Journal of Petroleum Science and Engineering 133 (2015) 192–200

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Numerical simulation of a patent technology for sealing of deep-sea oil wells using nonlinear finite element method

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ARTICLE INFO

Article history:
Received 25 November 2013
Received in revised form
28 April 2015
Accepted 12 May 2015
Available online 11 June 2015

Keywords:
Finite element
Thermal
Oil well
Melting
Seal
Thermite

ABSTRACT

For over 50 years bridge plugs and cement have been used for well abandonment, work over, and are still the material of choice. However the failures of cement abandonments using bridge plugs has been reported on many occasions, some of which have resulted in fatal consequences. A new patented product is designed to address the shortcomings associated with using bridge plugs and cement. The new developed tools use an alloy based on bismuth that is melted in situ using Thermite reaction. The tool uses the expansion properties of bismuth to seal the well. Testing the new technology in real field under more than 2 km deep sea water can be expensive. Virtual simulation of the new device under simulated thermal and mechanical environment can be achieved using nonlinear finite element method to validate the product and reduce cost. Experimental testing in the lab is performed to measure heat generated due to thermite reaction. Then, a sequential thermal mechanical explicit/implicit finite element solver is used to simulate the device under both testing lab and deep water conditions.

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1. Introduction

In this paper, a research program was implemented to assist BiSN-UK in developing a new technology that may help to eliminate the environmental pollution in the world due to abandoned oil wells. Government reports have warned for decades that abandoned wells can provide pathways for oil, gas or brine-laden water to contaminate groundwater supplies or to travel up to the surface. Abandoned wells have polluted the drinking water source for Fort Knox, Ky, USA, and leaked oil into water wells in Ohio and Michigan. Similar problems have occurred in Texas, New York, Colorado and other states where drilling has occurred. In 2008, gas from an abandoned well leaked into a septic system in Pennsylvania and exploded when someone tried to light a candle in a bathroom, killing the person, according to a 2009 draft report by the state's Department of Environmental Protection.

Bridge plugs are a mechanical plug that is used to provide a solid seal within a wellbore for plugging. Some bridge plugs are designed to be easily drillable in case the well is desired to be re-entered later. Bridge plugs are typically made of cast iron with duel slips with a sealing element between the slips.

The plug is designed to be set in a wellbore and then have cement set on top to provide a complete seal of the reservoir below. Oil wells with moderate to high-pressure gas use bridge plugs to seal the wellbore before cementing to reduce the chances of the pressurized water or gas to contaminate the cement (Working Document of the NPC, 2011). A cement retainer is a mechanical plug that can be set above a zone to be cemented. This type of plug is especially useful when plugging higher pressured zones that need to be squeeze cemented prior to plugging. Cement retainers are usually built from drillable material so will yield to later re-entry of the reservoir as needed. The cement retainer is set in the well in a method similar to that used for a bridge plug. Once the tool is set in the well, cement can be pumped through the plug to squeeze cement through the perforations or open-hole area below the retainer (Working Document of the NPC, 2011). Bridge plugs are manufactured from a number of materials that each has their own applicable benefits and disadvantages. For instance, bridge plugs made out of composite materials are often used in high-pressure applications because they are able to withstand pressures of 18,000–20,000 psi (124–137 MPa). On the other hand, their permanent use tends to lend itself to slippage over time due to the lack of bonding between the composite materials and the materials inside the wellbore. Bridge plugs fabricated out of cast iron or another metal may be perfect for long-term or even permanent applications, however, they don't adhere very well in high-pressure situations.

BiSN-UK is developing a new technology for sealing of oil wells

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http://dx.doi.org/10.1016/j.petrol.2015.05.010
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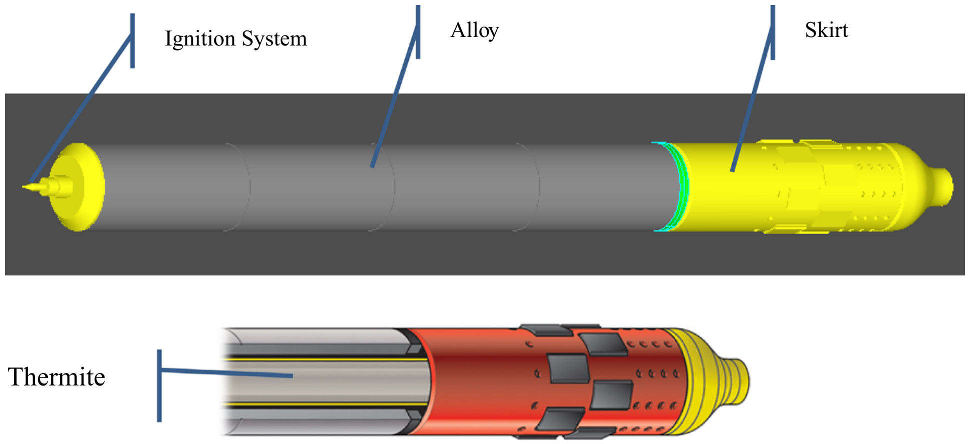

Fig. 1. BiSN new bridge plug technology.

under deep sea water. The new patent geometry is shown in Fig.2. The plug consists from three main components; ignition system, alloy jacket (bismuth alloy), skirt, and inner tube. The inner tube is filled with a thermite alloy mix, which is part of the ignition system. The plug is inserted in the center of the oil well. Then, igniting the thermite alloy mix generates enough heat to melt the alloy jacket. The melted alloy jacket fill the gap between the plug and the well's wall filling even any corroded surfaces or surface cracks. The melted alloy cools down and solidifies to keep the bridge plug in place under the pressure difference between deep-sea water pressure and gas pressure build up from inside the well. Bismuth is one of the few elements that expand on solidification and it is one of the reasons bismuth is selected for this patent design. The BiSN bridge Plug has been developed to be run on a standard wireline with no need for a workover rig. This greatly reduces the rig time needed to complete abandonments (P&A) or work overs. As well as providing a superior seal compared with bridge plugs, the costs are also significantly reduced due to the reduced rig time. Another advantage from using the BiSN bridge plug is the ability of repeating the sealing process after a number of years for assurance of sealing quality or its removal to use the oil well. The bismuth based alloy plug is also highly corrosion resistant and is not affected by Hydrogen Sulphide. The BiSN bridge plug offers a faster, superior and more cost effective solution to alternative products and bridge plugs on the market.

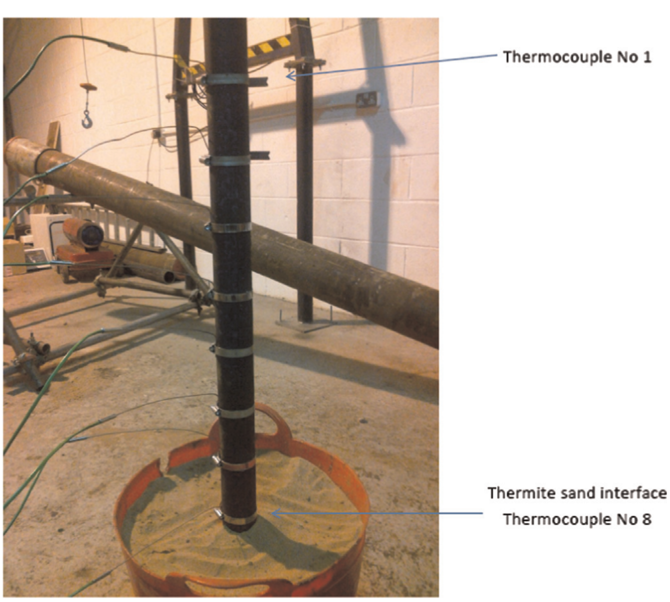

Fig. 2. Experimental setup of thermite heat reaction measurements.

The device is projected for sealing of oil well under seawater at depth up to 2000 m. An oil well may have a number of casings, which fit inside each other. Therefore, a well might start with an initial 20-inch diameter, drill a short distance, perhaps 200 ft, and then cement in a conductor casing and begin to drill a smaller diameter hole. Very common diameters for wells at the completion depth are 7 to 12 in. Slimholes are any well with less than 4.5 in. The device of 4.5 in. in diameter has been tested in the lab under atmospheric pressure environment but not at different mechanical/thermal conditions that exists at depth of 2000 m. Numerical simulation using nonlinear finite element method is used to validate the device functionality under harsh deep sea level conditions. Numerical simulations aim at achieving two objectives. First objective is to increase BiSN confidence in their mechanical design by validating its function at early stage of the development cycle and reduce the project cost by minimizing the number of prerequisite real field device tests. Second objective is to generate a virtual model of the sealing procedure that can be used in design optimization of the device.

BiSN developed a testing device that is capable of simulating the sealing process of oil well of size 4.5-inch case under test lab conditions. The testing device is capable of providing temperature distribution on the plug as a function of time, and provides an estimation of the critical pressure difference at which the bridge-plug starts to shift (after solidification). The test results show that the bridge-plug shifts at 4000 psi pressure difference. For the bridge-plug to pass the certification committee, it needs to hold pressure difference of 4000 psi for 5 min. The Sealing process consists of 4 discrete operations; thermite ignition, heat wave is travelling along the bridge-plug causing the alloy-jacket to melt. The alloy-jacket as it melts it shifts down along the plug under gravity and water pressure. Then, the alloy jacket solidifies and expands to seal the oil well. Two critical parameters should be investigated; the maximum stresses in the oil-well case due to the

Table 1
Material thermal properties.

Material property	Thermal conductivity (W/m K)	Density (Kg/m^3)	Specific heat (J/Kg K)	Phase transformation heat (KJ/Kg)
Sn–57Bi–1Ag	155.0	8720	188.28	46.5224
SA-335	39.5@21 °C 25.9@760 °C	7830	442@21 °C 969@760 °C	–

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