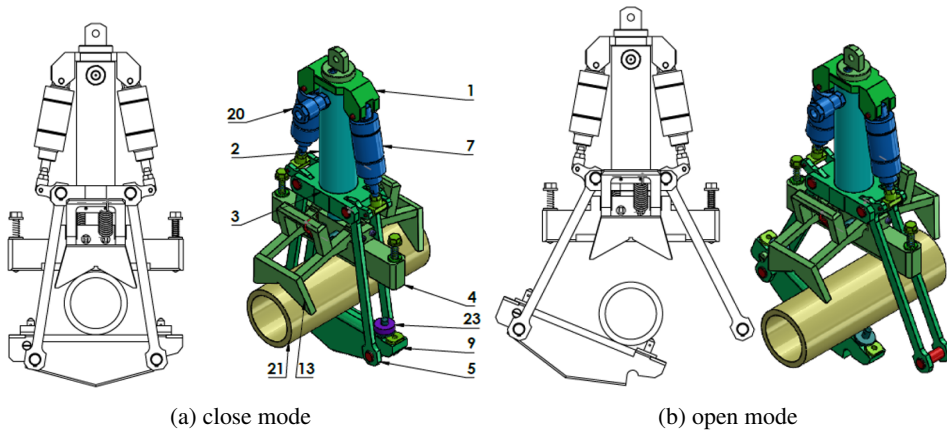


Fig. 4. Squeeze-off tool – version 2

is threaded to the top support 3. To the cylinder plunger, there is mounted the cylinder saddle 4 by means of the imperial thread. When the cylinder plunger with the cylinder saddle 4 moves down, the polyethylene pipe 21 is squeezed. Pneumatic cylinder 7 in extended mode will close the gate by moving arm 5 to lock position. Spacing sleeves 23 are used to limit the travel distance.

The pneumatic cylinder 7 in retracted mode will open the gate by moving arm 5 to the open position. The plunge of the hydraulic cylinder 3 is synchronized with the balanced arm 13 in order to hold the squeezing pipe in the position perpendicular to the cylinder axes. This squeezing tool is designed to be able to squeeze polyethylene pipes of different sizes, from 25 mm to 102 mm diameter.

### 1.3. Mechanical Development of cutter/saw tool for steel pipelines. Conceptual design of main assembly

The cutter/saw tool is built of three independently controlled components: the pipe gripper, the hacksaw and the hacksaw thrust actuator. Since it may be desirable to cut the pipe away from the center of the keyhole, in some cases even outside of the keyhole edge at the ground level (when bottom part of the keyhole is larger), the tool geometry had to be carefully considered. The developed cutter/saw tool is shown in Fig. 5. The center line of the hacksaw is offset with respect to the center of the keyhole by about 140 mm outside the keyhole edge. When service workers are performing service cut-off, the service pipe is normally cut close to the squeeze. It is desirable that the pipe should be clamped further away from the main. Therefore, the gripper offset with respect to the pole is approximately 240 mm.

As the first concept, the use of a pneumatic actuator for the pipe gripper has been considered. Our tests have shown that in order to positively clamp the steel pipe, substantial force is necessary. In the final concept, a hydraulic actuator was specified instead as a lightweight, powerful alternative. The hydraulic actuator

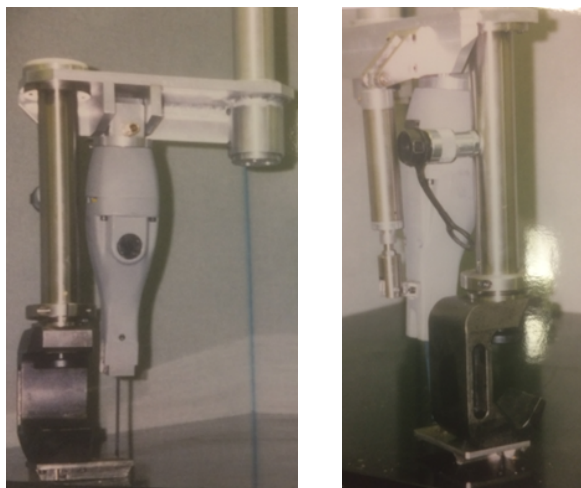


Fig. 5. Developed cut-off tool

similar to the one used for the squeeze-off tool but with much lower capacity (5 tons maximum) has been specified. The selected air-powered hydraulic pump drives the hydraulic actuator. Air pressure at the input of the pump is adjustable to limit the maximum clamping force of the gripper. It has been specified that the force in a range of 1 to 2.5 tons works well with most steel pipelines.

Standard reciprocating air saw Sioux Tools Inc. model No. 1300 has been specified and subsequently modified for remote operation. Spring-return pneumatic actuator provides the saw thrust. The geometry of the saw/thrust actuator assembly has been designed so that the force on the blade remains constant throughout the stroke of the actuator. The pressure applied to the actuator and therefore the thrust is adjustable within a wide range.

The conceptual design of the cutter/saw tool is shown in Fig. 6. The gas pipe line 25 is seated on the arbor press frame 1. Footing 2 is mounted to this frame, and can be removable if needed. The footing is protecting the metal cutting blade from the bottom of the tooling, which will minimize the blade breakage. The hydraulic cylinder 3 with acting force of 5 tons at 68.9 MPa [10000 PSI] is mounted to the arbor press frame 1. The pusher pin 5 is mounted to the piston rod of hydraulic cylinder 3. The pipe with flange 4 is the housing of hydraulic cylinder 3. It is also mounted to the press frame and is assembled with the frame weldment 6. The air saw 21 with reciprocating strokes 1800 per minute, with a power of 1hp, is pivoted on the frame weldment 6, by mounting flange with the pin 15. The air saw is pushed against the pipe by pneumatic cylinder 16 with coupling 18 and support of air cylinder 11. The air cylinder comes with a reverse single acting rod normally extended and spring-return. To handle the cut-off tool to the underground pipe, we use the holding tube with a horizontal handle 22. This cut-off tool can be used on steel as well on the polyethylene pipe lines.



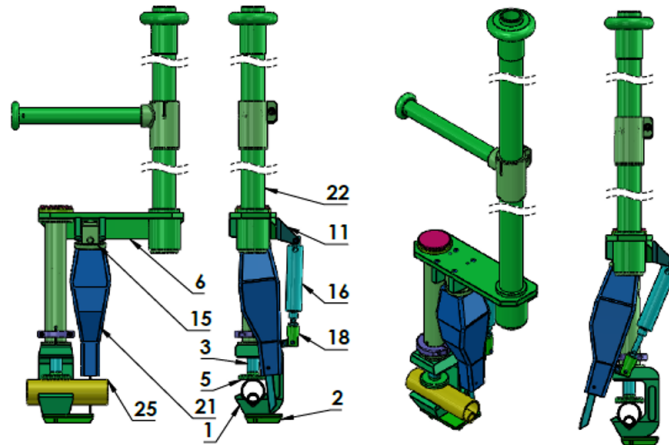


Fig. 6. Cut-off tool

### 1.3.1. Control schematics of the cutter/saw tool

The generated air from the compressor goes through the service unit of filter with water separator, regulator, lubricator and activates a compact air-powered hydraulic pump. This pump acts on the pipe gripper hydraulic actuator. Here we apply the combination of air-oil system in the pump. The advantages of this pump system allow us to power and control our tool. The oil provides smooth feed and the air provides fast action. Air can provide force to a large diameter piston that acts on a small diameter of hydraulic piston. Our control system also consists of two control toggle (pedal) operated 3-way 2 position valves. One valve controls the saw air motor, and the second one controls the saw thrust actuator.

## 2. Finite element simulation of high density polyethylene pipes crimping

The device for squeezing-off polyethylene pipelines is shown in Fig. 7. It enables crimping of pipes of various diameters made of HDPE (high density polyethylene) [7].

In order to select the diameter of the hydraulic cylinder and find the force required to tighten and close the pipe lumen (HDPE material), different pipe diameters were selected.

In addition, for comparative purposes, calculations were also made for one steel pipe (broader analyzes for steel pipes were performed previously). The following calculation models have been adopted: HDPE (material behaviors: elastoplastic, isotropic hardening) and steel (material behaviors: elastoplastic, isotropic hardening) with material coefficients taken from Tables 1 and 2. Calculations were carried out for pipe diameters as in Table 3.

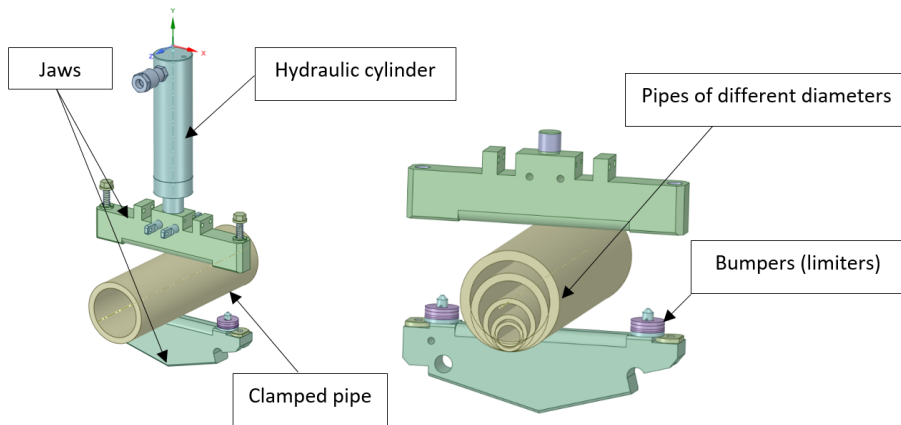


Fig. 7. The device for squeezing-off polyethylene pipelines

Table 1. Material coefficients

	HDPE [5]	Steel [6]
Young's modulus [MPa]	4.963 E+8	2.1 E+11
Poisson's number	0.44	0.3

Table 2. Coefficients for elastoplastic HDPE and steel material

HDPE		Steel	
Yield stress [MPa]	Plastic strain	Yield stress [MPa]	Plastic strain
12.9	0	414	0
15.7	0.0035	483	0.18
17.6	0.020		
26.1	0.131		

Table 3. Pipe diameters

Pipe No.	Outer (OD)/Inner (ID) diameter [mm]		HDPE	Steel
1	OD = 114.3,	ID = 92.075	+	+
2	OD = 88.9,	ID = 71.628	+	-
3	OD = 60.325,	ID = 48.641	+	-
4	OD= 41.91,	ID = 31.623	+	-
5	OD= 33.782,	ID = 26.035	+	-

The calculation model with the finite element mesh is shown in Fig. 8 (pipe No. 1 with OD diameter). The pipes were modeled with C3D8R elements (a spatial eight-node element with reduced integration). Due to the more complicated geometry of the jaws (rounding of the edges with radiuses), the mesh contained C3D10 elements (a spatial tetrahedral element of the second order with ten nodes). The problem to be calculated (also the contact of the inner parts of the pipes)

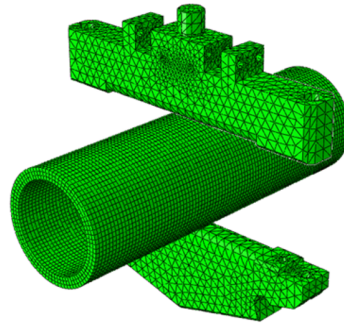


Fig. 8. Finite elements mesh of pipe No. 1

concerns the mechanics of contact. The contact pairs with an assumed friction factor of 0.19 were defined between the jaws and the pipe.

The nonlinear geometric (large deformations) static calculations were first carried out by displacing the upper jaw ("self-contact") of the inner walls and closing the lumen of the pipe (Fig. 9a). In the second step, the jaw was moved back to its initial position. The deformed HDPE pipe model is shown in Fig. 9b (pipe No. 1 ID = 92.075 mm). After a period of time, the shape of the polyethylene pipe should come back to the initial position.

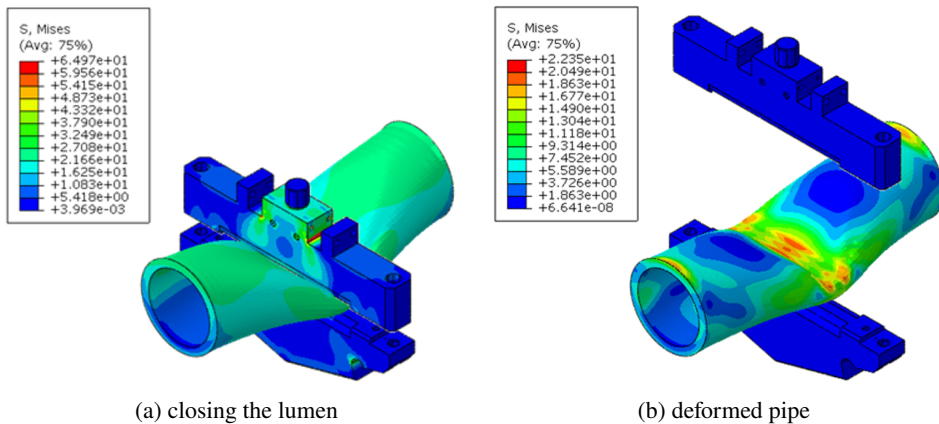


Fig. 9. Steps of deformations of the polyethylene pipe No. 1 (ID = 92.075 mm)

For each increment, in the first step (clamp), the change of the internal diameter of the pipes and clamp force were read. The diagrams for pipe No. 1 with the largest diameter of HDPE material and steel are shown in Fig. 10. To close this pipe (initial ID = 92.075 mm on the ordinate axis) the required force was about 5 T (54000 N) on the abscissa. The cross-sections of the closed pipe (ID = 92.075 mm) are shown in Fig. 9 (von Mises stresses), Fig. 11 (deformation in closed form), Fig. 12 (spring back phenomena), and Fig. 13 (deformations in closed form).

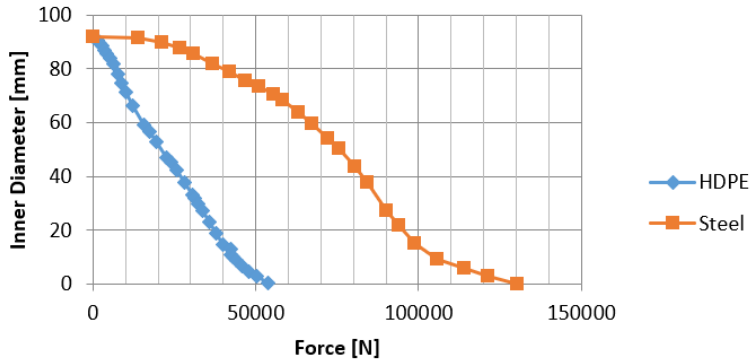


Fig. 10. Pipe No. 1 with the initial internal diameter ID = 92.075 mm

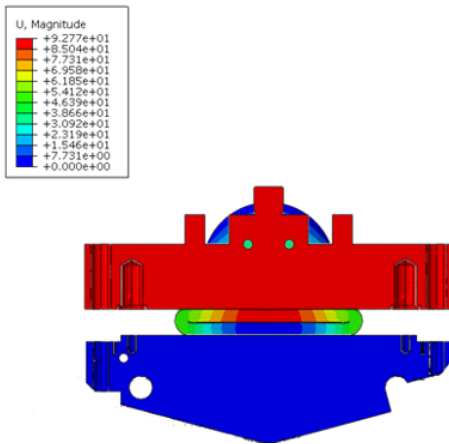


Fig. 11. Deformation in closed form

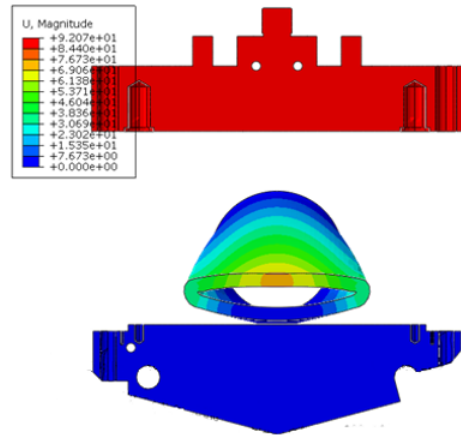


Fig. 12. Spring back phenomena

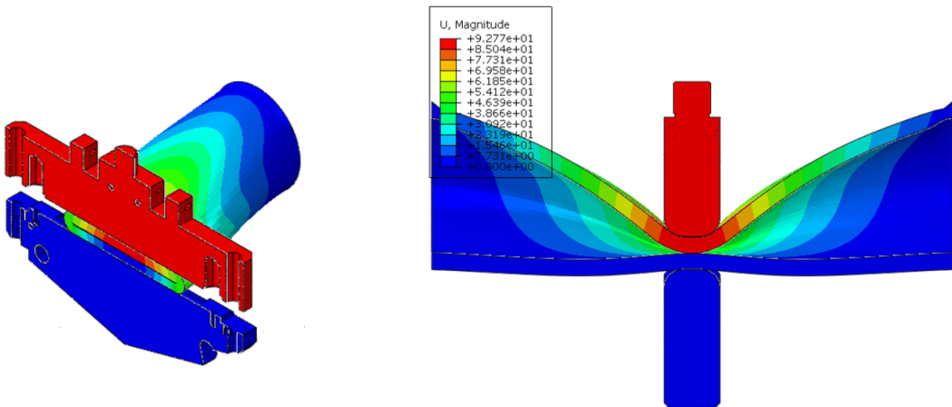
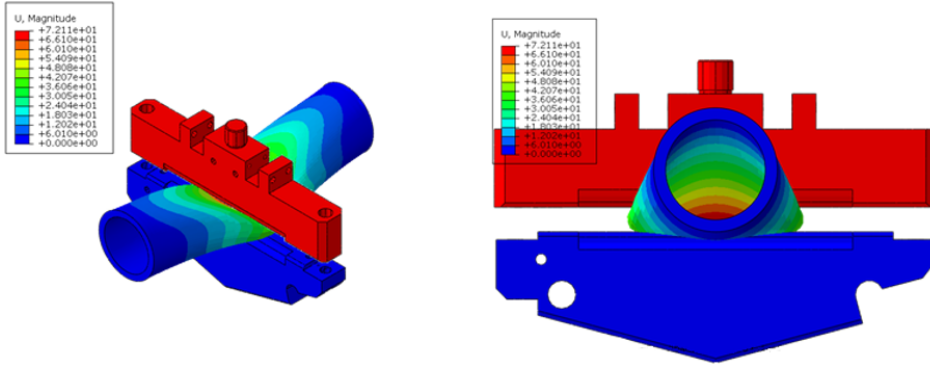
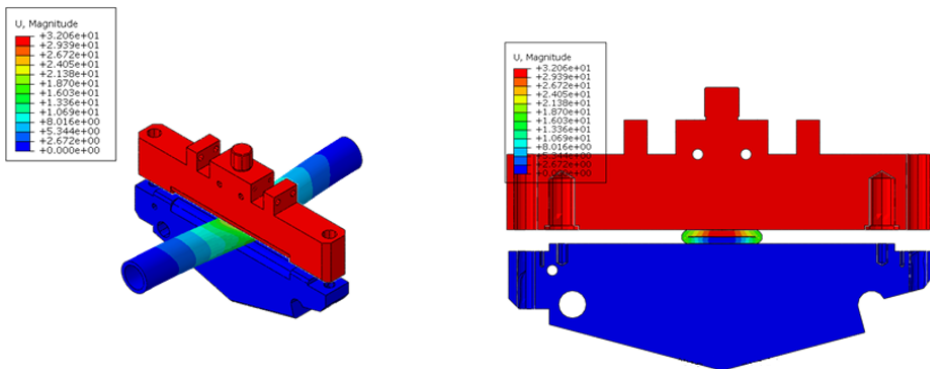


Fig. 13. Deformation in closed form

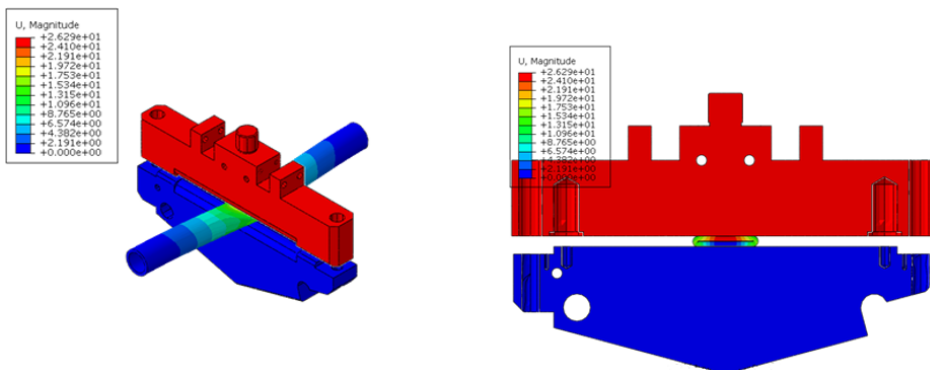
Clamped pipes with other diameters are shown in Fig. 14(a, b, c). Comparison of clamping force for pipe No. 1 made of HDPE and steel material is given in Fig. 15.



(a) pipe No. 2, inner diameter ID = 71.628 mm



(b) pipe No. 4, inner diameter ID = 31.623 mm



(c) pipe No. 5, inner diameter ID = 26.035 mm

Fig. 14. Clamped pipes with various diameters

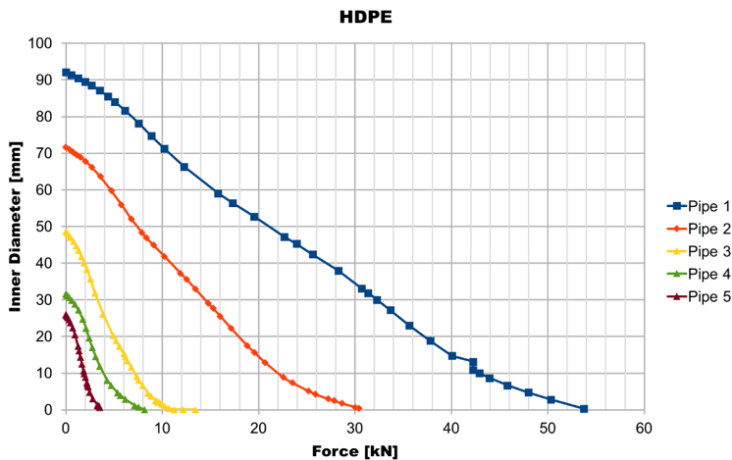


Fig. 15. Pipes No. 1-5, change in internal diameter (clamp) depending on the applied force

### 3. Topology optimization

Topology optimization in Abaqus starts with an initial model and determines an optimum design by modifying the properties and removing elements from the analysis. Optimization is an iterative process and the final result is a lightweight and durable component. Definition of optimization process contains an objective (i.e., to minimize the maximum strain energy), design responses (the input to the optimization), constrains and geometric restrictions. As an example, we will show topology optimization of a component (an arm) of squeeze-off tool as the act of an iterative process.

In order to reduce the weight of the device, optimization calculations were carried out using Abaqus/Tosca software. The initial model is shown in Fig. 16a. In the first phase of the calculations, the middle and upper sections of the arms

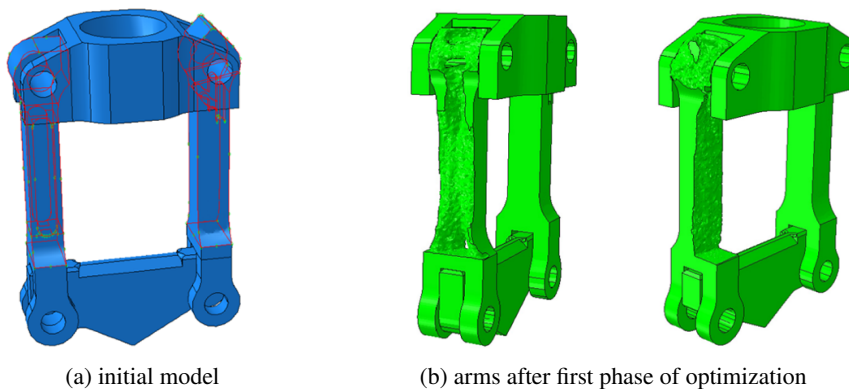


Fig. 16. Initial phases of optimization

(marked in red) were selected for optimization calculations. As a result of the first phase of the optimization calculations (Fig. 16b), the weight of the arms was reduced by 40% compared to the original weight.

The model from Fig. 16b was also subjected to further (second phase) optimization. Fig. 17 (right side) shows topology optimization of a component (an arm) of squeeze-off tool after a couple of first iterations. The result of the optimization process was a reduction in the weight and a change in the shape of the device. Based on the optimization results, grooves were made in the middle section of the arms for technological (machining) process. Finally, the weight of the device has decreased by 1.5 kg.

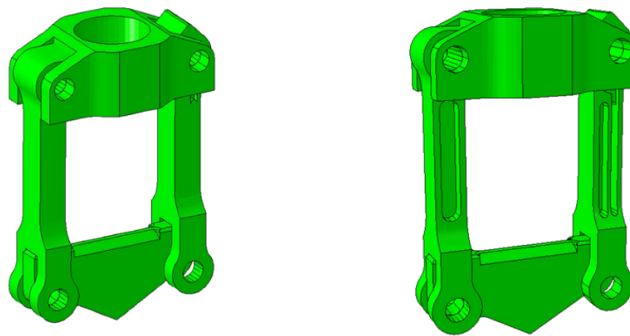


Fig. 17. Models: initial (on the left) and final topology optimization (on the right)

#### 4. Finite element simulation of high density polyethylene pipe cutting-off

The device for cutting-off polyethylene pipes is shown in Fig. 18a. It allows cutting off pipes of various diameters up to 70 mm. The numerical simulation was performed in the Abaqus v. 2022 finite element system (Fig. 18b).

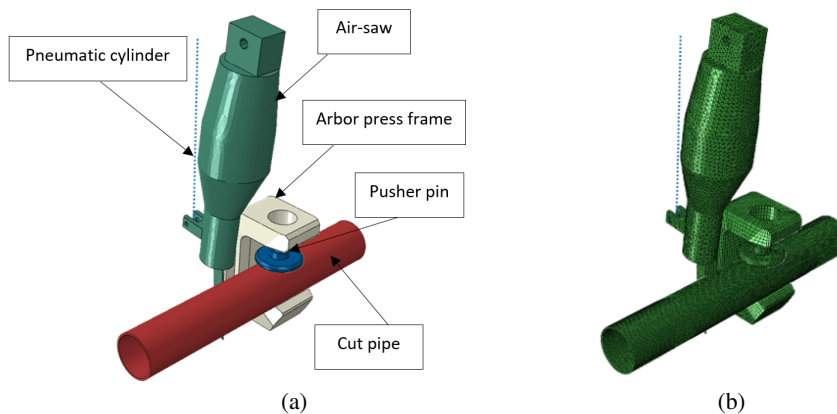


Fig. 18. Cut-off tool model and FE discretization

There are four parts in the model (Fig. 18): the air-saw, the pipe holder (Fig. 19, left side), the pusher pin (Fig. 19, right side) and the pipe. The air-saw is consisted of 77929 linear tetrahedral elements of type C3D4 (Fig. 18b). The link connection of the top pin is to be used to create boundary condition that allow rotation. The saw is pushed by connector elements of axial type; the saw has been pushed 50 mm that allowed cutting through the pipe. The pipe holding frame is modeled with 8310 linear hexahedral elements of type C3D8R. This part has been fixed at the top face. The pusher pin is modeled with 6046 linear hexahedral elements of type C3D8R. Boundary conditions allow for vertical displacement only. The pipe was modeled with 18400 linear hexahedral elements of type C3D8R. The length of the pipe that was used in the laboratory was 400 mm, and the outer diameter of the pipe was 60.3 mm, with the wall thickness of 4.8 mm.

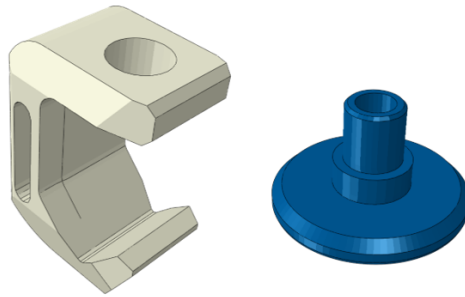


Fig. 19. Pipe holder (left) and pusher pin (right)

Simulation has been run with Abaqus explicit and a general contact model. One assumed hard contact of normal behavior and a penalty friction model with 0.3 value. The simulation consists of two analysis steps: (i) the pusher pin goes down by 5 mm to hold the pipe in the frame (Fig. 20) and (ii) the actuator extends by 50 mm with the phases of cutting through the pipe (Fig. 21).

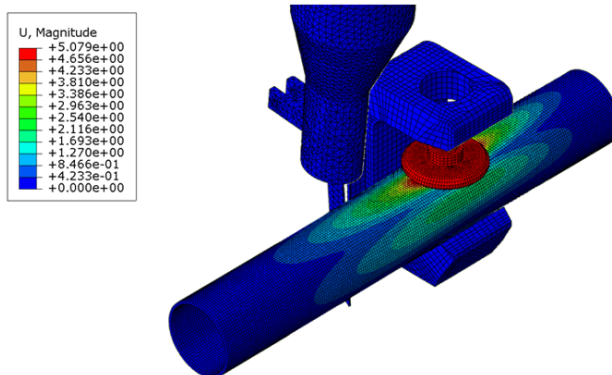


Fig. 20. Gripping the pipe with a pusher pin



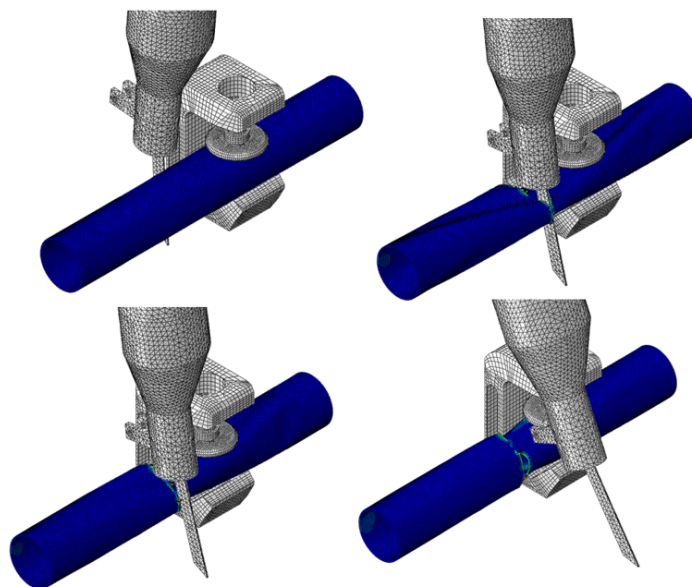


Fig. 21. Phases of cutting through the pipe

To establish what force was needed to cut through the pipe, we have used a pneumatic cylinder and applied air pressure to the cylinder to produce the necessary force. The values of the gripping forces (the force needed to hold the pipe in the device), the cutting and clamping forces for Canadian pipes are given in Table 4.

Table 4. The values of the gripping, cutting and clamping forces for Canadian pipes

Pipe, No.	Outer (OD)/inner (ID) diameter [mm]	Gripping force [kN]	Cutting force [kN]	Clamping force [kN]
1	OD = 60.325 ID = 48.641	11.57	7	13.4
2	OD = 41.91 ID = 31.623	6.7	4.75	8.18
3	OD = 33.782 ID = 26.035	4.4	4.5	3.5

Regardless of the results presented for pipes used in Canada, we also performed a computer simulation of for pipes produced in Poland. We have used two pipes for our laboratory: one pipe with the following dimensions: outer diameter 63.2, wall thickness 6.2 mm, length 470 mm and a second pipe one with outer diameter 90.1 mm, wall thickness 5.5 mm and length 580 mm, respectively. Experimental measurements were carried out independently on the Instron 8850 testing machine (Fig. 22). The pipes were pressed at a speed of 100 and 200 mm/min. However, the pressing speed had no effect on the results. The material constants needed for computer simulations were obtained on the basis of stress-strain characteristics, in accordance with the ISO 527-1.2 standard. It should be noted that the experimental results are in good agreement with the finite element results (see Figs. 23 and 24).



Fig. 22. Instron 8850 machine with tested sample

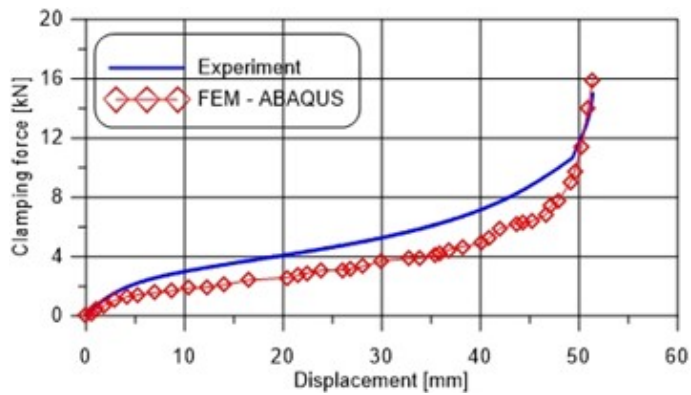


Fig. 23. Changes of the pipe outer diameter (63.2 mm) depending on the applied force. The clamping force is 15.86 kN (Abaqus), 15.03 kN (experiment)

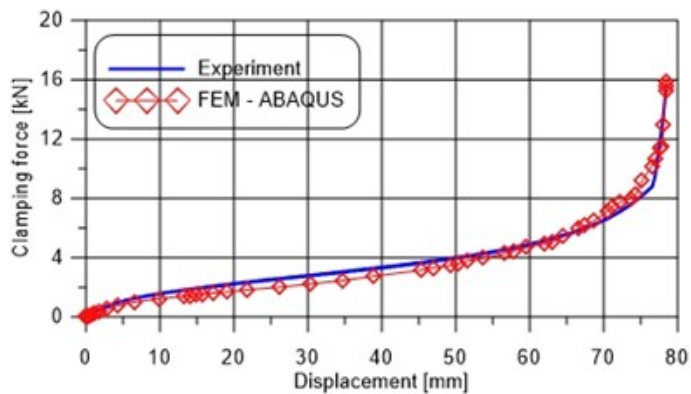


Fig. 24. Changes of the pipe outer diameter (90.1 mm) depending on the applied force. The clamping force is 15.88 kN (Abaqus), 15.56 kN (experiment)

## 5. Conclusions and recommendations

1. The field tests have proved that the squeeze-off tool is capable of performing operations for which it was designed. It can be used efficiently for both routine and emergency cut-off. Using the tool should help improving the quality and reduce the cost of gas company maintenance operations.
2. It is important to note, however, that the tools are prototype systems and were not designed for continuous use over a long period of time. Once they are thoroughly field tested, production versions of the tools should be designed and fabricated based on gas company recommendations.
3. Keyhole technology is very effective and attractive way of performing maintenance of underground pipes systems.
4. Research and development of new tools and optimization of existing ones can fulfill market demand.
5. Current finite element commercial systems (Abaqus, Ansys) are capable of performing accurate analysis. Abaqus/Tosca software is an efficient and straightforward tool to perform topology optimization for engineers.

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