An Independent Assessment of Shale Gas Operations and Impacts in Pennsylvania

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From the 3rd to 7th April 2016, members of the FracRisk consortium (www.fracrisk.eu) were hosted for a number of site visits by the Penn State Marcellus Center for Outreach and Research. The consortium members comprise a number of academics and applied science-related industry partners from across the EU. The aim of the visit was to enable consortium members to get broad hands on experience of the shale gas industry and regulatory framework which has developed in this region around the production of the resources located principally in the Marcellus shale. Here we describe a number of key impressions from the visit, with the aim of informing the debate about hydraulic fracturing (ie fracking) at the EU level. A number of recommendations, one of the objectives of Fracrisk, can be derived from this visit. *They are identified by italics.*

The visit to Penn State enabled members to put things into perspective, and to ensure that our understanding as to what is occurring, how it is occurring, the operational, regulatory and legal framework, and the consequences, are based upon reality rather than hypothetical understanding. The development of the shale gas industry in Pennsylvania, and by analogue the development in a new basin, with accompanying ancillary industries and effective regulation, can be expected to take a few years to emerge *in situ*, with a site-specific learning curve (and unfortunately with early errors). However the exploitation of the Marcellus shale has shown that it is possible to achieve a functioning, relatively low impact, heavy industry relatively rapidly with a stable low-error operation. As with any heavy industry, the pro's and the con's **must** be weighed by the established authorities who have local control.

The Marcellus and associated shales (Utica in particular, approximately 1000 m below the Marcellus) are low-permeability rocks which contain large amounts of natural gas. In the last 15 years, technology has been developed enabling the horizontal drilling of multiple wells from a single location, combined with the well-established (50 + years) technology of hydraulic fracturing ("Fracking"), to access the contained gas and provide commercially viable gas production. The local communities are aware of the economic potential and they can become, if they want, an active 'part' of the process of gas exploitation. Pennsylvania has experienced a complete change in the socio-economic dynamics in the last 10 years.

From a geological perspective, understanding the subsurface stratigraphy, the nature of any tectonic features such as faults, and having a good assessment of the local geomechanical conditions including the formation pressure and stress field, are essential to ensuring that the fracking operations are undertaken in an optimal and safe manner. Each frac job is different, with each tailored to the local conditions. Each basin presents unique characteristics in terms of stress fields, natural fracture patterns, gas volumes, subsurface pressures, etc.

Fracturing activities are planned so as to avoid major intersecting faults, such as thrust faults, as they can lead to the loss of part of the stimulation fluid and render the process ineffective, and potentially cause induced seismicity. In Pennsylvania, until recently there were no known examples of stimulation causing felt earthquakes. A few weeks ago (Monday 25th April) o there were 5 seismic events in a short time and space that correlated with fracturing, all between magnitude 1.7 and 1.9, which is below what humans can feel.

The subsurface location of a shale target has a significant influence on the amount of gas that can be recovered economically. Near-surface Marcellus rocks may have lost pressure laterally up-dip during post-glacial geologic time, in a natural process. However, faulting within the strata does not appear to lead to pathways through which gas escapes. The gas extraction industry performs detailed 3D-seismic surveys to enable accurate identification of suitable target zones and proper well positioning to obtain high productivity.

In practice, drilling/production companies identify areas of land they are interested in exploring and then potentially producing from. They then lease the land from (mostly-) willing land owners, undertake exploratory drilling to prove the resource, and if favourable, they then hold that land "under production" whilst several wells are drilled from a single pad. Under conditions of low gas production, or when the pipeline infrastructure is missing, the leased land can be held "by production", even though this does not generate any sales or revenue, either for the operator, or for the lease holders.

The development is undertaken by drilling and stimulating several wells from a single pad, each with its own lateral (horizontal, 2-3 km long) section aligned in the correct direction to maximise gas recovery. Pipelines to collect the gas are constructed, also on leased land, to the well pad; these are mostly buried by a few metres of earth (governed by regulations), except where they come to the surface for the provision of access points. The initial lease of the land (and associated subsurface rights) which provide funds to the land owners, changes to a payment system that involves a percentage of the revenue (called a "royalty") from the wells when in gas production, in the order of 12.5 to 20% of revenue, depending on the lease terms. The rate of gas production from a well decreases with time, and after approximately 20-30 years the amount of gas which a well produces may no longer be commercially viable (that is, the operational costs exceed the revenue from sales). Fifty percent of the total revenue from a well/stimulation is generated typically within the first 4-5 years of the well operation. A well may cost of the order of 8-10 million dollars to construct and stimulate. The gas production from a normal well is then expected to provide 10 Million dollars profit within 4-5 years, and overall a total revenues of the order of 20 M dollars within 20-30 years. When a well is no longer commercially viable, it may be refracked (with new costs) or plugged and abandoned. The drilling company is responsible for the abandonment operations, and initial monitoring of the well to ensure there is no leakage.

During the fracking operation, water under pressure is used to open naturally existing fractures and discontinuities, and also to develop new fractures within the rock. A proppant, i.e. fine sand, is added to the water so that whilst the water is flowing under pressure into these openings, the sand is also carried into the fractures. When the water pressure is released, the fractures remain propped open by the sand. To create the fractures, the horizontal well casing is isolated into ~100 m sections, then perforated in short intervals (~0.5 – 1 m) using small explosive charges, and then fracking fluids are injected with a volume of ~1000 m^3 per section. Each frack stage, or stage of treatment, takes 2 - 3 hours to perform. That section of the well is then isolated and the next section is fracked, etc.

Typically 10,000 to 20,000 m^3 of water will be used to complete a well, depending on the length of the laterals (the length of the horizontal boreholes). This water volume is equivalent to the size of three to four small houses, but spread over the 2-3 km length of the horizontal borehole. This can be imagined as a cylinder of water ~2.5 km long with a radius of 1.6 m. Approximately 1% of the fluid volume will be chemical additives, equating to 100 m^3, or a cylinder of water over 2.5 km with a width similar to the borehole diameter. Initially, during depressurization and the first couple of weeks of production, approximately 5-10% of the injected water will be recovered from the well (flow-back water), and within the lifetime of the well, between 50 to 70% of the injected water volume is expected to be recovered (although some of this volume may consist of water that was already present in the rocks). The remaining water is thought to be mostly absorbed by the shale as it replaces the gas during production, although there remains uncertainty as to the exact fate of the water.

The key chemical additives are viscosity controls (reducers, polymers and thixotropic substances), acids, corrosion inhibitors, scale inhibitors and biocides. These additives serve the short- and long-term operational efficiency of the borehole, reducing the amount of energy required to create the installation and significantly extending its lifetime; they also protect the gas against degradation from introduced microbes. Various databases exist as to which company uses what and where. Proprietary information is however not always disclosed (www.fracfocus.org). It should be noted that stray gas migration is reported by the Department of Environmental Protection, Pennsylvania, as the most common problem in contrast to the commonly assumed (in the press) water contamination derived from fracking additives. This may reflect the fact that gas tends to reach the surface fast, whereas the spreading of fracking fluids should be considered as somewhat delayed (a leak may never reach the surface because, being denser than in situ water, it will tend to sink) and considerably more difficult to detect.

Water injected into the shale comes into contact with in situ natural formation water, which is often saline, causing the concentration of dissolved ions in the frack fluid to increase with the prolonged contact with the shale. 80-90% of water produced from a well is normally re-used for future fracturing activities on other wells. The remaining 10-20% (which may have oily compounds or solid particulates) is transported by road to a specialised treatment plant, before being either returned to the surface waters as ~pure H_2O (with a clean up price of ~50$ /m^3), or is taken for injection into licensed disposal wells. Usually the solid residue other than salt from the clean-up process is taken to a normal landfill site. All residue is tested for normally occurring radioactivity. Should any be detected then the residue is taken to specialised landfill sites. Figure 1 illustrates salt extracted from the water during the clean up/treatment process.

Figure 1 Salt extracted during clean up treatment of flow back water

Control of fugitive gas leakage during flow-back and production should be straightforward with modern wells and high quality operators, thus Best Available Techniques (BAT) standards can be imposed realistically. However when gas bearing horizons are encountered above the target formation, it is sometimes necessary to flare the gas that comes to the surface during the drilling stage (this is a safety-driven option) because pipe lines are not already in place to take the gas, and the technical issues of well control during drilling may not allow for safe isolation of that "unwanted" gas.

During the drilling and fracking operation, there is significant road traffic and industry located at the well pad. The pad is a highly organised 3-5 acre space (Figure 2), which can contain several (often between 8 and 16) wells extending laterally in both directions parallel to the minimum stress direction, and laterals located horizontally at least 250 m apart. A water supply truck will contain 10 to 30 m^3 of water, thereby requiring of the order of 1000 truck trips during fracking operation to provide the necessary volume of water. Obviously, if there is a local water source which can be used, then this is preferred. The water is injected into the ground at a significant pressure, of the order of 50+MPa, with high flow rates, up to several hundred litres per second. To produce such flow rates, between 10 to 20 large truck mounted pumps are required. The injection procedure is controlled and monitored in real time, with key inputs being flow rate, well-head pressure and any microseismic signals which may be detected. Within the Marcellus shale, ~13,000 wells have been drilled and fracked, and so far there has only been five events in total, all in the last few weeks, where seismic activity can be linked to fracking (though less than 2.0 magnitude). Here we note that the widely publicized induced seismic events in Oklahoma have been shown to be related to the reinjection of waste water within a deep porous rock formation which is directly connected to critically-stressed crystalline basement rock. Some small fraction of the injected water comes from the fracking industry, but the majority of the water comes from normal oil well operations or other industries. The induced seismic events in Oklahoma are not a direct consequence of the fracking procedure. Once the fracking is completed, the pad is left with some well heads, gas / water separation plants, and possibly gas-compression facilities.

Figure 2 During a fracking operation (courtesy of Marcellus Shale Center)

Although oil companies and local land owners are the major winners in terms of financial gains, the oil and gas industry directly provides some 30,000 jobs to the Marcellus shale area (December 2014, Pennsylvania's Department of Labor and Industry), the gas price has fallen to about 30% of what it was just 6 years ago, and is currently approximately a third of the price in the EU. In addition there is a significant tax (called an "impact fee") revenue for local communities that spreads the financial benefits to much of the population.

The development of the gas industry in Pennsylvania (and elsewhere) has led to the need for adequate training of local people to create the large workforce required (in Pennsylvania, much of this training has been provided by colleges set up in association with Penn State Univ), and there has been the creation of a substantial local "ancillary" supporting industry. The industries which have grown up around the shale gas production include specialised water treatment facilities, several heavy engineering and supply companies, environmental consulting firms, pipe line construction, drilling, as well as downstream power generation and industry/manufacturing facilities. In addition the influx of money and personnel to the area has led to a "rebirth" of the hotel and accommodation industry. However the knock-on effect of the excessive supply in gas, and thus a drop in price, has led recently to a significant market readjustment, with a general overall reduction in the available finances to support growth. Not quite a boom and bust type condition, as the gas is still there and still profitable, and so far estimates suggest that only a small fraction of the resources has been exploited, rather a readjustment to match demand for the product.

Progress has several components:
• Training of local workforce and creation of local supporting industry
• Discovering the unexpected characteristics of the geology of the particular play type
• Construction of essential infrastructure, such as pipeline, in the right places
• Transport arrangements and identification of locations for service industries

Part of the problem in terms of the swing in the local economy has been the unfettered explosion of the development of gas wells. The first few years appear to have turned into a massive land grab by rival operating companies. Individual land owners were negotiating different prices for land leases and the profit percentage from different companies during production was also variable. The unregulated "market" of leasing resulted in some owners receiving less than 1% of what the average eventually settled to, whilst some (few) got a much more favourable deal. Where some land owners were not prepared to lease their land, legislation permits lessees to drill and produce gas from adjacent land areas, literally sucking the gas out from under those who did not secure a lease arrangement.

This arrangement is economically inefficient, as there are patchwork licensing grabs for land with duplication of drilling and duplication of pipelines; the excess supply of gas reduces the domestic sale price leading to exports.

The mineral rights laws within the USA fostered this "Wild West" situation, whereby everything that was underneath a parcel of land is considered to be the property of the land owner, and the free market conditions created a situation where some companies were able to obtain leases at prices that have later been shown to be ridiculous. Herein is the major difference to the situation throughout the European Union, where the mineral rights under the land belong to the state or to the crown, with, presumably, a more savvy approach to resource valuation.

Land grab consequences
• Overlap of infrastructure
• Different rates for different people
• Not all the community benefits in the same way
• Badly planned infrastructure
• A lot of land held (and thus no more lease payments) but gas not being produced (and so no rolyaty payments)

Efforts have been made to reduce the environmental footprint through technology development and regulatory supervision over the past few years. This is manifested through increased attention to all details during all stages (exploration, site construction, drilling, fracking, production, waste water treatment). Water recycling on the well pad has become the best management practice. It reduces both waste-water treatment costs and the risk of having trucks on the road. Most operations are governed by protocols, thus ensuring a base line for quality control and possibly facilitating risk identification and minimization. This is particularly illustrated in the fact that approximately half of all the wells within the Marcellus shale were inspected last year by the regulators (5946 wells inspected, a total of >13,000 inspections) and only ~210 inspections identified violations to the protocols. Of 10,000 wells drilled, only 32 have identified stray gas associated to them, and the number is declining.

The Department of Environment Protection in Pennsylvania (DEP) presented data collected in the field. The results of approximately 60 source-pathway-receptor cases (most of them being located in the south-western and north eastern part of PA) were scrutinized and presented. Using a bow-tie diagram very similar in concept with the one being developed in the FracRisk project, the DEP identified the key risk scenarios. An additional effect that the DEP had to address was the sudden huge commercial scale development where the regulations were not what they needed to be in the early stages of the development. Therefore, the regulator was faced with the development of the new regulations in very short timelines – having constantly to adapt and improve the situations, and fill the regulatory loopholes exploited by the companies.

Overall, it was apparent that the regulators were initially overcome and possibly unprepared and undermanned for what came. This favoured a reactive mode of response (i.e., respond to undesired events), rather than a proactive attitude (i.e., careful surveillance and monitoring before operations to prevent accidents). While the situation has improved dramatically in recent years, monitoring is still restricted to the gas wells and nearby water supply wells. A specific aquifer monitoring program should probably be developed at every site, which, in practice, would amount to regional coverage. It is evident that a recommendation for the EU would be to use part of the gas taxes to support regional regulators, possibly including asking oil companies to pay the government to hire independent monitoring companies that report to public environmental agencies.

The concept of “Presumptive Liability” presented by DEP – if there is a problem with a water supply within 2500 feet of the well –has put the onus on the operators to ensure best practise operational strategies, including the acquisition of baseline surveys before any operations commence. *Still, the concept needs to be enriched. The adopted distance may be far too short (gas may travel over long distances in a short time) and the direction needs not be equal in all directions (gas will tend to travel in the direction of steepest pathway slope). It appears that that a polygon of surveillance area, where stray gas or fracking fluids might arrive, needs to be defined in each case. If this area intersects the protection polygon of a supply well, special surveillance should be assumed, possibly including increased frequency of chemical analyses and deposit of a security or guarantee.*

Since the first commercial oil well drilled by Colonel Drake in 1859 in the north western part of PA, about 350.000 to 450.000 wells have been drilled in PA. Only half of those wells were probably sealed in any sort of effective manner. This leads to a major legacy issue. DEP is in charge of the so-called orphaned /abandoned wells. During 2015 DEP managed to seal 20. *Obviously, it is clear that the gas company must be responsible for the well for a certain period after closure, possibly including the deposit of a security or guarantee.*

In terms of construction and design, two key issues were identified to reduce the environmental footprint. This is a type of top-down risk approach, where the consequence of a problem are identified, and action is taken to ameliorate it. Both issues have been addressed during the last few years of the fracking industry in Pennsylvania.

First, the quality of the cementation of the casing and the depth of cementation are key issues during well construction. Un-cemented sections of casing are often left above the target shale formation and below and groundwater bearing strata. This leads to a natural short cut for fugitive gas to reach the shallow subsurface, and potentially impact groundwater. Additionally during fracking the casing is pressurised, so that the un-cemented section is placed under increased stress. However, these loads are routinely considered by engineers when they design wells. Perhaps a key issue is to educate and regulate industry to design and construct wells in ways that prevent the up-hole pathway issues that are the root cause of most migration risks. *It appears clear that the annular space between casing and formation must be fully cemented, that the cementation must be independently assessed and that the resistance of the casing to pressures expected during fracking must be proven prior to actual fracking.*

Secondly, companies have been increasing the quality of the secondary containment on the well pad in case of accidental waste spillage. It is now standard practise to have an impermeable liner across the site. However*, more work may be needed to ensure the reliability of storage tanks used to hold the flow back fluids that are to be recycled for future wells.*

Likewise the long-term integrity of the well completion has still not been tested and could possibly be of concern

The overall impression is that high volume hydraulic fracking is routine, and very manageable with experienced companies. *However standards need to be enforced by well-trained regulators who can rely on appropriate rules.*

Post-drilling stage, the visual impacts are comparable to other industries, such as agriculture (grain silos, huge barns), and companies that undertake manufacturing (legacy of industrial past). The visual impacts in Pennsylvania are far less than in most oil and gas developments elsewhere. In many ways this is to be expected. The development of horizontal well drilling technology means that a much larger area can be accessed from a single well pad, as opposed to conventional gas drilling. Images of a landscape dotted with well pads are evocative, but simply not correct (Figure 3). The "visibility" of the shale gas exploitation is much lower than wind turbines within the same area. The general impression after visiting was that there were no large disruptions in the landscape.

Figure 3 Overview of active gas production wells on a well pad

The regulatory frameworks within Pennsylvania, and the comparative EU states, are very different. Laws and regulators in Pennsylvania appear not to actively seek to protect the environment (such as water quality in aquifers), but are rather there to react to events that infringe the rights of others (such as the pollution of existing water wells) and apportion blame. This framework is built on a basis that the operators are expected to avoid causing harm, but will be held liable if it occurs. Meanwhile the parts of the aquifer that are not being currently used can be (and can continue to be) polluted. Within the EU, the water framework directive requires that all water bodies are returned to and maintained at a good qualitative and quantitative status.

There needs to be an appropriate regulatory framework that is capable of being adapted as the local shale resource characteristics become known. The framework has to meet the needs of companies as well as those associated with protection duties. Centralised planning could avoid some of the wasted costs and associated impacts discussed above.

Due to the different mineral ownership and stakeholder situation in Europe, there is a need to translate the lessons from Pennsylvania regarding monetary sharing/compensation, and a comparable level of that share has to be agreed. There is obviously a large disparity between the 1% of revenues currently promised to the nearby communities within the UK and the going rate in Pennsylvania of ~12% (approximately $1 billion in impact fees alone). *For the local community within the EU to accept the development of a new hydrocarbon industry, be it well regulated, environmentally friendly and of minimal visual impact, the payback needs to be worth the hassle and the perceived (even if unduly) risk*.

It is interesting to note that the EU definition of high volume hydraulic fracturing requires that more than 1000 m^3 of water be injected per fracturing stage, or 10,000 m^3 or more of water during the entire fracturing process. However it can be shown that between 2000-2010 some 44% of the fracked wells in the USA were completed by the injection of less than 10,000 m^3 of water. *It is clear that the definition of hydraulic fracturing must be based on the method and the goal, rather than on the volume of water involved.*

Generally, Pennsylvania/U.S. is at least 10 years ahead in terms of experience (even if this knowledge has been acquired by trial and error), whereas the EU is following a more conservative development. One issue which is often cited within the EU is the fact that the EU has a higher population density than the US and so the social issues surrounding the consideration of Fracking come to the fore. This perception may not be as applicable as thought, since the population density in the US is locally, in some shale developments, as dense as is typical in Europe.

Finally it is of note that whilst not offering in itself a zero carbon energy future, burning natural gas has a significantly lower CO_2 footprint than other fossil fuels. However even although large 800 MW gas power plants are being constructed near to shale gas production in Pennsylvania, there is no thought about using Carbon Capture and Storage technology to mitigate emissions from the use of the gas. Were it so, this truly could form a local, extreme high-density low-carbon energy source enabling the Paris CO_2 Climate Change targets to be met. *The EU should investigate whether shale gas development, coupled to local conversion to electricity (and space-heating water), with CO2 capture and storage, could be pioneered in a way to incentivise operators to integrate the entire process.*

The site visit did not reveal any show-stoppers in terms of unacceptable outcomes for the local environment or population. It showed that development can happen in ways that have impacts comparable with those of other distributed industries (agriculture, for example). Pennsylvania provides an example of shale development that appears to occur in ways that can be widely accepted by the population, and the lessons from there need to be translated into the European context. However, not all shale extraction in the world has progressed in a similar fashion, and there remains a need to examine other situations to ensure that the necessary lessons are learnt.