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JIPF
Journal International Perforating Forum

A Journal For The International Perforating Industry

Updates on Regional Symposia, Membership, Webinars and more

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Perforating Tunnel

Crushed Zone Evaluation:

A new measurement technique to quantify the hydraulic parameters of the crushed zone of a perforation tunnel in a Section IV Vessel test setup

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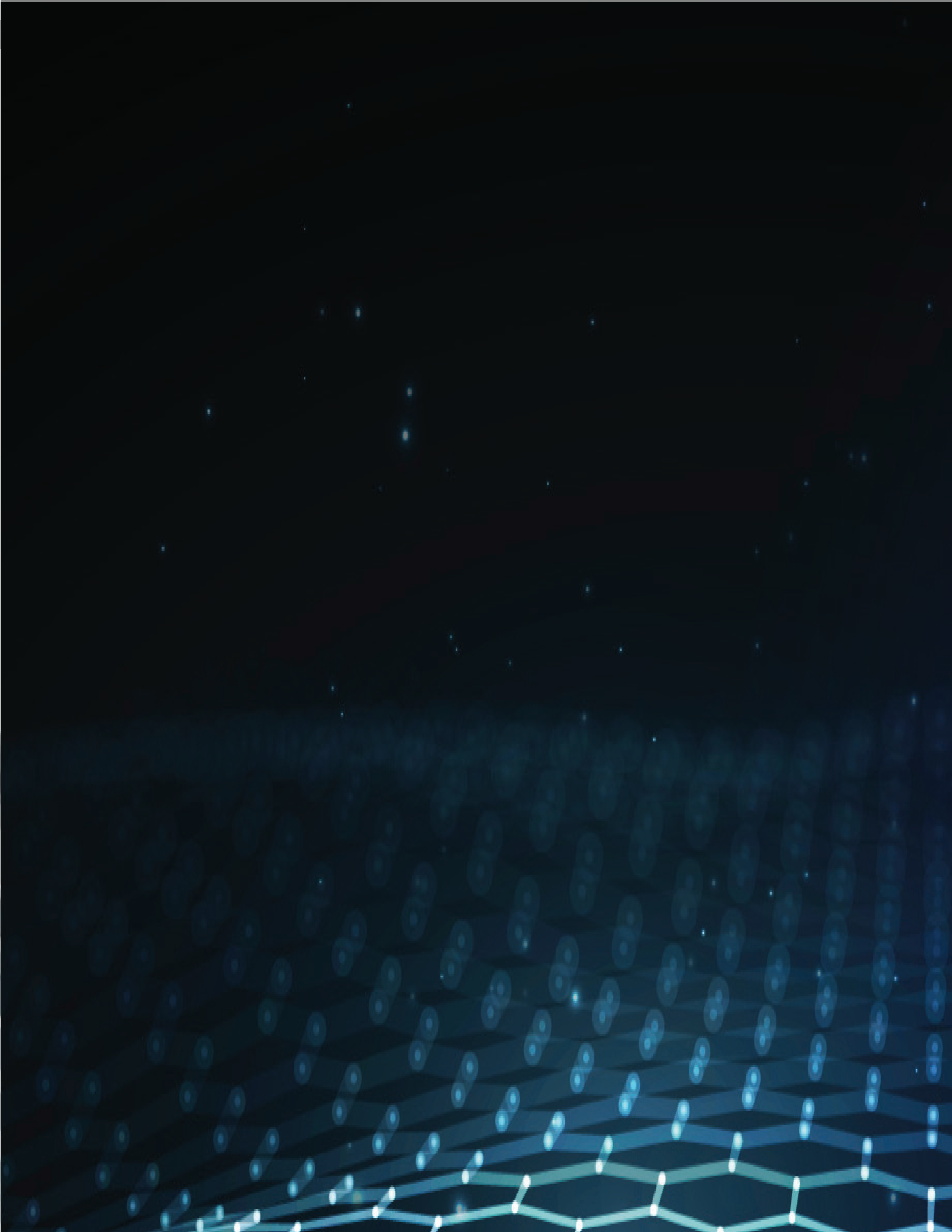

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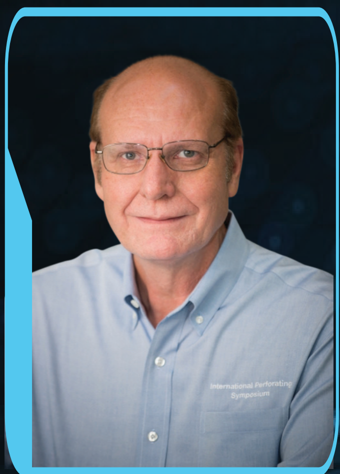
JIPF EXECUTIVE EDITORS' INTRODUCTORY MESSAGE

Technical journals such as the JIPF rely upon a strong Technical Editor staff. In this issue we will focus on our TE's. What motivates them, their areas of expertise, and how being a TE keeps them at the top of the industry.

What makes a good TE, besides the obvious deep technical knowledge? The willingness to do service for others and advance the industry.



John Carminati, EE JIPF

Benden Grove, EE JIPF

Sharing knowledge is rewarding and can spark ideas for the next major industry advancement. Being a TE also helps one become a better technical writer, develop an appreciation for article flow, and better understand the amount of detail necessary to effectively convey a message. It also provides insight into topics others believe are important.

We encourage you to hear from our TE's themselves in this issue. If you are interested in becoming a TE, please contact us at journal@perforators.org.

"Sharing knowledge is rewarding and can spark ideas for the next major industry advancement."

We are delighted to acknowledge our team of Technical Editors (TEs). These volunteers provide the essential peer reviews that contribute to the high technical quality of articles published in the JIPF.

Since the Journal's inception in 2016, we have had dozens of industry experts step forward to volunteer as TEs. 50 of those remain on the list (shown below), and 25 (highlighted) have reviewed articles that have spanned 5 issues of the JIPF.

Our team of industry experts represents a breadth and depth of experience – as consultants, and with operating, service, and manufacturing organizations. While all bring their perforating specialties to the table, many also have prior (or current) responsibilities outside of perforating. These additional perspectives bring further value to their TE role, to the JIPF, and to the perforating industry at large.

Achim Pabst	**Dave Ditty**	**Larry Albert**
Adam Dyess	**Dave Leidel**	**Larry Behrmann**
Alex Procyk	**David Atwood**	**Lian McNelis**
Andrew Werner	**David Ayre**	**Mark Brinsden**
Anthony Nguyen	**David Cuthill**	**Matthew Clay**
Bill Harvey	**David Smith**	**Meng Yu**
Bill Myers	**David Underdown**	**Niall Fleming**
Bob Haney	**Dennis Baum**	**Oliver Han**
Carlos Bauman	**Gerald Craddock**	**Parry Hillis**
Chip Levine	**Jacob McGregor**	**Rajani Satti**
Chris Chow	**James Barker**	**Ryan White**
Chris Hoelscher	**Jason McCann**	**Shaun Geerts**
Chris Sokolove	**Jason Metzger**	**Stuart Wood**
Christian Eitschberger	**Jim Gilliat**	**Thilo Scharf**
Clinton Quattlebaum	**Joern Loehken**	**Tim Andrzejak**
Dan Pratt	**John Rodgers**	**Tim LaGrange**
Dario Lattanzio	**Lang Zhan**	

IPFC BOARD OF DIRECTORS' MESSAGE

Mark Brinsden,
President, IPFC

John "JW" Segura,
Director, IPFC

Dear Colleagues,

I am hopeful that this year will see us return to some kind or normalcy following the impact of the COVID pandemic. However, with the Russian – Ukrainian war, supply constraints and rising inflation, we are in what has been coined a "new normal"!

I was encouraged by attending the Hydraulic Fracturing Technical Conference (HFTC) and the International Coil Tubing Association (ICoTA) earlier this year, to see both conferences well attended, with robust technical programs and exhibitions, hoping that this bodes well for our future. The IPS is planned to be held as scheduled this year on 26th -28th September.

Our IPFC and Industry is also in a new normal situation, with some regulatory requirements to satisfy and two new API documents to put into practice.

The first for the IPFC requires that we comply with export control of technology to sanctioned countries and persons. Needing us to put our presentations and documents in a controlled access environment, and limit access to non-sanctioned persons and entities. We plan to implement this by requiring membership of the IPFC, for a nominal fee, which should not be burdensome on those wishing to become members. There will be a mailout soon to explain this.

The second concerns the issuance of two new API documents. I wish to thank all those individuals and companies who have taken the time to participate in the revision and creation of these standards, your effort is truly appreciated.

The first API document is the long-awaited new 3rd edition of the API 19B published in July 2021 and heralds a new witness program for "Section 2" tests into stressed rock, which we expect will become the new standard for charge penetration comparison, rather than the existing "Section 1" system tests in concrete.

Additionally, a new practice, API 19PT (Perforating Tools), is expected to publish this quarter. It covers the reporting and validating of operational ratings of downhole perforating tools, by:

Alphie Wright,
Director, IPFC

David Atwood,
Director, IPFC

a) Providing well-defined operational ratings for functionality of downhole perforating tools as provided by the supplier/manufacturer, and
b) Defining levels of quality control for downhole perforating tools including validation requirements, acceptance testing, performance rating envelopes and service center requirements.

Finally, I cannot close without requesting that we all take extra effort for the health and safety of our co-workers and team members. Following the COVID downturn's resulting turnover of personnel, and the present upswing in activity, we must take extra care of our health and safety and that of our colleagues. In the last six months there have been two surface detonations, one of which resulted in a fatality. I hope that when the respective investigations are complete that we will be informed how they occurred and what steps should be taken to prevent reoccurrence.

Respectfully,

David Ayre
Vice President, IPFC
on behalf of the IPFC Board

David Ayre, Vice
President, IPFC

JIPF TECHNICAL EDITOR’ SPOTLIGHT

Have you ever wondered what makes a TE tick? Well, read on to hear many of their stories, in their own words.

David Atwood, P.E.

Principal Engineer
Schlumberger, retired

I am first and foremost a Mechanical Engineer, and a licensed Professional Engineer in 3 states. Most of my 42 year career was spent with two companies - TerraTek (11 years) and Schlumberger (23 years). In retirement, I try to stay active in all things perforating.

Being a Technical Editor for the JIPF and other organizations is an honor. I enjoy reviewing the work of colleagues, and in seeing where the next generation of perforating research will take us. My background allows me to provide a unique perspective on papers that JIPF publishes.

Chris Chow, Ph.D.

Owner
ProDuce Consulting, LLC

I've been involved with perforating testing from the beginning of my career and have seen the importance and value of lab tests as the basis for development of technology and software models. My role and interest as a Technical Editor is to continue the process of upholding sound practices in developing perforating technology.

Gary Craddock, Ph.D.

Senior Technical Advisor, Physics
Halliburton Jet Research Center

Gary applies computational tools, analysis, and testing in support of anything explosive or shock related. Prior to Halliburton, he has worked at SAIC, NumerEx, and Lawrence Livermore National Laboratory.

In his 40+ years of High-Performance Computing, Gary has researched Shaped Charges, Turbulence, Fusion, Computational Electromagnetics, and Pulsed Power Devices. He has over 20 refereed non-meeting publications, 15 SPE papers, 1 JPT paper, and multiple IPS/NAPS presentations since 2012. He is an author on 4 oil industry patents, and is a member of SPE and the American Physical Society.

Jim Gilliat

Perforating SME
Baker Hughes

44 year oilfield career including assignments in Canada, Asia, and the US. Employers included NL McCullough Wireline Services, Geo Vann/Halliburton, a small company that was acquired by Expro, and Baker Hughes (since 2013).

I currently serve as an SME in the Perforating Product Line. New technology has always fascinated me, and using it to do something "out of the box" has always served as a challenge and after 44 years in the business, it's what gets me to work in the morning.

Jörn Löhken, Ph.D.

Technology Research Manager
DynaEnergetics

Manages the technology research group and laboratories, including API RP19B Section II and Section IV test vessels. The TR group is focused on testing, research and the evaluation of new technologies for the perforating industry, and therefore actively follows and fosters new scientific contributions within the community. Since its establishment the group published several SPE papers and filed numerous patents.

Before joining DynaEnergetics, worked as a Geophysicist at the Leibniz Institute for applied geophysics on the topic of hydraulic fracturing for geothermal applications.

Jake McGregor, P.E.

Principal Petrophysical Applications Engineer
Halliburton Jet Research Center

Working in the field of perforating technology provides a wealth of interesting multidisciplinary engineering problems, which I enjoy being one of the many members of the community that works in this field. Participating as a technical editor for the JIPF allows me the rewarding experience of connecting with and contributing to this community.

Liam McNelis

Vice President R&D
DynaEnergetics

Having been involved in the perforating industry for 19 years, it is an honor and a privilege to review the research work and the technical innovations of my peers. I am motivated by research and product development where product safety is the main focus and also finding new ways to push the boundaries for product performance and system reliability.

Dan Pratt

Vice President Technology
Owen Oil Tools, retired

Recently retired following 42 years in the Oil &Gas Industry, the last 35 with Owen Oil Tools LP, a division of Core Laboratories. Principal experience was in the areas of design and manufacture of oil-field energetics / explosives products, primarily perforators. Served as Owen's Primary representative on the API Subcommittee on Perforating. Involved with the International Perforating Forum since its earlier inception as the CEA Perforating Symposia in 2007. Served as a Technical Editor for the Journal of the International Perforating Forum and was honored by the IPS in 2014 with its Industry Award.

Alex Procyk, Ph.D.

Upstream Editor
Oil & Gas Journal

Became deeply involved in perforating while employed as a completion engineer / production technologist for ConocoPhillips in what seemed like endless studies on perforation design, shooting conditions, clean-up, and inflow analysis for an offshore re-completion campaign. This involved many dynamic overbalanced / underbalanced / balanced tests with flowback analysis, crushed zone permeability measurements, effective perforation depth and diameter comparisons to prediction, gun swell evaluation, and so on.

Although thankless at the time, perforation technology eventually became a favorite completion topic. Combining this interest with current position as technical editor at Oil & Gas Journal provides an ideal fit for a JIPF Technical Editor.

David Underdown, Ph.D.

Senior Advisor
Chevron, retired

During my career I was Technical Editor for the SPE Monographs on Sand Control and Completion Fluids, and for the Journal of the International Perforating Forum. It was rewarding to be able to help authors with their technical papers, but it was very educational for me also.

Being a Technical Editor really helped me broaden my technology base as well as gain an appreciation for all the hard work being done by various individuals and companies. As a Technical Editor I learned that there are many ways to present technical information and data, and different writing styles which in turn helped me communicate my technical work better. Being a Technical Editor can be a lot of work, but it is very gratifying to help people share quality information with the rest of the technical community.

Lang Zhan, Ph.D.

Sr. Reservoir Engineer
Shell Development Oman

I see my primary role as a TE as evaluating perforating technologies from a reservoir engineer's perspective. I acquired perforating technology knowhow while working in Schlumberger's advanced perforating technology laboratory. Particularly, I gained understanding of dynamic underbalanced perforating through lab tests and modeling.

This helped me significantly after I joined Shell's unconventional technology team, where we recently demonstrated that perforating technologies are not limited to just creating perforation tunnels, but may have much wider applications to the industry. For example we've used dynamic underbalance perforating to provide benchmarking formation permeability results for reservoir modeling and field development (SPE 187063). Although the importance of perforating can sometimes seem invisible, there is significant opportunity to optimize perforating interval lengths and locations to reduce cost and improve the connection between hydraulic fractures and the wellbore. I hope my service as a TE can bridge perforating technologies and reservoir engineering to achieve a win-win situation for technology providers and asset companies.

Interested in becoming a TE? Send an email to journal@perforators.org. We'd love to hear from you.

CONTINUING EDUCATION/WEBINARS

In 2020 the International Perforating Forum (IPF) started a new initiative: The IPF Webinars. This initiative lead by the Continuing Education Chair of the IPFC has the mission to disseminate technical knowledge about Perforating to the industry professionals and students. A first webinar in 2022 is scheduled for June-July.

The webinar is an excellent way to connect to industry professionals and share knowledge.

We are looking for presenters for the 2022 Webinars. If you are interested in presenting one of our webinars, we would love to hear from you.

Also, we would love to hear from you, contact us at webinars@perforators.org and tell us more about the topic you would like to present.

Thank you,

Carlos Guedes.
Chair, IPFC Continuing Education

"We are looking for presenters for the 2022 Webinars. If you are interested in presenting one of our webinars, we would love to hear from you.

Also, we would love to hear from you, contact us at webinars@perforators.org and tell us more about the topic you would like to present."

YOUNG PROFESSIONALS

The last several years have come with unprecedented challenges to industry, the energy industry being no exception to that. There have been drastic reductions in workforces and therefore losses in experience within the perforating industry of oil & gas. Industry altering downturns and this loss of experience highlight the importance and need for an avenue to mentor the younger and future generations of employees. The IPFC sought out to develop a Young Professionals group for members within the perforating industry in 2016. The challenge presented to this committee was to try and develop opportunities for young professionals 35 and younger to connect and learn from the experienced experts of the industry. This specific challenge of passing on the lessons learned and hands on experience from the previous decades. Our industry is filled with unfortunate instances of learning lessons the hard way, it is imperative we do not forget these lessons and are able to retain this tribal knowledge as we advance forward.

The YP group would like to invite all individuals under the age of 35 to join and participate. The organization is focused on not only connecting current YP to senior members in our industry, but also as a link between the next generation of individuals and our community. This will include social gatherings, university outreach, and continuing education. It is the desire of the group to dedicate time and resources at future conferences to connecting the YP to the industry.

This group has unique opportunities to grow and expand to meet the demands and values of its members. We have faced many obstacles in the onset of this group, primarily being the fact that there are very few young professionals in the industry and geographically we are spread out over a large distance. This presents challenges with being able to organize events for people to attend. We are looking to work more closely with the Continuing Education portion of the IPFC to try and find more valuable opportunities to members of the industry. We highly encourage any interested to join in and participate and make this successful. We cannot do it without other YP and those who are able to mentor and provide valuable experience.

I personally have been involved with the IPFC since starting my career in Oil&Gas 10 years ago. I have found a lot of value on the society and its focus on perforating.

"I would also like to extend an invitation to any young person who would like to help step in as the chair of the YP group to contact us and let us know. Please send us an email at yp@perforators.org if you are interested. "
Thanks,
Shaun Geerts
Chair, IPFC YP

PERFORATING SAFETY

It has been a while since we have discussed Safety Concerns within our industry. COVID issues and travel restrictions have been the result of drastic changes over the past months and within our industry.

Over the past months there have been 2 perforating accidents that we are aware of.
One perforating accident was in Saudi Arabia where one person was seriously injured, and two others required medical attention. This was due to human error and was avoidable.

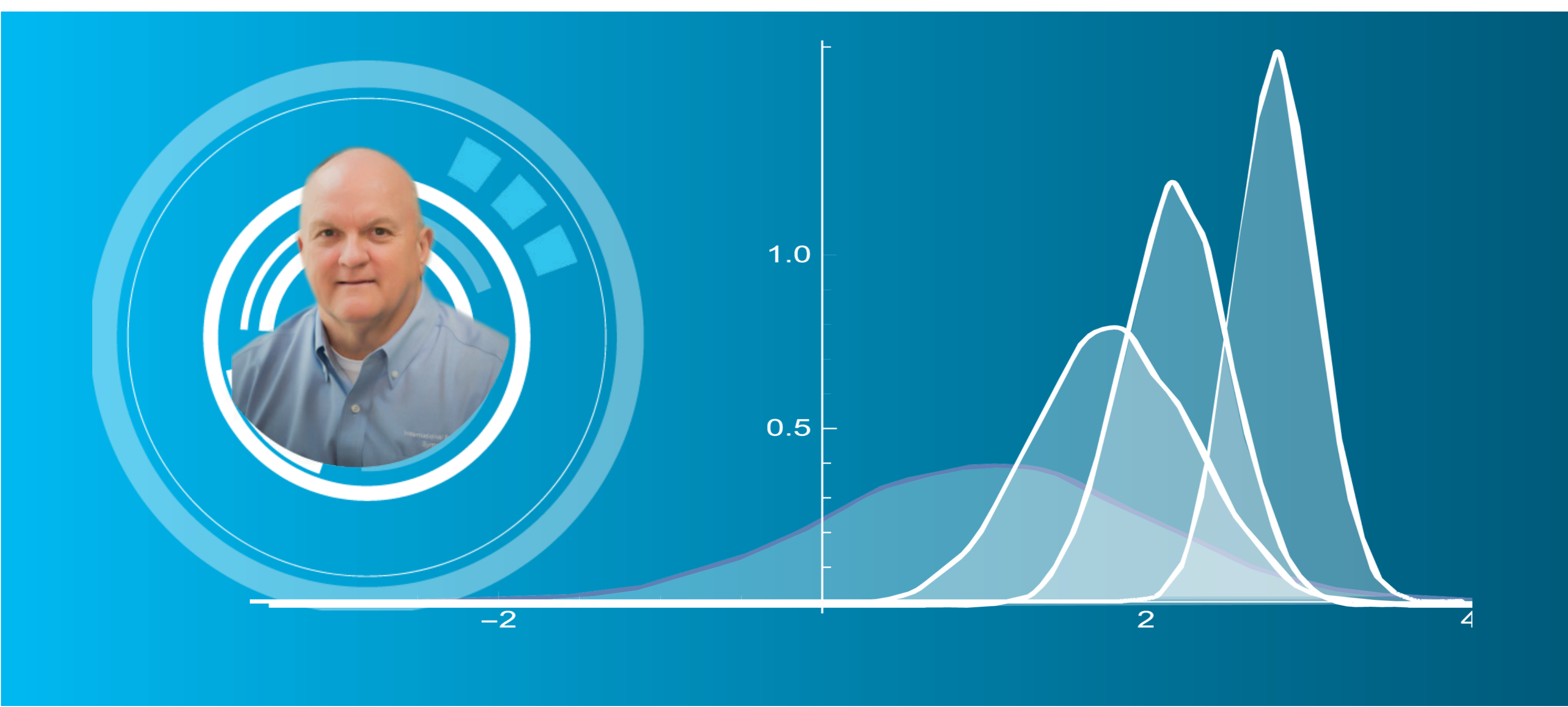
The other perforating accident was in Thailand with a fatality and others severely injured. Again, this was human error and avoidable.

When we receive the details of both incidents we will update the website with the information.

The API Recommended Practice 67 Third Edition (Oilfield Explosives Safety), to purchase and then download, is available on the API website (www.api.org). There have been many changes and inputs from the professionals involved in the Committees and Sub-Committees who worked extremely hard to provide as much valuable information and update with the latest material so that this information is available to all oilfield people within our industry. We recommend that all interested should purchase a copy.

Please submit incidents or near misses to our website at www.perforators.org and we will refrain for providing the name and company involved. Our responsibility is to report.

Stay Safe
Alphie Wright
Chair, IPFC Safety



PERFORATORS.ORG MEMBERSHIP

The IPFC (International Perforating Forum Company) BOD voted for launching a membership platform for our website. This came as a well needed solution to make our content exclusively visible to our members as our day and age requires our content to be protected from undesired web activity. This membership will put our forum along with other reputable organizations in the oil and gas industry who have been offering membership levels to professionals.

We encourage you to tap into our vast collection of resources and our extensive experience since its inception in 2008. As IPF's (International Perforating Forum) mission is to collect and exchange technical knowledge, we encourage our members to utilize these resources.

As a Perforators.org member, you'll receive:

- eligibility to attend conferences
- free access to online continuing education through our webinars
- free access to technical presentations from previous and current symposia
- a complimentary subscription to the Journal of International Perforating Forum
- a wealth of resources for networking, knowledge building and streaming content
- membership icon: use your IPF membership designation on email signatures, online profiles, or printed material such as resumes or business cards to promote your membership in IPF and your professionalism

David Smith,
Chair, IPFC Membership

REGIONAL SYMPOSIA

USA - IPS 2022

After a 2 years hiatus, planning for IPS 2022 is ready to kick off. The event is set for September 26-28 at the Moody Gardens Hotel and Convention Center in Galveston Texas. There are open slots for those that want to volunteer for any of the committees. We are looking forward to a great conference and excellent presentations. A high priority will be to increase E&P company participation, and ideas and suggestions to achieve this objective are welcome. Please put this in your calendar and consider actively participating by submitting a technical abstract, poster, volunteering, or both!

Larry Albert, Co-Chair IPS 2022
Matthew Clay, Co-Chair IPS 2022

LATIN AMERICA - SLAP

After two hard years for our industry, we are now happy to see how the activity is growing in many countries of the region. This increase in the activity also bring new technical challenges that need to be afforded. Un-Conventional production, Secondary recovery, and offshore production, are the activities growing in the region. It also brings many new players as operators and well service companies involved in the conventional fields.
Unfortunately, during these years, some members of the Latin American group left the industry or moved to another position or locations. We are now in the process of recruiting new members in order to re-build the group. Our goal is organize a symposium for the region no later than July 2023. As per the level of activity and its grow, the symposium will be developed in Argentina, Colombia, or Brazil.

Dario Lattanzio, Chair SLAP

ASIA PACIFIC - APPS

The previous APPS events were well attended and had healthy support from our generous sponsors and committee volunteers. We would like to ensure these symposia offer high quality content and be attended by the most interested delegates in the region as well as the global community. Easy, cost effective travel is key to this success.

The global pandemic situation is slowly improving for travel in the region however, as we learned last year, we must truly wait and see before planning another Asia Pacific Perforating Symposium. Even with the quarantines/restrictions reduced, anything less than completely unencumbered entry and departure will certainly have an impact on attendance for most any venue. Current oil pricing notwithstanding, we will look toward 2023-2024 for the next possible face-to-face symposium.

John P Davidson
APPS Committee 2011, 2013, 2018

MIDDLE EAST AND NORTH AFRICA - MENAPS

The last MENAPS was in 2016 in Muscat and was the third event in the region. The event was very well attended by the support o fPDO management after 2013 MENAPS and with an excellent contribution of our respected sponsors.

Due to the global pandemic MENAPS has not been carried over and has been missed for 5 years in the region. Since the constraints have been reduced and minimized the committee agreed to hold MENAPS 2022 in Cairo-Egypt in the second week of November 2022. The exact time and place will be announced soon based on the agreement with the hosting country policy and along events in the region.

Hanaey Ibrahim, Chair MENAPS

ARTICLE: PERFORATING TUNNEL CRUSHED ZONE EVALUATION: A NEW MEASUREMENT TECHNIQUE TO QUANTIFY THE HYDRAULIC PARAMETERS OF THE CRUSHED ZONE OF A PERFORATION TUNNEL IN A SECTION IV VESSEL TEST SETUP

Perforating Tunnel Crushed Zone Evaluation: A new measurement technique to quantify the hydraulic parameters of the crushed zone of a perforation tunnel in a Section IV Vessel test setup

Authors:

Jörn Löhken, DynaEnergetics Europe GmbH

Yannick Forth, Ruhr Universität Bochum, University of Liège

Liam McNelis, DynaEnergetics Europe GmbH

Bernd Fricke, DynaEnergetics Europe GmbH

Denis Will, DynaEnergetics Europe GmbH

Davood Yosefnejad, DynaEnergetics Europe GmbH

Jörg Renner, Ruhr Universität Bochum

Yannick Forth, PhD Student at the University of Liège. Yannick Forth holds a Bachelor's and Master's degree in Geosciences with focus on Geophysics. He wrote his Master thesis in cooperation with R&D section of DynaEnergetics GmbH on the determination of hydraulic parameters in laboratory tests. Before starting his current position as a PhD Student in Applied Geophysics in Liège, Yannick joined Solexperts GmbH as a Geoscientist working in the field of in-situ stress testing. Prior he shortly worked as a R&D Geoscientist at DynaEnergetics on developing a permeability measuring method.

Denis Will joined DynaEnergetics in 2013 as Flow Lab Technician for the petrophysical and flow test laboratory and is currently responsible for the research laboratory facilities, where he specialized on high pressure and high temperature equipment. Prior to DynaEnergetics he worked 20 years for Schroeder and Sons, Troisdorf, Germany.

Denis obtained a German explosives license in 2017 and is Co-Inventor on several US patents.

Bernd Fricke, R&D Engineer, joined DynaEnergetics in 2015 as Flow Lab Engineer for the petrophysical and flow test laboratory and is currently assigned to the company's intellectual property department. Prior to DynaEnergetics he worked for Balance Point Control a daughter of Superior Energy Services in Celle, Germany as Wireline Engineer for geophysical well logging, perforating and pipe recovery. Bernd is a lecturer for explosive safety in oilfield operations and he holds a Master's degree in economic geology from the Clausthal University of Technology and a Bachelor's degree in geoscience from the Leibniz University Hannover, both Germany. He is Co-Author in several SPE Publications.

Jörn Löhken, Technology Research Manager, joined Dynaenergetics in 2011 as an R&D Geophysicist, where he was responsible for product development and numerical simulations. In 2018 he assumed the role as manager of the technology research group and the research laboratories. Jörn is a member of SPE. He is an inventor on several oilfield patents as well as author and co-author of several SPE papers. Before joining DynaEnergetics, he worked as a researcher at the Leibniz Institute for applied geophysics on the topic of hydraulic fracturing for geothermal applications and at KMS Technologies on electromagnetic exploration methods. Jörn holds a Diploma and PhD in Geophysics from the University of Cologne.

Liam McNelis, Vice President of Research & Development, joined DynaEnergetics in 2003 as an R&D Engineer. In 2009, he assumed the role of R&D manager at DynaEnergetics and was promoted to R&D Director in 2018. He is currently responsible for the global R&D activities within the company. In 2004, he obtained a German explosives license, is a member of SPE and is an inventor on several oilfield patents. Previous to joining DynaEnergetics, Liam for Aixtron AG, as a process engineer for CVD equipment for the semiconductor industry. He holds an engineering degree from the University of Dublin, Trinity College.

Davood M .Yosefnejad, Reservoir/Flow Lab Engineer in the R&D Group joined DynaEnergetics Europe GmbH in 2017. He is responsible for numerical CFD simulation and ballistic testing of DynaEnergetics products under the real condition, such as Section IV tests. Additionally, he led several research and development projects. Davood has a Bachelor’s and Master’s degree in Reservoir Engineering from the Science and Research University of Tehran (Iran) and joined the Geoscience department at the University of Bonn, Germany in 2013 as a Research Assistant (PhD student). Davood holds a PhD degree in Geoscience form the University of Bonn and is Co-Authors of several publications.

Executive Summary

As part of conventional API 19B Section IV tests, typically a steady state flow is established to evaluate the hydraulic properties of the perforated rock. Test setups utilizing radial or axial flow in combination with accurate measurements of the tunnel geometry allow the calculation of parameters, like the CFE value, which quantify the impairment of the hydraulic parameters of the rock close to the perforation tunnel (crushed zone).

In this study we present the test results of an alternative measurement technique used to evaluate the crushed zone of a perforation tunnel. In this method the wellbore fluid pressure and consequently the flow rate into the rock is periodically altered. By varying the period of the signal change, it is possible to influence how deep or far the fluid enters the rock through the perforation tunnel. Short periods are preferably used to evaluate near perforation tunnel characteristics, while large periods are suitable to investigate the overall flow properties of the entire rock target.

The flow and pressure data were recorded for perforated rocks taken from Section IV tests and analyzed in cooperation with the Ruhr University of Bochum/Germany.The results are also compared to conventional Section IV tests, Computational Fluid Dynamics (CFD) Simulations thereof and evaluations of the crushed zone areas using the scratch test method.

Introduction

Shaped charges are commonly used to establish a flow path between the cemented wellbore and the reservoir. Depending on the completion type, the reservoir conditions and its geology, different parameters of the perforations are of importance to the reservoir engineer in charge of the well completion design. Features such as the perforation entrance hole diameter or its variation with clearance can easily be measured in surface tests. For penetration evaluation on cement, tests as described in API Recommend Practice 19B Section, section 4.1 (Section I tests) are still widely used although they do not represent real downhole conditions. A more realistic condition is already given by Section II tests (API RP 19B, section 4.2), which covers tests on stressed natural rock.

These tests provide already a much more suitable measurement of the penetration, as they have shown that the penetration is strongly depending on confinement and stress (Behrmann and Halleck, 1988) and on the rock strength. Values determined in such tests are normally much lower than concrete values, but much closer to the performance downhole.

On the other hand, Section II tests still neglect the effects of pore pressure, as well as wellbore dynamics, due to a lack of wellbore pressure. While the pore pressure directly affects the rocks resistance to a perforating jet (Harvey et al. 2012), the complex interaction of the wellbore pressure with the pore pressure during the highly dynamic process of a perforation shot significantly controls the geometry and clean-up of the perforation tunnel (Grove et al., 2011, Haggerty et al. 2012). Especially the latter one is of essential importance for the hydraulic characteristic of the perforation, namely its ability to conduct the flow from the reservoir into the wellbore.

The optimal method to evaluate the performance of shaped charges is therefore a Section IV test (Fig. 1), as described in API RP 19B, section 4.4. In addition to Section II tests, they include pore and wellbore pressures and even more important, they allow a measurement of the hydraulic properties of the perforation tunnel by flow measurements before and after the perforation shot.

Based on this data, hydraulic and geometric parameters can be measured for a given reservoir condition and provide the best possible forecast of the completion design performance.

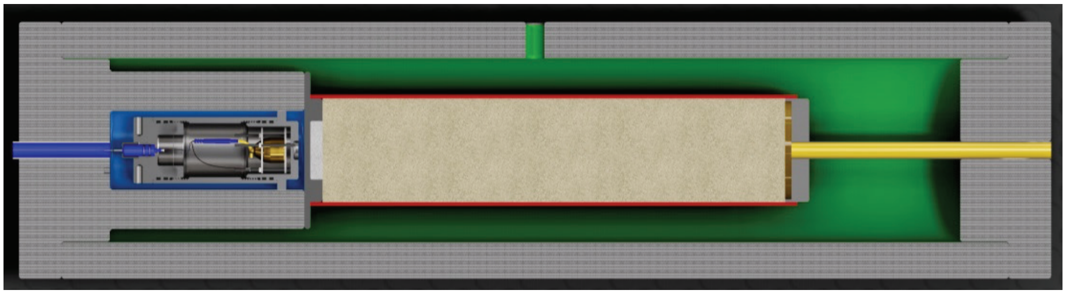


Fig. 1: Schematic of a Test Vessel for Section IV tests. The core is protected by a rubber sleeve (red) and subjected to a uniform hydraulic pressure. On one end it is covered by a flow distributor, which is used to transfer a pore pressure to the rock (yellow). On the opposed side a wellbore chamber (blue), hosting a perforation gun module, is located.

The importance of flow testing can be illustrated based on Fig. 2. In this example a 22.7 g shaped charge was shot into a Berea core with sufficient dynamic underbalance, which led to a visually clean tunnel.

Despite the underbalanced conditions, due to the shock wave traveling with high amplitudes through the rock, the pore space close to the tunnel wall will still be impaired or damaged (Fig. 3). The hydrocode simulation of such a perforation illustrates this compression of the pore space. This leads to a zone of significantly reduced permeability, which is often for simplicity assumed to be of constant thickness (Fig. 2, right), although this zone will vary in compression and geometry (Fig. 2, middle).

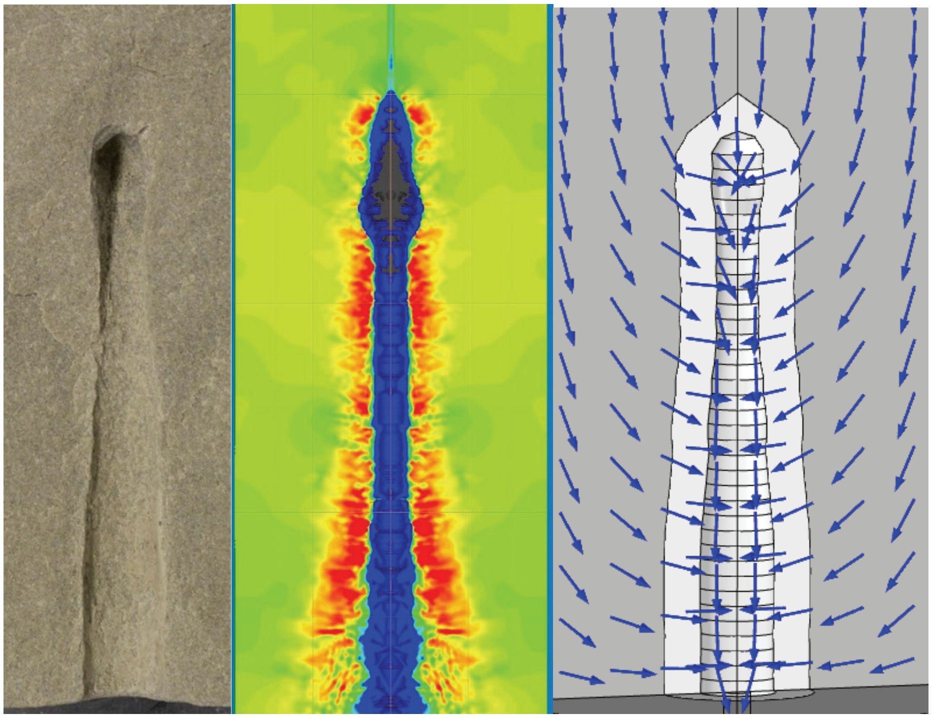


Fig. 2: Clean tunnel geometry on Berea rock (left), hydrocode simulation of the perforation and the surrounding pore compression with red being the highest (middle), and a CFD model of binary permeability model around the perforation tunnel (right).

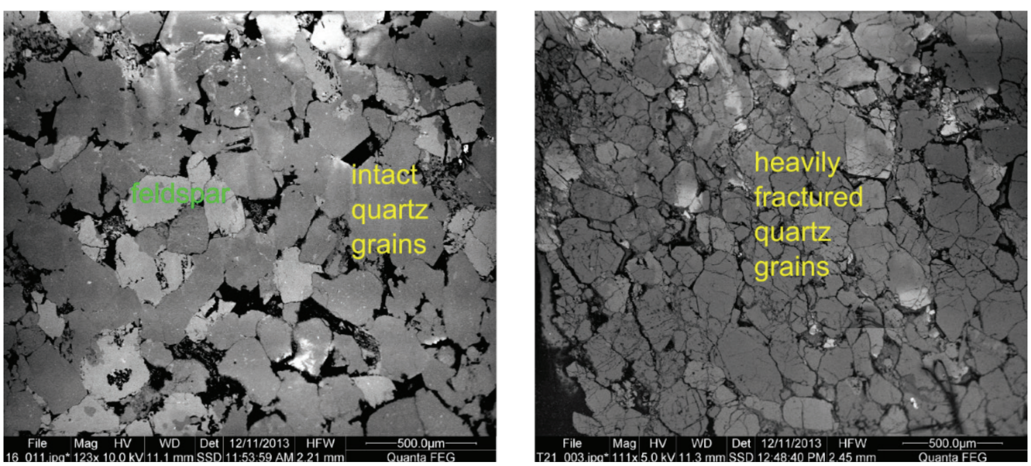


Fig. 3: Comparison of intact rock grains (left) and crushed grains at the tunnel wall (right). Picture taken from an internal study.

For the quantitative assessment of the crushed zone and the impairment of the hydraulic properties of the core, the API RP 19B (American Petroleum Institute, 2021) suggests several methods, which includes the calculation of productivity index (PI) and productivity ratio (PR) values, respectively and the derivation of the core flow efficiency (CFE).

The Productivity Index (PI) is given as the ratio of the flow rate and the pressure drop over the perforation, normalized to the viscosity of the fluid. For normal Darcy flow this will be constant for varying pressures, for non-Darcy flow additional terms must be considered. McGregor 2018 discussed using the Forchheimer equation to account for non-linear inertia effects or changing pore and fluid properties due to pressure changes. Especially for high flow rates and pressure differentials, respectively, non-linear effects can be observed leading to reduced apparent permeabilities of the rock at these conditions.

The Productivity Ratio (PR) is a first marker for the performance of perforation. It can be simply deduced from the ratio of PI value after the perforation shot and the pre-shot PI value. If the flow after the perforation is increased compared to the pre-shot value, the PR is greater one and vice versa. Depending on the setup of the flow measurement, also a convergent flow production ratio (CFPR) can be calculated. In this case the pre-flow was not conducted using an open face plate of identical diameter as the core, it was rather made utilizing a steel plate having a restricted outlet, e. g. a central machined hole of the anticipated diameter of the perforation.

PR and CFPR values can strongly vary on different rocks and will depend on the perforation depth, and the core length respectively. They are mainly useful to compare different charges under identical conditions and rocks.

Another assessment of the impairment of the rock permeability is the calculation of the CFE (Core Flow Efficiency), which compares the measured flow rate after the shot with an ideal flow through a tunnel of identical geometry, but without any impairment of the tunnel wall. This reference flow can be determined either analytically in case of radial flow or by means of Computational Fluid Dynamics (CFD) calculations (Fig. 4). By definition, this value ranges between zero and one, and can be used to derive parameters that can directly be used by perforation and well inflow models as an input (e.g., WEM). Fig. 4 shows such a simulation and how the derived model is applied for well inflow models.

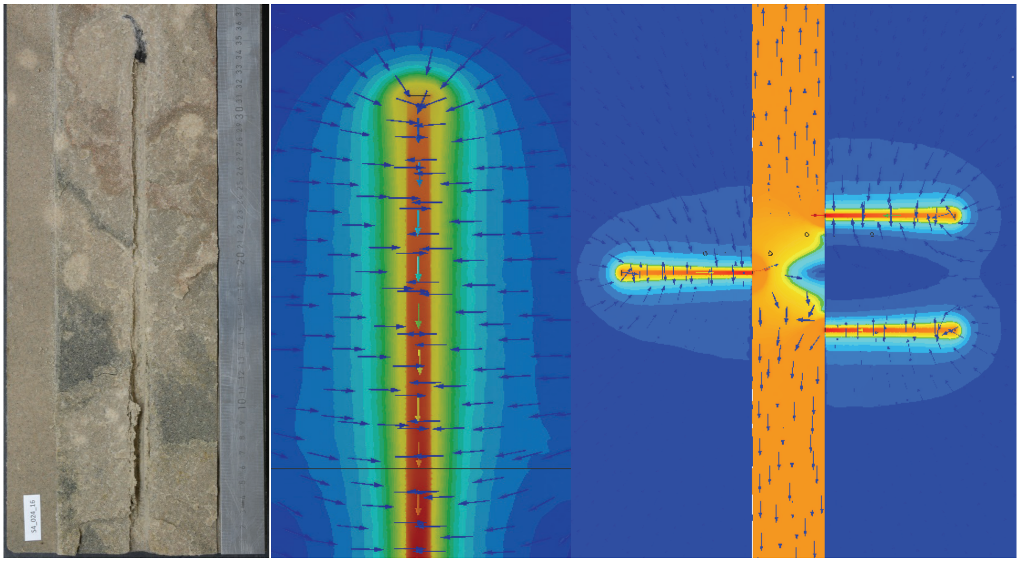


Fig. 4: Based on the tunnel geometry (left) a simplified model can be assumed for CFD simulations (middle) to determine the hydraulic parameters. Using these parameters as an input, more complex flow models, which cover several perforations in the reservoir, can be calculated (right).

The CFE is preferably measured by a radial flow setup, which puts emphases on the tunnel wall properties. Axial setups can be used as well but might lead to different results since the rock grains are affected differently by the perforation at the tip compared to the side wall. Also, a different cleanup of the tunnel due to the dynamic underbalance or static underbalance will lead to different tunnel volumes (Harvey et al., 2011, Haggerty et al., 2012) and distributions of the crushed zone depending on the flow setup.

Certain challenges for the measurement of the CFE were discussed by Grove et al. 2011, which are particularly the accurate and well-defined measurement of the effective tunnel geometry, namely its effective length and the diameter of the tunnels, when the crushed zone is deleted or removed. New procedures to minimize these influences were introduced by Grove et al. 2012 and Grove et al. 2013. Still the values of these parameters will depend on the engineer, who conducts the measurement, as determination of the crushed zone is subjected to an individual interpretation of rock strength. Heiland et al. 2009 measured the rock strength around a perforation tunnel using a scratch tester, showing that the rock strength continuously increases from zero to the original rock strength. While a brush might have a fixed maximum UCS value at which it may remove crushed rock, the strength of the crushed zone may differ based on the strength of the host rock. Therefore, especially for harder or high UCS rocks, the crushed zone may still have several thousand psi of strength and will not always be removed. Consequently, even if the measurements were taken carefully, different CFE values can be expected based on the operator, the used tools, and the rock itself.

Notwithstanding the difficulties in the determination of an accurate CFE, it is essential for the evaluation of the crushed zone and of high value for the operator. Firstly, to be able to accurately simulate the completion design, but also as a measure, if the perforation was cleaned-up by underbalance or Dynamic Underbalance (DUB) to its maximum potential, and therefore in evaluating if the amount of chosen DUB was optimal to clean up the perforations effectively.

The previously presented parameters were all based on flow measurements alone or in combination with geometrical measurements, which were used to deduce crushed zone properties. As already mentioned earlier, Heiland et al. 2009 presented direct measurements of the crushed zone using a scratch tester and combined them with thin section analysis to deduce the geometric and hydraulic properties of this zone. It became clear that the impairment changed gradually, rather than with a discrete jump. While scratching the rock can be implemented in the routine of Section IV tests, thin section analysis is very time consuming and needs additional assumptions about the correlation of the permeability with the pore space structure.

In the work presented here, we want to introduce a new method to evaluate the crushed zone permeability directly by means of sinusoidal flow measurements with different periods. This technology was so far employed in wellbores for reservoir and fault system characterization (Renner and Messar, 2006, Cheng and Renner, 2017), as well as for rock samples (Song and Renner, 2007). It is based on diffusion equation which was derived from the Darcy law and continuity equation, which allows for a depth correlation of the measured value as a function of the frequency of the pressure signal.

In analogy to other geophysical exploration methods like seismic or electromagnetics, the depth of investigation depends on the period of the signal in case the diffusion part of the governing equation cannot be neglected. A good example for the correlation is the effect of temperature variations on the soil temperature. Daily variations between night and day only alter the temperature of the soil in the upper inches, while seasonal variations affect several feet of the soil temperature. The longer the period, the deeper the penetration and the shorter the period the shallower the influenced volume. The same is valid for flow measurements. If the pressure differential is only applied for a very short period and reversed immediately, the fluid will not flow through the complete core, and is limited to a shallow region close to the inlet, while longer periods will allow the fluid to occupy the complete core.

Fig. 5 illustrates how this can be utilized practically in Section IV tests. In this example the pressure in the wellbore chamber is recorded, while an accurate syringe pump quickly pushes and sucks fluid in and out of the chamber and the associated rock. With an external function generator, the frequency of the signal as well as its shape, in this case a sinusoidal shape, can be controlled. This measurement can be repeated for several frequencies, right after the normal flow measurement, which was made to determine the post-shot flow. There is no need to remove the core, nor to decompress it, pointing to another possible advantage of this method - the permeability is measured under in-situ pressure conditions.

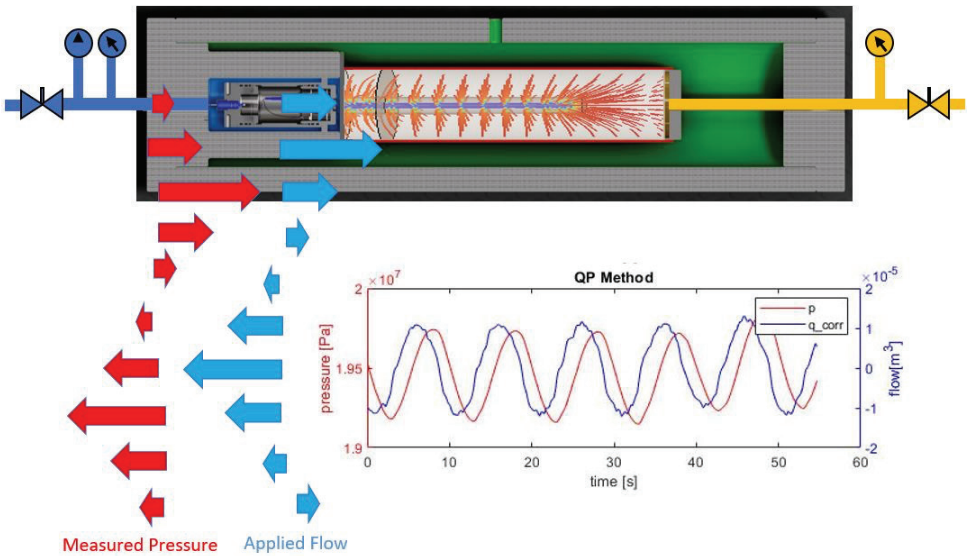


Fig. 5: Principle of periodic pumping in a section IV test vessel

The work presented in this paper builds upon previous work of the institute of geology, mineralogy, and geophysics of the Ruhr University Bochum/Germany, especially on the report of Forth & Renner, 2019.

In our paper we will compare the periodic pumping tests with two alternative methods: the measurement of the crushed zone with the scratch testing method as describe by Heiland et al. 2009 and a CFD simulation of the post flow under the assumption of a crushed zone of constant thickness and constant, impaired permeability.

Test Setup

For the tests an axial test setup was used. The cylinder sides were isolated by a rubber hose from any inflow or outflow, which equates to a no flow boundary condition. The cylinder top was connected over its full surface area to a pore pressure and the cylinder bottom to a wellbore pressure, so the that the dominant flow direction will be parallel to the axis of the core and the boundary conditions for the top and bottom are the pore and wellbore pressure values, respectively.

To conduct the tests, the configuration of the Section IV test vessel was slightly modified, and a new high speed syringe pump was used instead of the high-pressure piston pumps. In the standard setup a hydraulic pore pressure line connects the high-pressure piston pump and an accumulator with the vessel and further with the flow distributor of the pore pressure. Close to the entrance of the pore line into the vessel, a high-speed pressure gauge is installed on this line to record the pore pressure data. Newly installed was a shut-off valve between the piston pump and the high-speed pressure gauges, close to the gauge (Fig. 5), to cut the connection to the pump and the accumulator. This reduces the fluid volume of the system during the periodic pumping test. A similar modification was made to the wellbore pressure line. Additionally, a special syringe pump was installed between the shut-off valve and the pressure gauge via a T-fitting. After the desired wellbore and pore pressure were reached, the shut-off valves were closed and only the syringe pump remained in the system.

With this setup the pressure gauges of the vessel could be utilized in addition to the sensors of the syringe pump. A recording of the pore pressure, for example, allows for a determination if the flow has already entered the complete core or only a part of it.

The analogue input of the control unit of the syringe pump was connected to a function generator, which created a sinusoidal signal over a given voltage range and with the specified frequency (Fig. 6). The oscillations of the pressures were run with frequencies of 0.1 – 1.5 Hz. At higher frequencies the voltage range had to be reduced to account for the limitations of the pumping speed of the pump, hence only small amplitude could be applied.

A PC was used to record the pressure and flow values measured by sensors of the pump. The time on the Section IV PC and the measurement PC were synchronized to allow for the usage of sensor data of all gauges.

Fig. 6: The control unit of the syringe pump was connected to a PC, which recorded the measured flow rates and pressures. A function generator on the left was attached to the input of the control unit to regulate the flow rate.

For the calibration of the system the compressibility of the fluid as well as the fluid volume in the pressure lines and wellbore chamber must be known. These can either be measured separately and the overall system response deduced, or it can be calculated from 'direct' measurement in the system. For this purpose, the wellbore is closed with an unperforated casing plate, and pressure oscillations made and analysed. This directly provides the information on system compressibility without knowledge of fluid compressibility. In cooperation with the University of Bochum both methods were tested and provided similar values. For details see Forth & Renner, 2019.

A periodic flow measurement was made before the shot right after the pre-shot flow measurement for each test and a second measurement was conducted after the post-shot flow measurement.

Theory

The determination of the hydraulic properties from a periodic pumping test is achieved by applying an oscillating pressure signal on one face of a sample. The pressure and flow signals in front of the sample are recorded. Thereafter they are corrected to account for the compressibility of the fluid in the wellbore reservoir, which reduces the flow into the core (Forth & Renner, 2019). By calculating the phase shift between the flow maxima and pressure maxima, as well as ratio of the flow and pressure amplitudes (amplitude ratio), a comparison of the measured data to analytical solutions of the underlying diffusion equation can be made, which leads to the deduction of the hydraulic parameters.

A common practice is to start with Darcy's law which represents a convenient equation to calculate the permeability k, where q, p and η denote flow, pressure, and fluid viscosity. For an isotropic media it can be given by:

$$\vec{q} = -\frac{k}{\eta}\vec{\nabla}p \qquad (1)$$

First determined empirically from experiments by Darcy, the law was later derived from the Navier-Stokes equations (Whitaker, 1986). Nevertheless, the description of processes is limited to simple geometries, neglects storage properties, and disallows a time dependent consideration. As the Navier-Stokes equations form the governing model for fluid mechanics, an elaborate solution can be found.

Starting from the conservation of mass of fluid flow the continuity equation describes the transient change of fluid stored per unit volume of rock ζ and the corresponding specific discharge/flux

$$\frac{\delta\zeta}{\delta t} = -\overrightarrow{\nabla}\cdot\vec{q} \qquad (2)$$

With the use of the specific storage capacity β_s, a ratio of ζ and the pore pressure p, poroelastic effects can be considered (Bernabé et al., 2004; Bernabé et al., 2006).

$$\zeta = \beta_s p \qquad (3)$$

Applying Darcy's law to the continuity equation creates a time and place dependent description of pore pressure, the diffusion equation:

$$\frac{\delta p}{\delta t} = \frac{k}{\eta\beta_s}\nabla^2 p \qquad (4)$$

By solving the diffusion equation using the appropriate initial and boundary conditions, the determination of the hydraulic properties of the crushed zone is possible.

In the field of hydraulic behavior of rocks, two parameters are used for this characterization, a transport and storage property, which are in our case permeability and storativity S.

The latter one is given by

$$S = \beta_s \rho_f g L \qquad (5)$$

With L being the sample length, ρ_f the fluids density, and g the acceleration due to gravity.

To evaluate the two parameters with periodic pumping tests in a Section 4 setup, the given boundary conditions must be considered in the analytical solution of the diffusion equation. Due to the different dominating flow regimes, individual solutions are needed. The simplest approach is a cylindrical sample located axially between two reservoirs. It was introduced by Fischer 1992, Kranz et al., 1990 and Song & Renner, 2007.

This model was used in our study for an initial comparison of pre and post shot measurements. Due to the simple geometry, only a description of the complete sample is possible, not distinguishing the crushed zone, but therefore it is comparable to pre and post flow Darcy experiments.

A solution of the diffusion equation for a cylinder with a central bore can be found in Renner and Messar 2006. For further investigation of the crushed zone properties Forth & Renner, 2019 modified this solution and included two cylindrical zones around the bore, representing the crushed zone and the virgin rock. It was derived for a no flow boundary condition on the outside. As Forth & Renner, 2019 still observed some difficulties to match measured data, which might be related to the fact that the bore extends over the complete length of the cylinder, this model will not be further discussed in this paper.

The underlying theory of the work presented in this paper was described in detail by Song and Renner, 2007, Renner and Messar, 2006 and Forth & Renner 2019 and is suggested for further reading.

The application of a set of frequencies enables the investigation of the crushed zone thickness. Furthermore, periodic signals also contribute a variety of advantages in data processing:

- detection of a signal despite noise possible using a Fourier transformation,
- small pressure amplitudes are applicable, avoiding non-Darcian effects
- fast procedure with no need for a long equilibration
- and the variation of applied frequency and amplitude opens the possibility of different exploration objectives without a change of setup and long observation periods

Results

During the research project, three different rock types were tested. For this publication, we chose the example of the frequently used Berea Sandstone rock to illustrate the new method. Other tests were performed on Bentheimer Gildehaus Sandstone and Roter Bunt Sandstone.

For this test a Berea sandstone was subjected to 500 bar overburden pressure and 200 bar pore and wellbore pressure. The core was installed parallel to the bedding direction. The average permeability of the core was 108 mD measured only in the parallel direction. After the pre-flow measurements the rock was perforated using a 22.7 g deep penetrating shaped charge. An axial test setup was used for all tests. The flow measured after the shot was 15% higher than that before the shot, resulting in a PR of 1.15.

Figure 2 shows the perforation tunnel right after the shot and after the loose debris was removed with a soft brush. Due to a DUB of approximately 100 bar, the tunnel was cleaned up nearly over its entire length (Table 1). Fig. 7 displays the measured volume changes and pressures, which were recorded pre- and post-shot for this shot at a pumping frequency of 0.2 Hz or a period of 5s respectively. Further exemplary data for 0.5 Hz and 1 Hz are shown in the Appendix (Fig. A- and Fig. A-). Due to the pumping speed limitation of the syringe pump, only small pressure amplitudes of approximately 100,000 Pa (14.5psi) were possible, leading to injected volume of less than 1 ml. As can be seen in the plot, lower frequency oscillations as well a general noise was present in the data. To account for that, the raw data were manually processed, and transformed into the frequency domain using a Fast Fourier Transformation. The resulting amplitude ratio of the volume flux and the pressure, as well as the phase shift between volume flux and pressure changes are shown in Fig. 8 for all frequencies that were used in our test program.

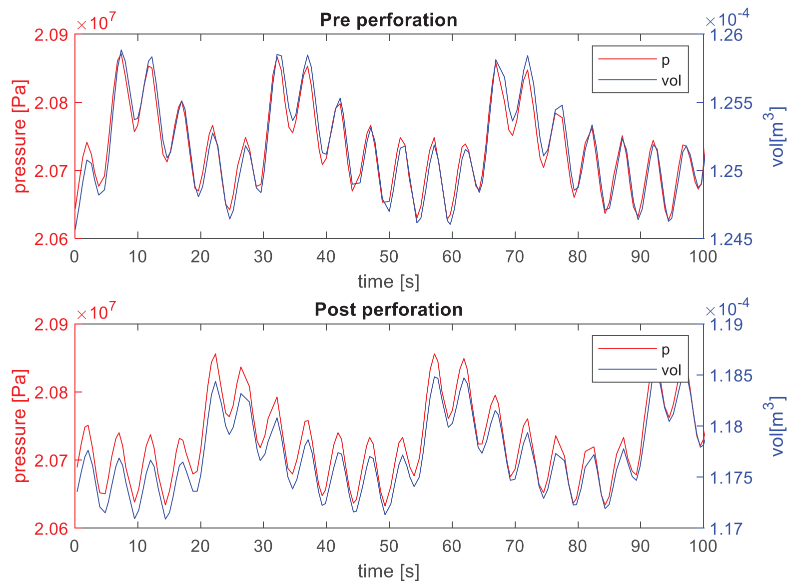


Fig. 7: Raw data of the flow for 0.2 Hz for the pre-shot and post shot test.

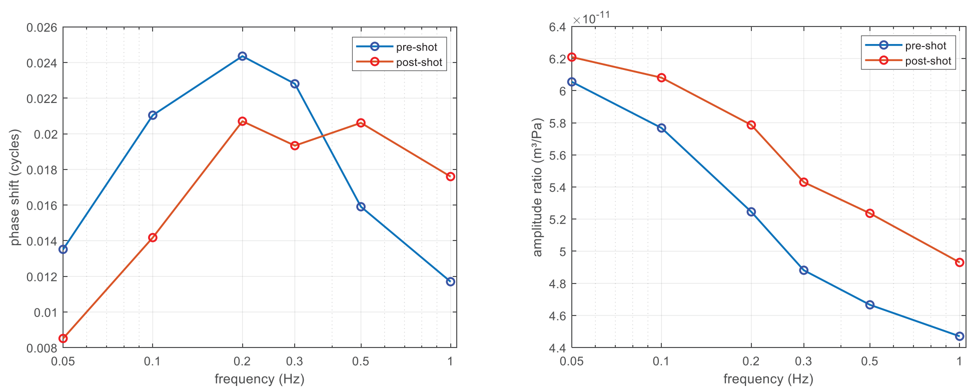


Fig. 8: Derived amplitude ratios and phase values. The pre-shot curves are shown in blue, the post shot curves are displayed in red.

What can be seen, is that the values of the amplitude ratio post-shot are for all frequencies higher after the shot compared the pre-shot values, indicating that more fluid enters the core at comparable pressures after the perforation. This points to an improved productivity and hence a PR of above 1. The phase values differ also between the two measurements, indicating a change of the flow characteristic.

As described in the theory section an analytical solution for a cylindrical model in an axial setup was used to deduce permeability and storativity values. They were calculated for each applied frequency and are shown in Fig.9. For the pre-shot measurement, values between 205mD and 500 mD were determined. For the post-shot measurement, we recorded lower values in the range of 200mD for frequencies above 0.1Hz, but with decreasing frequency both curves became nearly identical. As the high frequency measurements focus on shallow regions around the inlet and the tunnel wall, respectively, it can be deduced that deviations in permeability correlate with a crushed zone of reduced permeability.

Normally a constant value in pre-shot values would be expected, rather than the observed variation with a minimum at intermediate frequencies. While the increased permeabilities at very low frequencies might by related to the fact that the core is situated in an elastic rubber hose, the values at high frequencies might be already influenced by inertia effects, inhomogeneities of the rock, or local turbulences occurring in the complex test setup, which includes thin high-pressure pipes as well as the bigger wellbore chamber.

It should also be noted that the minimum permeability deduced from the periodic pumping tests (205mD) exceeds the value from the constant flow value, taken from conventional Section IV test (108mD), but remains in the same magnitude. Forth & Renner, 2019 discussed, that this mismatch can also be due to inaccurate determination of the system compressibility, which directly influences the determined flow.

For completeness the storativity values are also shown in Fig.9. In principle they describe the ability of the rock to store fluid, e. g. by elastic deformation of the pore space and the compressibility of the fluid therein. According to Song and Renner, 2007 it can also be related to the connected porosity. In our tests a difference between pre- and post-shot tests is visible at all frequencies with an intersection at around 0.4 Hz. A higher storativity is noticed for higher frequencies, which might correlate to a higher porosity in the crushed rock. While one might be inclined to relate this intersection point with the extent of the crushed pore space, more research will be necessary to confirm such a conclusion.

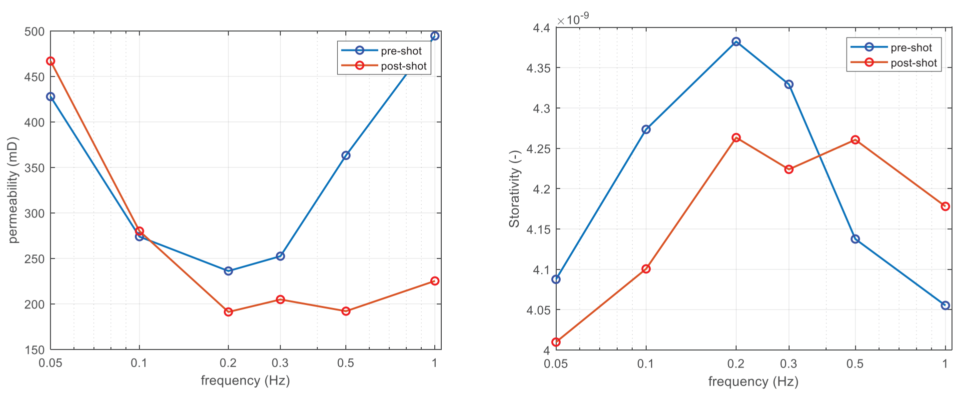


Fig.9: Derived permeability and storativity values as a function of the frequency

As a supplement to the periodic pumping tests, scratch tests as well as CFD simulations were run and will be presented in the following paragraphs.

Three UCS profiles were measured across the tunnel (Fig. 10) to quantify the extent of the crushed zone. To open the core, we cut two opposing notches as well-defined break points into the side wall with a saw and subsequently cracked the core into two halves with a hammer and a chisel. We used the second half of the core shown in Fig. 2 for the tests. Unfortunately, the core did not split in two identical halves, when we opened it. In addition, the surface of the cracked half was carefully leveled to get a plane surface, which reduced the size of the second half even further. Consequently, the tunnel length in the second half was much shorter.

For the bottom profile, which was close to the entrance hole, the strength of the impaired rock increases nearly linearly over 0.78" to approximately 65% of the host rocks strength and rises to the maximum value with another 0.78" (Fig. 11). A similar behaviour can be seen for the middle (Fig. 12) and top profile (Fig. 13), but with a reduced total crushed zone thickness of approximately 0.8" and 0.7". Since the latter two profiles do not extend perfectly radially, but more and more tangentially from the tunnel (Fig. 10), the crushed zone thickness might be overestimated, and should be even thinner. Generally, it is observed that the crushed zone thickness is reduced toward the tip. This variation of the crushed zone thickness as a function of the position in the tunnel nicely fits with the picture of the hydrocode simulation (Fig. 2, middle), as well as with observations on the flow through the crushed zone from Halleck et al., 1992.

Fig. 10: Three scratch test profiles (bottom, middle and top) were measured across the tunnel with approximately 2" distance between them on the second half of the rock shown in Fig. 2.

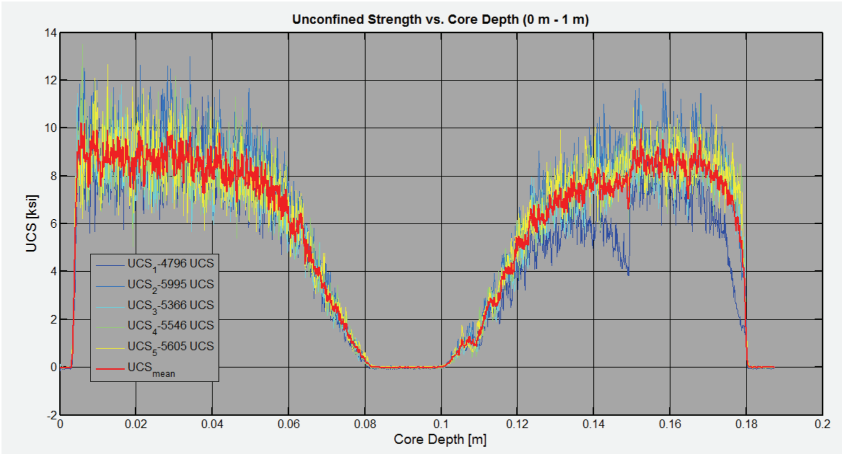


Fig. 11: UCS values taken from the scratch test for the bottom profile.

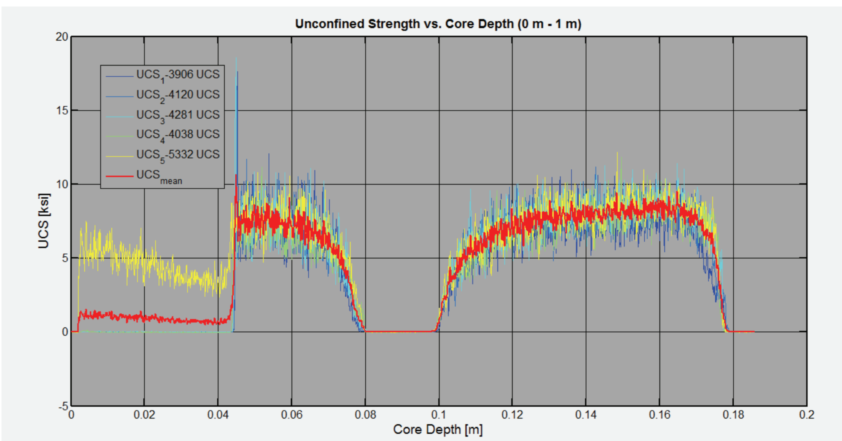


Fig. 12:UCS values taken from the scratch test for the middle profile.

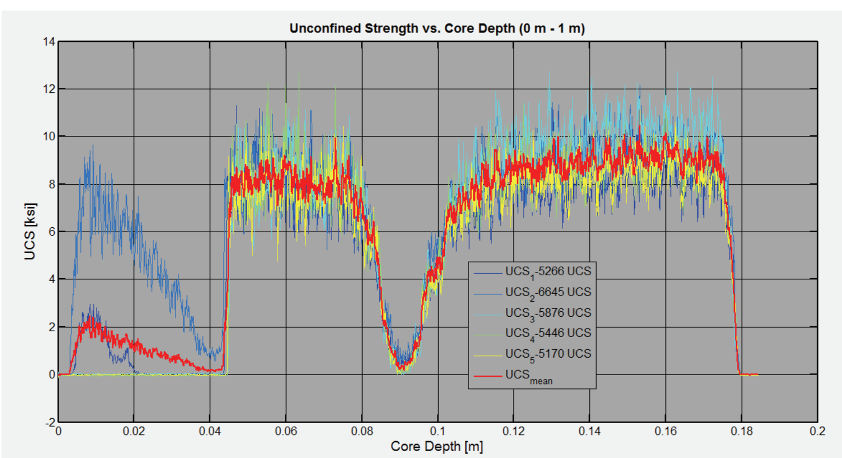


Fig. 13: UCS values taken from the scratch test for the top profile.

When using the determined thicknesses, it should be considered that the depth of the damage of the rock strength reaches deeper into the rock than the damage of the permeability (Heiland et. al 2009). This in turns means that the crushed zone thickness, which is assumed for flow simulations, should be chosen smaller than the crushed rock region taken from the UCS profiles.

Based on these results, we assumed a thickness of 0.75" for the impaired layer around the tunnel in our CFD simulation of the post-shot flow (Fig. 2, right picture).

To deduce a crushed zone permeability out of CFD simulations, the following steps were taken:

First the axial pre-flow was simulated to check if the simulation model delivers the same flow values for given rock permeability as the section IV test. After that the tunnel geometry was measured with a caliper, digitised, and imported in to the CFD modeling software. Around the tunnel a 0.75" thick zone was introduced representing the crushed zone. For the simulation the host rock permeability was kept at the pre-flow value, while the crushed zone permeability was varied iteratively until the simulated flow for the axial setup met the measured value. The measured values for the perforation and the deduced permeabilities are summarized in Table 1.

Although visually the tunnel seems to be clean, a reduction in permeability by 56% is observed. While this value represents a binary model with an average value for the first 0.75", the real crushed zone shows a gradual and continuous change in permeability, and consequently the maximum impairment will be even higher.

Nevertheless, a comparison of the CFD derived value of 56% reduction fits quite well with the difference in permeability from the periodic pumping test measured at the highest frequency, which showed a 54% decrease.

Table 1: Measured values and calculated permeabilities for the Section IV test shot of a 23g shaped charge on Berea sandstone.

Parameter	Value	Unit
Porosity	17.73	%
Permeability	108	mD
UCS	9739	psi
EHD	0.4	inch
TTP	9.36	inch
Open Tunnel	9.36	inch
Crushed Zone Permeability	47.6	mD
Crushed Zone Thickness	0.75	inch

Discussion

In the presented work we introduced a new method to evaluate the hydraulic parameters of the crushed zone. Additionally scratch tests were used to evaluate the extent of the crushed zone and CFD simulations were run to deduce an average crushed zone permeability for a binary model of the perforation tunnel, consisting of the tunnel, a crushed zone, and the virgin rock.

The periodic pumping tests, once the setup was installed, proved to be an easy to make measurement, supplementing conventional flow tests.

After processing of the raw data, amplitude and phase, values give already an indication of the of impairment of the rock around the perforations tunnel, which becomes even clearer after an interpretation of the data using a simple analytical cylindrical model. The values derived for 1Hz correlate fairly well with the permeability reduction deduced from the binary CFD model.

For comparison, the scratch test method was applied to investigate the homogeneity of crushed zone thickness along the perf tunnel. It became obvious that its thickness is not constant over the entire length, and that it becomes thinner toward the tip. Although it must be stated that complete measurements around the tip are missing in our research, so that our observations only cover the first half of the perforation tunnel. It is also worth pointing out, that the extent does not necessarily correlate with the reduction of the permeability. Looking at experiments of Grove et al. 2011, it seems that most of the flow enters the tunnel close to the entrance hole. This discrepancy might be caused by the definition of the crushed as we used it here. We defined it as the extent of the region, where the UCS strength is below the one of the virgin rock. Within this distance, it increases from zero to its maximum value. If this region is thinner, the rock might be more compacted and hence less permeable. Hence the thickness will not be strictly correlated with a permeability impairment, especially as fines in the pores will not be detected by a scratch test.

On the other hand, in a radial setup as was used by Grove et al. 2011, a bigger diameter due a thicker crushed zone reduced the distance to the outer boundary and hence the flow path is shorter. More research will be necessary to investigate the extent of the 3D geometry of the permeability impairment around the tunnel.

The study presented here is considered to be a first feasibility study if periodic pumping can be an additional option for future section IV tests. If the test results can be confirmed by more laboratory tests, they might have the potential to directly determine by flow tests, if a crushed zone is present and if sufficient DUB was applied to remove the impaired rock. For now, only a simple cylindrical model was used for the interpretation, so there is a need to utilize more complex models, as the radial two-layer model by Forth & Renner, 2019 or even more complex models.

Also, an assessment of the penetration depth of the signal (Song and Renner, 2007) was not discussed in this article. Forth & Renner, 2019 made sensitivity studies based on his model and found that crushed zone thicknesses in the millimeter range already manifest themselves in changes in the data although the diffusion depth was much higher. Still the applicability of these findings to the complex geometry of perforated rocks must be investigated and confirmed.

In the experiments, we also observed indications, that the periodic pumping test have the potential to identify cracks or bigger clay lenses in the core, which locally influence the flow, but will be not detected by normal flow unless a CT scan was made. More tests with inhomogeneous rocks are required for the confirmation. Last but not least, the test setup can be improved by employing faster and larger pumps as well as by reducing the fluid volume in the test setup. While smaller volumes will result in more accurate measurements, the faster syringe pumps may provide data for even higher frequencies, which in turn deliver data on very shallow regions.

Conclusions

Periodic Pumping tests can practically be conducted in Section IV test vessels on perforated rocks.

The results show frequency dependent hydraulic properties of the perforated rock and show the potential to measure a depth profile dependent permeability.

A correlation between the reduction of the crushed zone permeability compared to the virgin rock and the reduction of the measured high frequency permeability pre- and post-shot was observed, albeit in limited data sets.

Future research should address the applicability of further analytical models and depth of investigation relationships, as well as improvements of the test setup.

Nomenclature

β_s = *specific storage capacity, volume per pressure per volume, 1/Pa*

CFE = *Core flow efficiency, dimensionless*

CFPR = *Convergent Flow Production Ratio, dimensionless*

DUB = *Dynamic Underbalance, pressure, Pa*

ζ = *fluid stored per unit volume of rock, dimensionless*

η = *dynamic fluid viscosity, Pressure times time, Pa·sec*

EHD = *Entrance Hole diameter, Length, m*

g = *gravity of the earth, velocity per time, m/s^2*

k = *permeability, Area, m^2*

L = *Length of the sample, Length, m*

p = *pore pressure, Pressure, Pa*

$\vec{q}$ = *flux, meter per time, m/sec*

PI = *Productivity Index, Volume per time per pressure, cm^3/psi/min*

PR = *Productivity ratio, dimensionless*

ρ_f = *density of the fluid, mass per volume, kg/m^3*

S = *Storativity, dimensionless*

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Appendix

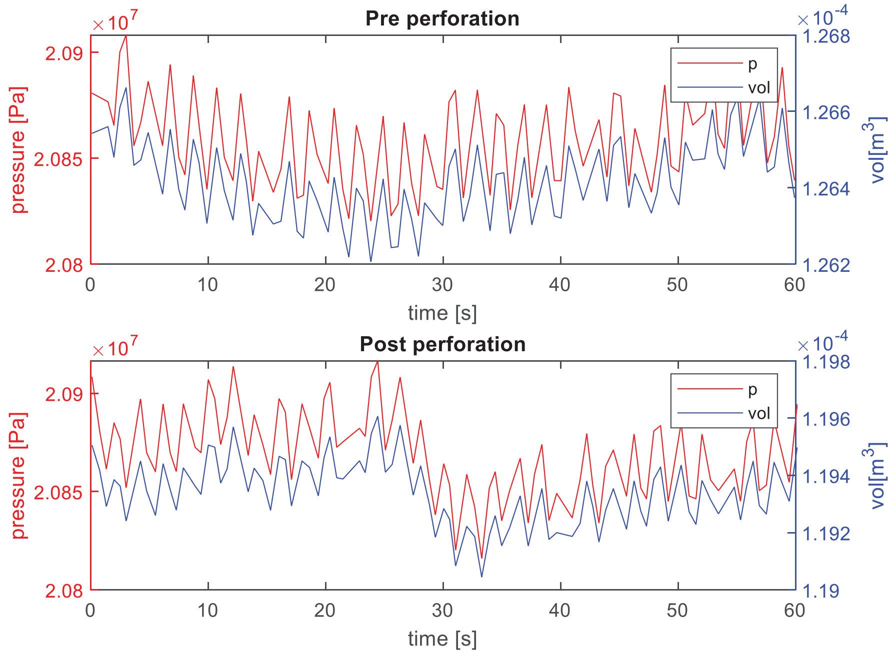

Fig. A-1: Raw data of the flow for 0.5 Hz for the pre-shot and post shot test.

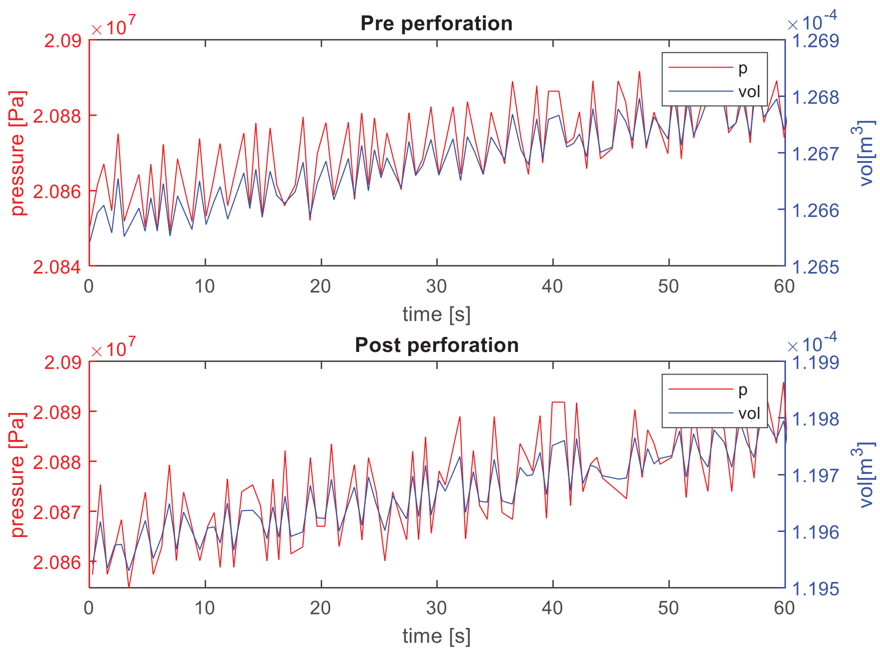

Fig. A-2: Raw data of the flow for 1 Hz for the pre-shot and post shot test.

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