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Coiled-Tubing-Conveyed Perforating in Shale

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Abstract

This is a study of the development and ultimate use of the CT (Coiled Tubing) Firing Transfer System used in three different scenarios and is a comprehensive examination of what specifically is required for use and the contrast between past and present methods in order to quantify perforating efficiency. The Coiled-Tubing-Conveyed CT Firing Transfer System has greatly improved Coiled Tubing perforating efficiencies when multiple zones are to be perforated during a single run in a well. Cost, capability and time, (cost of time) have always been limiting factors in bringing oil or gas to market profitably. The CT Firing Transfer System has been used in many hundreds of wells. An estimated 15,700 individual CT Firing Transfer Systems and perforating guns have fired over 90,000 perforating charges with a very high degree of reliability. The savings at the well site are substantial in direct imbedded equipment and maintenance costs savings to the end user over a period of just 3 years. The simplicity and methods of its use in many different scenarios have been developed and are in use successfully. Although originally developed for Coiled Tubing, the CT Firing Transfer System has also been used for Tubing Conveyed Perforating (TCP) applications.

Introduction:

The technology that has been obtained over the past years has unlocked a huge amount of hydrocarbons that were previously inaccessible. There have been major and minor developments, most by themselves not having a significant impact on efficiency or capability, but in the aggregate, these technical breakthroughs have added reserves that were thought to be inaccessible or unprofitable to produce. One such technical development is the CT (Coiled Tubing) Firing Transfer System.

In 2008 the need presented itself to find a way to perforate horizontal wells with multiple zones separated by tens or even hundreds of feet. Perforating on coiled tubing was for the most part accomplished by traditional perforating methods using time proven and available equipment. The result was that a typical perforating job on coiled tubing would require many round trips to complete. Each coiled tubing round trip carried with it the inherent risk associated with coiled tubing intervention.

The successful resolution of these challenges with the development of the CT Firing Transfer System has provided the industry with a user friendly system. This system reduces the length of multiple gun strings and provides higher efficiencies and cost savings for perforating companies and operators. The patent pending CT Firing Transfer System is now widely available and is designated the HTD-Blast System (Horizontal Time Delay Ballistic Assisted Sequential Transfer).

Definitions:

To understand this explanation concerning the CT Firing Transfer system it is necessary to explain the different tools and major components used to assemble a system for the purpose of perforating a shale well using Coiled Tubing in the context of this paper.

1. Firing Head: A mechanism for firing a detonator, in the case of CT or TCP a percussion initiated detonator. Firing heads are generally functioned by: the application of direct pressure from the surface; dropping a bar from the surface to impact against a firing pin; the application of differential pressure against the firing head; pumping a ball downhole to seat against and seal, then applying pressure to function the firing head.
2. Time Delay Fuse: Small diameter (0.750 in) steel housing, usually about 15 inches long. The time delay (TD) contains a pyrotechnic mix designed to burn slowly at a predetermined rate, most typically this assembly burns for approximately six minutes, and predictably faster as the well temperature increases. At the conclusion of the "burn" it detonates high order to initiate any adjacent Booster or Detonator.
3. Time Delay Fuse Igniter: A small diameter (0.375 in) pyrotechnic device that converts impact energy into a flame output to initiate the time delay fuse. Requires impact from a firing pin to activate.
4. Detonator: In the context of this paper is an explosive device that creates a high order detonation when a predetermined amount of force is applied suddenly, in this case the detonator being struck with force by a firing pin.
5. Bi-Directional Booster: An explosive filled aluminum cup ¼" diameter X 1-3/8" long. The Booster is open on one end to slip over the detonating cord so that the explosive inside is in contact with the explosive of the detonating cord. The Booster is used to transfer detonation from a detonator to detonating cord or to transfer detonation from one perforating gun assembly to another. The explosive typically used in this booster is HMX.
6. A Perforating Gun Assembly: A steel carrier, usually 3-1/8" or 3-3/8" in diameter (in the case of wells with 5-1/2" casing) containing explosive shaped charges that are individually phased one from the other according to the well requirement. Each of the shaped charges are connected one to the other with an explosive cord approximately ¼" in diameter, this is referred to as Detonating Cord. When the detonating cord is fired at one end of the gun all shaped charges are detonated virtually simultaneously.

All of the parts and component assemblies that were described above are available in numerous sizes and specifications to fit the majority of downhole well conditions and physical requirements. See Figure 1 for details of commercially available perforating string components.

It is a distinct advantage that each perforating gun firing is identifiable at the surface. When they are removed from the well the proper procedure for pulling the perforating guns can be used in order to save valuable time and to anticipate their safe removal, or prepare another gun or guns in the event that there has been a misfire.

To identify each gun firing, it is common for the service company to use a Shot Detection System. A Shot Detector is generally comprised of a recorder and a specially adapted microphone that attaches to the pipe at the surface so that each firing is heard and recorded for review if necessary.

Previous Method to Perforate Multiple Zones

In circumstances where Coiled Tubing is used to convey the perforating guns into the well the previous method required multiple firing heads (described above) in order to fire all of the perforating guns independently. Each of the guns would have: a Firing Head of some type, used to start the perforating process with the application of pressure; a Time Delay mechanism used to delay firing for five or six minutes or more; and finally, a perforating gun that would typically contain the required number of perforating charges.

In other circumstances the firing heads may be assembled in such a way to activate when different pressures are applied from the surface, because of the difference in time it takes to apply the different pressures it is a definite advantage that the guns fire with a time delay between activation and firing to be sure all Firing Heads have time to be functioned during pressure application and before the perforating gun detonates. This is important because once the perforating guns fire and the formation is exposed to the wellbore then pressure cannot be applied easily since the formation will absorb it.

Often in the case of perforating the toe of the well in shale, it is required that pressure be applied to the well from the surface in order to activate Firing Heads downhole. Perforating the toe of the well on coiled tubing was a costly and time consuming activity. Since there may be tens of hundreds of feet between zones, each perforating gun had to be run individually. Since there is typically a minimum of 4 guns used to complete the initial perforating operation, the CT Firing Transfer System has improved efficiency and reduced cost.

To initially resolve this problem a bottom hole perforating assembly using commercially available technology was used. From the bottom to top the assembly consists of (1) a perforating gun; (2) a pressure firing head with ported sub; (3) a perforating

gun; (4) a 6-minute time delay; (5) a pressure firing head with ported sub; (6) a perforating gun; (7) two 9-minute time delay fuses; (8) a pressure firing head with ported sub; (9) a perforating gun; (10) a drop ball differential firing head. See Figure 2 The perforating procedure was conducted as follows:

1) The assembly was run to the first zone to be perforated.
2) The annulus was pressured-up causing the bottom firing heads to function. The bottom perforating gun fired immediately while the six minute time delay fuse and the tandem 9 minute time delay fuses started burning.
3) The Coiled Tubing was pulled to the next perforating interval and stopped to wait on the 6 minute time delay to complete its burn.
4) The second perforating gun from bottom fired.
5) The Coiled Tubing was pulled to the next perforating interval and stopped to wait on the two tandem 9 minute time delays to complete their burn.
6) The third perforating gun from bottom fired.
7) The Coiled Tubing was pulled to the fourth perforating interval.
8) A ball was pumped down the coil tubing to the seat in the Ball Drop Safety Firing Head; pressure was applied against the ball to initiate the firing head.
9) The fourth perforating gun fired immediately after the firing head was initiated.
10) With the job complete the assembly was pulled out of the hole.

Although this procedure and the selection of "off the shelf" perforating tools was a significant improvement, there were still many deficiencies. The length of the overall assembly was too long so that lubricator length was a limiting factor. The hardware and extra explosive packages were costly. Maintenance and assembly was time consuming and required special consideration.

Development of the CT Firing Transfer System

A) Concept Identification and Development:

As a general rule the zones were relatively short so gun length in itself was not significant. However, various tools must be added together in a single tool string which required the overall length to be minimized for the deployment to be effective and safe.

One of the many challenges was deployment and retrieval of perforating guns through a lubricator above the wellhead or Blowout Preventer (BOP). The bottom hole assembly must fit inside the lubricator putting limits on the length of any firing system used to initiate the perforating guns. Since the accumulated lengths of all the firing systems would decrease the number of guns that could be run in a single CT tool string and the gun system must fit within the lubricator it was imperative to find a solution that minimized the length of the firing system.

In the interests of simplicity and efficiency and ultimately customer value, the concept solution must fit multiple gun systems ranging from 1.56 through 7.00 inches outside diameter and must operate with high reliability.

That being said it is a constant that different equipment suppliers produce equipment with differing tolerances. In some cases there is minimal effect, but where explosives are concerned it is always recommended that equipment should only be used in accordance with the recommendations of the manufacturer.

B) Concept Assembly and Testing:

It is advantageous that all of the perforating guns be initiated using a single firing head at the top or bottom of the assembly with a single application of pressure, (in cases where pressure is used to initiate). The CT Transfer Firing System allows for such a scenario. Consistent with this invention the first perforating gun in the assembly is positioned and the firing head is initiated detonating the gun.

When the first gun detonates the pressure and detonation force within the gun shears a flange on a firing pin and drives the firing pin forcefully against an igniter that initiates the burning of the pyrotechnic time delay connected to the adjacent gun. During the burn sequence the gun assembly is moved by coiled tubing and positioned adjacent to the next perforating interval in the well. This procedure is repeated until all of the guns in the assembly have fired. This was the scenario accepted to begin design and testing of the CT Firing Transfer System.

C) System Operating Parameters:

The CT Firing Transfer System was designed to allow the detonation of the Detonating Cord firing from the donor gun to detonate a Bi-Directional Booster. The detonation of the Bi-Directional Booster against the top flange of the Firing Pin causes it to shear. The high pressure of the detonation drives the Firing Pin down onto the Fuse Igniter that results in its firing which in turn activates the TDF. See Figure 3 for details.

The CT Firing Transfer System operating parameters are as follows:

1. Must withstand 10,000 PSI downhole pressure prior to detonation in the event of a gun leak.
2. Firing Pin must shear and travel from the detonation force of an approved Bi-Directional HMX Booster.
3. The system must withstand 10,000 PSI downhole pressure after firing.
4. The system must disassemble and clean-up with minimum effort.
5. There must be minimal damage to the crossover sub.
6. Must be adaptable to 1-11/16 inch though 7 inch gun systems.
7. Must transfer from perforating gun to Time Delay Fuse.
8. Must Transfer from a Time Delay Fuse to another Time Delay Fuse.

After the testing parameters were set and approved a detailed testing program was developed. After the significant lab and field testing program was completed and all parameters were met or exceeded, the CT Firing Transfer system was considered commercially viable and was released.

Typical Applications

A) CT Firing Transfer System on Coiled Tubing:

The CT Firing Transfer System requires careful job preparation, measurement and review. It must be emphasized that when the first gun is initiated all the guns in the string will fire in sequence. Once the system is activated, it cannot be stopped.

The operating procedure must be fully documented and carefully followed. The operator must know how far to pull up to the next interval after each gun has fired. It is important to identify when each gun fires, therefore a Shot Detector is recommended. Even with a Shot Detector, it may not be possible to detect each gun detonation. In this case the operator must pull the Bottom Hole Assembly (BHA) to the next interval at the correct time to avoid getting the perforating program out of sequence.

This configuration of the CT Firing Transfer System is the most prevalent in terms of perforating systems run on coiled tubing in shale wells. The system is composed of 1) Absolute Pressure Firing Head 2) A Perforating Gun Assembly; 3) A CT Firing Transfer Assembly; 4) A Time Delay Assembly; 5) A Perforating Gun Assembly; 6) A CT Firing Transfer Assembly; 7) Time Delay Assembly; 8) A Perforating Gun Assembly; 9) A CT Firing Transfer Assembly; 10) Time Delay Assembly; 11) A Perforating Gun Assembly. Refer to Figure 4 (note, items 6 though 11 not shown).

The perforating procedure is conducted as follows:

1) Run the BHA and position the first gun adjacent to the bottom zone.

2) Pressure up the annulus to activate the Absolute Pressure Firing Head (not shown). The first gun in the firing sequence will fire immediately.
3) Pull the CT up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
4) The second perforating gun in the sequence will fire.
5) Pull the CT up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
6) The third perforating gun in the sequence will fire.
7) Pull the CT up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
8) The fourth perforating gun in the sequence will fire.
9) If more than 4 guns are run continue this process until all Perforating Guns have fired.
10) Pull the CT with BHA out of the hole.

B) CT Firing Transfer System on Coiled Tubing, Plug and Shoot:

The CT Firing Transfer System in this application is used to set a plug and perforate during the same run into the well. Some of the well parameters for this application are as follows:

- A separate run to set a plug may not be advantageous.
- Cannot pump wireline perforating guns down the well.
- Shoe did not test on bottom before the initial TCP run.
- Shortage of water for wireline perforating pump down stages.
- Undesirable to pump excessive amounts of water due to environmental, formation, or other operation restrictions.

In order to set the plug using a Pressure Activated Firing Head it must be possible to pressure up the well bore to 2,500 psi above the wellbore hydrostatic pressure.

The operating procedure must be fully documented and carefully followed. The operator must know how far to pull up to the next interval after each gun has fired. It is important to identify when each gun fires, therefore a Shot Detector is recommended. Even with a Shot Detector, it may not be possible to detect each gun detonation. In this case the operator must pull the Bottom Hole Assembly (BHA) to the next interval at the correct time to avoid getting the perforating program out of sequence.

This configuration of the CT Firing Transfer System is rapidly increasing in use. The system is composed of 1) A Ball Drop Safety Firing Head on top; 2) Perforating Gun, 3) CT Firing Transfer 4) Time Delay Assembly; 5) A Perforating Gun Assembly; 6) A CT Firing Transfer Assembly; 7) A Time Delay Assembly; 8) A Perforating Gun Assembly; 9) Ported Sub; 10) A Pressure Activated Firing Head; 11) A Setting Tool; 12) A plug. Refer to Figure 5.

The perforating procedure is conducted as follows:

1) Run the BHA and position the plug at correct depth.
2) Pressure up the wellbore to 2,500 psi above hydrostatic pressure to initiate the Pressure Activated Firing Head which will activate the Setting Tool and set the Composite Plug.
3) Pull the CT up to the first perforating interval and pressure up the wellbore to test the plug.
4) Pump a Ball down to the seat in the Ball Drop Safety Firing Head, pressure up against the Ball to fire, the first gun will fire immediately.
5) Pull the CT up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
6) The second perforating gun from the top will fire.
7) Pull the CT up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
8) The third perforating gun from the top will fire.
9) Pull the CT up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
10) The fourth perforating gun from the top will fire.
11) If more than 4 perforating guns are run, continue this process until all guns have fired.
12) Pull the CT and BHA out of the hole.

C) CT Firing Transfer System on Tubing:

The CT Firing Transfer System in this application is used to perforate multiple zones during the same run into the well on tubing. The primary benefit of this application is the elimination of spacer tubing between guns. Spacer tubing is commonly used to space out guns in a TCP string when there are numerous zones to perforate. In one application in the Rockies an operator was able to use the CT Firing Transfer System to perforate 20 zones in one run without spacer tubing.

The operating procedure must be fully documented and carefully followed. The operator must know how far to pull up to the next interval after each gun has fired. It is important to identify when each gun fires, therefore a Shot Detector is recommended. Even with a Shot Detector, it may not be possible to detect each gun detonation. In this case the operator must pull the Bottom Hole Assembly (BHA) to the next interval at the correct time to avoid getting the perforating program out of sequence.

It is advisable that the tubing is marked at each location where pulling of the tubing will be stopped to position the next perforating gun on depth. This ensures the rig operator can pull up to each station without measurement. This pre-measuring saves valuable time and eliminates confusion that may result in perforating out of zone.

This system is composed of 1) A Ball Drop Safety Firing Head on top; 2) A Perforating Gun Assembly; 3) A CT Firing Transfer Assembly; 4) A Time Delay Assembly; 5) A Perforating Gun Assembly; 6) A CT Firing Transfer Assembly; 7) Time Delay Assembly; 8) A Perforating Gun Assembly; 9) A CT Firing Transfer Assembly; 10) Time Delay Assembly; 11) A Perforating Gun Assembly. Additional zones may be perforated by adding items 3, 4 and 5. Refer to Figure 6 (note, items 6 though 11 not shown)

The perforating procedure is conducted as follows:

1) Run the BHA and position the top gun adjacent to the bottom zone.
2) With paint or a tape, "mark" the tubing indication the location of the bottom zone.
3) Pull tubing to each interval and mark the tubing to identify each zone to be perforated.
4) Reposition the top gun adjacent to the bottom zone.
5) Pump a Ball down to the seat in the Ball Drop Safety Firing Head, pressure up against the ball to fire, the first gun will fire immediately.
6) Pull the Tubing up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
7) The second perforating gun from the top will fire.
8) Pull the Tubing up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
9) The third perforating gun from the top will fire.
10) Pull the Tubing up to the next perforating interval and stop to wait on the 6 minute time delay to complete its burn.
11) The fourth perforating gun from the top will fire.
12) If more than 4 perforating guns are run, continue this process until all guns have fired.
13) Pull the Tubing and BHA out of the hole.

Conclusion

In summary; the CT Firing System has been used in thousands of wells and has gained acceptance in horizontal perforating of shale wells throughout North America. There have been over 15,700 individual CT Firing systems and perforating guns using over 90,000 perforating charges. The savings at the well site have been estimated at hundreds of hours and thousands of dollars in direct imbedded equipment and maintenance costs to the end user over a period of 2-1/2 years. The reduced length of the firing system has reduced the number of runs required to perforate horizontal shale wells. This is the story of one system; one of many technical achievements that have made it possible for the exploitation of shale plays in North America and is becoming accepted for use in international shale plays.

Acknowledgements

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Figures

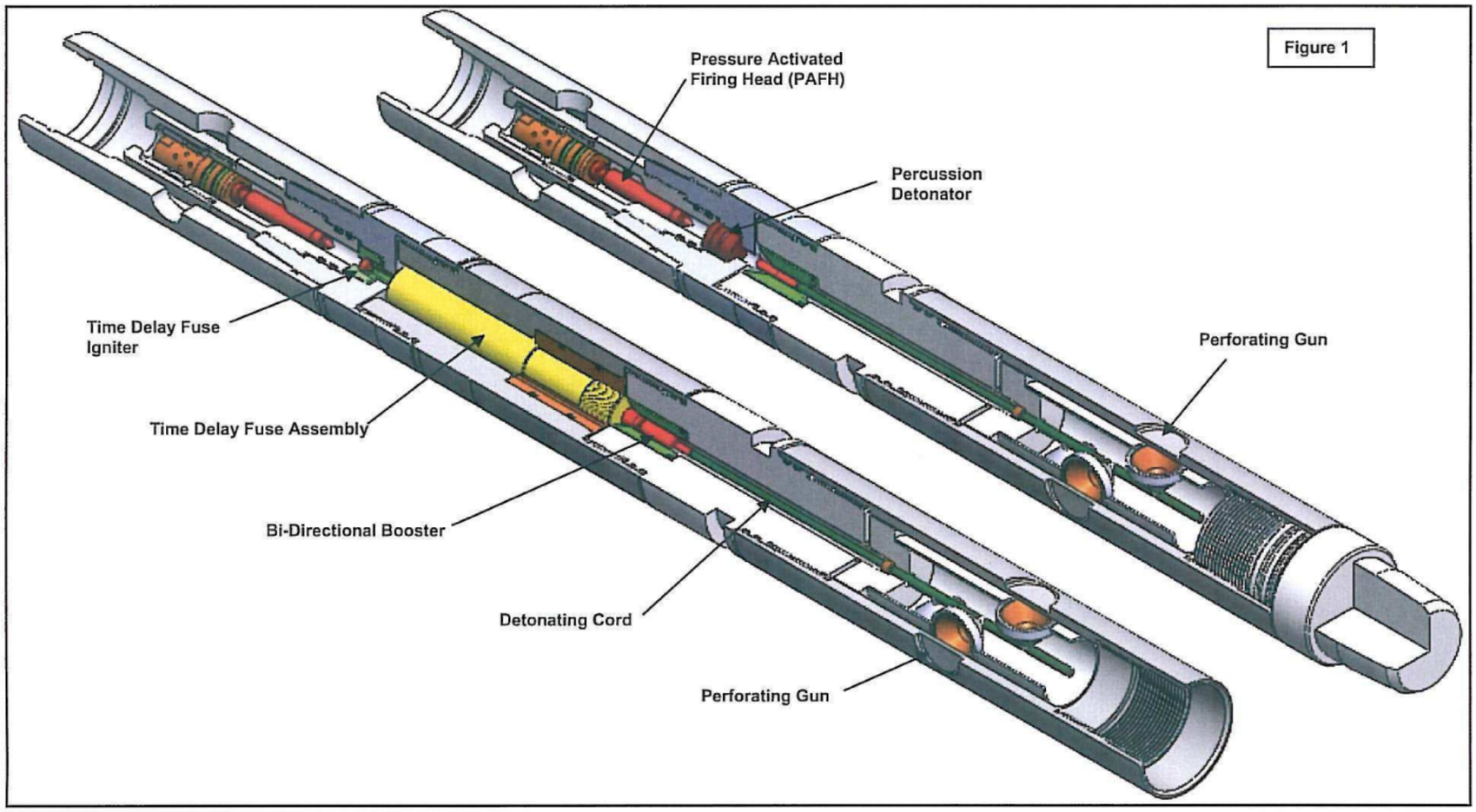
Figure 1
Pressure Activated
Firing Head (PAFH)
Percussion
Detonator
Time Delay Fuse
Igniter
Perforating Gun
Time Delay Fuse Assembly
Bi-Directional Booster
Detonating Cord
Perforating Gun

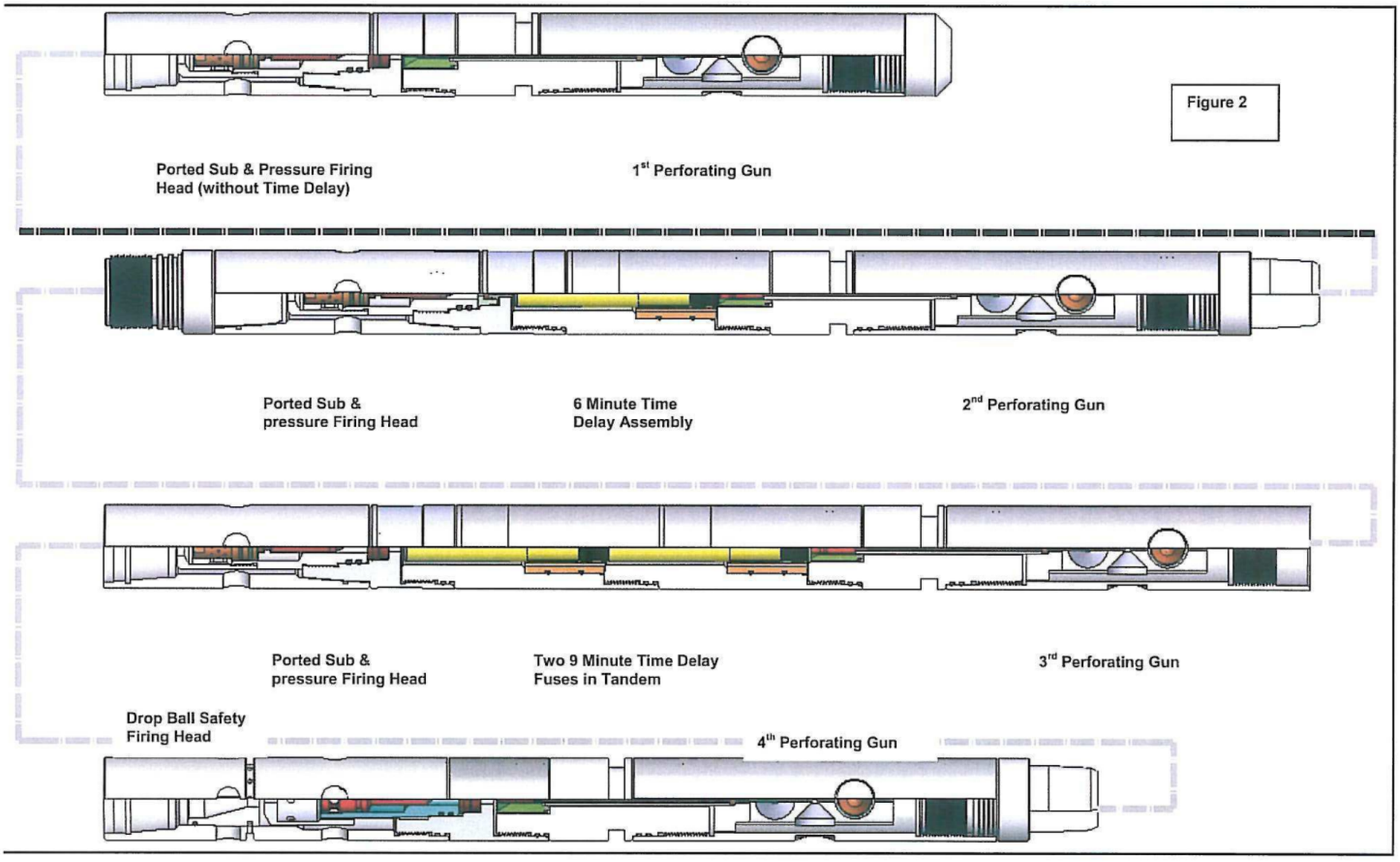
Ported Sub & Pressure Firing Head (without Time Delay)
1st Perforating Gun
Ported Sub & pressure Firing Head
6 Minute Time Delay Assembly
2nd Perforating Gun
Ported Sub & pressure Firing Head
Two 9 Minute Time Delay Fuses in Tandem
3rd Perforating Gun
Drop Ball Safety Firing Head
4th Perforating Gun

Figure 2

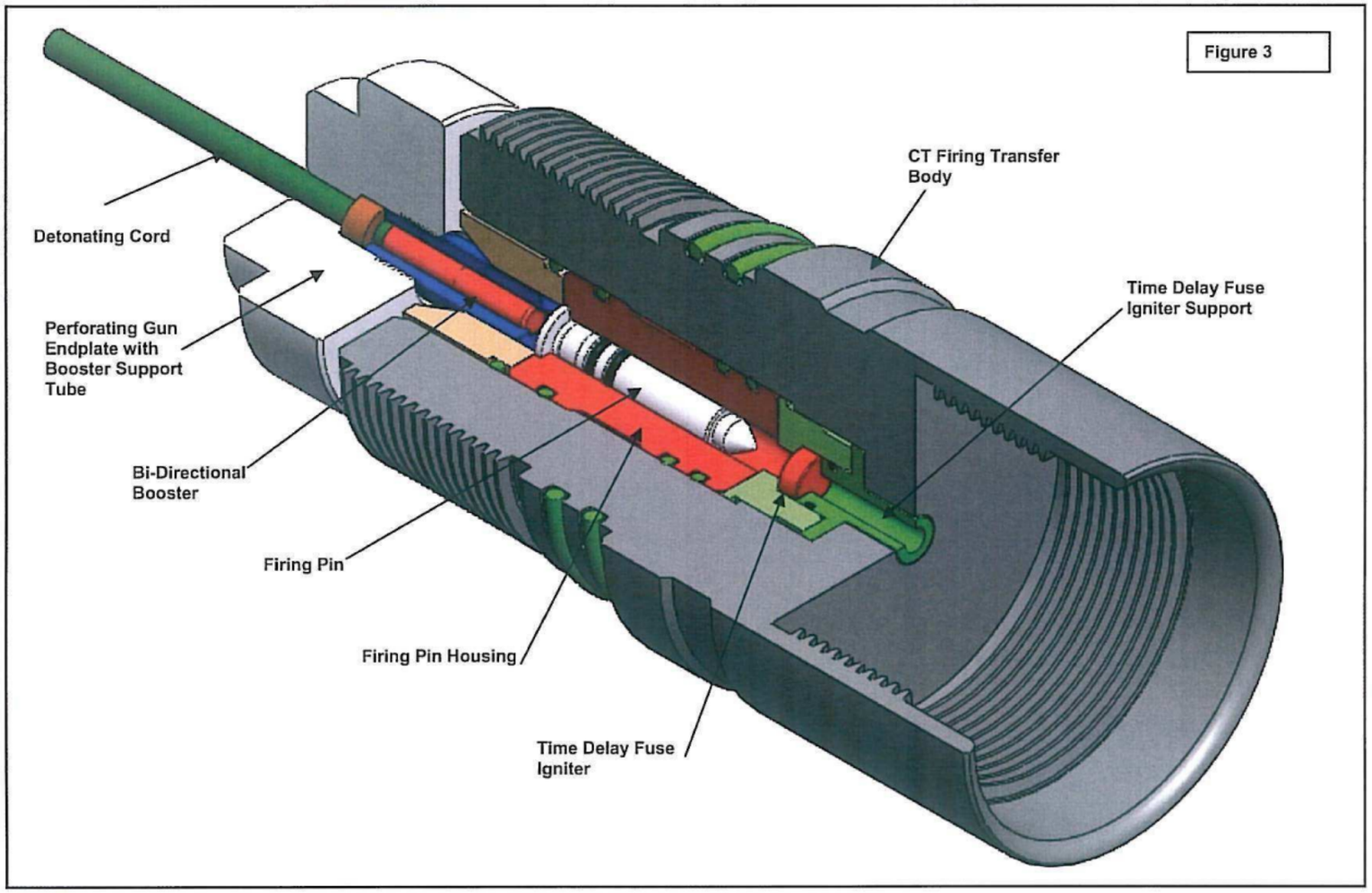
Figure 3
CT Firing Transfer Body
Detonating Cord
Time Delay Fuse Igniter Support
Perforating Gun Endplate with Booster Support Tube
Bi-Directional Booster
Firing Pin
Firing Pin Housing
Time Delay Fuse Igniter

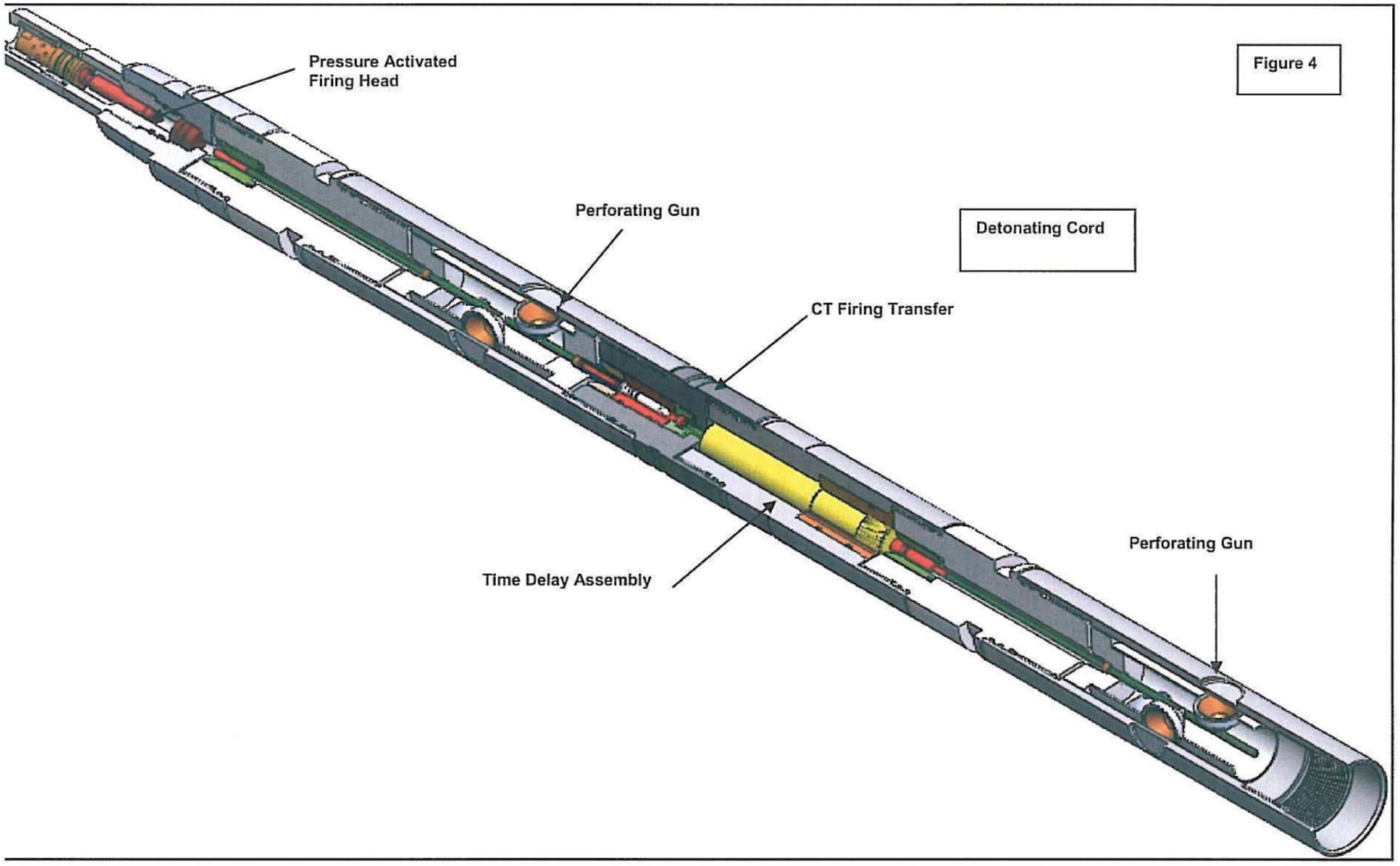
Pressure Activated
Firing Head
Perforating Gun
Detonating Cord
CT Firing Transfer
Time Delay Assembly
Perforating Gun

Figure 4

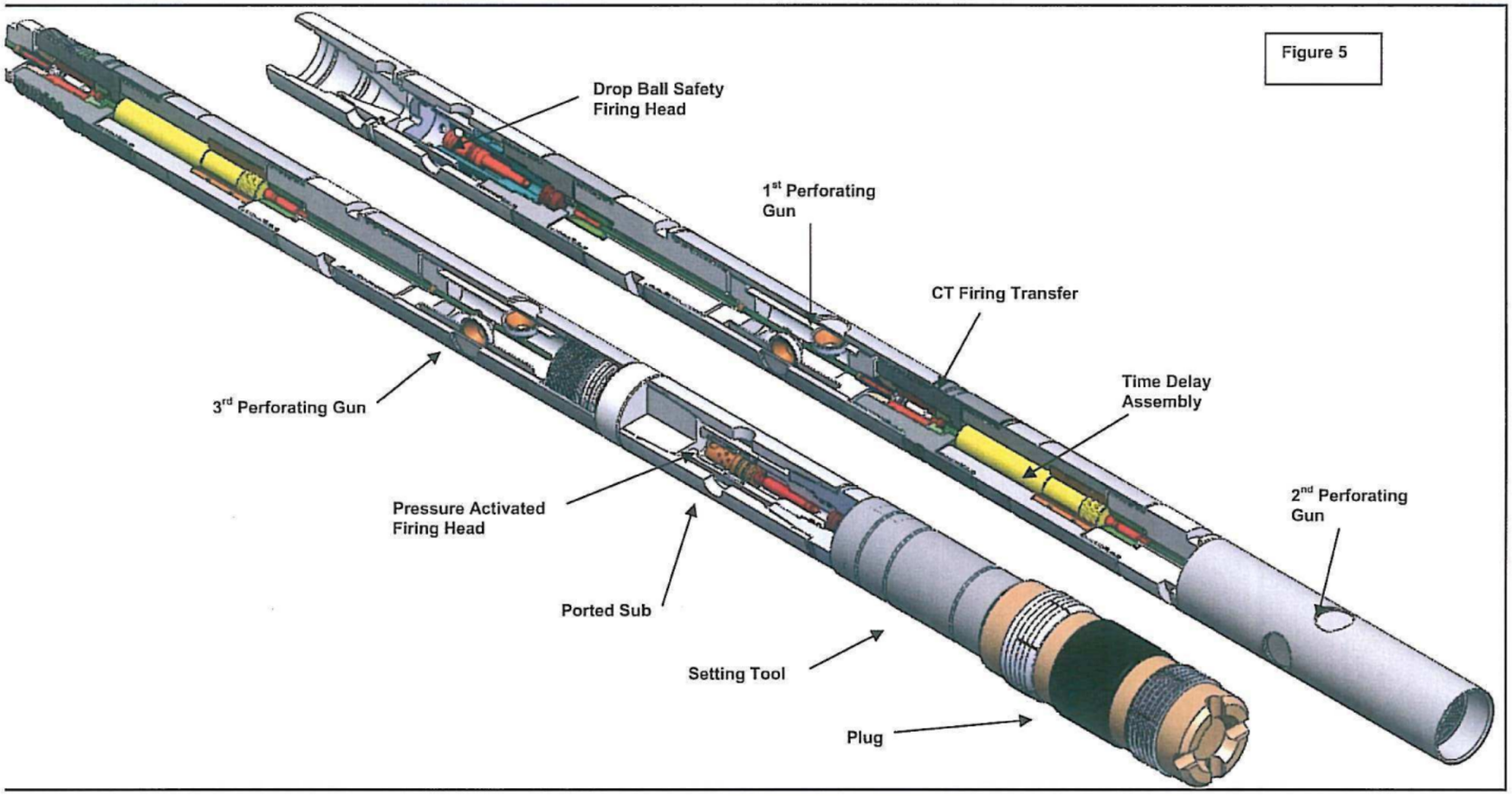
Figure 5
Drop Ball Safety Firing Head
1st Perforating Gun
CT Firing Transfer
Time Delay Assembly
2nd Perforating Gun
3rd Perforating Gun
Pressure Activated Firing Head
Ported Sub
Setting Tool
Plug

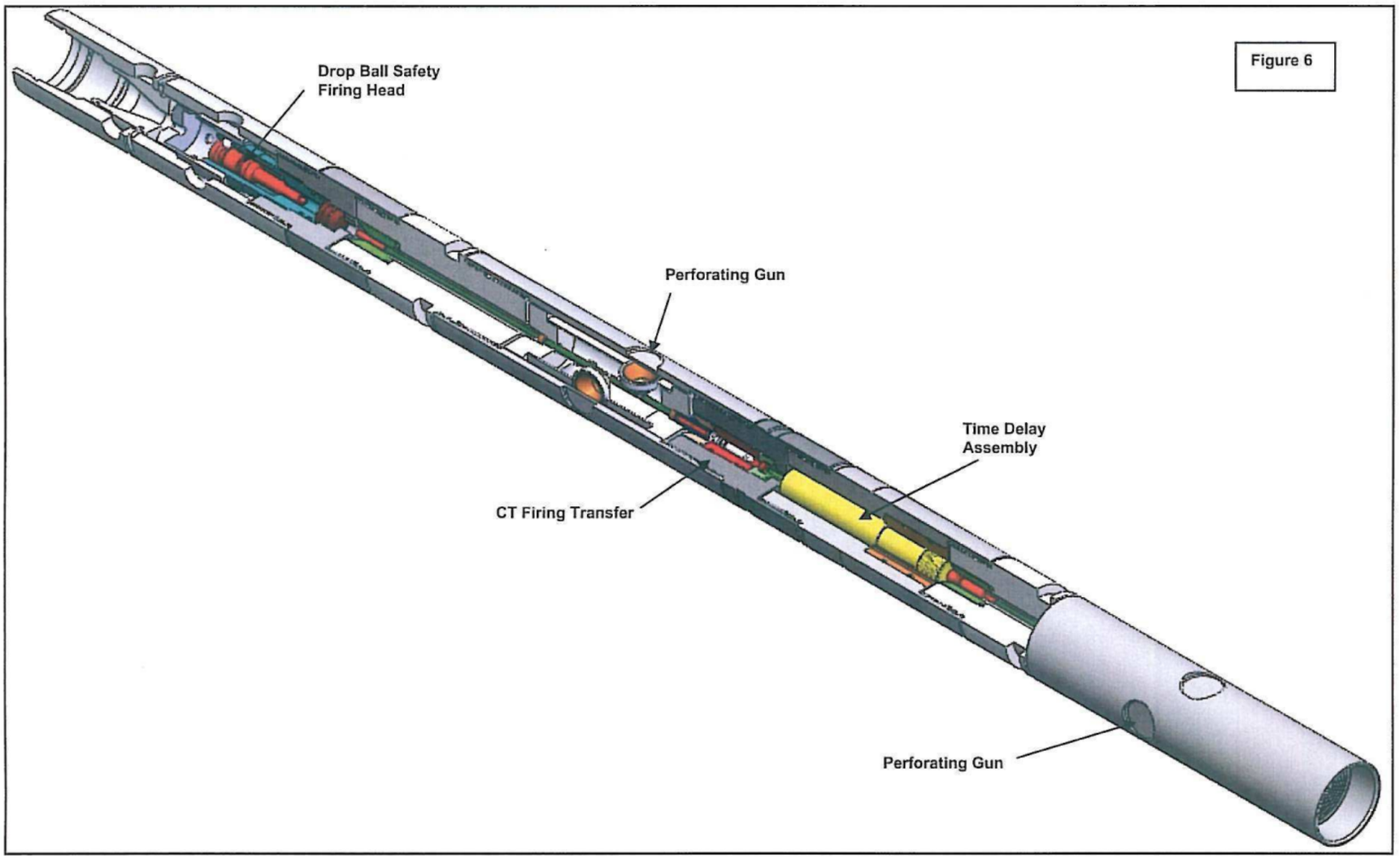
Figure 6
Drop Ball Safety
Firing Head
Perforating Gun
Time Delay
Assembly
CT Firing Transfer
Perforating Gun