Environment Agency

Review of software used by the oil and gas industry to model hydraulic fracturing

Chief Scientist’s Group report

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Professor Doug Wilson
Chief Scientist

Executive summary

To better understand the sensitivities of the hydraulic fracturing modelling process to different boundary conditions and input parameters, the Environment Agency asked the British Geological Survey (BGS) to review available software used by the oil and gas industry to model hydraulic fracturing.

Methodology

BGS searched available online literature to identify the names of software, and companies producing software, for modelling hydraulic fracture propagation. A brief academic literature review on the topic of hydraulic fracture modelling software was also performed.

Based on the internet search and literature review, a factsheet template was developed. This included categories for computer system requirements, licensing options, availability of training, technical features such as modelling approach and input parameters and whether there is any available literature and/or benchmark models. The template was sent to companies licensing active hydraulic fracture modelling software. A spreadsheet was then populated with as much information as possible, for as many software packages as possible, using information contained in the factsheets returned by companies, and from the available academic and online literature.

Key findings

Seven modelling packages were identified as the most commonly mentioned commercially available hydraulic fracturing software. Details of the full list of software identified are given in a spreadsheet provided as an appendix to the report.

From the review of available literature, it is clear that there has been significant advancement in the capability and accuracy of hydraulic fracture simulation software over the past few decades. However, the advancement is not universal, meaning that there is a broad range in the level of sophistication of currently available commercial software. Consequently, there is likely to be disparity between fracture geometries produced with different software using the same input parameters, and particularly between modelling software that use different modelling approaches.

For the most part, existing fracture simulators are limited to planar fractures, despite growing evidence that suggests induced fractures are more complex, tortuous and non-planar, and that fracture growth is complicated by the interaction of induced fractures with natural fractures. Coupling of hydraulic fractures with the existing fracture network is therefore essential if the full extent and connectivity of the hydraulic fracture network and stimulated rock volume is to be accurately quantified.

Calibration of input parameters so that the models match the results of in situ hydraulic fracture treatment monitoring appears to be routine practice for optimising hydraulic fracture treatments. This is particularly evident in new plays where little or no pre-existing models or hydraulic fracturing monitoring data are available.

At this stage of software development, relying on hydraulic fracture simulators alone as proof of compliance – particularly in new plays – appears unfeasible

In the absence of suitably calibrated models, one approach the regulators could take to address the uncertainty in hydraulic fracture model outputs is to:

- accept fracturing plans based on whether the input parameters used are reasonable for the formations, fluids and in situ stress conditions expected
- additionally require that the hydraulic fracturing is monitored, and the hydraulic fracture models updated, as continuing proof of compliance with permit conditions

It was concluded by BGS that future work should focus on:

- a more comprehensive review of the existing studies (to include recent and ongoing studies by the American Rock Mechanics Association)
- quantification of the likely ranges of the input parameters (principally in situ stress and rock properties) expected in UK shale gas plays

Contents

1 Introduction

To protect groundwater and to ensure compliance with the EU Water Framework and Groundwater Directives, the Environment Agency requires oil and gas companies to submit hydraulic fracturing plans (frac plans) for inspection. This inspection forms part of the assessment and management of environmental risks associated with the hydraulic fracturing operation and the determination of the relevant environmental permit (Environment Agency 2016).

Frac plans outline the proposed method and duration of hydraulic fracture activity as well as the proposed (modelled) hydraulic fracture geometry. These are usually based on hydraulic fracture models derived from well data and optimised for fracture fluid and injection schedule.

To better understand the sensitivities of the hydraulic fracturing modelling process to different boundary conditions and input parameters, the Environment Agency asked the British Geological Survey (BGS), a component body of UK Research and Innovation, to review available modelling software used by the oil and gas industry to model hydraulic fracturing.

At the outset, the BGS recommended that this work should be staged so that outcomes from preceding stages could be used to inform the specification of works in following stages. The initial proposal was for 4 stages:

- **Stage 1**: Identification of commercially available hydraulic fracturing software packages – to include software name, manufacturer, underlying modelling methodology, input parameters, academic/evaluation licensing options and prevalence of use in industry.
- **Stage 2**: Identification of a subset of software packages to use for sensitivity analysis – based on prevalence of use in industry and academic/evaluation licensing options, and to cover a range of the underlying modelling approaches. Note: the selection of software was expected to be significantly biased by the availability of the software for benchmarking based on the terms and conditions of the licensing agreement.
- **Stage 3**: Academic literature review and analysis of BGS corporate databases to obtain typical ranges for input parameters and boundary conditions appropriate for the UK. This would also include comparison with validation models used by candidate software.
- **Stage 4**: Benchmarking of selected software. To include comparison of the different software packages (using the same, or at least comparable, input parameters and/or standard models) and within-software parameter sensitivity analysis to identify which parameters are the most significant.

BGS proposed the following work programme for Stage 1 made up of 3 tasks:

- identification of commercially available software for modelling hydraulic fracturing

- development of a software factsheet template (see Appendix A)
- population of the factsheet spreadsheet (see Appendix B)

This report describes the outcomes of Stage 1 only.

2 Identification of commercially available software

BGS searched available online literature to identify the names of software and companies producing software for modelling hydraulic fracturing. In addition, it conducted a brief academic literature review on the topic of hydraulic fracture modelling software to identify historical software and software not easily identifiable by routine internet searches.

Where possible, the underlying modelling approach, input modelling parameters and other features were documented to allow software to be separated into groups with common attributes.

Details of the 7 most commonly cited and currently available commercial software are given in Table 2.1.

A full list of all the software identified is presented in Appendix B along with links to available web pages detailing further information about the software. .

The academic literature examined during the review is listed in the References and Bibliography section.

Table 2.1 Most commonly cited commercially available hydraulic fracture software

Company	Software	Contact details/further information	Response to request for information
Baker Hughes	MFrac, MShale, MFast	ReservoirSoftwareSupport@bakerhughes.com	Response received. Willing to be involved in benchmarking software.
Golder Associates	Fracman	fracman@golder.com	Response received. Possibly willing to be involved in a benchmarking study.
Schlumberger	Kinetix Stimulation Software Suite	www.software.slb.com/contactus-visitor	Response received. Willing to participate in benchmarking study.
Barree & Associates LLC	GOHFER	kevin@barree.net	No response
NSI Technologies	StimPlan	info@nsitech.com	Response received. Possibly willing to be involved in benchmarking study, depending on the workload.
Carbo Ceramics	FracPro	www.carboceramics.com/contact/carbo-corporate/fracpro	No response
FrackOptima	FrackOptima	http://frackoptima.com/contact	No response

3 Development and population of factsheet template

The factsheet template developed by the BGS includes categories for:

- computer system requirements
- licensing options
- availability of training
- technical features such as modelling approach and input parameters
- whether there is any available literature and/or benchmark models

Where available, the available literature is referenced in Appendix B and the References and Bibliography section of this report.

Copies of the templates were sent to companies licensing the most commonly cited and available hydraulic fracture modelling software (see Table 2.1). The responses received are given in Appendix C. This report will be updated with any future responses.

In addition to requesting information about the software, BGS also asked whether the companies would be interested in participating in a hydraulic fracture model comparison study to help the Environment Agency assess hydraulic fracture plans. The responses are documented in Table 2.1.

The completed hydraulic fracture software spreadsheet is presented in Appendix B. BGS has populated as many of the spreadsheet fields as possible, for as many software packages as possible, using the information supplied by companies, and from available online and academic literature.

4 Summary of literature review

Modelling hydraulic fracturing is a complex non-linear mathematical problem that involves the coupling of fluid mechanics with mechanical rock deformation and fracture mechanics. The problem is further complicated when the initial condition – a heterogeneous rock mass with heterogeneous in situ stresses – is further perturbed by the introduction of new fractures that may interact with existing fractures at variable temporal and spatial scales. Therefore it is not surprising that, due to modelling assumptions and simplifications, there are often significant discrepancies between the modelled hydraulic fractures and observations made in the field (Warpinski et al. 1993, Adachi et al. 2007, Wong et al. 2013, Gupta and Duarte 2015, Shahid et al. 2016).

The variation between the modelled fractures and those recorded is attributed to complex interactions between the injected fluid, rock formation, in situ stress, and existing and induced fracture geometries; these interactions are usually simplified or not taken into account from a modelling perspective. This may account for the apparent reliance by the industry on an initial period of model calibration, whereby 'free' parameters are calibrated so that model predictions match the field observations made during treatment. It is also worth noting that up to a five-fold variation in the fracture geometries has been documented between different model simulators using the same input parameters (Warpinski et al. 1993, Wong 2018).

Benchmarking studies and workshops by the American Rock Mechanics Association (ARMA) are also ongoing. Details of these studies are available to ARMA members via the following links:

- http://armarocks.org/hydraulic-fracturing-workshop-san-francisco-2017/
- http://armarocks.org/2018-arma-dgs-workshop/

4.1 Hydraulic fracture simulators

Solid (rock) deformation is usually modelled using linear elastic theory, the fluid flow by lubrication theory and the fracture propagation by linear elastic fracture mechanics (Adachi et al. 2007, Gupta and Duarte 2015). Fracture mechanics considerations appear to be dominant only at the tip of the fracture, and so for fracture geometry calculations, most simulators appear to consider coupled analysis in which governing equations of elasticity and fluid flow are satisfied everywhere except the very tip, where fracture mechanics considerations dominate. For the most part, models appear to use fracture toughness as the fracture propagation criterion (HYFRAC, TerraFrac, TRIFRAC, MFRACII, ENERFRAC, StimPlan), though there are a few that appear to use tensile strength (possibly GOHFER and FracOptima).

Adachi et al. (2007) stated that field-scale evidence from hydraulic treatments indicates the dominant control on hydraulic fracture growth is fluid viscosity, contradicting laboratory analysis (that occurs at much smaller scales), which indicates fracture toughness has a greater control, the latter being historically the dominant control in fracture simulators. Adachi et al. (2007) were of the opinion that the role of fracture toughness is practically negligible at the discretisation-scale of numerical simulators, as the effect of fracture toughness only dominates at the very tip and that fluid viscosity and leak-off process are the dominant factors in fracture growth.

Several modelling approaches have been employed since the 1950s. The first notable theoretical models were analytical solutions developed by Perkins and Kern ([1961] the PK model, later adapted by Nordgern [1972] to include fluid loss effects to become the PKN model), and Khristianovic and Zheltov ([1955] later adapted by Geertsma and de Klerk [1969] to give the KGD model). These two-dimensional (2D) modelling techniques first used gross assumptions about the fracture geometry and were not applicable to layered reservoirs. Consequently, they did not account for the variations of in situ stress that frequently occurred in layered formations (Adachi et al. 2007, Shahid et al. 2016, Gholinezhad et al. 2018). The models, or direct derivatives of them, were used routinely for design as recently as the 1990s (Adachi et al. 2007) and are still occasionally used today, but have been largely superseded by pseudo-three-dimensional (3D) models (P3D).

P3D models, first developed by Settari and Cleary (1986), were able to model variable height and width (that is, they did not have the fixed height/assumptions of the 2D models) and are essentially a modification of the PKN model to account for variation in fracture height (Shahid et al. 2016). The P3D models come in 2 varieties: a lumped model and cell-based model. The main limitations with P3D models are that, if there is unconfined height growth, then they tend to break down numerically; they also struggle to accurately model fractures developed in a layered system where a stiff layer is present between 2 softer layers (Shahid et al. 2016).

Planar 3D models (PL3D), developed between 1980 and 2000, were therefore developed to overcome these limitations. In these models, fully 3D elasticity equations are used to determine the fracture width as a function of fluid pressure. While more accurate than the P3D models, they are computationally far more intensive and thus are not suitable for simulating the interaction between induced fractures with existing complex fracture networks (Cohen et al. 2017). Both P3D and PL3D models are limited to planar fracture propagation in a plane perpendicular to the lowest in situ confining stress (Wong 2018)

Recent advances have led to the Stacked Height Growth Model (SHG), which seeks to overcome the limitations of the P3D and PL3D models so that the interaction between induced fractures and an existing fracture network can be modelled within a multi-layer model (Cohen et al. 2017).

4.2 Hydraulic fracture orientation and geometry

Broadly speaking, the overall orientation of induced fracture will be perpendicular to the minimum in situ stress. In normal faulting or strike slip stress regimes (minimum in situ stress is horizontal), the fractures will be vertical; in reverse/thrust faulting regimes and at shallow depths (minimum in situ stress is vertical), the induced fractures will be horizontal. However, the presence of existing discontinuities (fault network, joints and so on) or other planes of weakness (cleavage, foliation and so on) can lead to extensive branching and the formation of complex and non-planar fracture geometries (Shahid et al. 2016). Local and regional stress fields may vary depending on several factors including proximity to structures, depth, previous stimulation stages and geological formation.

The overall geometry of the fracture is controlled by a variety of interconnected factors. Broadly speaking, however, the overwhelming consensus in the literature is that hydraulic fracturing in rock formations can be related primarily to the flow of the fracturing fluid and the elastic deformation characteristics of the rock formation (Dougherty and Abou-Sayed 1984, Adachi et al. 2007, Shahid et al. 2016).

In general terms, the relationships between these properties and fracture geometry can be summarised as follows.

- In the absence of contrast in in situ stress, Young's Modulus and fracture fluid properties determine whether fracture propagates horizontally or vertically (Dougherty and Abou-Sayed 1984).
- Fracture length and width are governed by fluid injection rate and fluid viscosity (Abaa et al. 2013).
- High in situ stress difference will constrain vertical fracture growth.
- With high horizontal stress difference, hydraulic fractures dominate with random multiple branches, while with low horizontal stress difference, hydraulic fractures are partly vertical, planar fracture with branches (Zhou et al. 2010).
- High Young's Modulus will contribute to height growth near wellbore (Rahim and Holditch 1995).
- Thin layers (pay-zones) are also not likely to confine fractures as well as thick zones.
- The existing natural fracture network will have a significant effect on the geometry and extent of induced fractures and stimulated rock volume.

In summary, the factors most affecting fracture dimensions are therefore (Rahim and Holditch 1995; Adachi et al. 2007):

- in situ stress
- layer thickness
- Young's modulus
- Poisson's ratio
- fracture toughness
- relative contrast in fracture strength between layers

- fluid injection rate
- fluid injection volume
- fluid viscosity
- leak-off rate
- the pre-existing fracture network

4.3 General input parameters

- Thicknesses of individual layers of rock
- In situ stress
- Physical properties of individual rock layers: Young's modulus, Poisson's ratio, fracture toughness/tensile strength, porosity, permeability/fluid loss coefficient
- Fluid properties: density, rheology (Newtonian/non-Newtonian), viscosity, leak-off coefficients
- Treatment details: perforation/injection location(s), injection rate, injection volume
- Proppant details: size, density, concentration

4.4 Current UK legislation and hydraulic fracture plans

Current legislation within England on onshore hydraulic fracturing safeguards is provided by section 50 of the Infrastructure Act 2015, which inserted a new section 4A in the Petroleum Act 1998. The key paragraphs of section 50 related to groundwater are reproduced below.

> (3) Where an application is made, the Secretary of State may not issue a hydraulic fracturing consent unless the Secretary of State—
>
> (a) is satisfied that—
>
> (i) the conditions in column 1 of the following table are met, and
>
> (ii) the conditions in subsection (6) are met
>
> (b) is otherwise satisfied that it is appropriate to issue the consent.
>
> (4) The existence of a document of the kind mentioned in column 2 of the table in this section is sufficient for the Secretary of State to be satisfied that the condition to which that document relates is met.
>
> (5) But the absence of such a document does not prevent the Secretary of State from being satisfied that that condition is met.

Column 1: conditions	Column 2: documents
5 The associated hydraulic fracturing will not take place within protected groundwater source areas	A decision document given by the relevant environmental regulator (in connection with an environmental permit) which indicates that the associated hydraulic fracturing will not take place within protected groundwater source areas
6 The associated hydraulic fracturing will not take place within other protected areas	A notice given by the local planning authority that the area in respect of which the relevant planning permission has been granted does not include any land which is within any other protected areas

The Department for Business, Energy and Industrial Strategy (BEIS) has issued guidance on making an application for hydraulic fracturing consent under section 4A of the Petroleum Act 1998 (inserted by section 50 of the Infrastructure Act 2015) (BEIS 2017).

At the time of writing, published fracture plans are available for 3 onshore wells in England: Kirby Misperton KM-8 and Preston New Road 1 and 2. These are presented differently by each licence holder, but cover the requirements as stated in the legislation.

The fracture plans were produced using the P3D/PL3D method. All the plans note that they will evolve and be revised as fracking progresses and new information becomes available on how fractures propagate within the target formation (that is, model calibration from monitoring).

The mitigation methods are similar in all the fracture plans and include staged fracture stimulation with real-time monitoring feeding back into the model to calibrate and revise the fracture geometry.

5 Summary and conclusions

From this review of available literature, it is clear that there have been significant advances in the capability and accuracy of hydraulic fracture simulation software over the past few decades. However, this increased sophistication requires more input variables and thus an even greater requirement to understand and quantify the physical properties and behaviour of fluid and rock in the subsurface. The advancement is also not universal, meaning that the level of sophistication of currently available commercial software has a broad range. Consequently, there is likely to be disparity between fracture geometries produced with different software using the same input parameters and particularly between modelling software that use different modelling approaches (that is, PKN P3D, PL3D and so on).

For the most part, existing fracture simulators are limited to planar fractures, despite growing evidence which suggests the induced fractures are more complex, tortuous and non-planar (Gupta and Duarte 2016). Furthermore, evidence from field monitoring of hydraulic fracturing indicates fracture growth is complicated by the interaction of induced fractures with natural fractures (Adachi et al. 2007). The coupling of hydraulic fractures with the existing fracture network is therefore essential if the full extent and connectivity of the hydraulic fracture network and stimulated rock volume is to be accurately quantified. There appears to be to be very few commercially available simulators capable of this kind of sophisticated assessment – perhaps only Golder Associates' Fracman and Schlumberger's Kinetix Stimulation Software Suite.

The sensitivity of different modelling approaches to different input parameters (in particular in situ stress, Young's modulus and fluid injection parameters) is documented by a number of academic publications (Warpinski et al. 1993, Dougherty and Abou-Sayed 1984, Adachi et al. 2007, Shahid et al. 2016, Abaa et al. 2013, Rahim and Holditch 1995, Wong 2018) and is summarised in Sections 4.1 and 4.2. Furthermore, calibration of these input parameters so that the models match the monitoring results of in situ hydraulic fracture treatment, appears to be a routine practice for optimising hydraulic fracture treatments. The process of using hydraulic fracture simulators to design hydraulic fracture treatments, which are then monitored and used to further refine the models, appears to be a continuous iterative process throughout the well stimulation phase of operation. This is particularly evident in new plays, where little or no pre-existing models or hydraulic fracturing monitoring data are available.

Producing a single, or even series of benchmark models, that allow effective and direct comparison of results for software that use significantly different modelling approaches (that is, those that integrate the natural fracture network and those that do not) is unlikely to be feasible due to the wide variation in input parameters required by the different modelling approaches. Direct comparison of software that uses the same modelling approach is feasible, but in many cases, this study has already been done or is ongoing by others (Warpinski et al. 1993, ARMA workshops). Warpinski et al. (1993) noted an up to five-fold variation in the fracture geometries produced by different model simulators using the same input parameters. NB The results of the ARMA study are only accessible to members of ARMA.

It is not surprising that the oil and gas industry relies on active monitoring to help calibrate hydraulic fracture models given that:

- there is a disparity in the fracture geometries produced by different modelling software, which often employ different modelling approaches
- that most commercially available software does not model the interaction between induced fractures with the existing fracture

At this stage of software development, relying on hydraulic fracture simulators alone as proof of compliance – particularly in new plays – therefore appears equally unfeasible.

In the absence of suitably calibrated models, one approach the regulators could take to address the uncertainty in hydraulic fracture model outputs is to:

- accept fracturing plans based on whether the input parameters used are reasonable for the formations, fluids and in situ stress conditions expected
- additionally require that the hydraulic fracturing is monitored, and the hydraulic fracture models updated, as continuing proof of compliance with permit conditions

Given the conclusions set out in this report, BGS concluded that proceeding with stages 2–4, initially proposed at the outset of this work (see Section 1), was not an effective way to quantify the difference in the fracture geometry produced by software with different modelling approaches. For software with similar modelling approaches, these studies already exist or are ongoing. A more productive way forward would be to:

- produce a more comprehensive review of the existing studies (including those by ARMA)
- quantify the likely ranges of the input parameters expected in UK shale gas plays

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List of abbreviations

ARMA	American Rock Mechanics Association
BGS	British Geological Survey
KGD	Khristianovich–Geertsma–De Klerk [model]
P3D	pseudo-three-dimensional [model]
PL3D	planar three-dimensional [model]
PK	Perkins–Kern [model]
PKN	Perkins–Kern–Nordgren [model]

Appendix A: Factsheet template

Software		
Latest version		
Recommended system requirements	Operating system	
	Hard disk	
	Processor	
	Memory (RAM)	
	Graphics card	
	Other requirements?	
Additional software needed (pre/post-processing tools)?		
Licenses	Commercial type (price)	
	Academic (price)	
	Demo/evaluation license	Available?
		Limitations
Training provided	Available?	
	Price?	
Technical features	Numerical approach	
	Domain geometry	
	Bulk	Model (rigid body, linear elasticity, visco-elasticity, plasticity, damage…). Please, specify all that apply
		Parameters to be provided (density, Youn'g Modulus, Poisson's
	Fracture	Geometry (planar, penny-shaped…). Please, specify all that apply
		Propagation criteria
		Opening criteria
		Parameters to be provided (length, orientation…)
	Flow within the fracture	Geometry
		Model
		Parameters to be provided (density, viscosity…)
	Specially appropriate for…	
	Limitations	
Benchmark tests examples provided?		
Any available literature (manuals, conference papers, peer review journal papers, case studies tec.)		
Would you consider future participation in a hydraulic fracturing model comparison study to help facilitate hydraulic fracturing plan assessment by the Environment Agency England?		

Appendix B: Hydraulic fracture software factsheet spreadsheet

See separate spreadsheet

Appendix C: Returned factsheets

Software			StimPlan™
Latest version			Version 7.23
Recommended system requirements	**Operating system**		Windows
	Hard disk		5 GB
	Processor		Intel Quad Core
	Memory (RAM)		8 GB
	Graphics card		No Special Requirements
	Other requirements?		None
Additional software needed (pre/post-processing tools)?			None
Licenses	**Commercial type (price)**		Variable depending on modules
	Academic (price)		67% discount
	Demo/evaluation license	**Available?**	Yes
		Limitations	None
Training provided	**Available?**		Yes
	Price?		Variable depending on location
Technical features	**Numerical approach**		Finite element method (FEM)
	Domain geometry		3D
	Bulk	**Model (rigid body, linear elasticity, visco-elasticity, plasticity, damage…). Please, specify all that apply**	Linear Elastic
		Parameters to be provided (density, Youn'g Modulus, Poisson's	YM, PR, K_{Ic}
	Fracture	**Geometry (planar, penny-shaped…). Please, specify all that apply**	Planar 3D
		Propagation criteria	Linear elastic fracture mechanics (LEFM)
		Opening criteria	????
		Parameters to be provided (length, orientation…)	????
	Flow within the fracture	**Geometry**	2D
		Model	Poissel Flow
		Parameters to be provided (density, viscosity…)	Density, K', n', Pipe Friction,
	Specially appropriate for…		All planar fractutre cases/environments
	Limitations		Planar Fractures
Benchmark tests examples provided?			On Request
Any available literature (manuals, conference papers, peer review journal papers, case studies tec.)			Yes
Would you consider future participation in a hydraulic fracturing model comparison study to help facilitate hydraulic fracturing plan assessment by the Environment Agency England?			Possibly, depending on the work load requested

Software			**FracMan Reservoir Edition Pro** Provides all capabilities for creation, calibration/analysis including geomechanics of DFN reservoir fracture models, with the principal features: 1. Fracture Data Analysis and Integration 2. Discrete Fracture Network Geomodelling 3. Static and Dynamic Upscaling 4. Transient Dynamic Simulation 5. Fracture Clustering Analysis 6. Geomechanics Stress Simulation 7. Fault Reactivation / Induced Seismicity 8. Geostatistics Analysis 9. Hydromechanical Coupling Transient Simulation/Analysis 10. Advanced 3D Hydraulic Fracture (coupled geomechanics)
Latest version			7.7
Recommended system requirements	Operating system		Microsoft Windows
	Hard disk		Standard size 1Tb is satisfactory
	Processor		Intel i5 or i7 is satisfactory
	Memory (RAM)		Recommend 8Gb to 16Gb (or more)
	Graphics card		Standard is satisfactory. Nothing advanced required.
	Other requirements?		Most FracMan models can be developed and run on standard Windows laptop computers - standard specification
Additional software needed (pre/post-processing tools)?			None required
Licenses	Commercial type (price)		Depends on configuration and client. Commercial product range has List Price US$20k-$120k per seat. Discounts are available.
	Academic (price)		Depends on configuration and client. Range is Free of Charge to full commercial pricing.
	Demo/evaluation license	Available?	Yes
		Limitations	Fully functional
Training provided	Available?		Yes
	Price?		Depends on content. Typical 3day FracMan Reservoir Edition commercial training is $15k (everything included) for 5-10 attendees at clients offices
Technical features	Numerical approach		Combined full 3D Discrete Fracture Network (DFN) and full 3D Finite Element (FEM) method.
	Domain geometry		3D
	Bulk	Model (rigid body, linear elasticity, visco-elasticity, plasticity, damage…). Please, specify all that apply	User has options of using constant stress model or fully evolving stress model. Finite element stress model is isotropic/anisotropic elasticity. Our finite element solver does have visco elasticity in it - but we do not use it for hydraulic fracturing analysis.
		Parameters to be provided (density, Youn'g Modulus, Poisson's ratio, etc…)	Basic mechanical properties of: in situ stress (orientation and magnitude) and elastic material properties (Youngs Modulus and Poisson Ratio) are required for the rock matrix component.
	Fracture	Geometry (planar, penny-shaped…). Please, specify all that apply	Fracture geometry is a function of the geology that we observe. Our fractures are fully tesselated and are a function of the in situ rock mechanical properties (stiffness and stress) as well as the pumped fluid. Fracture geometry is geologically a function of stress magnitude and orientation.
		Propagation criteria	FracMan has a full 3D opening criteria that combines elements of PKN and KGD opening criteria as well as classical Griffith crack opening descriptions. Our full 3D approach permits 3D fractures of any geometry/orientation to open (unlike other simple pure PKN/KGD algorithms). 3D analysis approach considers both induced fractures and reactivated fractures
		Opening criteria	Combination of Griffith and Secor Pollard crack opening criteria.
		Parameters to be provided (length, orientation…)	Fracture geometry is a function of the geology that we observe. Our fractures are fully tesselated and are a function of the in situ rock mechanical properties (stiffness and stress) as well as the pumped fluid.
	Flow within the fracture	Geometry	3D
		Model	Mass balance
		Parameters to be provided (density, viscosity…)	Fluid properties (density, viscosity) as well as Proppant properties (density, concentration etc)
	Specially appropriate for…		Simulation of 3D hydraulic fracturing, waste water disposal, induced seismicity prediction, fault reactivation, DFN
	Limitations		Fully applicable to full 3D model geometry
Benchmark tests examples provided?			No. The benchmarks we use are based on clients data and form part of our integrated FracMan test suite
Any available literature (manuals, conference papers, peer review journal papers, case studies tec.)			Lots of public domain material available. ARMA and SPE/UrTEC conference papers freely available on web
Would you consider future participation in a hydraulic fracturing model comparison study to help facilitate hydraulic fracturing plan assessment by the Environment Agency England?			Possibly - we have supported the Environment Agency with frac assessments previously and are generally happy to do so. Also, Note the American Rock Mechanics Association (ARMA) did a similar study during 2017 which we participated in - this is public domain.

Software			MFrac Suite 12
Latest version			MFrac Suite 12
Recommended system requirements	**Operating system**		Windows 7, 8.1, and 10
	Hard disk		500MB is recommended
	Processor		Intel Pentium 4 or equivalent
	Memory (RAM)		At least 256MB
	Graphics card		
	Other requirements?		
Additional software needed (pre/post-processing tools)?			No
Licenses	**Commercial type (price)**		Available upon request
	Academic (price)		Free for Academic purposes
	Demo/evaluation license	**Available?**	Yes
		Limitations	Typically 30 days but can be extended
Training provided	**Available?**		Yes
	Price?		Negotiable
Technical features	**Numerical approach**		Other (please specify next to it)
	Domain geometry		2D/3D
	Bulk	**Model (rigid body, linear elasticity, visco-elasticity, plasticity, damage…). Please, specify all that apply**	LE
		Parameters to be provided (density, Youn'g Modulus, Poisson's	YM, PR, Stress,Fracture Toughness, Reservoir Pressure, Leak-off Coeff
	Fracture	**Geometry (planar, penny-shaped…). Please, specify all that apply**	Planar P3D and orthogonal fracture network
		Propagation criteria	Linear elastic fracture mechanics (LEFM)
		Opening criteria	Elasticity condition
		Parameters to be provided (length, orientation…)	Various fracture models can be selected, several options exist for fluid-loss, friction, roughness, tip effects etc.
	Flow within the fracture	**Geometry**	2D
		Model	Conventional/Koning
		Parameters to be provided (density, viscosity…)	Saturation, Permeability, porosity, injected fluid properties (e.g., specific gravity and rheology; Database contains commonly used fluids, can be extended with user-defined fluids)
	Specially appropriate for…		All fracturing design and also waterflooding operations.
	Limitations		Planar fractures orthogonal to wellbore, no longitudinal fractures, no breakdown calculations
Benchmark tests examples provided?			Yes
Any available literature (manuals, conference papers, peer review journal papers, case studies tec.)			Yes. ARMA frac model comparison, SPE 187253, SPE 138425. More available on request.
Would you consider future participation in a hydraulic fracturing model comparison study to help facilitate hydraulic fracturing plan assessment by the Environment Agency England?			Yes

Software			*Kinetix Shale* Reservoir-centric stimulation-to-production software in the *Petrel* platform	
Latest version			*Kinetix Shale* for *Petrel* 2017, release 1 (next release is for *Petrel* 2018, in October 2018)	
Recommended system requirements	**Operating system**		Windows® 10 or Windows 7 64-bit operating system	
	Hard disk		Fast rotational speed HDD (10K, 15K RPM) or SSD	
	Processor		Quad-core processor (best with a fast clock speed and high cache)	
	Memory (RAM)		16 GB RAM (64+ GB recommended)	
	Graphics card		Desktop: NVIDIA® Quadro® P4000 or NVIDIA Quadro P2000 Mobile: NVIDIA Quadro M3000M or NVIDIA Quadro M2000M	
	Other requirements?		The quality of the viewing experience increases with the size and number of monitors	
Additional software needed (pre/post-processing tools)?			*Petrel* E&P Software platform is required. *INTERSECT* High-Resolution Reservoir Simulator and *VISAGE* Finite-Element Geomechanics Simulator - recommended for production prediction and stress field changes model simulation	
Licenses	**Commercial type (price)**			
	Academic (price)			
	Demo/evaluation license	**Available?**	Yes	
		Limitations		
Training provided	**Available?**		Yes	
	Price?			
Technical features	**Numerical approach**		Other (please specify next to it)	The fracture models are based on either 3D Displacement Discontinuity Method (Planar3D), or Pseudo 3D approach (P3D and UFM models). *Kinetix Shale* also has a geomechanics model for computing 3D stress changes in reservoir due to fracturing and production which is 3D FEM (*Kinetix-VISAGE* Coupling). It also contains a production model which is based on FVM (uses *INTERSECT*).
	Domain geometry		3D	
	Bulk	**Model (rigid body, linear elasticity, visco-elasticity, plasticity, damage…). Please, specify all that apply**	Linear elasticity	
		Parameters to be provided (density, Youn'g Modulus, Poisson's ratio, etc…)	Layer depths, YM, PR, min horiz stress, max horiz stress, vertical stress, pore pressure, fracture toughness, permeability, saturations, fluid viscosity, thermal properties for each layer. For simulation of fracture interaction with natural fractures using UFM model, DFN will also be required.	
	Fracture	**Geometry (planar, penny-shaped…). Please, specify all that apply**	P3D and Planar3D are vertical planar models. UFM model simulates complex fracture networks with connected branches of fractures which can be non-planar, but are still vertical.	
		Propagation criteria	Linear elastic fracture mechanics (LEFM)	
		Opening criteria		
		Parameters to be provided (length, orientation…)	Orientation of the fracture. The rest of the fracture geometric parameters (length, height, width, shape) are predicted by the models.	
	Flow within the fracture	**Geometry**	Several options (please specify next to it)	Flow is 2D in Planar3D and P3D models, and 1D three-layer model in UFM (but can be in both horizontal and vertical directions when Stacked Height option is used).
		Model	Flow between parallel plates for Newtonian and power-law fluids	
		Parameters to be provided (density, viscosity…)	Density, n', k' of the fracturing fluids as function of temperature and exposure time, and leakoff coefficient, retained permeability factor, and friction parameters; Density, size, and conductivity of the proppants; Pumping schedule.	
	Specially appropriate for…		For simulation of all fracturing applications, either conventional reservoirs with planar fractures or unconventional reservoirs where complex fractures may be created.	
	Limitations		For P3D based models, it has known limitations associated with P3D which can predict too much height growth when frac grows from high stress layers into low stress layers.	
Benchmark tests examples provided?				
Any available literature (manuals, conference papers, peer review journal papers, case studies tec.)			Refering to Kinetix Shale Technical Document.Number of technical papers (including URTeC 2875581, 2876482 and other; SPE 172718, 172973, 170580, 170902, 167726 and other SPWLA), case studies and industry articles https://www.software.slb.com/products/kinetix?tab=Legacy.	
Would you consider future participation in a hydraulic fracturing model comparison study to help facilitate hydraulic fracturing plan assessment by the Environment Agency England?			Yes	

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