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Key components of modern engine fuels for internal combustion engines: the isoparaffins. Part 1. Light naphtha isomerisation

Jenő Hancsók, DSc (68)

Full professor
Faculty of Engineering, MOL
Department of Hydrocarbon- and
Coal Processing
University of Pannonia
HancsokJ@almos.uni-pannon.hu

András Holló, PhD (45)

Associate professor, head of Department,
Senior expert at MOL DS Innovation
Faculty of Engineering, MOL Department
of Hydrocarbon- and Coal Processing;
MOL Hungarian Oil and Gas Plc.
AHollo@MOL.hu

Zoltán Eller (30)

Scientific coassistant
Faculty of Engineering, MOL Department of
Hydrocarbon- and Coal Processing
University of Pannonia
EllerZ@almos.uni-pannon.hu

Géza Varga (42)

Honorary associate professor, Business
development manager
OT Industries
VargaGe@OTIndustries.hu

Zoltán Varga, PhD (46)

Associate professor, head of MOL course
Faculty of Engineering, MOL Department of
Hydrocarbon- and Coal Processing
University of Pannonia
VargaZ@almos.uni-pannon.hu

ABSTRACT

In our new series entitled 'Key components of modern engine fuels for internal combustion engines: the isoparaffins' blending components of the road fuels (gasolines and diesel fuels) and their impact on the product specifications are analysed and evaluated. In this review firstly the basic properties of the main fuel blending components are discussed then production possibilities of the best quality hydrocarbon streams blendable in unlimited ratios are evaluated.

COMPONENT STREAMS OF GASOLINE PRODUCTION

Principal schemes of a modern crude oil refinery for flexible production of gasoline and middle distillates (kerosene and diesel fuel) are shown on **Figures 1 and 2** (Hancsók, J & Kasza, T 2011). These reflect well that environmentally friendly, good quality gasolines are made from mixtures of crude oil and alternative

feedstock based blending components and high-efficiency additives.

The most important quality properties of gasolines are research and motor octane number, their difference (sensibility), energy content, heteroatom content, olefin- and aromatic content, volatility (distillation curve and vapour pressure) and stability.



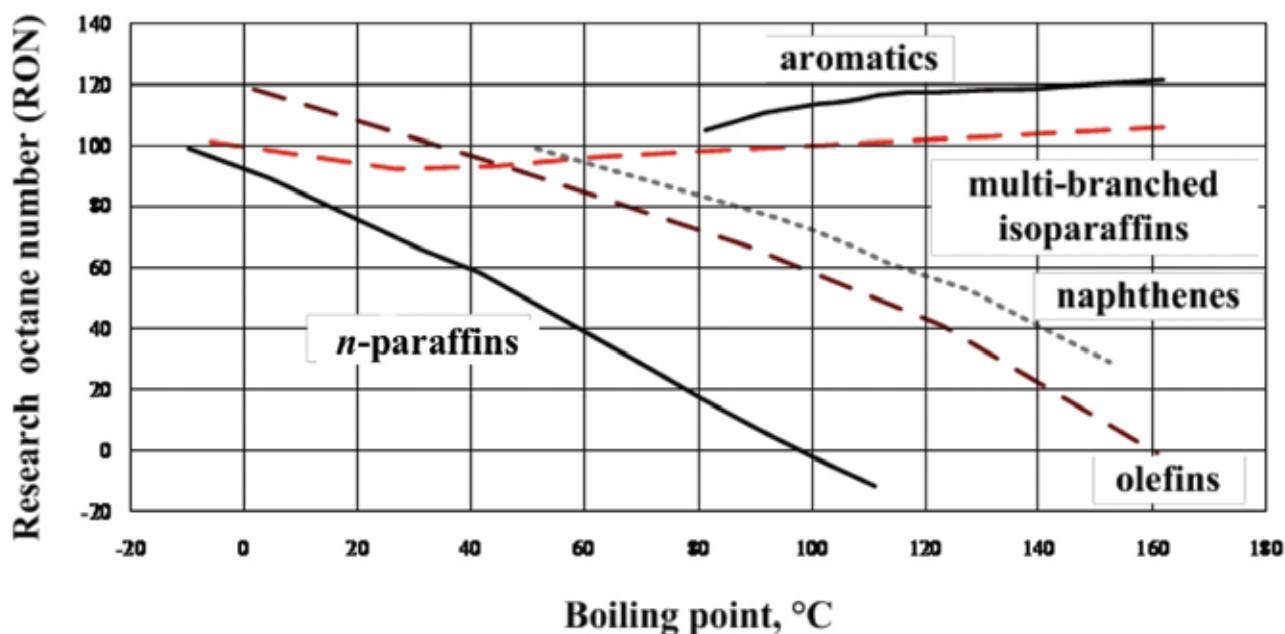


Fig. 3. Octane number of different hydrocarbons as a function of their boiling point

Knowledge of dependence of research octane number of various hydrocarbons from their boiling points is important for blending (see Figure 3 and Table 1) (Hancsó, J et al. 1998).

According to the prevailing EN 228 (2013) specification minimum research octane number of gasoline is 95.

Aromatic hydrocarbons have the highest octane number in the gasoline boiling range. However, they have high sensibility (i.e. high difference between research and motor octane numbers of the same component) and show carcinogenic effects. According to EN 228 (2013) aromatic hydrocarbon content of gasoline should not exceed 35 % (v/v) and benzene content – 1 % (v/v).

Although *olefins* boiling under 70 °C have relatively high octane number, they are not desired components, because they have high gum forming tendencies and high (atmospheric) reactivity and ozone forming properties near the soil. Higher boiling range olefins have lower octane number, at 160 °C nearly zero. Their sensibility is 12–14. According to EN 228 (2013) gasolines should not contain olefins more than 18 % (v/v).

Naphthenes (cycloparaffins) with higher boiling points (i.e. carbon numbers) have lower octane numbers, above 7 carbon number (about 110 °C) octane numbers decrease more rapidly. Cycloparaffin content of gasolines is not limited by different standards.

Generally, concentration of naphthenic hydrocarbons in gasolines is very low (generally <5%), and their synthetic production is very costly.

Normal-paraffins have very low, but *isoparaffins*, especially the multibranched ones have high (about 85–110) octane numbers (Hancsó, J 2008). This is one of the main reasons, why isoparaffin-rich fractions become the most important components of modern gasolines. Additionally, they have low sensibility (see Table 1), so they improve the octane number distribution (moderate octane number in the whole distillation curve). These fractions are practically free of sulphur, olefin and aromatics, they are non-toxic, have high energy content, their burning leads to relatively low carbon dioxide emissions (due to their relatively high hydrogen content (expressed by their chemical formula of C_nH_{2n+2}), moreover their biodegradation is easy. Their lower atmospheric (photochemical) reactivity and ozone forming ability must be also highlighted compared to olefins or aromatic hydrocarbons (Hancsó, J 2008). Among the same carbon number hydrocarbons, isoparaffins have the lowest density. Since gasolines are sold by volume, the isoparaffin-rich products streams are sources of significant profit for the manufactures.

Thus, the most favourable gasoline blending components from crude oil refining are those, what have high isoparaffin content, preferably of multibranched and methyl-isomer types (see Figure 4) (Hancsó, J 2008).

COMPONENTS	RON	MON	Sensibility	Energy content	
				MJ/l	MJ/kg
Paraffins					
<i>n</i> -pentane	61.7	62.6	-0.9	28.4	45.9
2-methyl-butane	92.3	90.3	2.0	28.1	45.8
2-methyl-pentane	73.4	73.5	-0.1	29.4	45.5
2,3-dimethyl-pentane	91.1	88.5	2.6	32.4	44.3
2,3,3-trimethyl-pentane	106.0	99.4	6.6	31.1	44.5
2,2,4-trimethyl-pentane	100	100	0.0	31.0	45.3
2,2,3-trimethyl-pentane	109.6	99.9	9.7	31.9	44.3
Cycloparaffins					
Methyl-cyclopentane	91.3	81.0	8.3	32.9	43.7
Cyclohexane	84.0	77.5	6.4	34.0	44.3
Methyl-cyclohexane	73.8	73.8	0.0	33.6	44.3
1,2-dimethyl-cyclohexanes	80.9	78.6	2.3	34.8	43.4
Ethyl-cyclohexane	46.5	40.8	5.7	34.4	43.4
Olefins					
2-methyl-1-hexene	90.7	78.8	11.9	31.2	44.1
3-methyl-t2-hexene	91.5	79.6	11.9	31.7	44.1
2,4-dimethyl-2-pentene	100.0	84.6	15.4	30.8	44.0
Cycloolefins					
1-methyl-cyclopentene	93.6	72.9	20.7	33.8	43.0
Aromatic hydrocarbons					
Benzene	120.0	98.0	10.0	35.5	41.0
Toluene	119.7	109.1	10.6	35.4	41.4
Ethyl-benzene	111.2	97.9	13.3	35.8	41.8
<i>n</i> -propyl-benzene	111.0	98.7	12.3	35.8	41.2
<i>i</i> -propyl-benzene	113.1	99.3	13.8	35.8	41.2

Table 1. Some properties of several gasoline components
RON – research octane number; MON – motor octane number
(Hancsók, J & Eller, Z & Kriván, E 2014)

As a consequence, production of multi-branched isoparaffin containing naphtha streams (as main or by-products) is very important in a crude oil refinery.

Based on the properties of the potential gasoline blending components (streams) (see Table 2) (Srivastava, SP & Hancsók, J 2014), and the actually required quality

specification of gasoline for transport use, the following product streams and crude oil refining technologies have special importance:

- ▶ C_5/C_6 isoparaffins obtained by separation of *n*- and *i*-paraffins in light naphtha (by distillation and / or molecular sieve)
- ▶ C_5 - C_6 isomerates

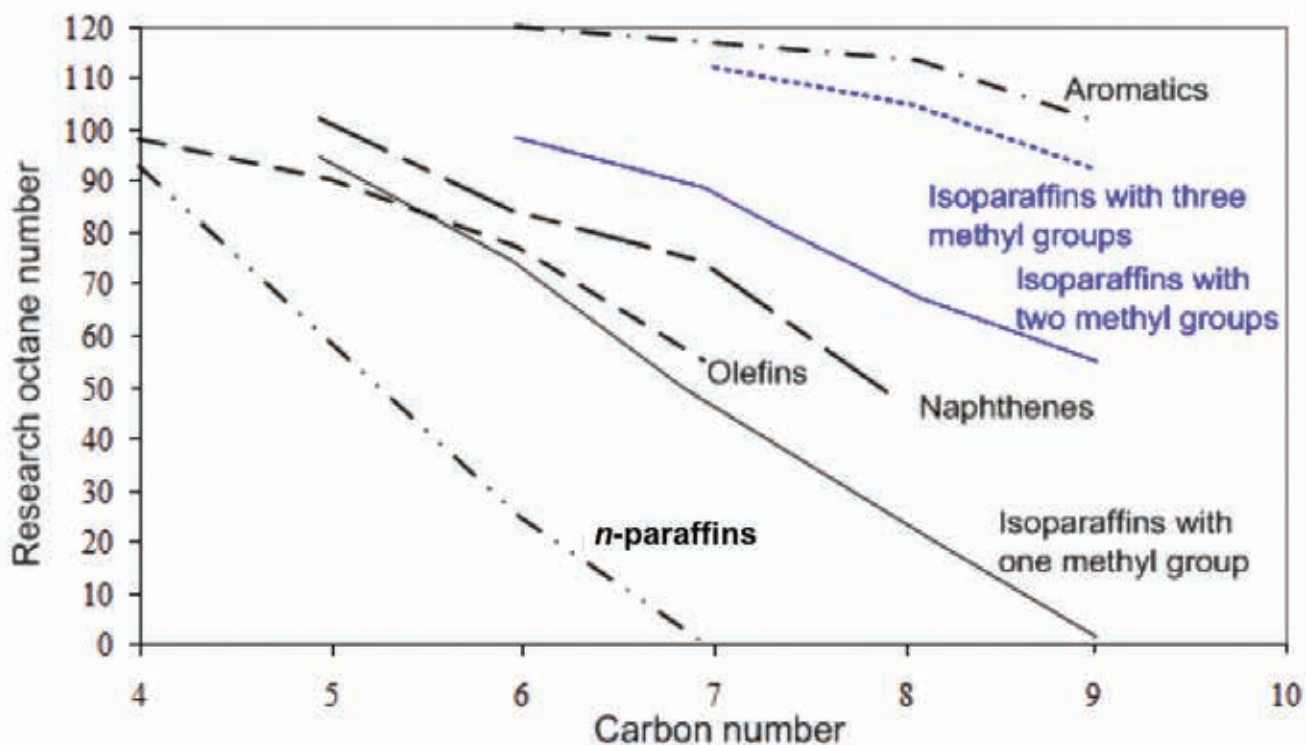


Fig. 4. Research octane numbers of hydrocarbon groups as a function of carbon number

COMPONENTS	PROPERTIES					
	RON	MON	Distillated up to 100 °C, %(v/v)	Sulphur content, mg/kg	Aromatic content, %(v/v)	Olefin content, %(v/v)
Butanes	96	95	100	453	≤10	0
Straight-run naphtha	65	64	90	82	≤10	0
FCC-naphtha	92	79	50	51	5–200	40
Reformate	101	89	30	48	≤1	0
C ₃ /C ₄ alkylate	92	90	50	41	≤10	0
Isomerisate (with circulation)	92	91	100	141	≤10	0
Dimer-naphtha	94	82	10	-	≤10	98
MTBE	118	100	100	53	≤10	0
Bio-ETBE	118	102	100	27.6	≤10	0
Bio-ethanol	111	92	100	16.2*	≤10	0
Typical gasoline quality summer winter	≥95	≥85	≥40-65	≤45-70	≤10.0	≤18.0
	≥95	≥85	≥40-70	≤60-90	≤10.0	≤18.0

Table 2. Typical properties for gasoline blending components

*Blending vapour pressure: about 124 kPa

- ▶ Different alkylates (obtained directly or indirectly)
- ▶ Naphtha fraction received by targeted dimerisation / oligomerisation and possible hydrogenation (indirect alkylation) and
- ▶ High isoparaffin containing byproducts within the naphtha boiling range (e.g. received in *n*-paraffin conversion of gas oils or in base oil production by hydro-isomerisation or hydrocracking of high paraffin containing oil distillates).

In this article we focus on the C_4 – C_6 isomerisation and its importance.

ISOMERISATION OF LOW CARBON NUMBER *n*-PARAFFINS

Isomerisation in the crude oil refining means skeletal rearrangement of lower value and unfavourable hydrocarbons (mainly *n*-paraffins) to more valuable branched hydrocarbons with better fuel properties – without changing the carbon number in the molecule.

ISOMERISATION OF *n*-BUTANE

By isomerisation of *n*-butane in an exothermic catalytic process isobutane is produced. Equilibrium concentrations of *n*- and *i*-butanes are shown on **Figure 5** (Hancsók, J & Eller, Z & Kriván, E 2014). The skeletal isomerisation results in significant octane number increase (from 92 to 100).

Isobutane is mainly used for alkylate production. Furthermore, by dehydrogenation of isobutane, isobutylene can be produced, what can be a feedstock for indirect alkylation and synthesis of ethers (methyl-*tertiary*-buthyl-ether – MTBE, bio-ethyl-*tertiary*-buthyl-ether – bio-ETBE, etc.). Isobutane is also used as a feedstock in production of several petrochemical monomers (e.g. methacrylic acid, methacrolein).

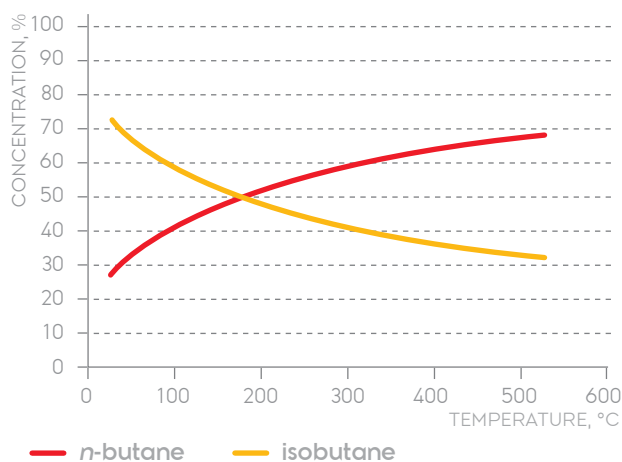
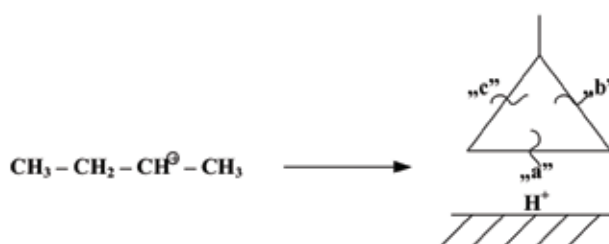


Fig. 5. Equilibrium concentration of isobutene / *n*-butane

According to the most accepted reaction mechanism, *n*-butane's skeletal isomerisation goes through carbenium ion (a trivalent carbon with one positive charge) formation from an intermediate alkyl-cyclopropane ring. Isocarbenium ion is formed by cracking of "a" bond of alkyl-cyclopropane and the isocarbenium ion will be hydrogenated to isobutene:

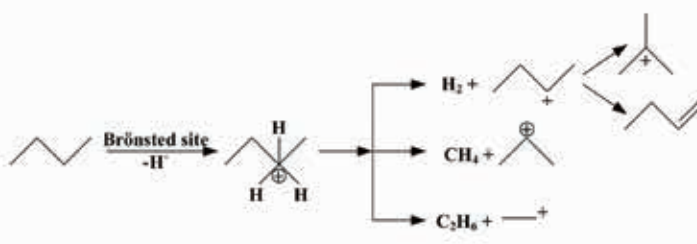


Mechanism of skeletal isomerisation depends on the type and strength of acid sites.

Carbenium ion is formed from *n*-butane at Lewis acid sites via hydride ion drain, what isomerates to create an isocarbenium ion and then isobutane with hydride ion addition (Hydrocarbon Publishing 2010Q1):



Carbonium ion (a pentavalent carbon containing molecule with one positive charge) is formed via proton addition at Brönsted acid sites. Carbonium ion can be converted (by dehydrogenations and / or cracking) into several substances (Chao, KJ & Wu, HC & Leu, LJ 1995):



Dimerisation of C_4 fraction can take place on platinum / sulphated zirconia catalyst what has lower acidity than zeolites. C_4 isomers can be formed from the eight carbon number intermediate products via β -cracking. The product mixture contains C_2 – C_6 hydrocarbons (Adeeva, V & Sachtlar, WHM 1997; Liu, H et al. 1995; Echizen, T et al. 2004; Luzgin, MV et al. 2003):



Feedstock of butane isomerisation contains 70–90% *n*-butane. This fraction can be received from different distillations in crude oil processing, from cracking technologies, furthermore in natural gas processing and preparation of crude oil. During the cracking processes, isobutane is also formed and its concentration can be up to 20–30% in the C₄ fraction. Additionally, C₄ fraction can contain propane, C₅ hydrocarbons and sulphur compounds; the last can be removed by alkaline washing.

Isomerisation of *n*-butane is carried out after high degree drying and desulphurisation of feedstock (its sulphur content should not be higher than 0.1–0.5 mg/kg) in one or more serially connected reactor(s) with fixed catalyst beds. The isomerisation process parameters are 130–210 °C, 20–35 bar total pressure, 1.5–2.5 m³/m³h liquid hourly space velocity (LHSV) and 2:1–3:1 hydrogen-hydrocarbon molar ratio. The product yield is as high as 95–98 % (v/v) and it contains 50–55% isobutane. Isobutane is obtained from the distillation of the feedstock and the product mixture as column head product (containing about 96% isobutene).

Side product of the column is *n*-butane-rich fraction, and the bottom product is C₅₊ fraction (mixture of pentanes with increased *i*-C₅ content received from feedstocks comprising C₅). The side product is recirculated into the isomeriser reactor. For separation of *n*-butane / isobutene mixture one or two columns are applied (see Figure 6) (Meyers, RA 2004). Hydrogen consumption of isomerisation is very low (about 0.05%) therefore recirculation of hydrogen-containing gases is rarely applied. The received 1.5–2% propane and (during the cracking reactions) methane and ethane are used as heating gas.

The most popular catalyst group for *n*-butane isomerisation is Pt(0.3–0.4%) / Al₂O₃ / chlorine (4–8%) used in Honeywell-UOP Butamer™ process (Meyers, RA 2004) (here are more than 100 plants in the world). Another catalyst, Pt / sulphated metal oxide (mainly zirconia) is used in Naftehim process for *n*-butane isomerisation (Urzhuntsev, GA et al. 2014). Isomerisation plants with Pt / sulphated metal oxide catalyst do not need the costly preparation of the feedstock, but the available *i*-C₄ concentration is lower

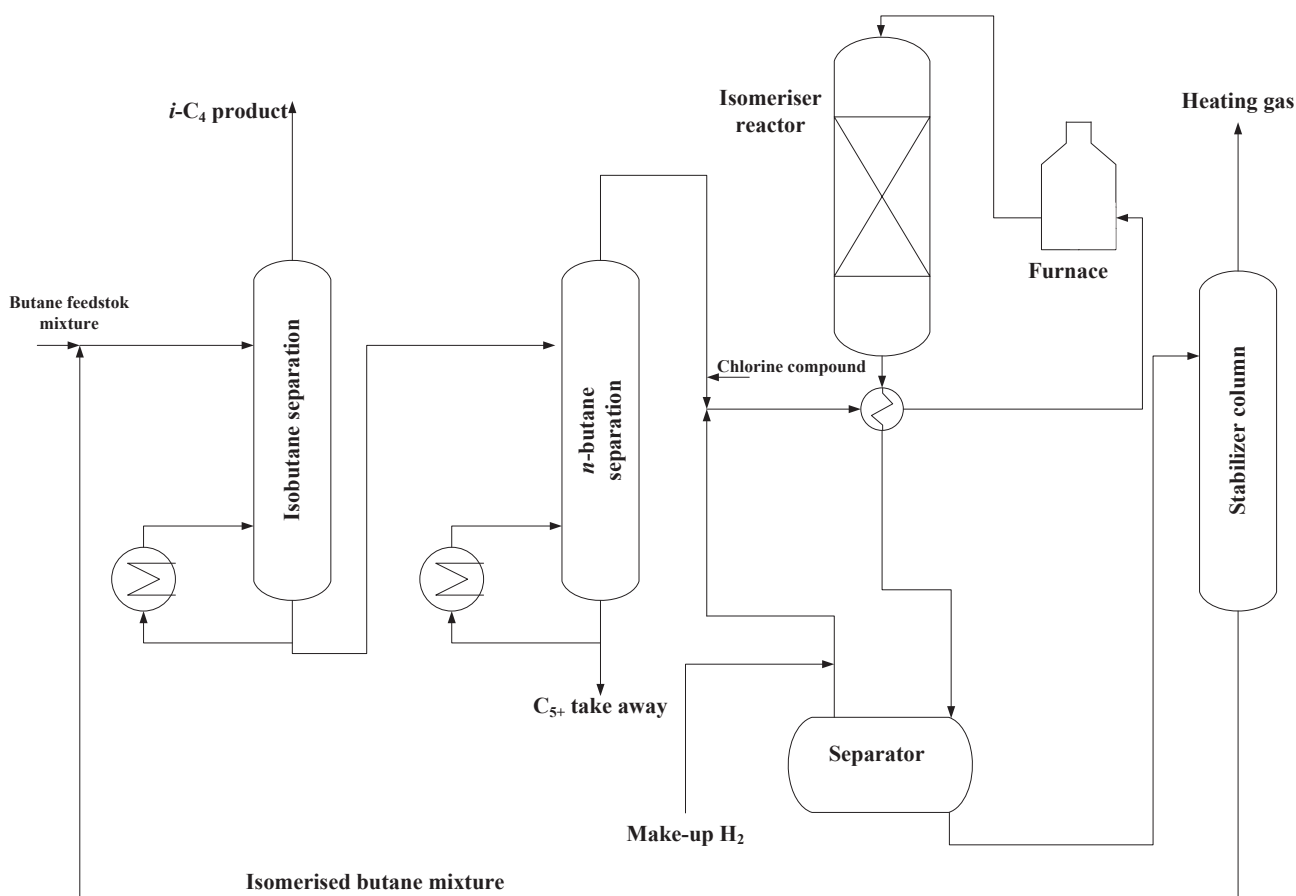


Fig. 6. Principal scheme of *n*-butane isomerisation (Boiling points: *n*-C₄: -0.5 °C, *i*-C₄: -11.7 °C)

(by 4–6% absolute deviation), because their higher operating temperature (above 200 °C) (see Table 3) (Meyers, RA 2004; Urzhuntsev, GA et al. 2014).

ISOMERISATION OF *n*-PENTANE AND / OR *n*-HEXANE FRACTIONS

C₅-C₆ isoparaffins can be obtained by distillation and / or molecular sieve separation from light naphtha fractions or by catalytic isomerisation of suitable normal chain hydrocarbons (product is called isomate). In the last process, *n*-paraffin-rich, low octane number (RON 30–65) C₅-C₆ (incl. C₇ < 2–3%) fractions are converted into high octane number (RON 80–94) isoparaffin-rich gasoline blending components without changing carbon number.

High isopentane and isohexane containing fractions are one of the most important blending components of modern gasolines, because they have the above mentioned advantageous properties (high octane number, low sensibility, free of sulphur, olefin and aromatics, non-toxic, lower CO₂ emissions). Demand for C₅/C₆ isoparaffins is continuously increasing for the following reasons (Hancsó, J & Kasza, T 2011):

- ▶ In the fifties and sixties they were used as octane number improvers
- ▶ In the seventies, eighties and nineties, in parallel with the withdrawal of lead compounds and

limitation of benzene content of gasoline, and in the lack of other, appropriate environmentally friendly blending components they become very important high octane number components

- ▶ From 2000 the even lower benzene and the reduced aromatic contents requirements of gasoline increased the demand for isoparaffins having good research octane number, motor octane number, and octane number distribution
- ▶ Their ability to decrease the research octane number 'donation' due to their lower sensibility (i.e. difference between research and motor octane numbers: 1–3)
- ▶ Isoparaffins can compensate for octane number loss from desulphurisation of cracking (FCC) naphtha
- ▶ Limitation of MTBE and benzene blending (e.g. in the USA MTBE was phased out by May 2006, and benzene content decreased to 0.62 % (v/v) after 2010); isoparaffins can be used for their substitution
- ▶ Their capability to equalise the boiling point range increase caused by ETBE and other heavier ethers (e.g. TAME – *tertiary*-amyl methyl ether)
- ▶ Change in the distillation specifications
- ▶ Requirement for hydrocarbons with higher hydrogen content as fuel (due to their higher energy content, and lower CO₂ emissions) and
- ▶ Profit making based on relatively cheap feedstock availability and lower density of isoparaffins.

APPELLATION	CATALYST	
	Pt/Al ₂ O ₃ /Cl	Pt(Pd)/sulphated metal oxide
Process and catalyst licensor	Honeywell-UOP	Naftehim
Sulphur content, mg/kg	yes	no
Water content, mg/kg	<1	≤200
Reformate	<1	≤20
Operating conditions		
Temperature, °C	130–200	140–220
Pressure, bar	25–32	10–15
Weight hourly space velocity (WHSV), h ⁻¹	2.0–4.0	2.0–4.0
H ₂ /butane molar ratio	0.3	0.5–1.0
Chlorine promotor, mg/kg	10–50	–
<i>n</i> -butane conversion (once-through), %	60–65	58–60
C ₄ + yield, %	95–99	90–95
Isobutane selectivity, %	98	94–95
Catalyst time-on-stream, year	3–5	8

Table 3. Main parameters of *n*-butane isomeriser processes

Blending octane number (BON) of one methyl branched C_5/C_6 isoparaffins is higher by 8–10 units, than the average of their research and motor octane numbers, what is a great advantage (see Table 4) (Hancsók, J & Eller, Z & Kriván, E 2014). (BON is measured for the blend of 20 % (v/v) of the specific hydrocarbon and 80 % (v/v) of a 60/40 isooctane/*n*-heptane mixture.) We note that in the case of light naphtha with high cycloparaffin content (produced from specific crude oils) BON can be higher than the actual RON by 20–30 units. This phenomenon can be explained partially by synergic / antagonistic interactions between hydrocarbons (matrix effect), and partially by sphere shape of molecules, so it is in relationship with the molecules' compression tolerance. For example blending octane numbers of similar-shaped molecules (e.g. cyclohexane and benzene) vary moderately, while the difference between BONs of linear and isoparaffins can be higher (see Table 4). (We note that six carbon number cycloparaffins and benzene can often be found in C_5/C_6 fractions.)

As Table 4 indicates, physical properties of linear alkanes change moderately (e.g. boiling point increases) with increasing carbon number.

Isoparaffins with higher number of branches show higher volatilities (and lower boiling points) than those with less branches, i.e. branching decreases boiling point. Generally, the stronger the attractive intermolecular forces between molecules of a substance, the more energy needed to evaporate the liquid into the atmosphere, i.e. the higher its boiling point. Intermolecular forces depend on the shape of the molecule. For example, van der Waals dispersion forces are proportional to the surface area between the molecules. As a result the straight chain alkanes have higher boiling points than the branched isomers. For the same reason and the steric inhibition of molecules, density of isoparaffins – except some species – are generally lower than that of the *n*-paraffins with the same carbon number. Lower density is an important economic benefit of isoparaffins (Hancsók, J 2008).

In summary, C_5/C_6 isoparaffins with their favourable physical and chemical properties contribute to the good engine start ability and suitable warming-up characteristics (characteristic curve), furthermore to the sufficiently high front octane number (for part of gasoline distilled up to 100 °C) and the moderate octane number distribution.

HYDROCARBON	PROPERTIES					
	Boiling point, °C	Density, g/cm ³ at 15.6 °C	Vapour pressure (RVP), kPa	RON	MON	BON RON
<i>n</i> -butane	-0.5	0.585		95	92	
<i>i</i> -butane	-11.7	0.563		> 100	99	
<i>n</i> -pentane	36.1	0.6312	94.4	61.7	62.6	62
2-metil-butane	28.0	0.6248	130.5	92.3	90.3	99.5
2,2-dimethyl-propane	9.5	0.5967	247.5	85.5	80.2	100
Cyclopentane	29.0	0.7505	63.3	101	85.0	141
<i>n</i> -hexane	69.0	0.6640	32.0	24.8	26.0	19
2-methyl-pentane	60.2	0.6579	43.6	73.4	73.5	82.5
3-methyl-pentane	63.2	0.6640	39.4	74.5	74.3	86
2,2-dimethyl-butane	49.7	0.6540	63.6	91.8	93.4	89
2,3-dimethyl-butane	58.0	0.6664	47.7	103.5	94.4	96
Cyclohexane	80.8	0.7834	21.0	84	77.5	110
Methyl-cyclopentane	71.8	0.7535	29.1	91.3	80.0	107
Benzene	80.1	0.8845	20.7	108.0	98.0	113

Table 4. Main properties of some C_4 – C_6 hydrocarbons
RVP – Reid vapour pressure

Based on all of these favourable physical and chemical properties the share of blended low carbon number isoparaffins in the gasoline pool can be significant, about 10–12%. Demand for isoparaffins increased continuously until 2007, then has stabilised at a somewhat lower level. This is reflected well on the European isomerisation capacity change (see Figure 7) (Hydrocarbon Publishing 2010Q1). In 2013 the worldwide isomerisation capacity was equal to roughly 2.0% of the total processed crude oil. However, this value differs from region to region: 3.9% in the USA, 3.07% in Canada, 4.07% in Western Europe, 0.95% in the former Soviet Union and in Middle and Eastern Europe, 0.8% in Middle and South America, and 0.79% in Africa. The figures indicate that the relative isomeriser capacity is significantly higher in the developed regions than in the less developed ones. This ratio is about 2.3% in Hungary, representing only about 60% of the corresponding value in developed countries (Hydrocarbon Publishing 2010Q1).

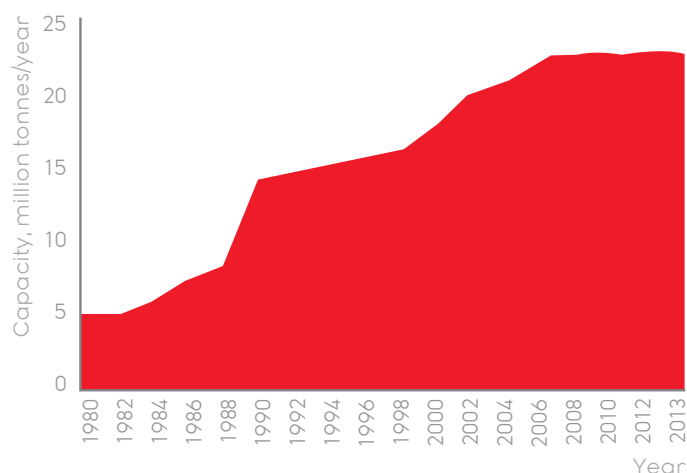


Fig. 7. Light naphtha isomerisation capacities in Europe

Thermodynamics of C_5/C_6 isomerisation

Isomerisation reactions of n -pentane and n -hexane are slightly exothermic (see Table 5). Increasing of temperature reduces formation of the high octane number isopentane and 2,2-dimethyl-butane in the equilibrium mixtures (see Figure 8). Octane numbers of open-chain C_5 and / or C_6 paraffin equilibrium mixtures change according to the abovementioned (see Figure 9) (Hancsók, J & Eller, Z & Kriván, E 2014).

Feedstocks of isomerisation plants can contain cycloparaffins (mainly methyl-cyclopentane) therefore it is useful to know how the equilibrium composition of

ISOPARAFFINS	REACTION HEAT (25 °C), KJ/MOL
from n -pentane	
2,2-dimethyl-propane	-19.93
2-methyl-butane	-8.04
from n -hexane	
2,2-dimethyl-butane (2,2-DMB)	-18.39
2,3-dimethyl-butane (2,3-DMB)	-10.59
2-methyl-pentane (2-MP)	-7.12
3-methyl-pentane (3-MP)	-4.44

Table 5. Reaction heats of n -pentane and n -hexane isomerisation

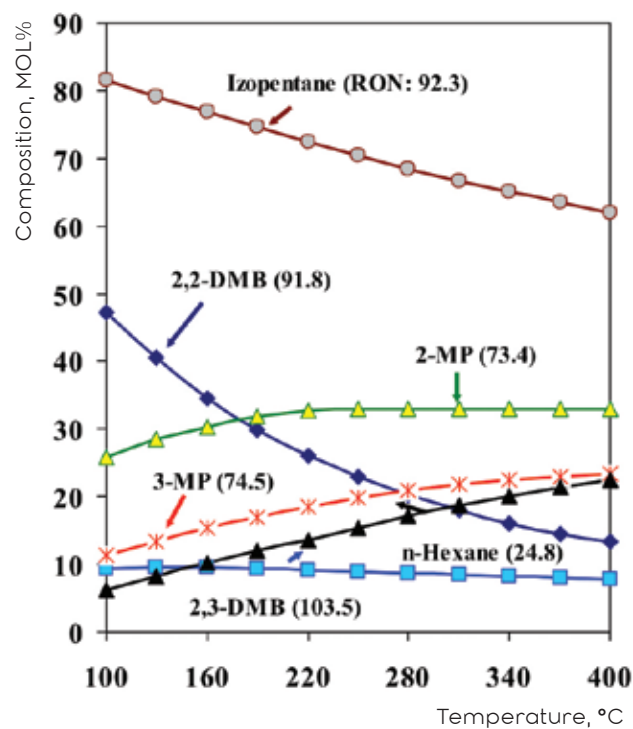


Fig. 8. Equilibrium concentrations of isopentane and hexane isomers

cyclohexane–methyl-cyclopentane system changes as a function of temperature. As Figure 10 shows, increasing of temperature is favourable to formation of the higher octane number methyl-cyclopentane ($RON_{\text{methyl-cyclopentane}}^{\text{cyclohexane}}$: 91.3; $RON_{\text{cyclohexane}}$: 84.0), just opposite to the behaviour of the open-chain C_5 and C_6 paraffins as illustrated in Figure 9. Therefore, when processing high cycloparaffin containing feedstocks, there is a need for compromises to determine the optimum operating temperature.

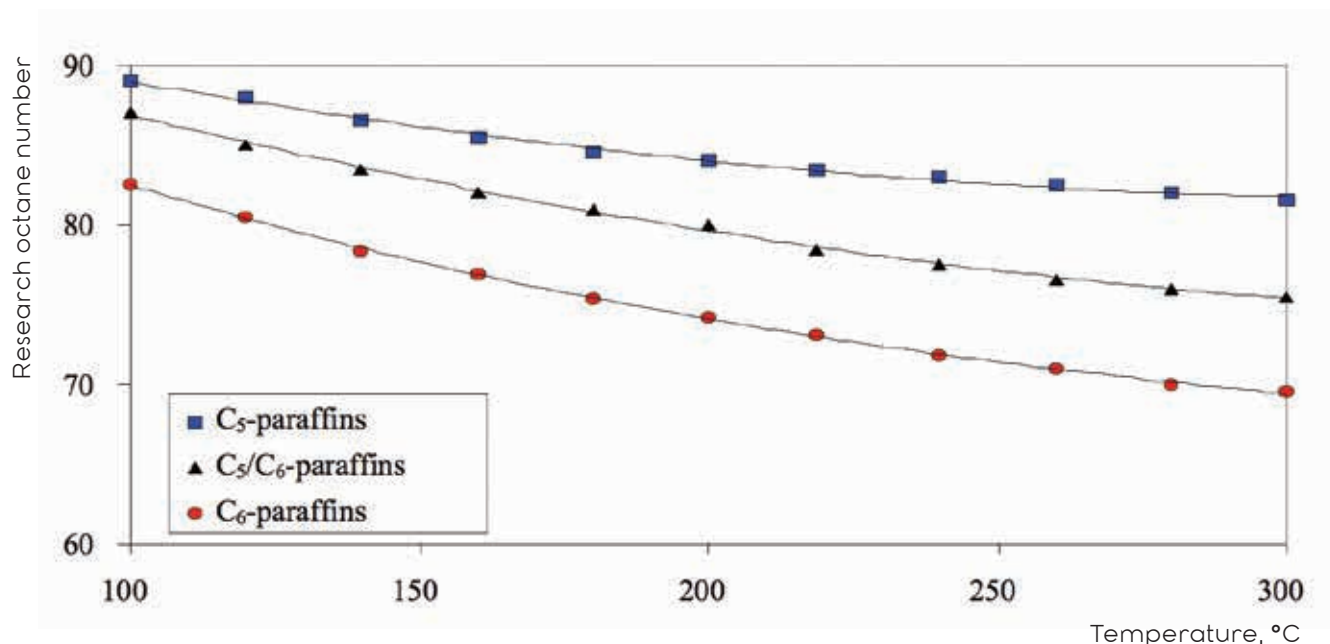


Fig. 9. Research octane numbers of equilibrium mixtures of open-chain C₅ and / or C₆ paraffins as a function of temperature

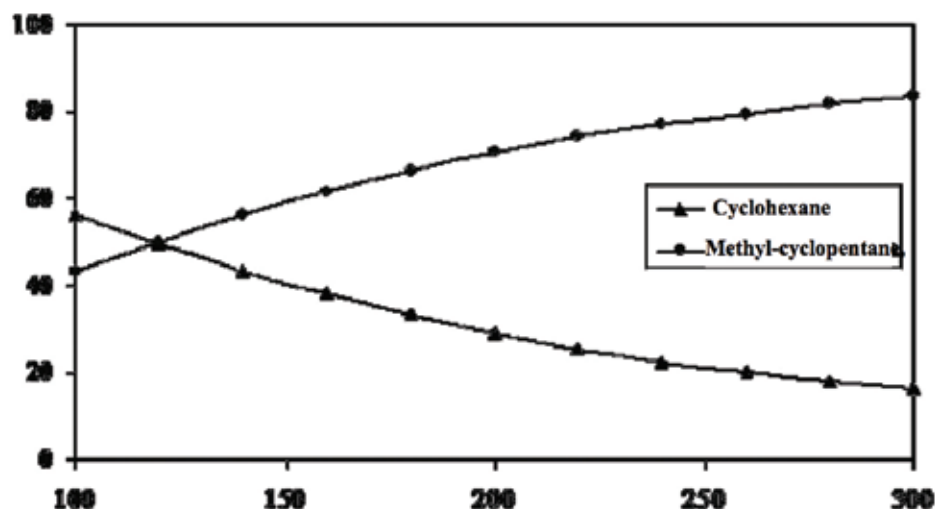


Fig. 10. Equilibrium composition (MOL%) of cyclohexane and methyl-cyclopentane as a function of temperature (°C)

If the benzene content of the feedstock is higher than 1%, the knowledge of benzene-cycloparaffin equilibrium as a function of temperature is important. Under the conditions of isomerisation, quick hydrogenation of benzene to cyclohexane can take place (Hancsók, J 2008).

According to the abovementioned composition analysis of the feedstock is recommended, and the right choice of catalyst and operating parameters for the actual feedstock is very important to get maximum advantage from isomerisation.

Skeletal isomerisation mechanisms of C₅-C₇ hydrocarbons

Conventional isomerisation reaction scheme of C₅-C₇ alkanes over bifunctional catalysts can be explained by skeletal transformation via alkyl-carbenium ions (Olah, GA & Molnár, Á 2003; Weisz, PB 1963; Lopez, G et al.1978; Ribeiro, F & Marcilly, C & Guisnet, M 1982; Otten, MM & Clayton, MJ & Lamb, HH 1994; Guisnet, M & Fouche, V 1991). Olefins are formed (from alkanes) on metal sites what is followed by their diffusion toward the acid sites of the catalyst.

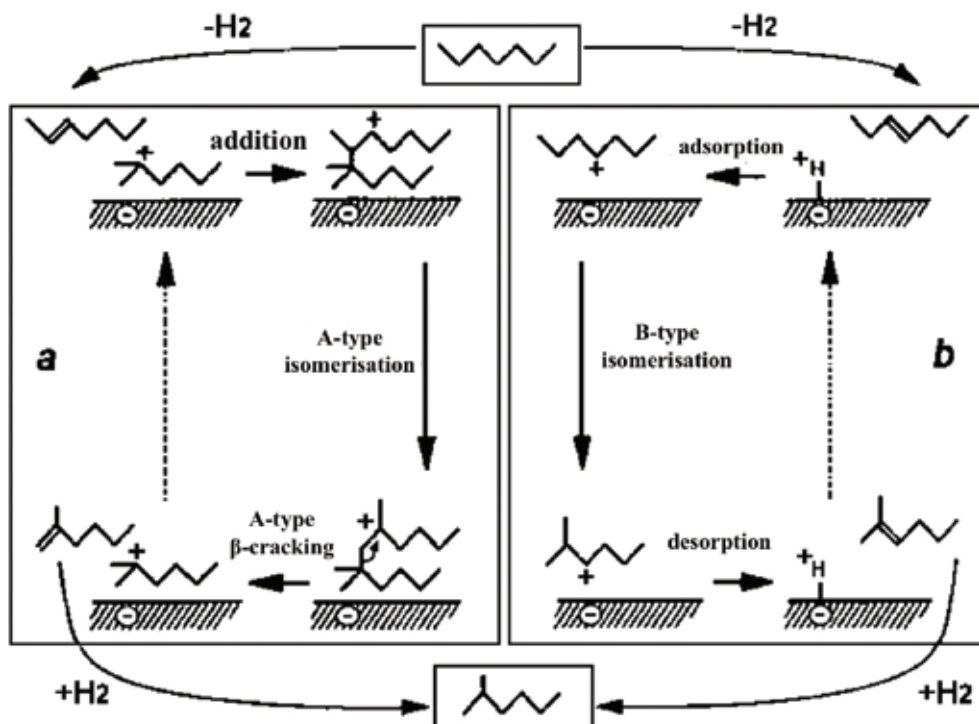
Isomerisation of *n*-heptone on Pd/H-beta zeolite

Fig. 11. Comparison of bimolecular and conventional monomolecular isomerisation mechanisms in case of 2-methyl-hexane formation (a - bimolecular; b - monomolecular)

On the acid sites *n*-carbenium ions are formed with positively charged hydrogen ion addition. *N*-carbenium ions are isomerised to isocarbenium ions, which can transform back to isoolefins and then isoparaffins.

The classic monomolecular (Weitkamp, J 1978; Blomsma, E & Martens, JA & Jacobs, PA 1996), bimolecular or mixed isomerisation mechanisms of light individual normal hydrocarbons on noble metal / zeolite catalysts via carbenium ions, based on several publications (Blomsma, E & Martens, JA & Jacobs, PA 1996; Chao, KJ & Wu, HC & Leu, LJ 1996; Blomsma, E & Martens, JA & Jacobs, PA 1995) are presented on Figures 11 and 12.

According to several researchers skeletal isomerisation of alkanes is carried out via intermediate protonated, supposedly monomolecular and methyl-branched cyclopropane ring (Figure 13) (Weitkamp, J 1978; Blomsma, E & Martens, JA & Jacobs, PA 1996; Weitkamp, J 1982; Fajula, F 1985; Guisnet, M et al. 1987; Alvarez, F et al. 1989; Holló, A & Hancsó, J & Kalló, D 2002; Martens, JA & Jacobs, PA 1990). Higher ethyl-, propyl-, butyl-branched isomers are supposedly formed via higher cycloalkane rings (Martens, JA & Jacobs, PA 1990).

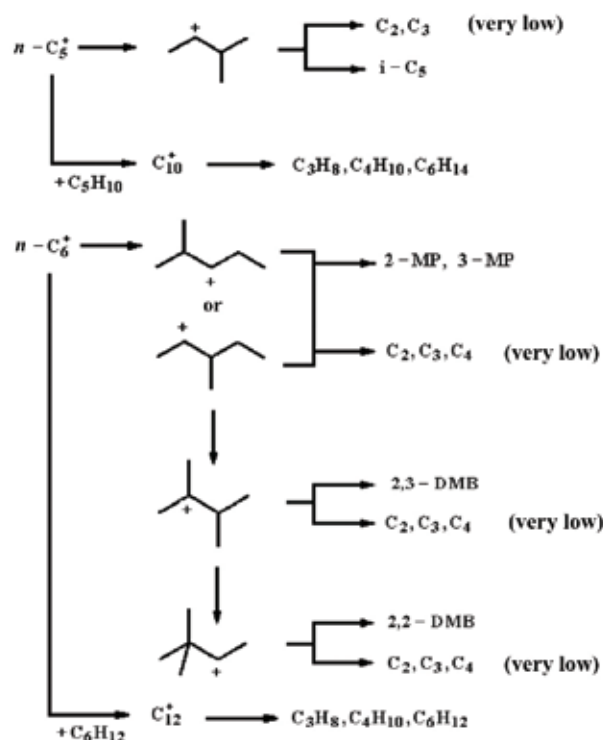


Fig. 12. Mechanism of *n*-C₅ and *n*-C₆ carbenium ion isomerisation on bifunctional zeolite catalysts (Chao, KJ & Wu, HC & Leu, LJ 1996)

16 CHALLENGES ▶ Key components of modern engine fuels for internal combustion engines: the isoparaffins. Part 1. Light naphtha isomerisation

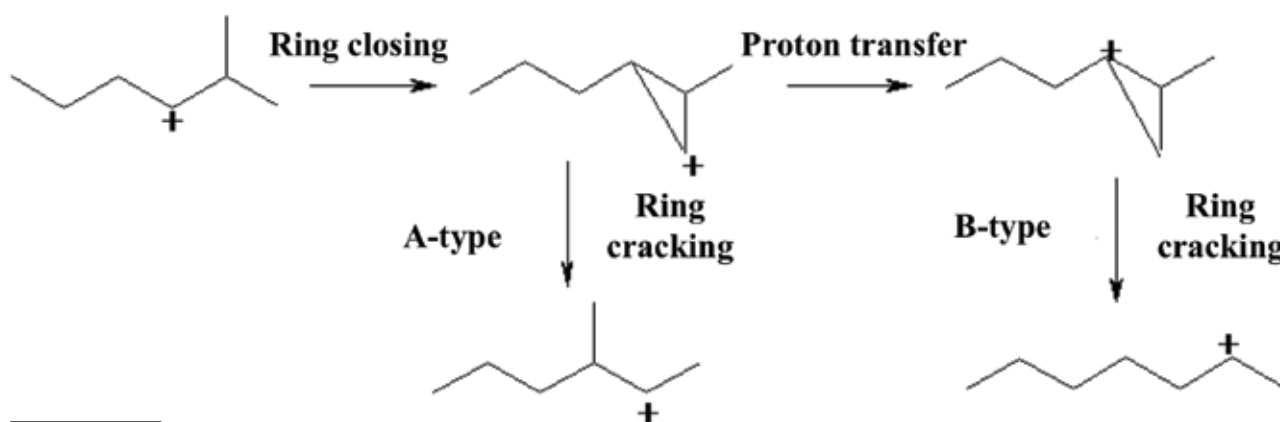


Fig. 13. Monomolecular mechanism of isomerisation via cyclopropane intermediates

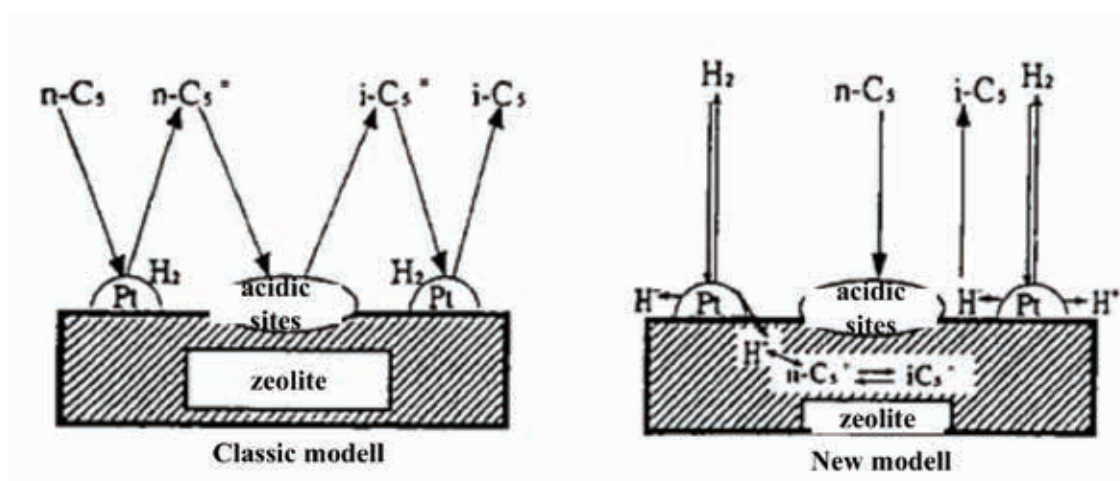


Fig. 14. Reaction models of *n*-pentane isomerisation on Pt-containing catalyst

Gas phase proton and hydride ion (from hydrogen) play an important role in another suggested mechanism of *n*-pentane isomerisation (see Figure 14) (Zhang, A et al. 1995; Fujimoto, K & Maeda, K & Aimoto, K 1992). They improve the activity of alkanes and stabilise the intermediate products, what contributes to the high isoparaffin yield.

In the above mentioned classic bifunctional mechanism selectivity and reaction velocity depend on the properties of the hydrogenation and acid sites of the catalyst, and the diffusion between these sites. In case of 'ideal' isomerisation mechanism skeletal transformation and cracking of the carbenium ion on the acid place are the rate determining reaction steps (Pichler, H et al. 1972). Diffusion of the olefin intermediates between hydrogenation and acid sites can play an important role. Guisnet with colleagues (Guisnet, M et al. 1987) studied deeply the relationships between ratio of acid and hydrogenation functions of Pt/HY zeolite in *n*-heptane

transformation. After changing the catalyst's platinum content between 0.1–1.5% and Si/Al content between 3.9–35.0, they found the number of acid sites (n_A) has strong effect on activity, selectivity and stability of the catalysts, where the adsorption heat of ammonia was higher than 100 kJ/mol, moreover the number of free metal sites (n_{Pt}) has effect too. Effect of metallic and acid sites to the *n*-heptane isomerisation can be seen in Table 6 (Fajula, F 1985; Guisnet, M et al. 1987).

If ratio of n_{Pt}/n_A is enough high (>0.17) the catalysts are ideal for hydroisomerisation. Olefin intermediates contact only some acid sites between two hydrogenation sites, and undergo only one transformation. This could be isomerisation or cracking. Isomerisation of *n*-heptane is carried out in a series of steps illustrated on Figure 15. Possibility of contraction of olefin intermediaries on acid sites between two hydrogenation sites is very low. Thus coke formation reactions – what contribute to the deactivation of catalysts – are suppressed.

n_{Pt}/n_A	<0.03	0.03–0.17	>0.17
Activity	low	maximum	maximum
Stability	low	average	excellent
Selectivity			

Table 6. Impact of the ratio of metal and acidic sites on the isomerisation activity, stability and selectivity of Pt/HY catalysts

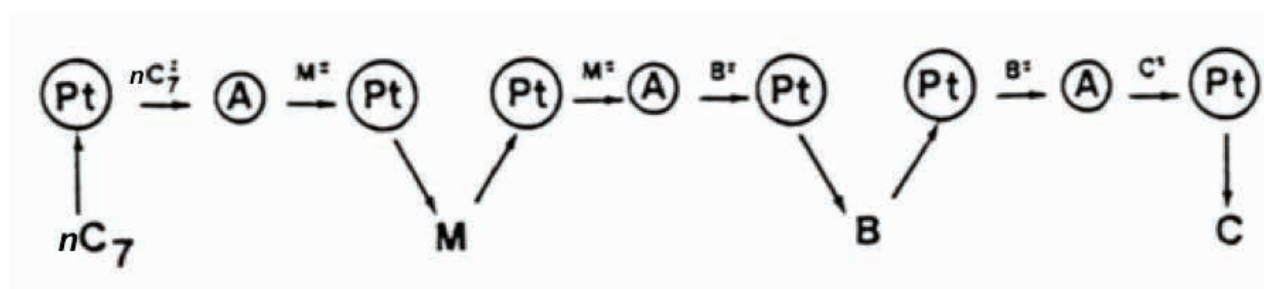


Fig. 15. Conversion of *n*-heptane on Pt/HY catalyst of $n_{Pt}/n_A > 0.17$ (M – monobranching; B – double branching; C – cracking products; A – acid sites)

Industrial realisation of C_5/C_6 isomerisation

Feedstocks of light naphtha isomerisation can be the following:

- ▶ Light naphtha fractions of natural gas processing plants
- ▶ (Desulphurised) straight-run naphthas (with boiling range of 25–82 °C)
- ▶ Bottom product of gas fractionating plants
- ▶ Light naphthas of hydrocracking processes
- ▶ Hydrogenated light coker-naphtha
- ▶ Raffinate from aromatic extraction
- ▶ Light reformat (rarely).

Feedstocks of light naphtha isomerisation must be pretreated by desulphurisation and / or drying in order to meet the contaminant tolerance of the applied catalyst. Adsorbents were developed by Honeywell-UOP

and Johnson Matthey to remove total mercury content from feedstock to protect the catalyst and maintain its activity (Hydrocarbon Publishing 2014Q4).

Catalysts. Temperature dependencies of the presented thermodynamical equilibrium compositions and octane numbers of the equilibrium mixtures give unequivocal proof that the isomerisation of light naphthas must be carried out at the lowest possible temperature. Based on this and for maintaining catalyst stability, low and middle temperature hydroisomerisation catalysts are applied in the last 15–20 years. Temperature limits of **Table 7** (Hancsó, J & Baladincz, J & Magyar, J 2008) are self-chosen values, they can be overlapped (Hancsó, J & Baladincz, J & Magyar, J 2008; Corma, A & Serra, JM & Chica, A 2003; Nefthim 2011; Farid, A & Boucenna, A 2010; Sadighi, S et al. 2013; Hidalgo, J et al. 2014).

18 CHALLENGES ► Key components of modern engine fuels for internal combustion engines: the isoparaffins. Part 1. Light naphtha isomerisation

Requirements	High temperature	Middle temperature	Low temperature
Favourable temperature, °C	min. 300	200–300	max. 200
Catalysts	Pt(0.5–0.6%)/g Al ₂ O ₃ /F F: 3–4%	Pt(0.3–0.5%)/HY zeolit Pt(0.3–0.5%)/H-Mordenite	Pt(0.3–0.4%)/ Al ₂ O ₃ /chlorine (7–10%) Pt/sulphated metal oxide Mixed metal oxide
Required feedstock quality			
Sulphur content, mg/kg	80–100	50–100	below 0.1
Nitrogen content, mg/kg	2–5	max. 1	below 0.1
Water content, mg/kg	20–100	50–100	below 0.1
C ₇ +, %	max. 5	max. 1	max. 1

Table 7. Catalysts and feedstock requirements for isomerisation of C₅/C₆ paraffins

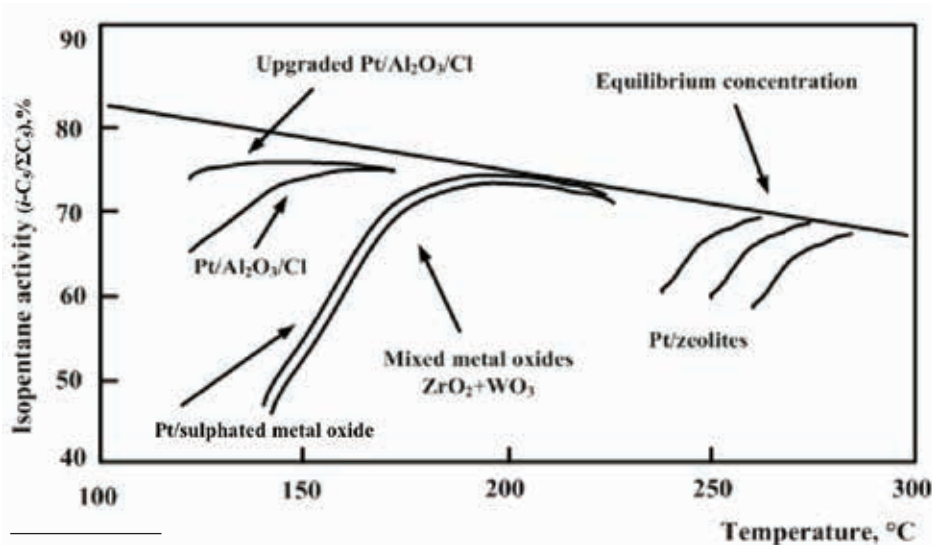


Fig. 16. Comparison of the activity of commercial isomerisation catalysts

As Figure 16 indicates product mixtures with the highest *i*-pentane yield (and the highest octane number) can be obtained on Pt/Al₂O₃/Cl catalyst (with once-through transition) (Corma, A & Serra, JM & Chica, A 2003).

Recent isomerisation catalyst research focuses on the reduction of demand for the expensive platinum, especially through the application of different metal oxide catalysts and synthesis methods, e.g.

- Aluminium promoted sulphated zirconia (SO₄²⁻/ZrO₂-Al₂O₃), having higher thermal stability and higher catalytic activity caused by its increased acidity (alumina)
- Gallium promoted sulphated zirconia has even higher thermal stability and catalytic activity

- Different synthesis methods include reflux driven zirconia gel, sulphuric acid addition to mesoporous ZrO₂-SiO₂ synthesis mixture, and copper oxide promoted sulphated zirconia with (*cis*)-MCM-41 support (MCM – Mobil composition of matter).

There are many papers about the tungsten oxide (WO₃) addition to noble metal catalyst, e.g. Re/Ga₂O₃/WO₃/ZrO₂ or Pt/WO₃-ZrO₂ catalysts, SAPO (silica-alumina-phosphates) molecular sieve and MoO₃/TiO₂ catalysts. Researchers of University of Pannonia and Hungarian Academy of Sciences got patent protection (P1200439 – Catalyst and process for selective hydroisomerisation of paraffin hydrocarbons and process for catalyst production) for a new composition catalyst.

Main C₅/C₆ isomerisation processes

However, with the reduction of the temperature of isomerisation to 100 °C or in case of the production of equilibrium product mixture isomerate having max. 90 RON can be produced. The reason of this is that unconverted *n*-paraffins have very low octane number (RON: *n*-C₅: 62; *n*-C₆: 25). So, octane number increase of isomerates is obtained with different effective separation of lower octane number 2- and 3-methyl-pentanes and *n*-paraffins with different methods (distillation – trayed, packed, and / or molecular sieve).

Many versions of C₅/C₆ isomerisation processes are known. Generally, every plant is comprised of a *feedstock pretreating unit* (desulphurisation and / or dryer and *i-/n*-paraffin separator) and an *isomerisation unit* (with product stabilisation), moreover one further *i-/n*-paraffin separator unit. This last can serve as a feedstock pretreating unit, too. In a lot of cases, there is a 'hydrogen-rich gas' treater plant section. The main differences between the processes can be the following:

- ▶ Pretreating of the feedstock (drying, desulphurisation, *i-/n*-paraffin separation, and their methods)
- ▶ Number of isomerisation reactors (one or more) and their internal structure
- ▶ Composition of the applied catalyst, its placement in the reactor, activation, regenerability
- ▶ Once-through hydrogen transition or hydrogen recirculation application

- ▶ Most important technological parameters (temperature, pressure, liquid hourly space velocity, hydrogen / hydrocarbon molar ratio, activating agent addition, type and quantity of activator, etc.)
- ▶ Source, pressure and purity of make-up hydrogen
- ▶ Method of *i*- and *n*-paraffin separation (distillation – trayed, packed, and / or molecular sieve).

The listed attributes are the operating conditions of the isomerisation technologies, too. If higher liquid hourly space velocity is applied, higher temperature must be used for the same product quality, but the available thermodynamical equilibrium concentration of isoparaffins will be lower (!), and hydrocracking reactions must be considered as well. This is what would happen, if the activity loss of catalyst is compensated with temperature increasing.

The simplest classification of the isomerisation processes can be made on the basis of the operating temperature ranges of catalysts: low temperature (under 200 °C), middle temperature (200–300 °C) and high temperature (>300 °C) processes can be differentiated. Main properties of the most important processes are summarised in Table 8 (Hancsók, J & Baladincz, J & Magyar, J 2008; Hancsók, J 2008; Domergue, B & Watripont, L 2005; Bui, ChH & Nguen, VT & Ahmetov, AV 2008).

Categorisation by operating temperature	Owner(s), licensor	Process specification									
		Catalyst	Feedstock after pretreatment				Operating temperature, °C	Product properties			
			Sulphur, mg/kg	Nitrogen, mg/kg	Water, mg/kg	Benzene and C _n , %		Yield, %	<i>i</i> -C ₅ /ΣC ₅	2,2-DMB /ΣC ₆	RON**
Low temperature max. 200 °C	Honeywell-Universal Oil Products Co. (UOP)	Pt/Al ₂ O ₃ /Cl*	<0.1	<0.1	<1	<2	120–160	≥ 98.0	~73	~32	94
		Pt/Al ₂ O ₃ /Cl	<0.1	<0.1	<1	<2	120–160	≥ 98.0	~74	~33	94
	AKZO	Pt/Al ₂ O ₃ /Cl	<0.5	<0.1	<1	<2	120–160	≥ 98.0	~72	~31	93
	Albemarle/Total, Axens	Pt/Al ₂ O ₃ /Cl	<0.5	<0.1	<1	<2	120–160	≥ 98.0	~72	~31	94
	NPP Neftekhim (Russia)	Pt/sulphated metal oxide	≤2	≤1	≤10	<2	120–180	≥97.5	~73	~32	93
	Honeywell-UOP	Pt/sulphated metal oxide	<1.0	<0.5	<50	<2	160–200	≥96.5	~72	~21	92
	Süd-Chemie (Clariant)	Pt/sulphated metal oxide	<1.0	<0.5	<50	<2	160–200	≥96.5	~70	~21	92
	ExxonMobil	ZrO ₂ + WO ₃	<1.0	<0.5	<20	<2	175–200	≥96.0	~70	~20	91
Middle temperature 200–300 °C	Honeywell-UOP	Pt/zeolite/ Al ₂ O ₃	<10	<2	<100	<5	240–260	≥96.0	~66	~18	91
	IFP – Axens	Pt-H-mordenite	<10	<2	<50	<5	250–260	≥96.0	~65	~18	91
	Süd-Chemie (Clariant)	Pt-H-mordenite	<10	<2	<50	<5	250–270	≥96.0	~65	~18	91
	Ripp (Sinopec)	Pt/zeolite	<2	<2	<50	<5	230–270	≥96.0	~66	~18	91
	Indianoil	Pt/zeolite	<200	<2	<200		240–280	≥96.0	65	17	91

Table 8. Main properties of the most common isomerisation processes

Pressure range: 2–30 bar

Liquid hourly space velocity (LHSV): at low temperature: 1.5–3.0 h⁻¹, at middle temperature: 1.0–3.0 h⁻¹

Hydrogen / hydrocarbon molar ratio: 1.0–3.0:1, except * where: 0.1–1.0:1

2,2-DMB – 2,2-dimethyl-butane; RON – research octane number; **depends on the recirculation of low octane number components

Both the kinetic and thermodynamic limits of the obtainable isoparaffin concentration must be considered to get the optimal results of $n\text{-C}_5/n\text{-C}_6$ isomerisation. So, considering only the thermodynamic equilibrium concentration approach (QTECA, %) is not enough. Isoparaffin concentration of a product mixture can be higher in a case of a low QTECA, if the isomerisation was carried out on a catalyst operating at lower temperature (Figure 17) (Hancsók, J 2008).

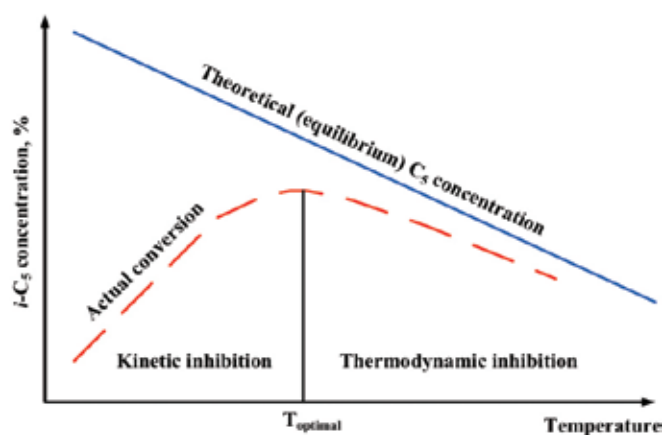


Fig. 17. Change of $i\text{-C}_5$ concentration in the isomerate as a function of temperature

Based on octane number and yield of isoparaffin and cycloparaffin hydrocarbons obtained by separation, relative and absolute efficiencies of isomerisation can be calculated (Hancsók, J 2008) as follows. (Boundary condition: separation of i - and cycloparaffins from n -paraffins is theoretically 100%.)

Relative efficiency of isomerisation (IRH_T):

$$\text{IRH}_T = \frac{\text{IAH}_T}{\text{IAH}_{T_e,T}} \cdot 100$$

where

IRH_T – relative efficiency of isomerisation at T temperature, %

IAH_T – absolute efficiency of isomerisation at T temperature, %

$\text{IAH}_{T_e,T}$ – absolute efficiency of isomerisation at thermodynamic equilibrium at T temperature

T – temperature, °C

T_e – calculated from the theoretical (thermodynamic equilibrium) composition, °C.

Absolute efficiency of isomerisation (IAH):

$$\text{IAH} = \frac{Y_{(i\text{-C}_x + c\text{-C}_x)} \cdot \text{RON}_{(i\text{-C}_x + c\text{-C}_x)}}{100}$$

where

IAH – absolute efficiency of isomerisation, %

Y – yield of hydrocarbons, what the calculation refers, %

RON – research octane number. ($i\text{-C}_x + c\text{-C}_x$) – iso- and cycloparaffins.

IRH and IAH values can characterise performance of industrial catalysts and the effects of the operating parameters (mainly of temperature and liquid hourly space velocity – LHSV). To get the relative efficiency data, there is a need for QTECA values at the given temperature(s).

Equilibrium compositions at the given temperatures can be easily calculated using specific polinoms (Nelder-Mead nonlinear simplex method). These are the following for some C_5 - and C_6 iso- and normal-paraffins (c indicates concentration in mol%, T – temperature, °C) (Hancsók, J 2008).

C_5 hydrocarbons

$$c_{2\text{-MB}} = 90.7160 - 0.0975 \cdot T + 6.4550 \cdot 10^{-5} \cdot T^2 \text{ and}$$

$$c_{n\text{-C5}} = 100 - c_{2\text{-MB}}$$

$$\text{where } 100 \leq T \leq 420;$$

C_6 hydrocarbons

$$c_{2,2\text{-DMB}} = 77.5994 - 0.3593 \cdot T + 5.6646 \cdot 10^{-4} \cdot T^2$$

$$\text{where } 100 \leq T \leq 200 \text{ and}$$

$$c_{2,2\text{-DMB}} = 61.3432 - 0.2095 \cdot T + 2.2424 \cdot 10^{-4} \cdot T^2$$

$$\text{where } 200 \leq T \leq 400;$$

$$c_{2,3\text{-DMB}} = 6.0440 + 0.0503 \cdot T - 1.8276 \cdot 10^{-4} \cdot T^2$$

$$\text{where } 100 \leq T \leq 145 \text{ and}$$

$$c_{2,3\text{-DMB}} = 10.3362 - 4.7260 \cdot 10^{-3} \cdot T - 4.1440 \cdot 10^{-6} \cdot T^2$$

$$\text{where } 145 \leq T \leq 400;$$

$$c_{2\text{-MP}} = 13.4676 + 0.1548 \cdot T - 3.0631 \cdot 10^{-4} \cdot T^2$$

$$\text{where } 100 \leq T \leq 290 \text{ and}$$

$$c_{2\text{-MP}} = 29.3688 + 0.0222 \cdot T - 3.3638 \cdot 10^{-5} \cdot T^2$$

$$\text{where } 290 \leq T \leq 400;$$

$$c_{3\text{-MP}} = 2.9153 + 0.0951 \cdot T - 1.0996 \cdot 10^{-4} \cdot T^2$$

$$\text{where } 100 \leq T \leq 400;$$

$$c_{(n\text{-H}_x)T} = 100 - (c_{2,2\text{-DMB}} + c_{2,3\text{-DMB}} + c_{2\text{-MP}} + c_{3\text{-MP}})T$$

$$\text{where } 100 \leq T \leq 400.$$

More than 90% of isomerisation plants use catalysts or technologies developed by Honeywell-UOP, so the development process of industrial isomerisation can be traced on the example of this company. Figure 18 (Hancsók, J & Eller, Z & Kriván, E 2014) illustrates that

from the introduction of high temperature catalyst in the 1950s' to the present day technological variations the main driving forces of development of isomerisation catalysts were quality improvement of gasoline (e.g. octane number increase, lead content decrease and termination, total aromatic content decrease, benzene content reduction), decrease of capital and operating

costs (via feedstock and energy savings, lower hydrogen consumption), and human health and environmental aspects.

The most effective and economical light naphtha isomerisation processes operate – as we mentioned – with low temperature catalysts (e.g. $\text{Pt}/\text{Al}_2\text{O}_3/\text{Cl}$, see Figure 19).

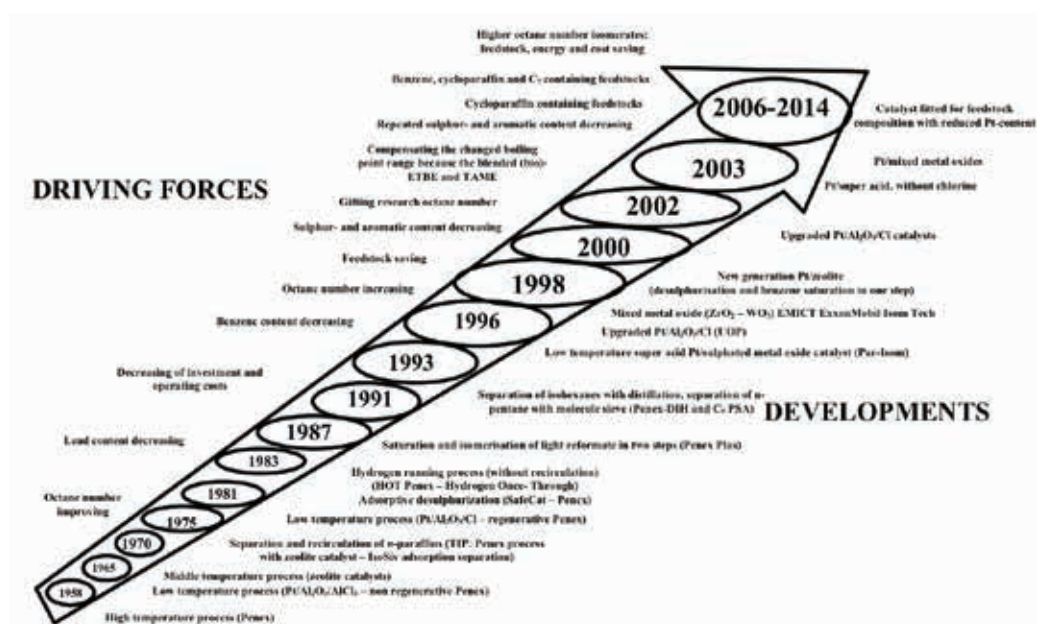


Fig. 18. Driving forces of isomerisation catalyst and technology development

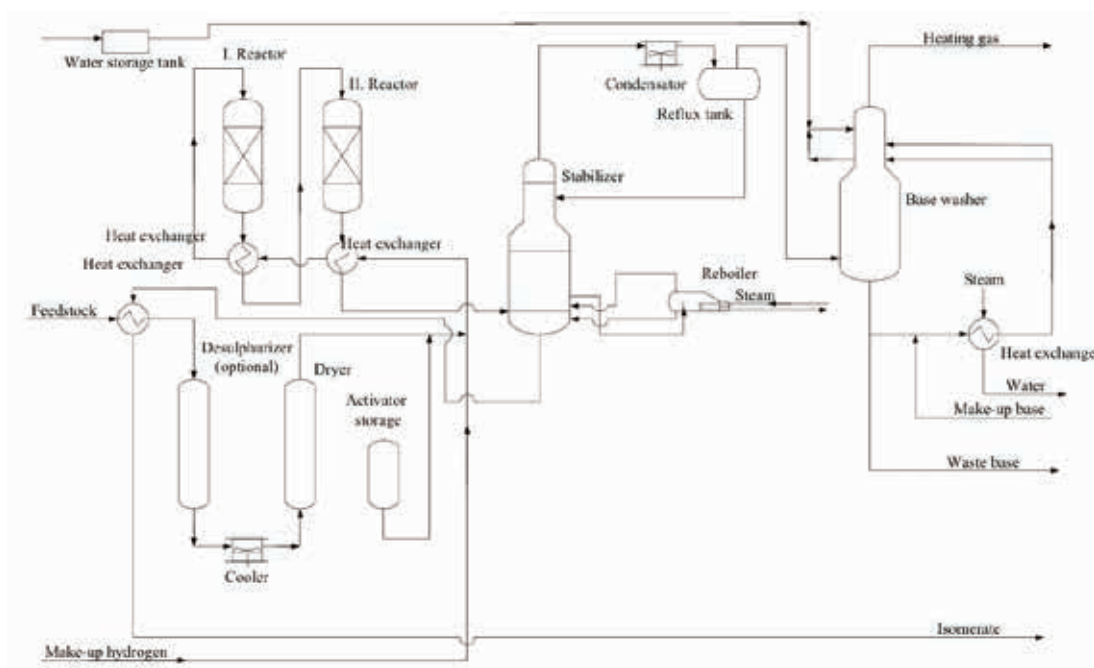


Fig. 19. Principal scheme of the most simple low temperature isomerisation plant (once-through, without hydrogen recirculation and furnace) (Meyers, RA 2004)

The main advantages of the low temperature isomerisation processes compared to the high temperature ones are the following (Hancsók, J & Kasza, T 2011; Hancsók, J 2008):

- ▶ **Feedstock savings**
 - Lower quantity cracking products because of lower rate of hydrocracking reactions at lower temperature
 - Lower quantity of recirculated *n*-paraffins because the higher conversion to *i*-paraffins at the same temperature and lower rate of hydrocracking
- ▶ **Energy savings (lower CO₂ emissions)**
 - Lower reaction temperature ($\Delta T = 120\text{--}140\text{ }^{\circ}\text{C}$)
 - Lower hydrogen recirculation flow rate because of the lower H₂ / hydrocarbon molar ratio
 - Lower energy for separation of *n*- and *i*-paraffins and recirculation because of the higher conversion (because *n*-paraffins are received in low quantity)
 - Furnace is needed only at the start-up of the plant, because of the low operating temperature (reaction heats from benzene saturation and *n*-hexane isomerisation can be used for preheating the feedstock)
- ▶ **Significant capacity increase** because of the lower *n*-paraffin recirculation (at the same LHSV and catalyst quantity), or **lower catalyst quantity** at the original capacity, this means cost efficiency
- ▶ **Higher isoparaffin yield** (by 6–10 absolute %) at the same quantity and quality of the feedstock (feedstock savings), because of the following:
 - Higher conversion to isoparaffins in once-through transition mode
 - Quantity of byproducts is lower (by 3–5 absolute %)
 - Quantity of recirculated hydrocarbons is lower by 8–9% after the *n*-/*i*-paraffin separation, due to the lower cracked product yield
- ▶ **Lower hydrogen consumption** (and CO₂ emissions reduction in hydrogen production) because of the lower degree of hydrocracking reactions at low temperature (hydrocracking is a large hydrogen consumer: $C_n H_{2n+2} + H_2 \rightarrow C_m H_{2m+2} + C_{n-m} H_{2(n-m)+2}$). No need for H₂ circulation compressor in many cases, especially in case of hexane-rich feedstocks and application of different circulation methods. This means shorter payback period
- ▶ **High octane number isomerates help** to minimise gasoline RON giveaway in crude oil refining (the standard motor octane number can be obtained only if the research octane number is higher by 1–2 units than the required value) and

- ▶ **The product mixture has higher octane number** (by 2–5 units) at once-through systems; this means USD 2.0–2.5 million yearly product value ('value added') increase in case of a 150 000 t/y isomerisation plant (see Figure 20). For example if RON improvement of isomerate by 1 unit costs 3 USD, then RON improvement by 4 units would result in about USD 2 million per year product value increase in 150 000 t/year capacity plant.

Recent developments focus on cost reduction of the lower temperature isomerisation (e.g. by lowering noble metal content), improvement of process flexibility and composition / impurities (e.g. sulphur, water) tolerance of the feedstock and of corrosive materials.

Only 82–84 octane number isomerate can be obtained with once-through mode of isomerisation on the most active Pt/Al₂O₃/Cl catalyst. Higher octane number isomerates can be received only by separation of low octane number components before or after the isomerisation process. Product having 90–94 research octane number can be produced with the technological order presented on Figure 21 (Meyers, RA 2004). Application of the two isopentane separator units in one plant needs compromises. We note that by using a suitable active catalyst and technological structure, in case of separation and recirculation of *n*-paraffins and methyl-pentanes, isomerate with MON 94, RON 98–102 and sensibility 8–10 units can be received (and these properties are very similar to the ones of reformate).

BENZENE SATURATING ISOMERISATION

The initial boiling point of naphtha feedstock for reforming has been increased (over 70–80 °C) to obtain low benzene containing reformate (since benzene content of gasolines was maximised at 1 % (v/v)). Thus the quantity of unprocessed light naphtha is increasing in a refinery. This straight run naphtha contains C₆ hydrocarbons (e.g. methyl-cyclopentane, cyclohexane, benzene) and low quantity of C₇ hydrocarbons (<2%), too (benzene and toluene can be formed from these compounds at the conditions of naphtha reforming). Its (2–6%) benzene content depends on the origin of crude oil and can be processed by benzene saturating isomerisation (Palmer, ER & Shipman, DR 2008; Hancsók, J et al. 1999). In this process total saturation (hydrogenation) of benzene and skeletal isomerisation of *n*-paraffins are carried out in one step.

At the isomerisation of cycloparaffin- and benzene-containing feedstocks for example on Pt/H-mordenite catalyst, cyclic compounds decrease the degree of isomerisation (e.g. as a consequence of strong

adsorption of benzene on metal sites and partially on acid active sites). However, below 3–4% benzene content of the feedstock, process has numerous advantages to compensate this decrease (MSZ EN 228:2013; Palmer, ER & Shipman, DR 2008; Hancsók, J et al. 1999; Hancsók, J et al. 2007; Szoboszlai, Zs & Hancsók, J 2009). These are the followings:

- ▶ Total hydrogenation of light naphtha benzene content is a very fast and exothermic reaction, so lower reactor inlet temperature can be applied (resulting in energy savings, and lower CO₂ emissions)
- ▶ Benzene content of isomerisation products is lower than 0.01%
- ▶ In case of high methyl-cyclopentane and low cyclohexane containing feedstocks the cyclohexane formation from benzene inhibits the conversion of methyl-cyclopentane to lower octane number cyclohexane (RON_{m-cp}: 91.3, RON_{c-h}: 83.5). (Generally, straight-run naphtha fraction for benzene saturation has the mentioned composition, because boiling point of *n*-C₆ is 69.0 °C, that of methyl-cyclopentane is 71.8 °C, while that of cyclohexane is 80.8 °C.)

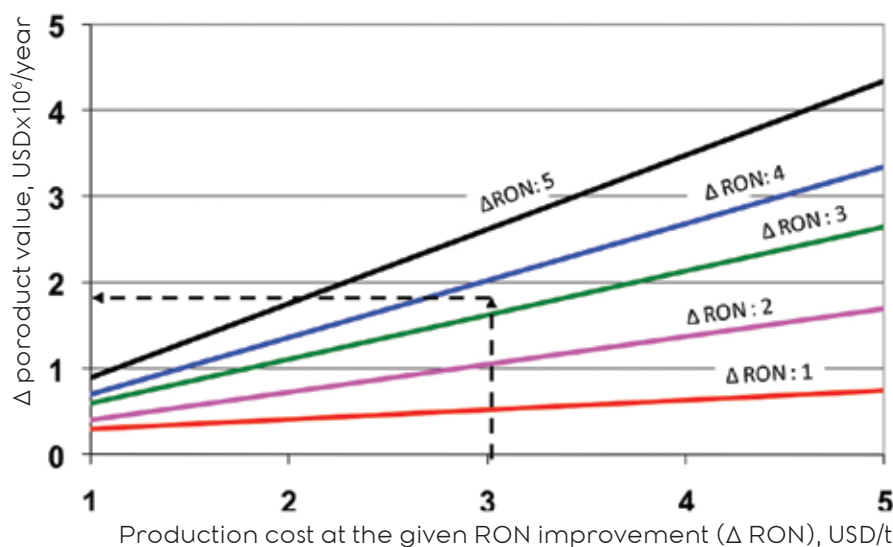


Fig. 20. Value improvement of product ('value added') as a function of production cost (of octane number increase) (at 150 000 t/year feed-stock capacity)

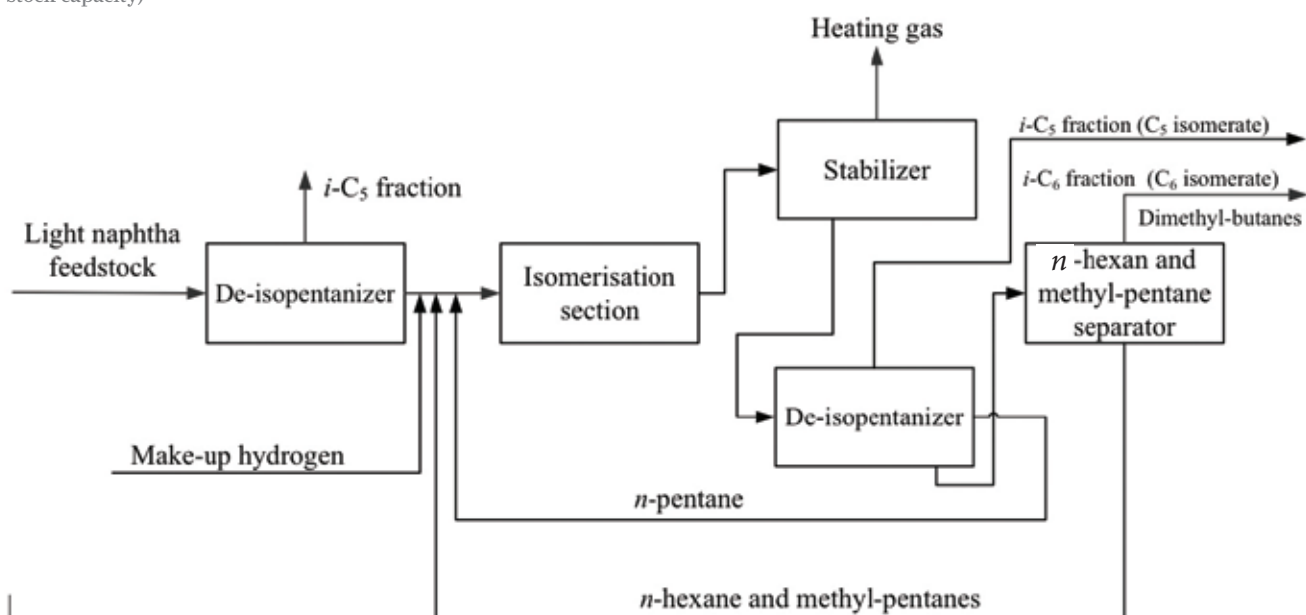


Fig. 21. Isomerisation with maximum recirculation of the low octane number components (Meyers, RA 2004)

- ▶ Octane numbers of cyclohexane received by saturation of benzene, but especially of its mixture with the forming methyl-cyclopentane have higher octane numbers, than the isoparaffin mixture of *n*-hexane ($n\text{-C}_6 + \Sigma i\text{-C}_6$) (see Figure 22) (Hancsók, J & Holló, A 1997).
- ▶ For feedstocks with not more than 3% benzene content octane numbers of iso- and cycloparaffins are nearly the same after the *n*-paraffin separation. Increasing benzene content inhibits isomerisation to a larger extent, but this is equalised as a result of high octane numbers of cyclohexane and methyl-cyclopentane received from benzene (as Figure 22 shows at 260 °C octane number of equilibrium mixture of cyclohexane and methyl-cyclopentane is higher by 11 units than the octane number of equilibrium mixture of open-chain C_6 isoparaffins). C_6 isoparaffins could be received, if *n*-hexane is in the feedstock instead of benzene. Important to note, that methyl-cyclopentane only can be formed from cyclohexane, if the methyl-cyclopentane

concentration in the reaction mixture is lower than the thermodynamic equilibrium concentration at the studied temperature)

- ▶ At the appropriate operating parameters saturation of benzene (to form cyclohexane) and isomerisation of cyclohexane into methyl-cyclopentane take place until the equilibrium concentration, without serious losses to ring-opening reactions. This is very important, because in case of ring-opening reactions lower octane number 2- and 3-methyl-pentanes are formed moreover ring-opening reactions consume a lot of hydrogen; so the cycloparaffin content of the feedstock is important.

Catalyst systems of $\text{Pt}/\text{Al}_2\text{O}_3$ /chlorine are suitable for benzene saturating isomerisation (at up to 4% benzene content of feedstock). Application of two serial reactors (160–170°C and 120–130°C), or two beds in one reactor are suggested with different technological parameters (incl. chlorine quantity) (see Figure 23) (Hancsók, J et al. 2007).

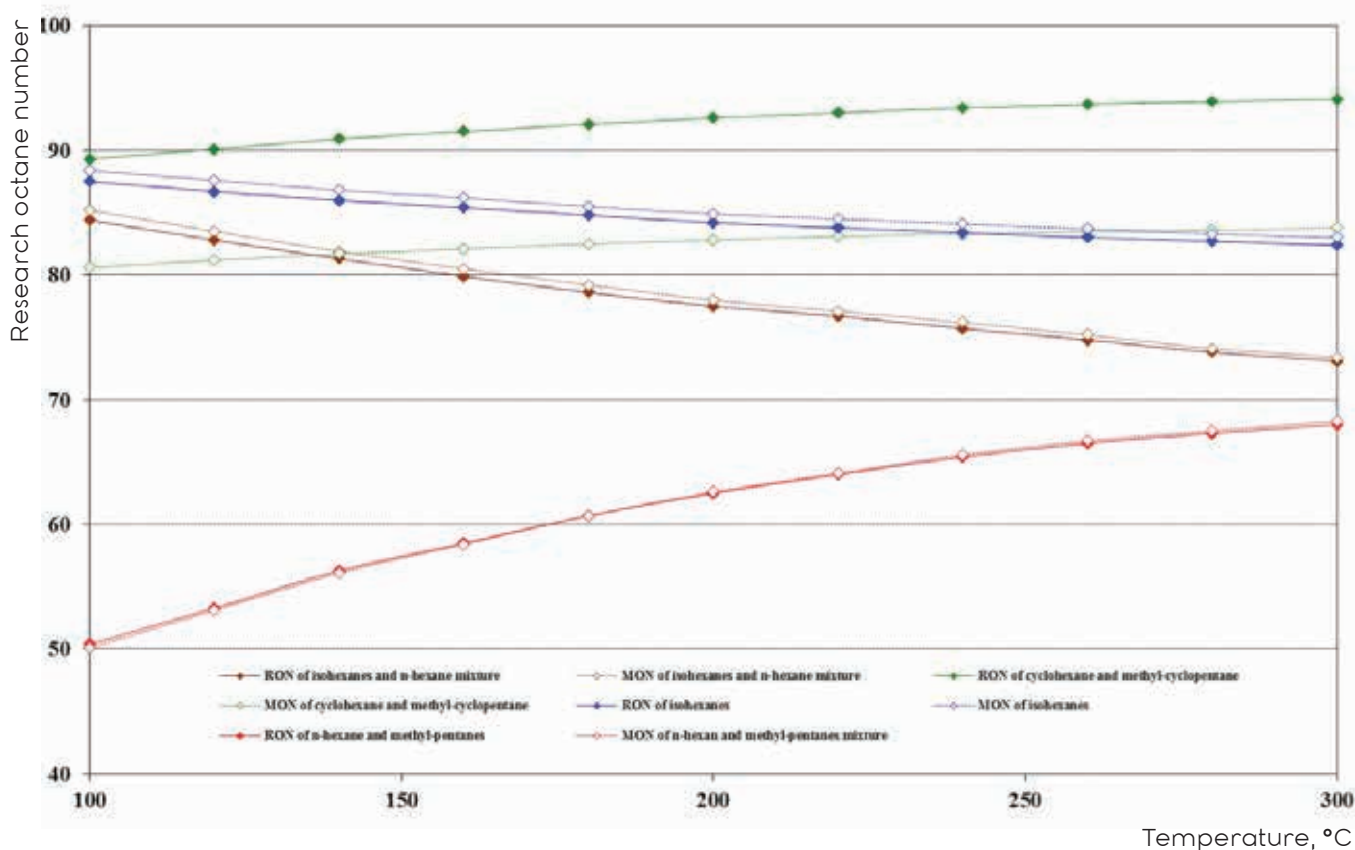


Fig. 22. Octane numbers of different hydrocarbons as a function of reaction temperature (calculated curves from equilibrium compositions and blending octane numbers)

The newest catalyst developments of Honeywell-UOP are the unknown compositions of PI-242 and PI-244 (with lower Pt content), regenerable Pt/super acid catalyst with the advantages of Pt/Al₂O₃/Cl and Pt/sulphated metal oxides. According to Honeywell-UOP the product mixture has lower octane number only by 1–3 units compared to the obtained product on Pt/Al₂O₃/Cl catalyst. This catalyst does not contain chlorine therefore there is no need for chlorine addition. The activity of catalyst decreases only a little bit at 10 mg/kg water content of the feedstock, and to a larger extent at 30 mg/kg water content, but not in an irreversible way: there is no need for feedstock drying. Other advantage of the catalyst is that the furnace can be omitted from the process because of the low operating temperature (150–180°C). The disadvantages of the catalyst compared to Pt/Al₂O₃/Cl – besides the lower activity – are the lower selectivity and the lower liquid product yield and the higher H₂ / hydrocarbon ratio (recirculation compressor should be applied).

Catalytic membrane reactors for isomerisation are also suggested. For example a combination of Pt/Al₂O₃/Cl catalyst with zeolite membrane would let through only low octane number components with one methyl-

branching to the catalyst (Gora, L & Jansen JC 2005). Catalytic distillation is also suggested to obtain higher isoparaffin yield and improve energy efficiency and economics (Parputs, OI et al. 2014).

The share of isopentanes and isohexanes in good quality gasolines is 5–15%, while in the premium grade gasolines it can reach 20–30%.

We presented a possible example for profitable operation of C₅/C₆ isomerisation plant in a crude oil refinery on **Figure 20**. As it can be seen about 4 units of RON increase would lead to about USD 2 million product value ('value added') increase in case of a 150 000 t/year capacity plant. This is extremely important, if we consider the octane number increase of blending components in the higher ranges (over RON 85).

SUMMARY

C₅/C₆ isomerates, what are the products of light naphtha isomerisation, are essential components of modern, high hydrogen- and energy-containing, clean burning gasolines. They are sources of significant profit due to their low density (and relatively high volume).

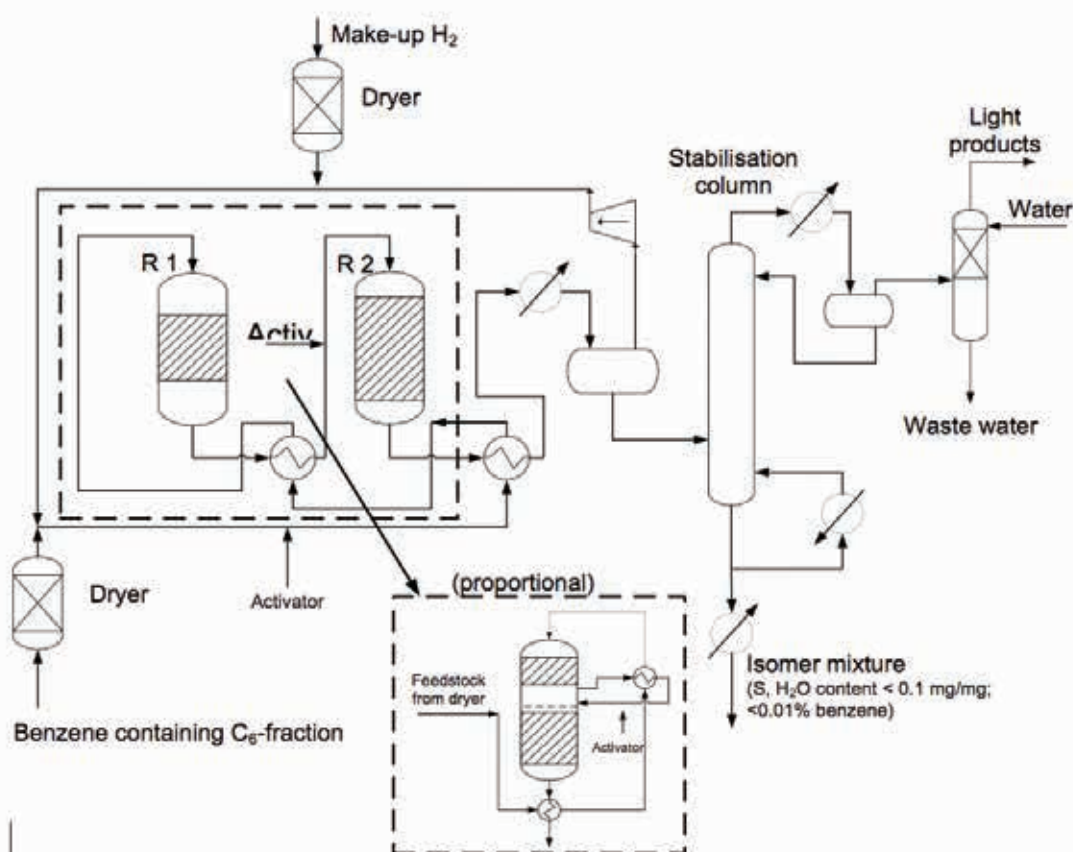


Fig. 23. Scheme of isomerisation of benzene containing hexane fraction

High isoparaffin concentration and octane number of liquid product mixtures can be obtained at the applicable lowest temperature. This is the temperature at which the given catalyst shows high activity and selectivity at the necessary and economic liquid hourly space velocity (capacity).

Two or divided bed reactor(s) with internal cooling can be applied, what makes possible the achievement of equilibrium concentration of isoparaffins in the product mixture.

Composition of feedstocks should be determined for considering the equilibrium concentrations and octane numbers of each component and the possible ways of chemical conversion. In this case isomerisation of benzene containing (3–4%) feedstocks can be carried out economically. With the so called benzene saturating isomerisation (saturation of benzene and isomerisation in one step) technically benzene free and high octane number products can be received. Octane numbers of once-through isomerates can be improved up to 94 by separation and recirculation of lower octane number components (*n*-paraffins and 2-, 3-methyl-pentane). It is important to highlight that sensibility of isomerates is a low positive number, so product can be obtained with 89–91 motor octane number. This allows to reduce the research octane number giveaway, thus contributing to higher profits.

Keywords: light naphtha, isomerisation, catalyst, thermodynamics, kinetic, development of industrial processes

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Prof. Jenő Hancsók, DSc was the first at the Department, who had prepared and defended his thesis (entitled 'Quality improvement of engine fuels on catalytic way') for doctor of Hungarian Academy of Sciences, since professor József Varga (head of department 1952–1956) had done. Author and co-author of 10 professional books published in Hungary and in the USA, and more than 850 scientific papers in international journals and conference proceedings. He holds 14 patents that are partly applied in the chemical industry.



Zoltán Eller works at MOL Department of Hydrocarbon- and Coal Processing since 2010. He makes a PhD thesis entitled 'Investigation of biojet fuel production possibilities'. He is author and co-author of more than 40 scientific paper. Zoltán graduated as a chemical engineer (MSc) in 2010 at University of Pannonia.



Zoltán Varga, PhD worked for more than 3 years for MOL DS Development, before rejoining University of Pannonia at the end of 2009 as the coordinator of the MOL Hydrocarbon and Petrochemical Technology specialisation. He is author and co-author of more than 50 scientific and technical articles and papers. He graduated as a chemical engineer and later received PhD degree from University of Pannonia.



András Holló, PhD joined MOL in 2000 and worked in various managerial and expert positions in different SCM and R&D fields. He works currently on legislative and product development issues in MOL and leads the MOL Department at Pannon University, Veszprém. He has MEng and PhD degrees in chemical engineering, University of Veszprém and MBA degree, Budapest University of Technology and Economics.



Géza Varga joined MOL Group in 1999, and his first job was to develop high performance detergent-dispersent lubricating oil additives. From 2001 he held various positions in MOL Downstream organisation including Development director of INA and Development director of MOL Hungary. On 1st September 2014, he joined OT Industries as a Business Development manager. Géza graduated as chemical engineer (MSc) in University of Veszprém in 1997, and after two year post-graduate course he became a research engineer.

EOR CO₂ project Croatia, environmental aspects

Karolina Novak Mavar, PhD (37)

SD&HSE expert

INA d.d., E&P BD, SD&HSE Department

Karolina.NovakMavar@INA.hr

ABSTRACT

Production of residual hydrocarbons can be done by different tertiary, EOR (enhanced oil recovery) or EGR (enhanced gas recovery) methods. An EOR method largely applied on 'depleted' oil reservoirs is injection of carbon dioxide when a part of the produced carbon is turned back into the reservoir in the form of carbon dioxide (CO₂). At the same time carbon dioxide is regarded as the primary greenhouse gas contributing to global warming and climate change. Up to our knowledge INA EOR CO₂ injection project Ivanić and Žutica represents the largest on-shore EOR project in Europe. Due to the significant amount of CO₂ recovered from and injected into the reservoir special environmental protection measures shall be implemented in different project phases. After providing information on the EOR by CO₂ injection the article delivers information on the Ivanić and Žutica EOR CO₂ project, with special attention to its environmental aspects.

INTRODUCTION

After application of primary (natural flow, artificial lift) and secondary (water flooding, pressure maintenance) oil recovery methods about two third of geological reserves remain in the reservoirs (Sečen, J 2005). By the tertiary, so called enhanced oil recovery methods the reservoirs' pressure is supported due to alteration of natural forces in the reservoirs. The alteration is caused by the injected media affecting the reservoir conditions (physicochemical properties of the reservoir system, like surface tensions for water / oil / gas systems, viscosity differences, and reservoir heterogeneity), and can result in an economically viable additional hydrocarbon extraction (Sečen, J 2006; Al-Jarba, M & Al-Anazi, BD 2010; Tunio, SQ et al. 2011).

Oil fields suitable for the application of methods for improving oil recovery by injection of CO₂ can be approximately described by the following values (Sarapa, M 1981; Stalkup, FI 1980):

- Viscosity of oil at temperature 15 °C (μ_o) <12 mPa s
- Density of oil at temperature 15 °C (ρ_o) 825–865 kg/m³
- Residual oil saturation ("the ratio of the immobile residual oil volume divided by the the effective porosity")¹ (S_{or}) >25% and
- Initial reservoir pressure ("measured in a discovery well")² (p_i) >100 bar.

By CO₂ injection oil recovery usually increases by 10 up to 14% (Sarapa, M 1981; Sečen, J 2006).

Numerous laboratory studies have identified positive effects of CO₂ application in order to increase oil recovery: (a) significant reduction in oil viscosity and increment in water viscosity, (b) change in oil and water density, (c) swelling of oil, (d) evaporation of oil, (e) increase in reservoir rocks permeability, (f) changes in the wetting ability of rocks, (g) the possible occurrence of dissolved gas regime (Sečen, J 2006; Al-Jarba, M & Al-Anazi, BD 2009; Novak, K 2015). Although oil displacement is possible in both immiscible and miscible conditions, miscible conditions completely overcome capillary forces which retain residual oil in the pore space. Establishment of the miscible zone depends on pressure, temperature, reservoir rock and crude oil composition (Taber, JJ & Martin, FD & Seright, RS 1997).

Currently there are several dozens of active EOR and EGR projects all over the world. INA Exploration and Production Business Division started the pilot project of CO₂ injection into the reservoir Gamma 2/4 of the Ivanić oil field in 2001 by water injection. In late 2003 it was proceeded by CO₂ injection into the injection well Iva 28. After two cycles of alternating injection of water and CO₂ the obtained results confirmed effectiveness of CO₂ and justified the launch of the EOR project. EOR project started in October 2014 represents the first tertiary method application in Croatia and at the same time INA's most important upstream investment project in the continental Croatia. The project aims to enhance

¹ viewed 26 March, 2016, <http://www.glossary.oilfield.slb.com/Terms/r/residual_oil_saturation.aspx>.

² viewed 26 March, 2016, <http://www.glossary.oilfield.slb.com/en/Terms/i/initial_reservoir_pressure.aspx>.

hydrocarbon production by alternating injection of carbon dioxide and water into the mature oil fields in the Sava Depression (Croatian Part of the Pannonian Basin System), Žutica and Ivanić.

The whole technological process comprises several stages, incl. preparation of CO₂ for transport, transport by pipeline to the injection well, well injection, production and collection of produced hydrocarbons, and is monitored by relevant process and safety equipment. The system is closed and there is no CO₂ leakage during regular operation and normal technological process. Discharges are possible only in case of incidents (pipeline rupture, breakthrough of CO₂ through possible fractures of the cement bond in the injection wells annular, and surface leakage of process equipment).

Due to harmful effects on human health and entire ecosystem which could be caused in case of higher CO₂ concentration appearance, INA E&P BD pays special attention to health, safety and environmental protection measures applied. Special environmental target of the project is the strong contribution to CO₂ emissions reduction. Although the EOR / EGR projects using CO₂ extracted from produced 'fluids' do not belong to the standard carbon storage projects, primarily due to fossil fuels production and because they do not (permanently) dispose CO₂ generated in the combustion of fossil fuels, experience and obtained data can be very helpful for commercial application of such technologies.

PHYSICO-CHEMICAL PROPERTIES OF CO₂

Carbon dioxide is a chemical compound composed of two oxygen atoms covalently bonded to one carbon atom. The gas is colourless and in small concentrations odourless. Carbon dioxide is considered nontoxic. It is not a hazardous substance. The air we breathe contains about 0.03 v/v% carbon dioxide. At higher concentrations, it is characterised by sharp, sour smell which can cause a feeling of suffocation and irritation. In concentrations above 5 v/v% it is considered life-threatening.

CO₂ is a medium chemically reactive and non-flammable. Physicochemical characteristics of CO₂ are shown in Table 1. CO₂ is the anhydride of the carbonic acid (H₂CO₃), which is quite unstable in aqueous solutions and breaks down to carbon dioxide and water (<http://encyclopedia.airliquide.com/encyclopedia.asp>). At standard pressure and temperature, the density of CO₂ is about 1.98 kg/m³.

Physical state of CO₂ depends on temperature and pressure. The equilibrium states of matter established under certain conditions of pressure and temperature are given in the phase diagram (Figure 1). The diagram curves separate equilibrium states of two phases. The point at which all three phases coexist, determined by the intersection of all the curves in the diagram, is called the triple point (5.1 bar, -56.6 °C). At atmospheric pressure and temperature of -78 °C, CO₂ directly converts to solid, without creating a transient liquid phase.

Chemical formula		CO ₂
Molecular weight		44 kg/mol
Melting point		-57 °C (216 K)
Boiling point		-78 °C (195 K)
Density	at 0 °C and 1.013 bar (gas)	1.976 kg/m ³
	at 0 °C and 34.8 bar (liquid)	914 kg/m ³
	at -56.6 °C and 1.013 bar (solid)	1 512 kg/m ³
Solubility		0.145 g in 100 g of water
Critical point		31.1 °C; 73.8 bar
Triple point		5.1 bar, -56.6 °C
Density at pressure at the critical point		468 kg/m ³

Table 1. Physicochemical properties of CO₂ (<http://encyclopedia.airliquide.com/encyclopedia.asp>)

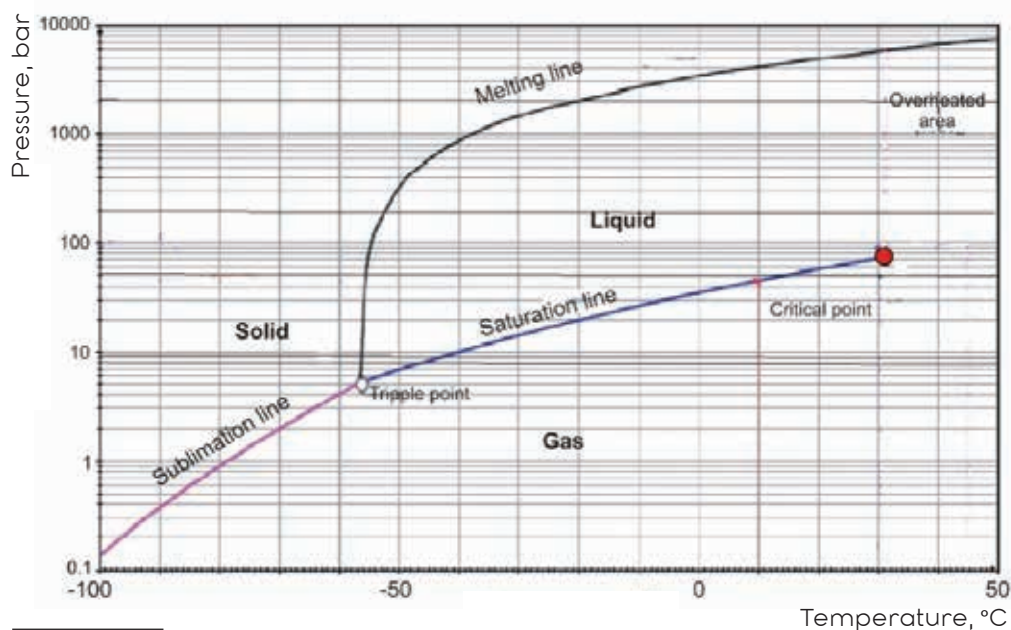


Fig. 1. CO₂ phase diagram (Novosel, D 2009)

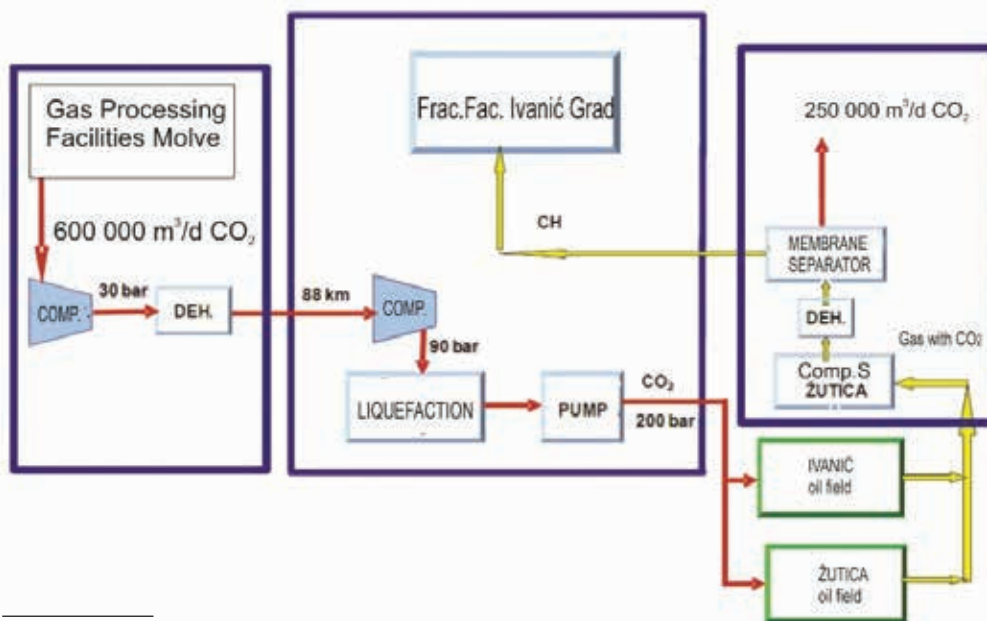


Fig. 2. . Simplified block diagram of the EOR project (Novosel, D 2009)

At atmospheric pressure, CO₂ is gaseous. At temperatures between -56.6 and +31.1 °C, and pressures of at least 5.1 bar, CO₂ is in liquid form. Liquid CO₂ cannot exist at atmospheric pressure (1 bar). At temperatures below -56.6 °C, CO₂ can occur in the solid state. Compressed CO₂ snow, generated by depressurising liquid CO₂, is called dry ice. Heating up of the dry ice at atmospheric pressure does not cause melting but instead sublimates to form gaseous carbon dioxide.

BASICS ABOUT IVANIĆ AND ŽUTICA CO₂ EOR PROJECT

Molve field's (Northern Croatia) gas reservoir contains high proportion (23–26%) of naturally occurring CO₂ (Malvić, T & Velić, J 2010). Natural gas produced from the gas-condensate fields of the Drava depression is purified from acid gases (CO₂, etc.) and mercury, then CO₂ is compressed and dehydrated in the Gas processing facilities Molve (GPFM) (see Figure 2). The received 600 000 m³/day of dry CO₂ is transported from GPFM

– via a 20", 88 km long pipeline – to the Fractionation facilities Ivanić Grad (FFIG) where the gas is further compressed and liquefied. Next, CO₂ is transported by pipeline under high pressure (200 bar) to the injection wells of the fields Ivanić and Žutica, in quantities of 400 000 m³/day and 200 000 m³/day, respectively.

Within the project, apart from existing 88 km pipeline, another 56 kilometres of new pipeline, as well as two compressor stations (Molve and Ivanić Grad) were built. Gas processing facilities Molve (a) and Fractionation facilities Ivanić Grad (b) are shown on Figure 3. See geographic location map of the facilities in Figure 4.

During the 24 years of the project (starting in October, 2014) about 5 037-million m³ of CO₂ will be injected in the reservoirs of these fields, what will result in additional hydrocarbon production (3.4 million tonnes of oil and 599 million m³ of gas). Due to geological and physical conditions 2 325-million of CO₂ will be produced together with associated gases. CO₂ separated from the associated natural gas by membrane technology at the location of the compressor station Žutica and could be reused for the further EOR purposes.

Prerequisites to EOR project's implementation were modifications of mining operations and reconstruction of existing wells in fields Ivanić and Žutica, for



Fig. 3. (a) Gas Processing Facilities Molve (GPFM)



(b) Fractionation Facilities Ivanić Grad (FFIG)



Fig. 4. Geographic location of the facilities

their conversion into alternating CO₂ and water injection. Having in mind corrosive features of CO₂, special attention was paid to selection of surface and underground equipment materials.

ENVIRONMENTAL ASPECTS

The EOR system is closed and there is no possibility of CO₂ leakage during regular operation and normal technological process. Discharges are possible only in case of incidents (e.g. pipeline rupture, breakthrough of CO₂ through possible fractures of the cement bond in the injection wells annular, and surface leakage of process equipment).

Density of CO₂ injected into the reservoir is less than the density of most reservoir 'fluids' therefore CO₂ migrates to the top of reservoir and then spreads laterally along the border with the sealing rock. Leakage of CO₂ from the reservoir to the surface can occur for technical (due to old, deep, improperly sealed wells) or natural (due to fractures and faults) reasons.

The environmental aspects of the EOR project Ivanić and Žutica are to be considered before, during and after project implementation in order to monitor, prevent or minimise the project's possible negative effect on the environment and nature. The project's positive effects on the environment is reflected in CO₂ emissions reduction.

PREVENTION AND MONITORING OF NEGATIVE IMPACT OF CO₂ ON THE ENVIRONMENT

CO₂ leakage is prevented from the surface facilities and pipelines by the *use of corrosion-resistant materials*, and from the reservoirs – *by maintaining the mechanical integrity* of the wells.

Typical corrosion-resistant materials are: SAE 316 stainless steel, fiberglass and carbon steel. Casing and tubing can be made of glass reinforced plastic, epoxy resin or cement. Metal parts packers and bolts are nickel-plated or made of other high nickel alloys.

Overlying impermeable cap rock (sealings) prevents CO₂ migration upward into shallower layers. A well is considered a potential migration path since it forms a direct link between the surface and the reservoir, but also because it is made of materials that may corrode over time. Components of the injection well, relevant for maintaining mechanical integrity and preventing migration of 'fluids' from the reservoirs to potable water aquifers and surface are casing, tubing, cement stone and packer. *Internal mechanical integrity* is characterised by the absence of CO₂ leakage through the packer, tubing

and casing. Internal mechanical integrity can be preserved by proper selection of equipment materials. The well has *external mechanical integrity* if there is no significant 'fluid' movement through vertical channels adjacent to the well bore. External mechanical integrity can be achieved through the use of proper cement and properly done cementing (Gaurina-Medimurec, N & Pašić, B 2011).

CO₂ leakage from pipelines or geological reservoirs could have negative impact on humans and natural surroundings, i.e. vegetation, soil, and surface water quality. Although its concentration in soil up to 20–30% can favour plant fertilisation, higher concentration is harmful to vegetation (this effect could be localised around the gas vent only). Furthermore, dissolving of CO₂ in water reduces its pH (a measure of acidity / basicity). Determination of the condition of the soil, water and the environment before starting CO₂ injection creates the basis for all future measurements and monitoring of project's impact on the environment. Basic research, with the purpose of conducting an environmental baseline survey, was done by the licensed environmental experts in 2014, just before starting CO₂ injection into the Ivanić field. It covered pedosphere, biosphere, hydrosphere and atmosphere quality determinations. Water, soil and vegetation sampling and analysis have been done for 26 points of the transport system (including locations along pipeline route GPFM–FFIG, the city of Ivanić and the area of the mining plots Ivanić and Žutica), which pose the highest risks.

Quantitative and qualitative determination of the parameters took into account surface features, such as topography, population density, infrastructure and ecosystems. Scope of service included examinations of water, soil, air, and forest ecosystems. The measurement results will serve as a reference for all future measurements, or to detect harmful effects on the environment, particularly drinking water.

When CO₂ is emitted in the open or flat area, it rapidly diffuses into the air. As CO₂ is heavier than air, increased concentrations can be expected near the ground and in the natural depression areas. Additional measurements were done on locations with identified increased risk of leakage, such as block stations, junctions and injection wells. With respect to presence of hydrogen sulphide (H₂S) in the gas stream, beside CO₂ concentrations, H₂S concentrations were also measured in air. Temperature, relative humidity, and air pressure were also recorded.

The average results of temporary measurements done on 26 points of the EOR CO₂ transport system during June–July 2014 are shown in [Figure 5](#). The measuring points

are divided into two elaborates. First elaborate covers locations along pipeline route to the Fractionation Facilities Ivanić Grad, residential area of Ivanić Grad, and the Ivanić mining plot (Figure 5 a), c) and e)), while the second one covers the area of the Gas processing facilities Molve and the Žutica mining plot 5 b), d) and f). The results are in the framework of expected values for this part of Croatia.

Institute for Medical Research and Occupational Health, Zagreb (IMI) conducted temporary air quality monitoring at the mobile station positioned at the Fractionation facilities Ivanić Grad and Compressor station Žutica. The results of the hourly and daily mean concentrations of hydrogen sulphide in relation to the prescribed limit values are shown in Figures 6 and 7. The measured concentrations are well below the threshold limits.

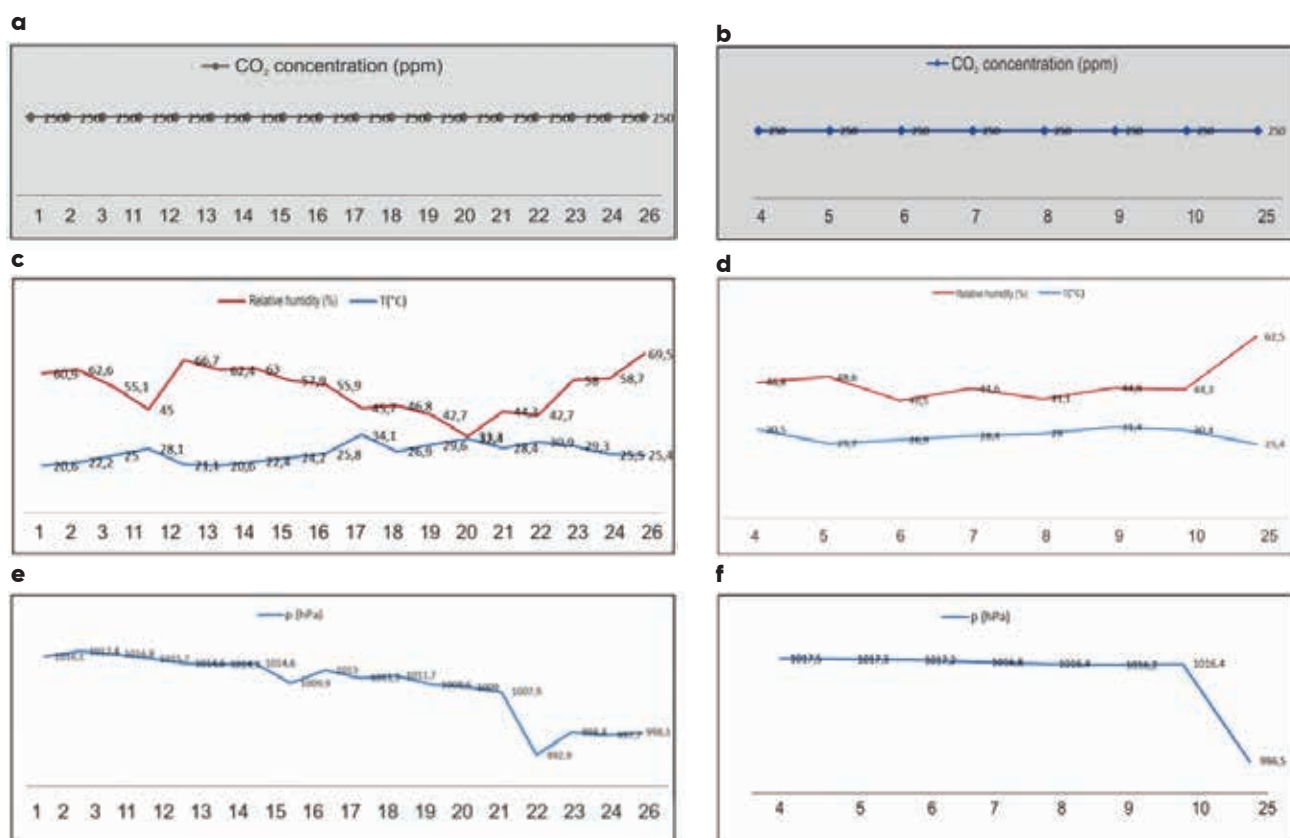


Fig. 5. Temporary measurement results of CO₂ concentration in the air (a and b), temperature, relative humidity (c and d), air pressure (e and f) for 26 points of the transport system

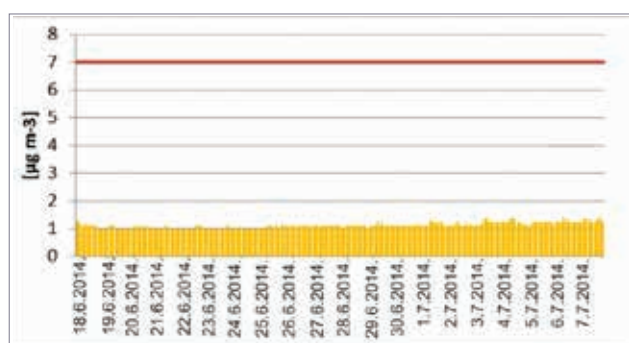


Fig. 6. Hourly average concentrations of H₂S, Fractionation facilities Ivanić Grad (the upper line indicates the limit value)

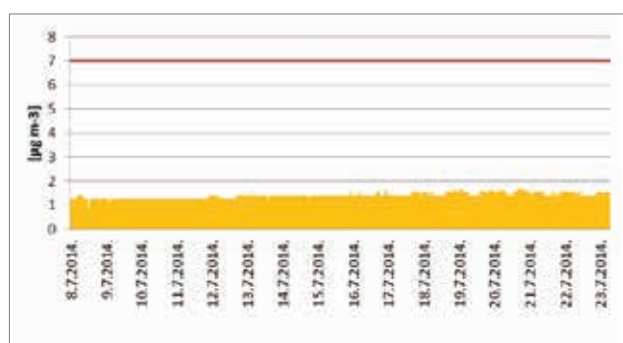


Fig. 7. Hourly average concentrations of H₂S, Compressor station Žutica (the upper line indicates the limit value)

Dissolution of CO₂ into groundwater decreases its pH value and leads to release of some elements from aquifer rocks. In the frame of water analysis we assessed the ecological and chemical status of surface (streams and stagnant) water and groundwater, as defined in the related Croatian 'Regulation on water quality standards' (published in the Croatian Official Gazette no. 73/13). Analysis of *surface and groundwater* included examination of the following parameters: temperature, appearance (colour, odour, clarity), pH, BOD₅ (biochemical oxygen demand 5-day technique) and COD (chemical oxygen demand), content of free and bound CO₂ (bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻), alkalinity and acidity, dissolved oxygen content, content of hydrogen sulphite (bisulphite) (HSO₃⁻) and sulphide (S²⁻), and content of TOC (total organic carbon).

The baseline study of water quality was done by Public Health Institute of the Koprivnica-Križevci County. It included ground water analysis at eleven piezometric wells at Žutica and surface water analysis in seven locations.

Soil contamination in the Republic of Croatia is regulated by the Ordinance on protection of agricultural land from pollution (chemical and biological degradation), NN 9/2014. Chemical analysis of soil covered the measurements of the following parameters: total nitrogen, mineral nitrogen, pH, humus, mobile aluminium, hydrolytic acidity, total sulphur, total carbon, CO₂, and H₂S.

CO₂ concentration in soil was measured by Honeywell's portable gas detector GasAlertMicro5 IR (Figure 8). The research goals required reliable data on the environmental conditions, especially temperature, pressure and relative humidity, as well as temperature and moisture content of the soil. Rain water and air temperature affect the moisture content in the soil and soil temperature, which ultimately indirectly affect carbon dioxide emissions from the soil, soil temperature and moisture content of the soil. Measurement results are shown on the Figures 9 and 10. Determined values are in range of expected values in this region and represent the basic values for all future measurements.

Alongside the technological route of the pipeline forest ecosystems are present. These are mainly natural, self-sustainable ecosystems managed by and operated by Croatian Forests Zagreb. Impacts the CO₂ EOR on the agricultural and forest ecosystems are to be analysed by measuring the concentration of

CO₂ and H₂S in the leaves and soil. Baseline research was done in three different forest ecosystems / three experimental plots and included identification of health and vitality of forest ecosystems. Results show that damage to trees depends on the species: it varied from 45.8 % to 58.33% in case of oak (*Quercus robur*), sessile oak trees (*Quercus petraea*) were of good vitality, while 16.7 % of beech trees (*Fagus sylvatica*) were degraded. These results will serve as reference for future monitoring of the possible gas leaking impact of the CO₂ EOR on the species.



Fig. 8. Application of gas detector on the site

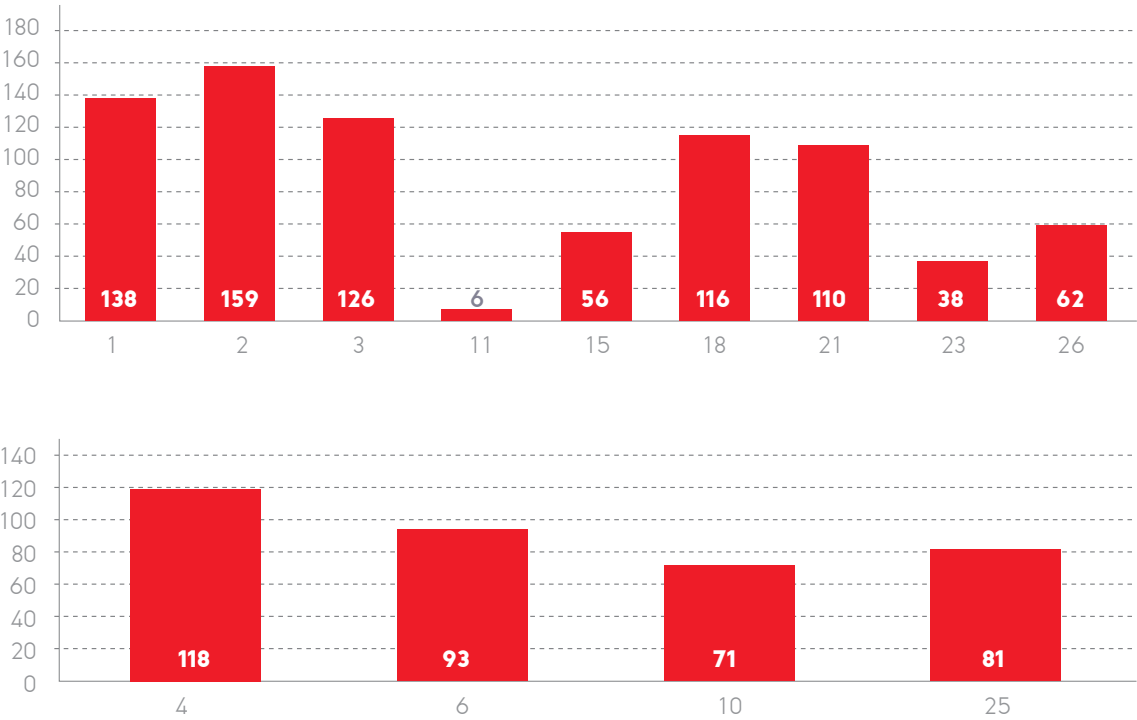


Fig. 9. Soil flux, C-CO₂, kg/ha-day

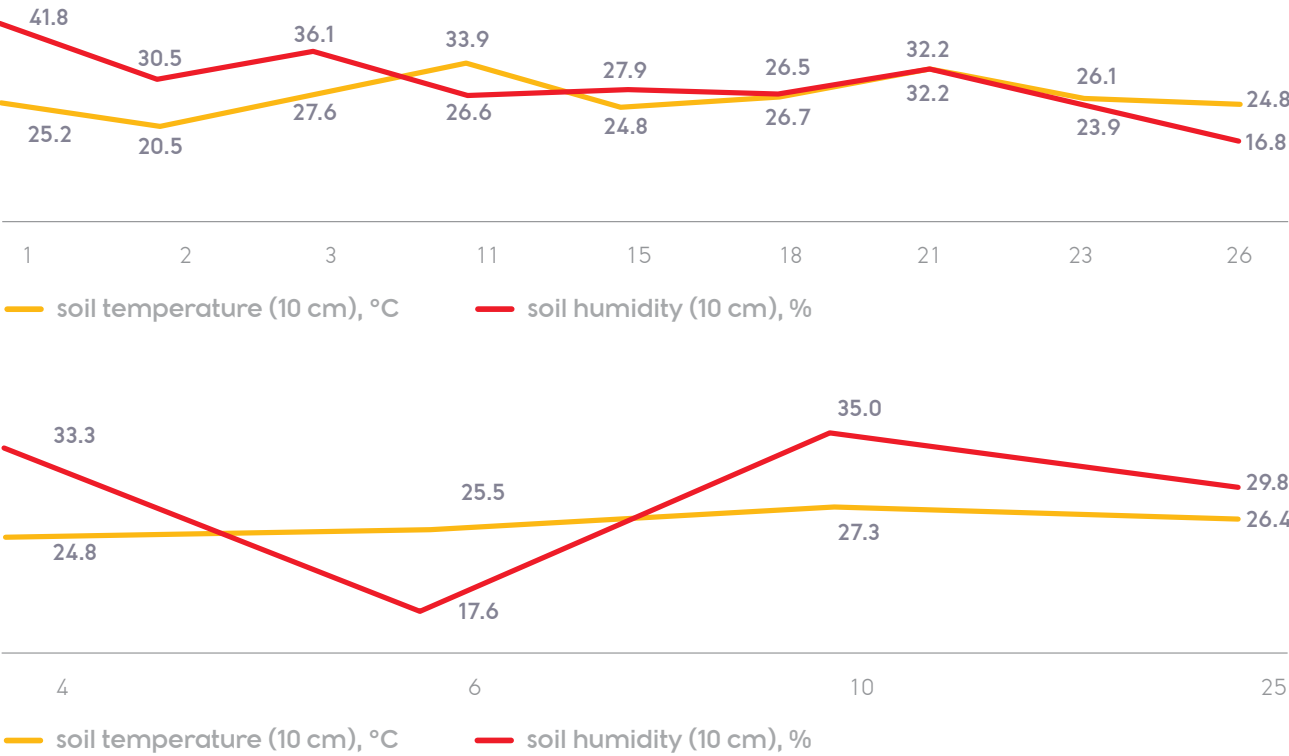


Fig. 10. Temperature, °C and relative humidity, % of soil at 10 cm depth



EMISSION REDUCTION ACHIEVED BY THE PROJECT

Global increase of the Earth's surface temperature, i.e. global warming, is caused by the greenhouse effect which occurs due to the capturing of infrared radiation by high concentration of the greenhouse gases in the atmosphere. CO₂ is responsible for 9–26% of the total greenhouse warming effect (Hrnčević, L 2008; Novak, K & Malvić, T & Simon, K 2013). The Republic of Croatia became the party of the 1992 United Nations Framework Convention on Climate Change in 1996 and took the commitments of countries listed in Annex 1 (developed countries). The Kyoto protocol has entered into force in Croatia in 2007; Croatia committed to reduce its emissions of greenhouse gases by 5 percent in relation to the base year (1990), over the commitment period from 2008 to 2012. Actually, Croatia has decreased its total GHG emissions (with land use, land-use change and forestry – LULUCF) from the 1990 about 29.6 million tonnes of CO₂ equivalent to roughly 19.4 million tonnes by 2013, i.e. by about 34.5% (CAEN 2015).

The Republic of Croatia joined the EU Emissions Trading Scheme (ETS) in 2013, by transposing the ETS directive into the national legislation through the Regulation on emissions trading of greenhouse gas emissions, published in Croatian Official Gazette no. 69/12. EU ETS and its impact on INA are outlined in a previous article (Zec, M 2015).

The 2015 United Nations Climate Change Conference COP 21 and the 11th session of the Meeting of the Parties to the 1997 Kyoto Protocol “adopted the first-ever universal legally binding climate deal, the Paris Agreement. The agreement sets out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2 °C. The agreement is due to enter into force in 2020.” The EU “is already taking steps to implement its target to reduce emissions by at least 40% by 2030” (EC 2016).

EU ETS system covers carbon dioxide emissions generated in the process of fossil fuel combustion in INA's Upstream sites Fractionation facilities Ivanić Grad and Gas processing facilities Molve. The facilities entered the ETS system under criteria of fuel combustion plants with the capacity above 20 MW. Carbon dioxide separated from natural gas is used to increase the recovery of hydrocarbons within the EOR project Ivanić and Žutica. Before the start of the EOR project these facilities were parts of the national non-ETS fee obligation system, regulated by Croatian Authority,

Fund for Environmental Protection and Energy Efficiency, according to the principle ‘pay as much as you emit’. (All non-ETS stationary emission sources with yearly emission quantity greater than 30 t fall under the fee obligation system.)

As it is indicated before, the EOR project would result in average in $(5\,037 - 2\,325) / 24 = \sim 113$ million m³ CO₂, i.e. in about 203 thousand tonnes CO₂ sequestration in a year. According to the latest available National Inventory Report (NIR 2015), in 2013 Croatia emitted about 13.5 million tonnes of CO₂ (incl. LULUCF) and CO₂ emissions are on a declining trend. Thus, CO₂ sequestration being implemented in the frame of INA EOR project Ivanić and Žutica from October, 2014 would reduce the country's yearly CO₂ emissions by more than 1%.

DISCUSSION AND CONCLUSION

Enhanced oil recovery (EOR) methods increase the economic value of existing fields. However, transport and injection of CO₂ into deep wells for oil recovery may pose environmental issues. Therefore, in order to avoid environmental damage environmental impact of the project must be considered in phase of planning, execution and after its closure.

The impact of the EOR project Ivanić and Žutica on the environment is considered in all project phases. Although it is about closed system where CO₂ leakage is possible only in case of incident, leakage prevention is done by selection of corrosion-resistant materials, while its possible migration from the reservoirs is avoided by naturally presented impermeable cap rocks and by maintaining the mechanical integrity of the wells. The established system of environmental monitoring which includes air, soil, surface and underground water quality analysis during the project and after its closure, represents reliable tool for detection of the possible leakage.

Besides the possible negative effects, enhanced oil recovery by injection of CO₂ has multiple positive effects on the environment. Such a project uses maximum of existing infrastructure and thus reduces the impact on soil and population since it does not occupy new surface. However, main positive effect on the environment is seen through emission decreasing. Application of EOR projects can significantly reduce CO₂ (greenhouse gas) emissions in the air. Reports on emissions indicate that Republic of Croatia has met the required reduction of GHG emissions, however, this is not as a result of actually applied methods and technologies, but the

consequence of reduced industry activities.

CO₂ sequestration being implemented in the frame of INA EOR project Ivanić and Žutica from October, 2014 would reduce the country's yearly CO₂ emissions by more than 1%. Another environmental benefit of the project is in the fact that the project can provide experience and data important for carbon capture and storage technology development and its commercial application.

Keywords: EOR project, Croatia, CO₂ emissions



Karolina Novak Mavar, PhD

joined INA Oil Industry Ltd, Oil and Gas Exploration and Production Business Division in 2007. Karolina graduated as a mining engineer and received her PhD degree from

Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb. As an author and co-author she has published several papers and participated in numerous professional conferences. She actively participates in work of various professional associations.

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How employee engagement drives business results?

MOL Group practices of regularly asking colleagues on how to make MOL a better place to work

Mic Sanda Adela (30)

Expert

MOL Group HR, Capability Development & Strategic HR

SAMic@MOL.hu

Ágnes Inzsöl (31)

Expert

MOL Group Internal Communications

Alnzsol@MOLgroup.info

ABSTRACT

The article discusses the general importance and drivers of employee engagement, what the oil and gas industry benchmarks are, and what MOL Group companies have done to act on the results. The article provides best practices and actions that have been taken by the Flagship companies¹ of MOL Group following the previous 2012–2013 survey. In the last part, the 2015 communication campaign is introduced, since it had a critical role in reaching the highest possible number of employees. The employees' feedbacks are invaluable, since every opinion counts in building the company a better place to work. (This article does not discuss the 2015 Roundtable Survey results.)

INTRODUCTION

The need for employee engagement has been constantly increasing, as shown by several international studies. It is now proven that the business is directly and indirectly affected by the level of engagement. At individual level as well as part of a team, engaged employees can influence the business results which is measured by objective indicators. Committed employees are more productive, willing to go the extra mile, thus creating values for the customers and all stakeholders. They are more willing to talk positively about their company and even recommend it as a good place to work. Nowadays, the oil and gas industry players are not only facing a fierce competition for talents (even within the tech industry), while operating in a tough economic environment, satisfied and loyal employees are the most important 'assets' of a company.

In the light of this, it is critical to regularly measure the engagement level in an organisation, listen to the employees and take actions to make the company an even better workplace. At the end of the day, it is a mutual win-win situation.

In this article we discuss the general importance and drivers of employee engagement, what MOL Group companies have done to act on the results. In addition,

we share the highlights of the latest communication campaign, and what we did to reach as many employees as we could to fill in the survey.

WHAT IS ENGAGEMENT AND WHY IS IT IMPORTANT?

"In an era of ... corporate transparency, greater workforce mobility, and ... skills shortages", employee engagement has "emerged as top" focus "for business leaders" and companies worldwide, according to Deloitte's 2015 Global Human Capital Trends survey (Deloitte 2015).

According to one accepted definition, **employee engagement** is the state of emotional and intellectual involvement and commitment that leads people to do their best work. Basically, it can be manifested in three ways based on the 'Aon Hewitt Employee Engagement Model' (see [Figure 1](#)):

- ▶ **Say:** employees talk consistently positively about the organisation to their colleagues, to customers or future employees
- ▶ **Stay:** employees "have an intense desire" to stay with the organisation
- ▶ **Strive:** employees go the extra mile and "engage in behaviours that contribute to the business success" (Aon Hewitt 2012, p. 5.).

¹ Flagship Companies (FS): certain dedicated MOL Group companies which control, support and provide Functional Unit services to Operating Companies belonging to their areas of operation

According to “report of more than 550 executives”, high-level employee engagement (with the same score as strong executive leadership) is the 3rd key factor that most likely brings success – after high-level customer service and

effective communications (Harvard Business Review Analytic Services 2013, pp. 1, 4.). Moreover, the same study reveals the relations between **employee engagement and profitability** along the service profit chain (see Figure 2).

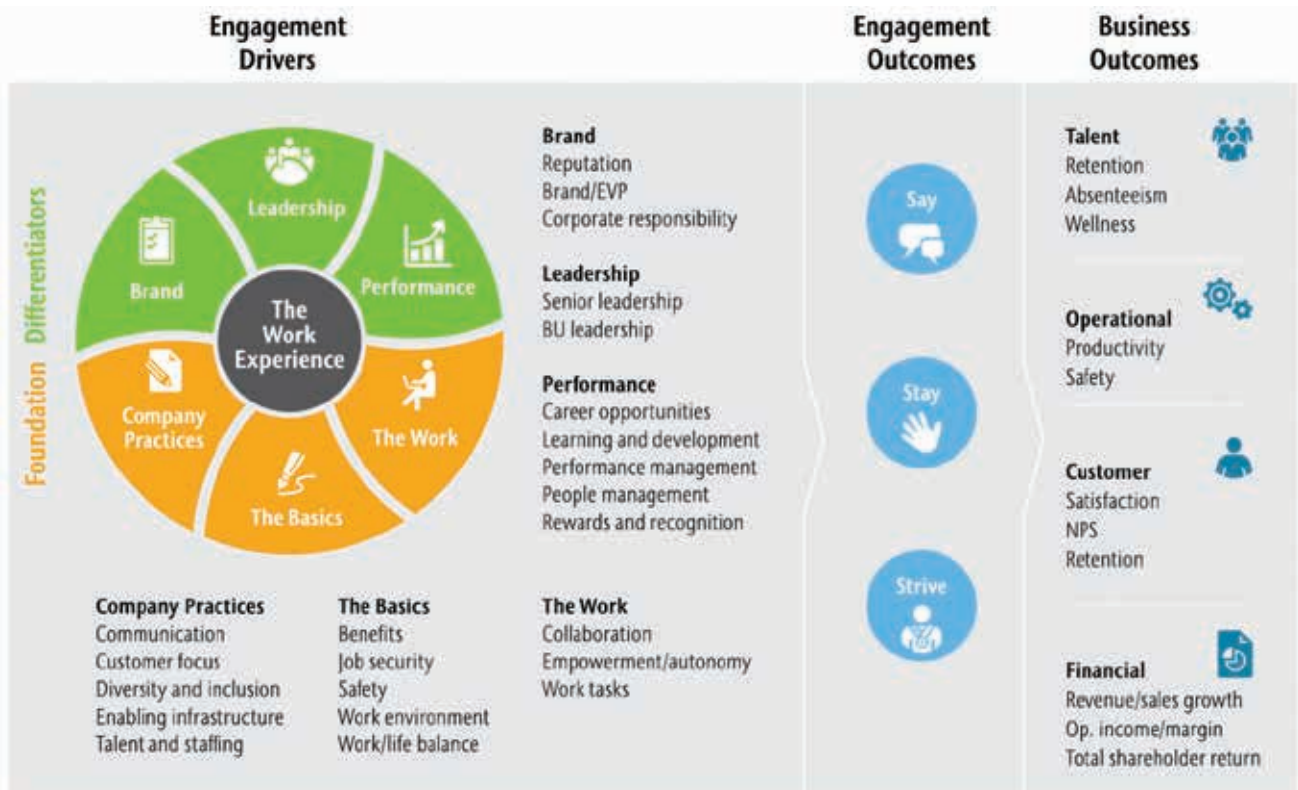


Fig. 1. The Aon Hewitt Employee Engagement Model (Aon Hewitt 2015, p. 9.)
(EVP – employee value proposition, NPS – net promoter score)

THE LINKS IN THE SERVICE- PROFIT CHAIN

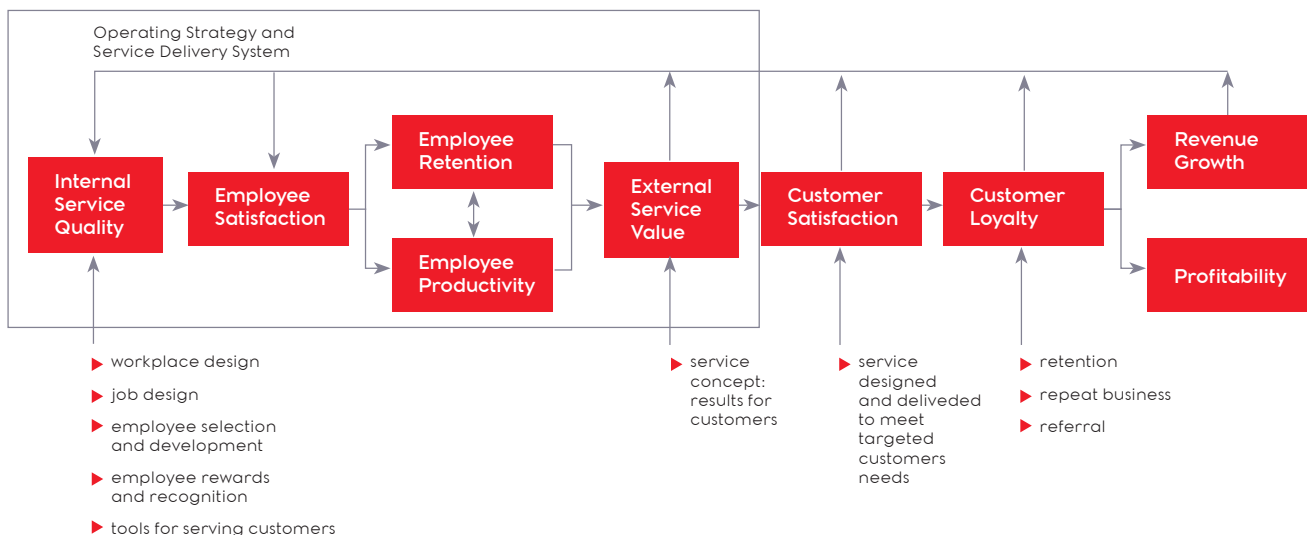


Fig. 2. The service-profit chain (in: Harvard Business Review Analytic Services 2013, p. 14., source: Heskett, JL et al. 2008)

Employee satisfaction stems from “support services and policies that enable employees” to be productive and create value for the customers (Heskett, JL et al. 2008). If the customers’ needs are met, they will be satisfied and if they continuously experience high quality service, they become loyal. Ultimately, loyal customers drive profit and growth. From the business point of view, we can see the ripple effect through the service profit chain. Employee engagement drives business performance as well (Aon Hewitt). As the Aon Hewitt studies show, engagement has measurable effect on a company’s financial performance (see Figure 3).

According to the ‘MacLeod review’ (MacLeod, D & Clarke, N 2009) employee engagement contributes to:

- **Profit.** A 2006 „Gallup study ... of earnings per share (EPS) growth of 89 organisations found that the EPS growth rate of organisations with engagement scores in the top quartile was 2.6 times that of organisations with below-average engagement scores” (in: MacLeod, D & Clarke, N 2009, p. 11).
“Those with engagement scores in the top quartile averaged ... 12 per cent higher profitability” than in the bottom quartile (in: MacLeod, D & Clarke, N 2009, p. 11; original source: another Gallup 2006 survey based on the examination of 23 910 business units).
- **Customer relationship improvement.** “Those with engagement scores in the top quartile averaged 12 per cent higher customer advocacy” than in the bottom quartile (in: MacLeod, D & Clarke, N 2009, p. 11; original source: another Gallup 2006 survey based on the examination of 23 910 business units)
- **Productivity improvement.** “Those with engagement scores in the top quartile averaged ... 18 per cent higher productivity” than in the bottom quartile (in: MacLeod, D & Clarke, N 2009, p. 11; original source: another Gallup 2006 survey based on the examination of 23 910 business units)

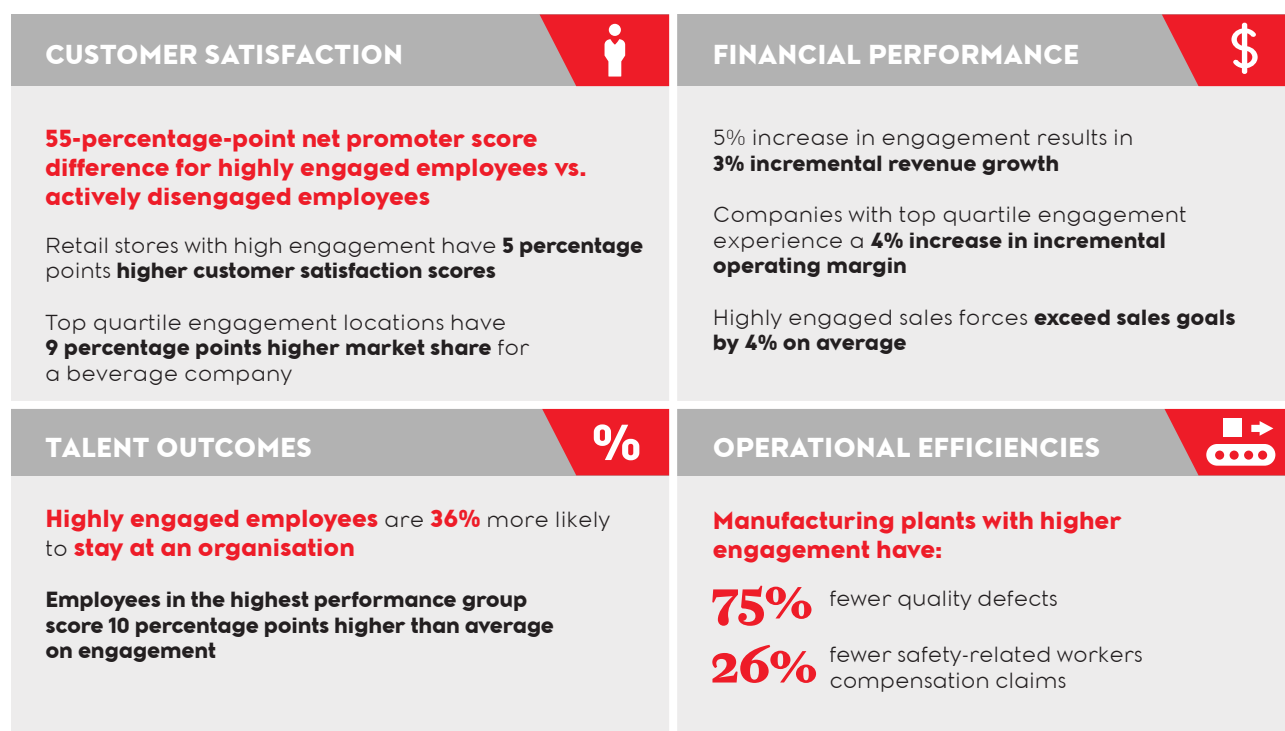


Fig. 3. Employee engagement drives business performance (Aon Hewitt)

business units). „CLC's 2004 Driving Performance and Retention through Employee Engagement report found that companies with above average employee commitment were in 71 per cent of cases achieving above average company performance for their sectors" (in: MacLeod, D & Clarke, N 2009, p. 37; original source: Corporate Leadership Council 2004, 'Driving Performance and Retention through Employee Engagement – Executive Summary')

- ▶ *Innovation.* "Fifty-nine per cent of engaged employees say that their job brings out their most creative ideas against only three per cent of disengaged employees" (MacLeod, D & Clarke, N 2009, p. 12, original source: Krueger, J. & Killham, E 2007, 'The Innovation Equation', Gallup Management Journal). Engaged employees are more likely search out new methods, techniques and transform innovative ideas
- ▶ *Fewer missed days of work due to illness.* "Engaged employees in the UK take an average of 2.69 sick days per year; the disengaged take 6.19" (Gallup 2003 survey). A 2007 CBI report states „that sickness absence costs the UK economy £13.4bn a year" (MacLeod, D & Clarke, N 2009, p. 14)
- ▶ *Improvement in employee turnover retention.* „Those with engagement scores in the bottom quartile averaged 31–51 per cent more employee turnover" (in: MacLeod, D & Clarke, N 2009, p. 11; original source: another Gallup 2006 survey based on the examination of 23 910 business units).

WHAT ARE THE OIL AND GAS INDUSTRY BENCHMARKS ON EMPLOYEE ENGAGEMENT?

In the oil and gas industry some surveys have been conducted to reveal what drives employee engagement.

A recent USA-based survey published by Mercer (Mercer 2015) revealed that job security ranked highest in terms of importance, meaning that oil and gas employees are more concerned about keeping their jobs when organisations cut their investments. We may assume that this trend will shift once the oil prices settle or rebound. This implies that oil and gas employees are less focused on base pay than job security which "compared to other industries ... is atypical". However, in terms of total rewards, the workforce segments showed some variability "by geography, industry segment and job level". "Refining employees are ... less-focused on job security than other segments, while placing greater emphasis on career opportunities, retirement and incentive / bonus."

Not surprisingly, older, more experienced and higher-tenure employees valued retirement plans and healthcare coverage more, while the career advancement seemed to be less important for them.

As an Aon Hewitt report based on survey data from sample of US employees collected during the economic crisis (in 2009–2010) (Aon Hewitt 2013) shows, employee engagement becomes critical in times of change. The most engaged employees remain resilient during strategy transformation or restructuring, while "the percentage of actively disengaged employees increases" as a result of such changes.

Hay Group points out (HayGroup® 2013) that the decreasing oil prices have created a turbulent business environment, in which oil and gas companies are facing the **engagement challenge**. This means that "oil & gas employees rate their organisation lower compared to those at the world's high performing companies" ("firms that consistently achieve around twice the global average return on investments, assets and equity"): they rated 8% lower "for their ability to retain talent", and 13% lower in terms of intention of staying "with the company for more than 5 years".

WHY ENGAGEMENT IS IMPORTANT TO MOL GROUP SENIOR LEADERS?

Employee retention and decreasing turnover is critical in achieving strong business performance. In light of this, MOL Group has conducted Roundtable engagement surveys every two years since 2006 and has acted directly upon the results.

The three key pillars of employee engagement:

1. **Pulse of the organisation** that helps to identify where to act. This helps to compare the different perceptions of employees and managers and to identify potential gaps
2. As the **foundation for business**, engagement is essential to making things happen
3. **It is a part of leadership** and everyday life, and requires continuous effort to do the right thing in every area of the business.

MOL Group senior management is committed to regularly checking engagement, and taking actions on improvements. Since the previous engagement surveys we have launched several projects and initiatives to reflect and act upon feedback received. Based on the latest results, in 2016 we will continue to develop action plans to implement projects that will bring tangible results for our employees' well-being.



As Zsolt Hernádi, Chairman and CEO of MOL Group declared, „for MOL Group, employee engagement is a strategic part of a healthy and productive workplace and represents a priority for our human capital and business strategy. It is clear to the Group that engaged individuals and workgroups are more productive, more likely to stay with their organisation. This has all been supported by recent studies. Therefore, engaging our employees is a key factor for the lasting success of our business. Each MOL Group employee helps us meet our business goals and makes our company a great place to work.”

In an interview about the 2015 employee engagement approach, Zdravka Demeter Bubalo, MOL Group Human Resources Vice President, shared three useful steps to create awareness around employee engagement at work:

- “Define your own engagement. Think about how you work best and what conditions set you up for success
- Use your strengths to form positive engagement habits. Establishing positive, consistent habits at work can help you change your environment and create higher professional engagement
- Be accountable to yourself for your success. Take responsibility and empower yourself by setting measurable, realistic goals, stay focused and head in the right direction to attain them.”

What do our Flagship companies do to strengthen engagement? Reflecting on the past years, here are some examples from the initiative.

MOL FLAGSHIP

Following the previous, 2012–2013 employee engagement survey, the strategic directions had to be further improved and clarified, therefore the MOL Hungary Programme was launched. Some of the key results of the Programme were:

- Employee-level KPIs (key performance indicators) were derived from the Programme
- Over 1 300 participants attended our roadshows at five locations, where managers introduced the Programme.

SLOVNAFT

Based on the previous, 2012–2013 employee engagement survey results, several tailor-made learning & development (L&D) initiatives were run in the company addressing internal clients' most pressing needs. The aim was not only to improve technical knowledge and skills, communication and management skills of the target audience, but also to strengthen common platform of the mutual communication within the company. Some examples are:

- Project management programmes: one-year tailor-made modular training programme for project managers plus the managers of the DS Development / Project management departments
- Lean six sigma programme for Logistics: one-year modular training programme for department leaders and specialists, or ‘innovators’.

INA

Between the previous, (2012–2013), and the current (2015) employee engagement surveys, INA also took actions to ensure that improvements take place based on the survey results. Change agents helped employees become aware of that lots of actions have been taken following the data collections. Some examples are:

- ‘Leading positive organisational change’ to empower champions in the skills needed to prepare the process of change, to implement change, to motivate and manage people during the change process
- Focus groups to check the engagement pulse of the organisation and to create action plans for 2015. Altogether 12 focus group discussions were held with 133 participants across the company. One of the key areas was INA Supply Chain Management (SCM) where all employees participated in action planning using the specific change management methodologies ‘four rooms of change’ and ‘six thinking hats’.

HOW CAN COMMUNICATIONS CONTRIBUTE TO A SUCCESSFUL ENGAGEMENT SURVEY?

Identifying strengths and opportunities for improving engagement has always been a priority in MOL Group, however, the reliability of survey results heavily depend on the number of respondents. Communications need to ensure that we use all possible tools and channels and the right call to action to get colleagues to fill in the survey.

Knowing MOL Group’s measures on areas such as employee satisfaction, management / leadership effectiveness and working environment would give us tangible objectives for change.

Sharing opinions via engagement survey requires openness and trust from all our colleagues, coming from diverse backgrounds: different cultures, countries, businesses, and levels of the organisation. It is much less likely to get the desired outcome, unless we communicate the exact goals, the expected outcomes, and process of the survey in a transparent way.

How do we get our colleagues involved and encourage their participation by interactive communications that fits all cultures and all levels?

VISUAL ENGAGEMENT

The first time our colleagues meet the survey call-to-action is through the key visual of the campaign, which has developed a lot during the past 10 years.

The original logo and key visual were meant to represent a real conversation; people sharing their opinions with another, face to face. Both the poster visual and the logo suggest that the aim of the survey is to be open and honest while sharing opinions in order to make the necessary improvements (see Figure 4).



Fig. 4. The original Roundtable logo and key visual

In line with the more modern visual trends, in 2015 we developed a new, eye-catching internal communications concept and visual to raise awareness of the approaching survey.

The aim was to communicate about the survey in the most natural way we can, at the same time, making sure that the visuals are really catchy for those whom we talk to. We had to ensure that we show the right visuals for both blue collar and white collar colleagues. Therefore, we developed two different routes of the same concept. The pen simply represents the symbol of filling in the paper survey, and a mouse is the variant of it; it refers to filling in the survey online (Figure 5. a, b).



Fig. 5. a. The logo and key visual from the 2015 employee engagement survey campaign



FOCUS ► How employee engagement drives business results?

MOL Group practices of regularly asking colleagues on how to make MOL a better place to work



Fig. 5. b. The logo and key visual from the 2015 employee engagement survey campaign

These two objects were the central elements of all communications materials, because while they are really simple, they are also symbols of expressing individual thoughts and opinions. With giving the logo a facelift, our aim was also to simplify the existing one while also expressing – again in the most easily understandable way – that all opinions count. Therefore, we developed a round-shaped logo, in a symbol used for personal ideas or quotations.

USER-FRIENDLY COMMUNICATIONS

What is the key to reaching both blue collar and white collar colleagues and ensure that they participate in the survey? We could not do it without high-level endorsement. Therefore, each occasion top management also participates in call to action. Communications usually starts with a kick-off email from the Chairman and CEO to all colleagues, and a call to action from each company's CEO.

In 2015, beyond a clear call to action package to all local managers, we also needed to ensure that we highlight how significantly easier it has become to fill in the survey compared to the previous years. There were 50% less questions to answer, the survey took a maximum of 15 minutes to fill in, and unique links also for mobiles, as well as eye-catching collection boxes ensured that colleagues can submit their surveys in the most convenient way.

IT IS ALL ABOUT THE TIMING

Although the Roundtable communications had been announced before the actual survey in the previous four occasions too, in 2015, we decided to take an advertising-type of 'teaser' approach in developing the campaign. This meant that in the first phase of the campaign, we did not communicate the Roundtable itself, we just unveiled the partial message with the partial visual: 'this pen can talk' for blue collar colleagues, and 'this mouse can talk' for white collar colleagues (see Figure 6).

The feedback of colleagues exceeded all expectations: by the end of the 'teaser' period, everyone was asking each other what the visual stood for. Following the 'teaser' period, it was much easier to call our colleagues' attention to the actual survey and its deadlines.

DIVERSIFIED INTERNAL CHANNEL MIX

For the international rollout of the communications campaign, we were using all our existing channels to draw attention of the survey, from CEO letters to posters, to intranet banners and reminder emails and online articles.

Additionally, we were eager to add unique and extraordinary tools to ensure successful campaign implementation in the 'teaser' period. On our global intranet, Group Portal, we developed a pot meter where all countries could see how they rank in terms of response rate. In the canteens, we introduced for the first time tray papers as a call to action tool.

We reinforced the call to action messages also in the rollout period, on all channels from TV screens to log-in screens, roll-ups and small gifts. In the office buildings, we placed branded mouse in each conference room that colleagues could take away, and on production sites, branded pens were distributed with the call to action message in local languages.

In the last days of the survey period, we also added countdown banners in order to remind colleagues of the approaching deadline.



Fig. 6. Partial message in the first phase of the campaign

Beyond the unique extra tools, we constantly made use of traditional channels like email, intranet, log-in screen and bulletin boards. Following the survey period, we expressed our appreciation to our colleagues for sharing their opinions in emails, online banners, news articles and local surfaces.

In 2015, the Group-wide response rate grew from 65% to 80%, compared to the previous survey in 2012/2013. The user-friendly survey surfaces and simplified questions together with intensive communications resulted in an outstanding response rate.

Compared to previous years, the visual engagement, targeted messages for both blue collar and white collar colleagues, the use of a timely and catchy 'teaser' phase and the new mix of the above mentioned traditional and novel tools like a pot meter, tray papers proved to be successful in reaching all the diverse teams of colleagues in various countries from all businesses at all organisational levels.

During the campaign, it was crucial to emphasise that all our employees' opinion count. Every voice, every idea and every opinion counts as we are all part of MOL Group's success story and each member of our team affects the results of our business. By working together, we strive to achieve the best.

CONCLUSION

Making engagement happen is not about a development programme or tools or technology. It is not about managing to a score. It is not about 'HR's survey'. It is about *culture* and *leadership*. Culture is about changing and aligning people, programmes, and infrastructure to drive a consistent set of beliefs, decisions, and behaviours in an organisation. Leaders are in unique position to set the tone, demonstrate the value of human capital, link people to the mission of the organisation, and act in consistent, and authentic, and strategic ways to make engagement happen.

Keywords: employee engagement, Roundtable survey, communication campaign

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Mic Sanda Adela has over 8 years of progressive experience in all aspects of human resources. She joined MOL Group in 2014 and manages the following key areas: Employee Engagement, Diversity & Inclusion, Group onboarding process and building capability for HR. Sanda Adela graduated as International relations and European Studies specialist at Spiru Haret University, Bucharest. She obtained a Certificate in HR Practice from Chartered Institute of Personnel and Development, London.



Ágnes Inzsöl has 7 years of marketing communication experience in the field of content development, PR, online marketing and research that she gained both at multinational companies and at leading communication agencies. She joined MOL Group in 2015 where her main tasks are managing the development of MOL Group Panorama quarterly magazine, ensure information sharing by content creation and supporting businesses and functions with planning and implementing communication activities. Ágnes holds an MSc degree in marketing from Corvinus University of Budapest and an MBA degree from Saint Louis University, Missouri, USA.

Reviewed by Rita Csernai



50 years of Danube Refinery Százhalombatta¹– Part 2

ABSTRACT

In 2015 we celebrated the 50th anniversary of putting first production facility, distillation unit AV-1 of MOL Danube Refinery into operation. On the occasion of this important event, we publish an article containing the most important developments, changes and achievements of the past 50 years in the oil processing activity at Százhalombatta. This is the second part of the publication. First part of the article was published in the 2015/2 issue (pp. 44–51) of MOL Group Professional Journal.

DEVELOPMENTS IN THE PAST DECADE

In the first quarter of the last decade, MOL's whole Downstream area enjoyed the benefits gained from the large investments, implemented at the right time and with well defined objectives, which – in addition to the fast growing demand for refinery products – further strengthened the Group's market positions.

The global economic and financial crisis started in the fall of 2008 had an adverse effect on the oil sector, too: crude oil prices and refinery margins dropped significantly, the demand for oil products fell compared to previous level and forecasts, and the refinery capacity utilisation decreased. The negative impact of these trends appeared particularly in Europe to be reckoned with in the long run, as well. The continent is the industry's 'sick man', where consumption has declined for the last 10 years, while the region – despite the refinery closures having occurred since 2008 – has a considerable excess capacity. Another big problem in the sector is the structural imbalance: there is a significant surplus of gasoline with a decreasing possibility to find market, and the fact that diesel output from refineries in the region is continuously lower than the demand. Several countries and regions have been prepared to make up Europe's diesel deficit, like Russia, the US and the Middle East countries. In Europe's diesel market a further increase of competition is expected.

MOL as a whole, including the Downstream area, within this the Refining also reacted quickly to the crisis in order to gain competitive advantage, strengthen market positions, preparing for the period when the business environment becomes more favourable. The following steps have become necessary as main responses:

in the short run:

- Review of previous investment plans and
- Cost reduction – 'tightening the belt'

in the longer term:

- Improving efficiency and
- Flexibility in production and product structure.

Over the past decade, a much greater emphasis has been put on human capital development: involvement of workforce, its motivation, professional training and development of personal skills, innovation and cooperation. Meanwhile, the organisation has continuously developed and changed, as well.

REFINERY INVESTMENTS

The magnitude of investments after 2005 was much smaller than those realised in previous times, and these had been completed before the start of the crisis. Their implementation was mainly justified by regulatory compliance and cost efficiency considerations.

New sulphur recovery unit Claus-6

The construction of a new sulphur recovery unit was primarily made necessary to meet legal requirements. According to the legislation, by 30th October, 2007 the conversion of sulphur recovery plants with capacity over 50 tonnes per day was expected to achieve a minimum conversion of 99.5%. In addition, with the implementation of the EU 2005 project (see Part 1 of this article) – in the context of reducing the sulphur content of fuels – the sulphur recovery capacity requirements in the Danube Refinery were increased. For the continuous operation three equal large-capacity sulphur recovery units were necessary.

¹ This article is based on 'Our common success story' published in October, 2015 by MOL. The Editorial Board thanks Mr. László Galambos, the director of Refining HU for the permission

Considering the above, in 2007 the sulphur recovery unit Claus-6 was built and commissioned and the Claus-4 unit was restructured. (At the same time the unit Claus-3 – for being its economical transformation not possible – was closed. The Claus-5 high conversion unit continued to operate.)

FCC flue gas cleaning unit

The principal aim of the investment project was to meet a more stringent HSE requirement, i.e. to reduce the amount of solid pollutants – dust – leaving to the air with the flue gas during operation, which was made possible by incorporating an electrostatic precipitator. As a result of other significant changes during the development also the availability of the plant has improved.

Boiler plant

For decades, about 50% of the total steam consumption of the Danube Refinery had been satisfied by the Danube Thermal Power Plant (DERT). (The other 50% was derived from steam production linked to the refining processes.) Due to the continuous and massive increases in the price of steam, a decision was made to build an own steam generation unit – a boiler plant –, which came into operation in late 2007. Thanks to this, the price risk of external steam purchases disappeared. Another advantage is that the transport costs of the utilised steam and the pipe loss had been reduced, and the security of supply has been improved. However, the possibility of further purchases from DERT persists. The decision about the actual purchase are always be taken depending on the steam demand trends of the Refinery, on its own steam production capacity and on the actual price of steam from external sources.

Biofuel development programme

In 2003, the European Union adopted a multi-stage directive, according to which for the total amount of transport fuels used, a certain proportion of renewable fuels are to be added to. These added substances are called biocomponents. For gasoline, this component is alcohol or its ether derivative, e.g. ethyl *tertiary* butyl ether (ETBE), for diesel, in Europe they are chemically modified versions of vegetable oils derived mainly from rapeseed, fatty acid methyl esters (FAME). In addition, also used cooking oil is applied in a growing proportion as raw material.

MOL's biofuel development programme is being implemented with the cooperation of all downstream organisations. Along the supply chain, main tasks were to ensure proper raw materials from biocomponents, to make developments (production technology, recipes, additives, etc.), to prepare the logistics system according to needs, to control quality at predefined points in the

process, and to inform the customers – mentioning only the most important ones.

Conversion of MTBE plant into ETBE plant

The conversion of the existing MTBE (methyl *tertiary* butyl ether) plant into ETBE (ethyl *tertiary* butyl ether) plant was necessary in order to meet requirements of 'Biofuel directive' 2003/30/EC of the EU. On the basis of ethanol produced from raw materials of biological origin (wheat and maize) purchased from external sources, from 1 July 2005 the Danube Refinery started the production of fuel component known as bio-ETBE and its blending to motor gasoline.

PRODUCT RANGE AND PRODUCT STRUCTURE

In 1966, the first full year of normal operation the Refinery produced 59 different products – fuel oils, gas oils and gasoline grades (the quantity of other products was very little at this time). Most of the fuel oils went to satisfy the needs of the nearby Danube Thermal Power Plant. The lubricants also belonged to the important target products of the first years: as soon as the dedicated units were constructed their production could be started. From 1970, from the completion of the first aromatics unit, more and more chemical products were supplied from the Refinery. They, as well as the base oils and paraffin had an important role in the upswing of the 'hard currency' exports, which were a priority in the 1970s and 1980s. Increase in the base oil and wax production was facilitated by the rising production of the high quality crude oil from Algyő, Hungary. There was a time when DKV was one of the largest paraffin producers and exporters in Europe.

The number of products turned out in 1973 and 1984 exceeded 100 and 200, respectively. The higher value added products represented an ever-increasing proportion through the increase in the complexity, incl. deepening of processing. The fluid catalytic cracker commissioned in 1984 was the beginning of a new era in the improvement of the product slate, and another significant step forward came with the delayed coker for residue upgrading implemented in 2001. Both projects resulted in an increase in the proportion of motor fuels and petrochemical feeds, and a reduction in the production of fuel oils. The commissioning of the catalytic cracking unit facilitated the escalation of the fuel exports to the West.

In 1990 the Refinery was producing nearly 300 different products. In addition to meeting the domestic demands the company was at that time exporting its products to 26 countries of the world, even to overseas. That time the export sales volume ratio reached 20 to 25%.



Today nearly 35% of the product quantity turned out by Danube Refinery goes to foreign markets. Motor fuels dominate the exports. The most important areas of export are Austria, the Former Yugoslavian countries (implemented mainly via local MOL Group companies) and Germany. Compared to the production volume the export of the aromatics and base oils with a high profit margin is well above the average level, and they are sold outside the Mid-Eastern European region as well.

CONTINUOUS EFFICIENCY IMPROVEMENT

To achieve this goal, the management of Downstream organisation initiated and launched a number of programmes, supporting each other in several cases. The implementation got realised with mobilising and involving of a wide range of people working in the organisation. Due to the large number of actions not only the operating profit improved to a large extent, but also the professional knowledge of the participants increased. Further benefit is the development of innovative and proactive capability, widening knowledge sharing and cooperation.

'EIFFEL PROGRAM'

The acronymic name of 'EIFFEL Program' launched in January 2008 within the **Refining & Marketing Division** comes from the term of Efficiency Improvement Framework. The name reflects the effort to implement in practice the improvement opportunities explored through concrete experiences of daily operation and to sustain the results achieved in the long term. The programme counts on the innovative ability, individual ideas and active initiatives of the staff. The first station of any idea emerged is the third level head of the business units, who appoints responsible persons to study and make a report on the same, whereby he decides on the implementation. The collection of ideas is carried out by a coordinator in each organisation, who at the same time gives support for analysis and evaluation of the idea. There have been many proposals suitable for implementation not only in the given plant, but in several refining production units, too or even within the whole MOL Group. The 'EIFFEL Program' is ongoing even today. In the Refinery organisation the profit improvement achieved in the wake of implemented ideas has been in the magnitude of several billion Hungarian forints. For their submitted ideas and outstanding work in the programme nearly 300 colleagues received cash rewards.

'NEW DOWNSTREAM PROGRAM'

The main objective of the programme launched in 2011 was to allow MOL Group's Downstream to return among the best in Europe by the end of 2014,

through improvement of the operational efficiency and effectiveness. Based on estimates of the individual business areas the Downstream leadership set a target of USD 500 million clean CCS-based (current cost of supply-based) EBITDA (earnings before tax, depreciation and amortisation) by 2014. Based on the potential identified, the efficiency improvement initiatives may be grouped as follows:

- Energy management
- Production flexibility and product structure
- Maintenance, plant availability
- Hydrocarbon losses and
- Organisational efficiency.

In the period 2012–2014, at Danube Refinery the profit increasing impact of the implemented actions was about USD 77 million.

'NEXT DOWNSTREAM PROGRAM' (NxDSP)

It was launched as a continuation of the 'New Downstream Program'. Its objective is to further improve Downstream EBITDA with strong free cash flow generation over the coming years (see separate article on NxDSP on p. 70).

In the field of Refining, efficiency improvement actions are concentrated essentially in areas similar to those in the 2012–2014 period. Their goals are to improve Refinery flexibility, to increase the yield of more valuable products, to reduce losses, improve energy efficiency, improve availability, and – as a new element – enhance the petrochemical integration.

The Lean performance-improvement programme started in Slovnaft, later was extended to the other organisations of MOL Group. In the Danube Refinery the Lean programme started officially in spring of 2013. As it has been said in unfavourable business environment, with the fall of operating result, the first reaction is usually to reduce costs. This is inevitable, but by itself it does not ensure a long time survival of the improvement of operating result. According to Lean the emphasis should be put on mentality, on work style changes and on raising awareness. Only activities creating value for the customer should be made.

The Lean programme, using shared ideas of navigators (selected workers, drivers of the programme) and of employees will help employees in the production units carry out their work more easily, and where appropriate, in other ways than before. International experience has shown that a 5–7 year period is needed to make a company and its major organisations fully implement Lean philosophy and its practical application, without the risk of return to earlier modes of thinking and of acting.

WORKPLACE SAFETY

Crude oil refining is an activity with increased risk of fire and explosion, and in order to minimise the risk during operations strict safety measures are required. The basic principle of safety is prevention. This was taken into consideration in the design of the Refinery; the process units have been built relatively far from each other thereby reducing the possibility of escalation in case of a possible fire. The safety and fire protection standards of the company were tightening together with the installation of new units and more and more sophisticated processes. The use of protecting clothing and other protecting equipment, the gas concentration meters installed in the units in the highest fire hazard classes, the fire fighting steam systems, and the foam flooding systems all increased the efficiency of both prevention and fire fighting. In addition to the installed gas detection system in 2011 mandatory use of personal gas detectors during work was introduced, further reducing the exposure. To serve injured persons in a possible incident, a well equipped gas rescue and first aid service has been established.

In the past years important upgrades have been made in order to improve the fire alarming network and the fire fighting equipment, and to increase the technical safety in general. With the expansion of the quenching water network the high pressure fire water supply has significantly improved in the Danube Refinery.

Unparalleled in this country high capacity foam fire engines and foam water guns have been purchased. The newly purchased hose laying equipment and diesel engine driven booster pump continued to increase the water supply availability. The amount of water required

for extinction can be secured even in case of total loss of power. The fire protection functions of Danube Refinery are provided by FER Fire Fighting Co. established in 1995 and after the reorganisation owned fully by MOL. In special cases they are assisted by a fire fighting brigade of 120 persons. The Refinery is paying great attention to the theoretical and practical training of its employees who regularly participate in fire fighting drills for this purpose.

In accordance with the legal requirements in the Refinery each year internal protection exercises are conducted, where representatives of the authorities, as observers may first-hand evaluate the success of the interventions.

In the Refinery it is possible to demonstrate the dangerous activities carried out there, to the civilian population of the surrounding communities so they can personally ascertain the safety of operation.

The review of activities and their strengthening according to the process safety management (PSM) procedures has received a new impetus since 2012 to the present day. So was introduced the strengthened supervision of sections stagnant or dead due to maintenance activities, as well as the use of a number of PSM performance indicators in organisational and employee levels.

The Refinery has made considerable efforts to ensure safe working. In this area enhancing of HSE awareness played a key role.

The number and the downward trend of frequency of accidents in Danube Refinery can be well observed in **Figure 1**. In the territory of the Refinery no accidents resulting in loss of working time have occurred.

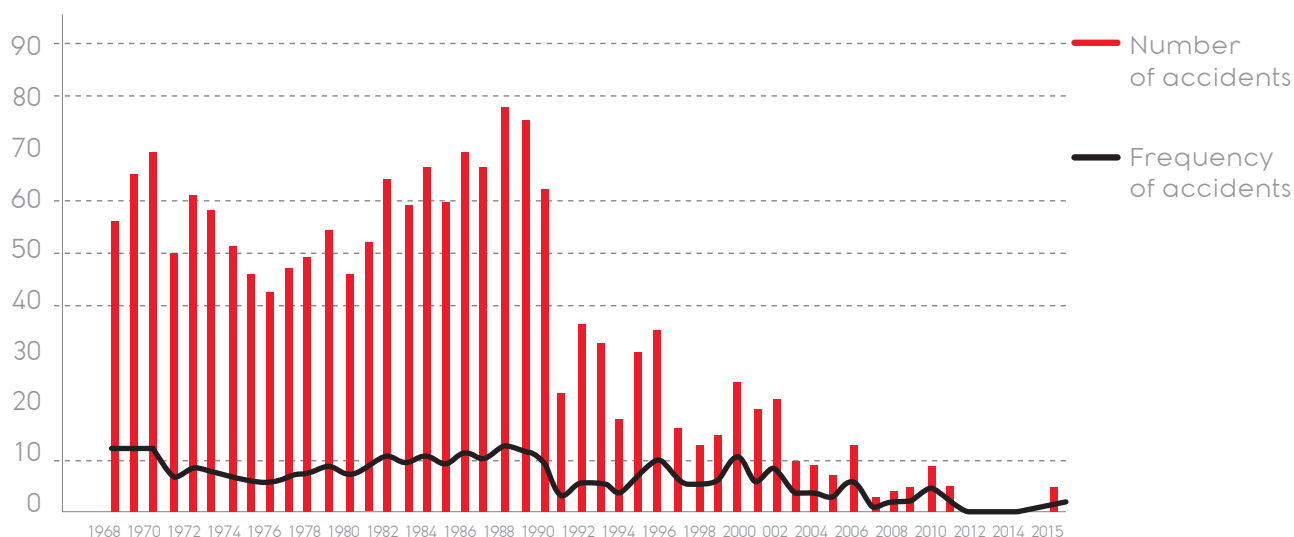


Fig. 1. Number of accidents and frequency of accidents (i.e. number of accidents per one million working hours) at Danube Refinery

ENVIRONMENT PROTECTION

Crude oil processing is a complex industrial activity performed at a large scale in a concentrated place in respect of installation. It results – through the hazardous substances emitted into the air, discharged to the surface waters, the soil and ground water – in an unavoidable load to the environment. At the same time a refinery can do a lot in order to reduce this load. The three key elements in the environment protection activity are prevention, disposal of hazardous wastes generated, and monitoring.

In the initial period of operation the reduction of processing losses – such as leakage and evaporation from pipes and tanks – was the most significant step in mitigating the environmental load, in addition to the reconstruction of the wastewater treatment plant.

Later a change in attitude had happened in this area partially because the applicable legislation became more stringent: the importance of prevention increased. Due to that, in the 1980s 15–20% of the investments already served environmental protection purposes, directly or indirectly. From 1995 on, when the Hungarian environmental act came into effect, the economic and environmental aspects of operation were taken into consideration increasingly at an identical weight in making the decisions concerning the Refinery. For the new projects the application of the best available techniques (BATs) became a definite objective. The second part of the 1990s was characterised by both the compliance with the existing EU legislation, and the preparations for the expectedly more stringent statutes.

Since 2006 Danube Refinery's activity has been regulated by an integrated environmental permit in replacement of specialty permits typical in the past.

AIR

Initially the air pollution by hydrocarbon vapours and gases, which escaped into the atmosphere during tank filling and discharging, and also due to leakage of the process systems was addressed. Today the reduction in the emissions of carbon-monoxide, sulphur-dioxide and nitrogen oxides is the most important task. Significant results have been achieved also in this area through the environmental projects (construction of sulphur recovery units, implementation of residue upgrading, reconstruction of incinerator, etc.) in recent decades. In order to reduce nitrogen oxide emissions combustion units have been refurbished, and furnace burners have been replaced in various plants.

In 2004–2005 MOL launched a comprehensive programme to monitor and control emissions of greenhouse gases responsible for global warming. To

mitigate the carbon dioxide emissions, a variety of energy efficiency improvement actions were launched, such as revision of tube furnaces and of rotating machines as well as more efficient operation of the distillation columns.

SURFACE WATERS

Oil refining is an extremely water-intensive technology. One way of reducing water pollution is the reduction of water consumption. For that end a 'recycled water for cooling' system was installed in the Refinery as early as in the 1960s. For cleaning the wastewaters from the various process streams oil separation and recovery equipment and wastewater treatment facility were installed. Through the modernisation of the wastewater treatment unit at a later date the quantity of oil discharged with the effluents was further reduced. In 1993, a biological wastewater treatment unit was built. Later on, Danube Refinery started necessary investments in due time, to meet the more stringent EU discharge limits effective as from 2005; wastewater system has been modernised and a new biological wastewater treatment unit has been built. Reconstruction of the sewage lifting unit began in 2014.

SOIL AND GROUND WATER

One of the potential consequences of refinery operations is soil pollution, due to which the soil or the ground water may be damaged on the long term. For the examination of the ground water level at the beginning of the 1980s a network of monitoring wells was established. To prevent further spread of hydrocarbon pollution detected in the analysis a groundwater protection system has been built up.

WASTE MANAGEMENT

Danube Refinery makes efforts to minimise hazardous waste generated during the operation and to comply with the increasingly stringent regulations. The disposal of hazardous wastes generated in the operations of the Refinery is made primarily in the incinerator plant commissioned in 1981, which is connected to a heat recovery boiler system. The modernisation of this equipment was completed in 2005.

About 85% of the waste from the Refinery's scrapyard will be recovered in some form. By 2005 waste previously accumulated in Danube Refinery territory (mainly acid tar) had been disposed and the 'negative legacy of the past' completely eliminated.

AMBIENT NOISE

In 2009, the noise impact range of the Refinery was determined by noise mapping of the area. The noise map was made by measuring of the noise sources; a model was made, taking into account factors that influence noise spreading (e.g. shading and reflection).

ENERGY MANAGEMENT

Crude oil refining has a very high energy requirement therefore the safe and economically viable energy supply for the refinery production was a dominant aspect in the location of Danube Refinery. This is why the Refinery was built near Danube Thermal Power Plant, which could meet the steam and electric power demand of the Refinery's process units.

Though due to the introduction of more modern processes the specific energy consumption has improved, the new and newer units kept increasing the total energy consumption of the Refinery. As the complexity of the Refinery was increasing so were the quality requirements of the energy supply. To meet the demands the construction of new let down stations, the reconstruction of the existing ones and an expansion of the total supply system were required.

Because of the increase in the price of the energy sources the Refinery was introducing energy rationalisation measures from the end of the 1970s, and started to implement its own steam generation at an increasing rate through waste heat recovery. However, the fact that the Refinery is located on a relatively large area and certain loss rate through the long supply lines is unavoidable sets a limit to the reduction of the energy costs.

The safety of supply has a priority importance in the energy supply since a possible upset – in addition to that

it would cause a serious trouble in the complex refinery processes and would result in loss of production – may damage the equipment. In the past 30 years there were three major power failures in the Refinery. The power supply to the protection, operation and signal circuits of the most important consumers such as the process control and electric power supply systems is provided by uninterrupted power supply systems.

By 2014, the annual power consumption by Danube Refinery had reached 600 thousand MWh (this equals to the consumption of about one quarter million homes) (see Figure 2), which is mostly provided by the power transmitted via the 120 KV line installed from power plant DERT. The incoming electric power is transformed to 6 KV voltage level by the transformers of the three receiving stations. Additionally the steam turbines of the Refinery also produce a smaller amount of electric power.

A portion of the Danube Refinery's steam consumption is produced by the refinery plants' built-in heat recovery equipment units. At the same time, however, the Refinery technological processes require also a constantly available steam supply independent from the in-house steam generation.

From the start of the Refinery until the end of 2008, the required outside portion of the steam consumption was supplied from Danube Thermal Power Plant via pipeline. After that, own Boiler plant constructed on the territory of the Danube Refinery has become an independent steam supplier.

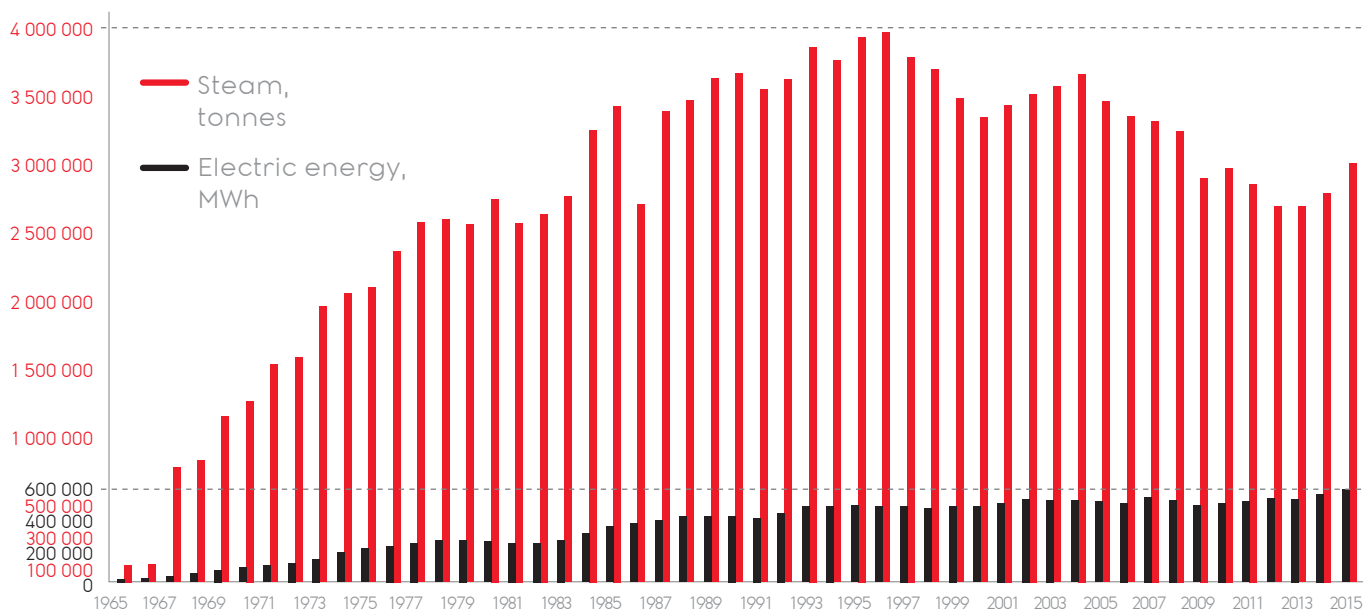


Fig. 2. Historical energy consumption of Danube Refinery



The plant is equipped with five pieces of medium pressure steam boiler, each one capable to generate 50 t/h of steam, out of which two are operated with fuel oil; the other three units use fuel oil and natural gas to produce steam. Thanks to the unique design, the Boiler plant is capable to adapt flexibly to sudden changes in steam demand from the refinery plant units. Our objective is for the near future to convert two boilers for burning of fuel gas produced in large quantities during the refinery processes and / or natural gas. In 2014, the steam consumption of Danube Refinery was about 2.6 million tonnes, out of which 2.2 million came from own generation (see [Figure 2](#)).

There is considerable potential to improve efficiency in energy use. As a result of measures taken in the past four-year period, the energy bill of the Refinery decreased by HUF 16 thousand million in total which means an 11% saving per year. Improving the efficiency of energy use for refining not only increases MOL Downstream's competitiveness, but also supports the sustainable management and the conservation of the environment for future generations.

The EU energy efficiency directive 2012/27/EU requires large companies to conduct energy audits by 15 December 2015. MOL Plc. complied with this obligation by introducing and operating an energy management system corresponding to ISO 50001, for all activities of the organisation.

Danube Refinery actively contributes to the implementation of energy policy of MOL: during the preparation to the audit the company scanned all details of its energy consumption, identified the factors influencing it, and developed energy performance indicators and elaborated a continuous monitoring system for the same. Seeks modern, energy efficient solutions for application and encourages innovation activity aimed at its development.

Energy audit was realised in October, 2015 by SGS (Société Générale de Surveillance) a leading inspection, verification, testing and certification company. Since then, Danube Refinery has a certified energy management system.

MAINTENANCE

The basic function of the maintenance organisation is to ensure the availability of the refinery equipment, to troubleshoot in case of upsets, and to minimise the time lost in production. The scope of the activity covers the works associated with mechanical, electrical, process control and building maintenance.

Even before the first process unit AV-1 was started up a small team commenced the provision of functions associated with the operation maintenance from 1963. During this period the production units – in accordance with the then accepted practice – were shut down for a major overhaul every year. In the 70s, based on the experience gained, and with the modernisation of both the materials used, and diagnostic and corrosion protection methods applied, Danube Refinery could change over to the biannual turnaround cycle. A central maintenance workshop was established, and additional local workshops were functioning in the Refinery. In peak periods of work nearly eight hundred employees – approximately one quarter of the total headcount of that time – were performing maintenance activities.

In 1979 DKV joined the Repair Services of the COMECON countries, under which a regular exchange of skilled workers was practiced, and assistance was provided to each other amongst the member companies of the Services in peak work periods.

In line with MOL's strategy to improve the efficiency the separation and outsourcing of non-core activities were started at the beginning of the 1990s, and this procedure has brought along changes within the maintenance organisation and in its work. Initially the functions not requiring special skills were outsourced in the first place. Throughout the 1990s six 100 percent MOL owned maintenance companies were established in the area of Refining.

In 2001 important steps in the transformations were the accurate definition of the maintenance management functions, and the establishment of a small team to perform this activity. The objective of the central maintenance organisation is to ensure the technical availability and reliability of the refinery equipment at a standard satisfying both the current market needs and the production requirements. Through a merger of four maintenance affiliates in the same year a so called single service company was established, which has an overall responsibility for performing any and all refinery maintenance works on the basis of a long-term contract.

The Refinery maintenance strategy developed in 2002 placed the emphasis on the prevention and on the turnarounds scheduled for many years in advance within the maintenance activities. The implementation of turnarounds in a project system commenced in the same year. The functions of the Central Turnaround Office established at that time cover all elements of this complex work process from preparations to financial evaluation.

The most appropriate indicator for the effectiveness of the maintenance activities are the mechanical availability of the production units expressed in percentage, and the time period between two failures.

The basics of the risk-based maintenance outlined in the strategy were laid down in the mid-2000s. Building on those, after 2009 with the development of processes and systems used in the Refinery, along modern reliability-focused maintenance approach, the plant availability further increased. As part of this, the condition monitoring and diagnostic tools got fine-tuned, which allowed to extend the cycles of turnaround time to five or six year periods and to improve the turnaround lead time. As an international recognition of this working-level, Danube Refinery was honoured – first from the Central European region – with ‘HART Plant of the Year’ award in 2010.

In 2015, in the framework of the ‘Next Downstream Program’ a three-year programme called ‘UpTime’ was launched by the organisation with the aim at increasing the availability of plants. Strategic actions developed in the context of this – such as the development of special maintenance policies for key assets, renewal of event investigation process, bringing corrosion protection to a higher level – gives a good chance to reach the target of 97% operating availability by 2018.

THE REFINERY TODAY

Today Danube Refinery is functioning as part of the integrated Production organisation of the Downstream division (RMD) in MOL Group. The Refinery harmonises its activities with the other production units of the Group: with the refineries of SLOVNAFT and INA, with MOL Petrochemical (former TVK) and with Hungarian Zala and Tisza refineries.

The cooperation covers investment activities, planning of turnarounds and helping each other with material streams in case of unscheduled shutdowns and the sharing of experience.

The production plans are optimised at the Group level. Operational management of the refineries is done at the local level.

The most important data of the Refinery:

- ▶ Area: 800 hectares
- ▶ Number of plants: 55
- ▶ Distillation capacity: 8.1 million tonnes / year
- ▶ Quantity of processed crude oil: 6.5 million tonnes (2015)

- ▶ Other processed feedstock: 1.2 million tonnes (2015)
- ▶ Product sales from own production: 7.0 million tonnes (2015)
- ▶ White products extracted from the processed crude oil: 5.3 million tonnes, 81.4% (2015).

To judge the modernity of a refinery is difficult and is not free from subjective elements. However, there are properties, based on which a real picture can be obtained. As regards the capacity Danube Refinery ranks amongst the large refineries in the region. This has a dominant importance in terms of specific material, energy and labour requirements.

An indicator often used for comparing refineries is the Nelson index, which reflects the depth of crude oil processing, namely the complexity of the refinery. The Nelson index of Danube Refinery is 10.6, which is very high in the region, only the refinery in Bratislava functioning as part of MOL Group has a value higher than this.

Since 1990 the Refinery has had itself evaluated regularly in the study performed biannually by analysing and consultancy firm Solomon Associates. The last ones of these studies made on the basis of data from 2012 and 2014 demonstrate that the financial indices of the Refinery are comparable to those of the best ones participating in the study. "Over the past five years, Danube Refinery has consistently placed in the first quartile of European refiners on a Net Cash Margin basis. It is a core asset in MOL's refining portfolio." – says WoodMackenzie, the well-known oil industry analysing company.

POSSIBLE DEVELOPMENT DIRECTIONS FOR THE FUTURE

For MOL Downstream Refining organisation efficiency and production flexibility are key success factors. As in the markets of MOL diesel shortage continues to be expected, while motor gasoline is surplus – in varying amounts –, the main direction of development in the coming period is to increase diesel production. The timing and exact manner of implementation depends primarily on the evolution of market conditions. A number of concept ‘is on the drawing board’, prepared in advance, waiting for the business environment to become more advantageous so that these projects are ‘set to be launched’ in a relatively short period of time.

Márta Krámer, Dr.

Security of energy supply – Strategic stockpiling

Anikó Lévai (45)

Head of Stockpiling and Trade
Hungarian Hydrocarbon Stockpiling Association
Levai.Aniko@HUSA.hu

ABSTRACT

Fossil fuels, especially crude oil play globally a decisive role in the energy consumption. Assuring the security of oil supply has key importance in countries which have high dependency on imported crude oil and petroleum products. Even temporary difficulties in oil production or in transport, or a significant increase of the world market price of these products may evoke serious disruptions in oil-importing economies. Strategic oil stocks help avoid or at least reduce adverse effects and improve energy security. The article describes the evolution of the strategic stockpiling and introduces the Hungarian stockpiling practice in details.

INTERNATIONAL HISTORICAL BACKGROUND

ENERGY SECURITY BEFORE AND AFTER THE 1970S

After the Second World War – compared with other issues such as trade and security – states have been much slower to build international institutions for energy security governance. Until the early 1970s, there was almost no structured energy cooperation among the world's major energy-consuming nations.

The national energy markets were mostly self-supporting: majority of the energy consumed in the largest countries was also produced within national borders. This was especially true for coal, which was the most important commercial fuel until the mid of 1960s when its share began to fall throughout the world. Concurrently, the share of oil nearly quadrupled. Oil thus became the first commercial fuel to be traded internationally in large quantity.

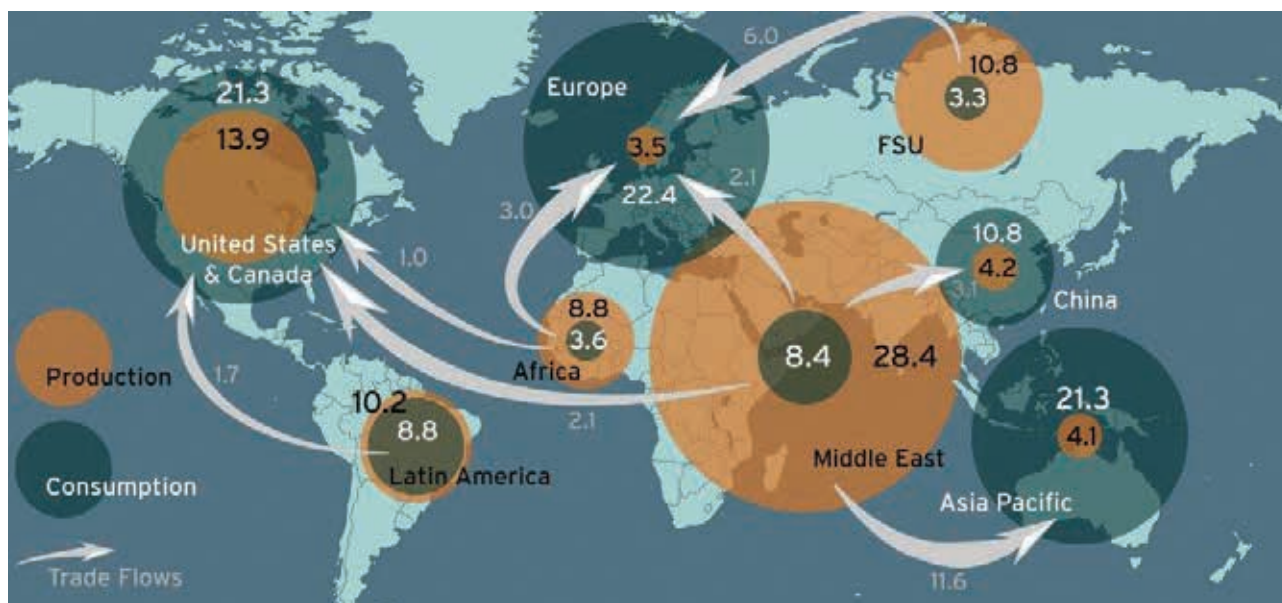


Fig. 1. World's oil and oil product trading map, Mbbbl/day
(viewed 21 March, 2016, <http://www.energyfuse.org/?s=oil+trading+map>)

The two superpowers – the United States and the Soviet Union – possessed abundant domestic oil reserves. The Soviet Union was even a small net importer, the US, in turn, was by far the world's largest oil producer and was self-sufficient in oil supply till the end of Second World War. Due to geological depletion its spare capacity had disappeared at the end of 1960s and it produced only three-quarters of its consumed oil quantity at that time, it became net importer.

Meanwhile, as the oil production in the Western countries – concentrated in the Organisation Economic Cooperation and Development (OECD) – stagnated, their demand had grown significantly. Geographical imbalance of supply and demand increased, and that imbalance still remains for today (see Figure 1).

Returning to the 1960s, the international oil trade was dominated by small group of oil companies, which were exclusively American and Western European origin. The so called 'Seven Sisters' were vertically integrated companies: they simultaneously owned, produced and transported crude oil and oil products. Formal cartel agreements and the oligopolistic market structure provided these companies with ample profits and enabled industrialised countries to import oil at declining prices. This system brought forth in parallel the collapse of colonial power. The oil-exporting countries began to negotiate increasingly favourable deals: they forced the renegotiations of royalties, taxation and cost-sharing schemes. They had begun to organise themselves into two clubs. In 1960 the Organization of Petroleum Exporting Countries (OPEC) was created with the aim of reducing dependence on the international oil companies and "in order to secure fair and stable prices for petroleum producers; an efficient, economic and regular supply of petroleum to consuming nations; and a fair return on capital to those investing in the industry" (OPEC 2016). In 1968 the Organization of Arab Petroleum Exporting Countries (OAPEC) was established in response to the third Arab-Israel War and with the aim to prevent oil transport to the countries which were supporting Israel.

The Yom Kippur War in 1973 brought about the first major oil crises. The pro-Israeli position of the US and the Netherlands in that conflict led OAPEC to impose oil embargoes on these two countries. As a result, global oil supplies fell about 9% in the last quarter of 1973 and oil prices quadrupled. That was the time for oil-exporting countries to discover the political utility of their so called 'oil weapon'. These events alerted policy makers in the industrialised countries to the extent of their dependence on oil imports. By November 1974 agreement was reached on the International Energy Program (IEP), establishing

the International Energy Agency (IEA) as an autonomous agency of the OECD. The IEA was started off with 16 signatory states and with two main principal tasks: managing an emergency scheme to cope with potential oil supply shortfalls and the obligation to keep strategic oil stocks. Today IEA is made up from 29 member countries. Hungary joined the IEA in 1997, Slovakia in 2007 (the Ukraine, Romania, Serbia, Croatia and Slovenia do not have memberships in the IEA).

FRAMEWORKS OF THE IEA AND THE EU LEGISLATIONS ON STRATEGIC STOCKS

THE INTERNATIONAL ENERGY AGENCY'S EMERGENCY RESPONSE SYSTEMS

Imbalance of supply-demand is conspicuous among the OECD states (see Table 1). Ensuring security of supply and solidarity among the major industrial countries is a core objective of the IEA. "The Agency's emergency response system is therefore a key feature of the organisation. The IEP, which is contained in the IEA's governing treaty, commits participating countries to the following measures:

- ▶ Maintain emergency oil reserves equivalent to at least 90 days of net oil imports
- ▶ Undertake programmes of demand-restraint measures to reduce national oil consumption, and
- ▶ Participate in oil allocation among IEA countries in the event of a severe supply disruption" (CEPS 2011).

Stock release is the most commonly used among the emergency response measures at hand: it is the most effective first line of defence for providing additional oil to an undersupplied market and can be complemented by other emergency measures during a coordinated action. *IEA countries are obliged to hold stock levels equivalent to at least 90 days of their net imports.* Stocks are generally held either by industry or a combination of industry and a public entity, i.e. by the government and / or agency established to fulfil this role. IEA member countries are holding 4.2–4.3 billion barrels of public and industry oil stocks, which represent at least 180 days of net imports (see Fig. 2). The bulk of this total (60%) is in industry stocks, which include commercial stocks as well as strategic stock obligations imposed by the respective governments. It is not possible to clearly demarcate what is commercial and what is strategic in the industry stock pool.

"The duration of available stocks is a function of the *drawdown rate*." Calculating with an average drawdown rate of 4–4.5 million b/d, the duration – only for the public stocks – would be approximately one year (CEPS 2011).



Unit: million b/d

	1985	1990	1995	2000	2005	2010	2012	2015
DEMAND								
Americas	19.1	20.7	21.8	24.3	25.9	24.1	23.6	
Europe	12.8	13.8	14.8	15.3	15.7	14.7	13.7	
Asia Oceania	5.7	7.4	8.9	8.9	8.9	8.2	8.6	
Total OECD	37.5	41.9	45.4	48.6	50.5	47.0	46.0	
FSU	8.9	8.2	4.3	3.8	3.9	4.1	4.5	
Europe	0.8	0.9	0.6	0.6	0.7	0.7	0.7	
China	1.8	2.3	3.4	4.6	6.7	8.9	9.8	
Other Asia	3.1	4.5	6.2	7.8	9.0	10.7	11.3	
Latin America	3.1	3.5	4.1	4.7	5.0	6.1	6.4	
Middle East	2.9	3.3	4.3	4.7	5.9	7.3	7.7	
Africa	1.7	2.0	2.2	2.5	3.0	3.5	3.7	
Total non-OECD	22.3	24.6	25.1	28.6	34.1	41.4	44.0	
Total demand	59.9	66.5	70.5	77.2	84.7	88.4	90.0	94.4
SUPPLY								
Total OECD	20.3	19.0	21.0	21.9	20.2	18.9	19.9	
Total non-OECD (non-OPEC)	20.3	22.7	20.5	22.6	27.2	29.9	29.5	
Total non-OPEC	41.7	43.2	43.3	46.6	50.0	52.6	53.3	64.4
Total OPEC	17.6	23.9	27.4	30.8	34.8	34.7	37.6	32.0
Total supply	59.3	67.1	70.7	77.4	84.8	87.3	90.9	96.4

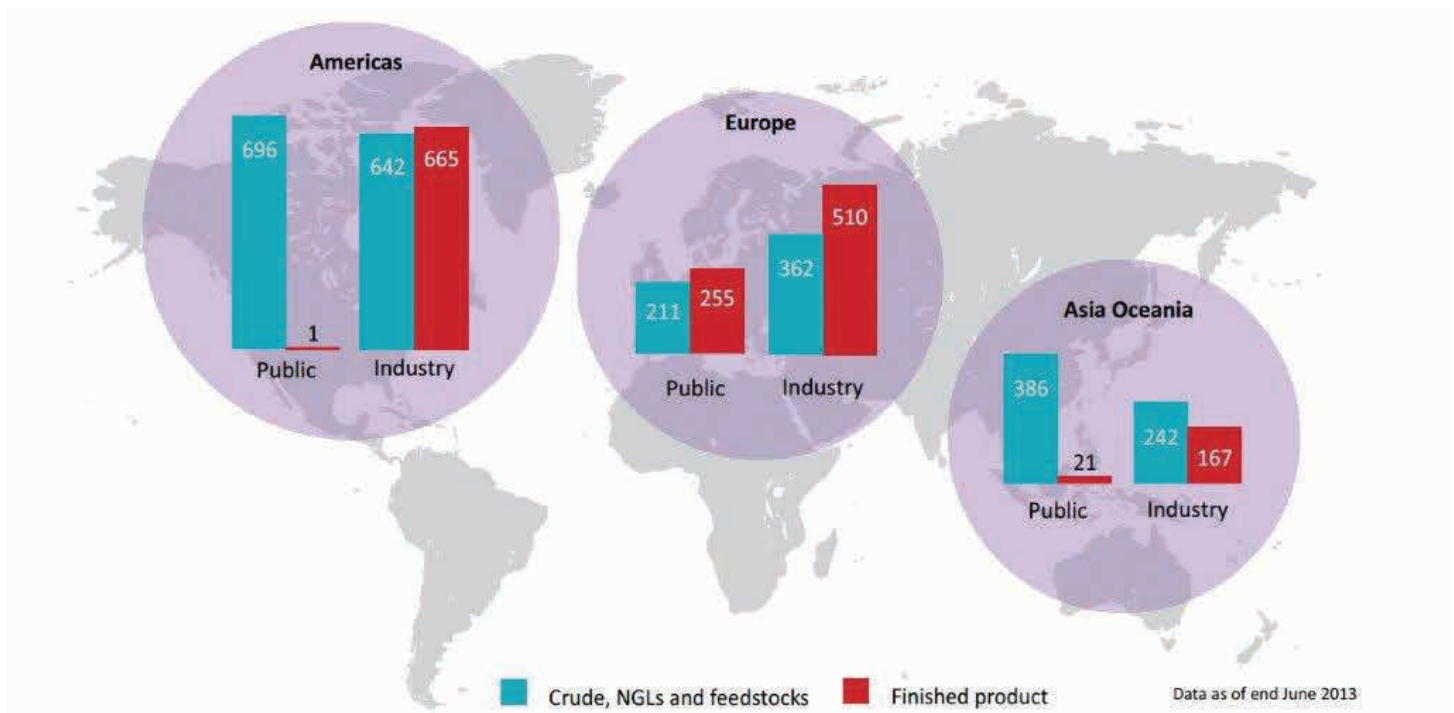
Table 1. World's oil supply-demand (viewed 21 March, 2016, <<http://www.iea.org/publications/freepublications/publication/ENERGY-SUPPLYSECURITY2014.pdf>>, p. 17; <https://www.iea.org/oilmarketreport/omrpublic/>)

During an oil supply disruption, member countries can release stocks through various options. In countries where there is a substantial obligation on industry to hold stocks, the most common course of action is for the government to allow, temporarily, a decrease in industry's compulsory stockholding levels in line with the country's share of the total IEA response. For countries with publicly held stocks, stock release typically involves offering specified amounts from these public reserves for sale or lease (IEA 2014).

IEA's member *states are entitled to count stocks held abroad* physically or in form of 'ticket' in order to fulfil their minimum stockholding requirements. The primary reason of this stockholding practice is the better logistic, such as at a neighbouring country's port where volumes are unloaded and delivered by pipeline (e.g. the Italian port of Trieste for Austrian stocks). Stocks counted towards the minimum obligation can also include those

held under bilateral agreements between governments, which guarantee access to such stocks during a crisis. This creates efficiencies in stockholding, especially for countries with insufficient storage capacity or in which a major demand centre is located on or near an international border. Interconnectivity of the oil market infrastructure can also facilitate spare storage capacity or more cost-effective storage by utilising capacity in neighbouring countries. This flexibility is often an important means of enabling industry participants to meet stockholding obligations imposed by the government. In other cases, the company or agency does not own the stocks but has the right – based on short-term lease contracts or tickets – to purchase them in a crisis.

"A large part of the stocks held abroad is in the form of *ticket arrangements*. The use of tickets is quite common in IEA Europe, because, based on the common market, major oil companies see Europe as a whole or as several large regions.



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Note: oil stocks as of end-June 2013

Fig. 2. Total IEA's oil stocks by region (in million barrels) (viewed 21 March, 2016, <<http://www.iea.org/publications/freepublications/publication/ENERGYSUPPLYSECURITY2014.pdf>>, p. 24.)

They recognise an opportunity to use cross-border ticket agreements with different countries to optimise their stocks in relation to their obligations" (IEA 2014). Nevertheless, several IEA countries do not support such stockholding ticket arrangements, including Hungary.

The IEA stockholding obligation does not define whether stocks has to be held in the form of crude oil or refined oil products. IEA countries that also belong to the EU typically hold product stocks based on EU regulations which require that at least one-third of the obligation has to be covered by finished oil product. Each individual member country has the right to decide holding reserves in either crude oil or refined oil products, depending on specific factors. One factor is the storage cost, which can be significantly higher for oil products than for crude oil. Member states with a large refining industry hold likely more crude oil, which provides them greater flexibility in times of crisis. In countries, where the domestic refining capacity is limited or the oil product imports have a

large share in domestic demand, emergency stocks consist rather of refined products.

The IEA's emergency response system, using stock release has been activated three times: (1) during the outbreak of hostilities in the Gulf ('Desert Storm'), (2) after the damages caused by Hurricanes Katrina and Rita in oil rigs, pipelines and refineries in the Gulf of Mexico in 2005 and (3) in response to the prolonged disruption of oil supplies from Libya in 2011. "The IEA activated its contingency plan on 17 January 1991 to make available to the market 2.5 million barrels of oil per day. But the market turned around almost immediately after the outbreak of hostilities, and the IEA's intervention proved unnecessary" (CEPS 2011). In relation to the hurricanes and to Libyan supply disruption, the IEA member countries released 60 million barrels crude equivalent in both case, and decided to increase the indigenous production and to apply demand restraint. In the collective action, 2005 Hungary participated as well: 120 thousand tonnes of crude oil were released at that time.

EU LEGISLATION

The growing dependency on energy was a particular concern for Europe as well. It is one of the world's biggest oil and gas importers. Half of its total energy consumption is imported, most of them from Persian Gulf, Russia and North-Africa. Aim of the European energy policy was from the beginning to enhance the security of energy supply.

“Council Directive 68/414/EEC of 20 December 1968 was the first piece of legislation” (CEPS 2011) on concerning oil stocks. The directive noted the growing dependence of the EU on oil imports and the gravity of the consequences of “any difficulty, even temporary, having the effect of reducing supplies of such products imported from third States” (CEPS 2011; EC 1968). It required maintaining stocks of oil products to at least 65 days' average daily internal consumption in the preceding calendar year (EC 1968).

“Council Directive 98/93/EC ... introduced several modifications to the 1968 Directive” (CEPS 2011), including the introduction of the minimum 90 days' average daily internal consumption level for mandatory stocks of oil products. “Part of internal consumption met by derivatives of petroleum produced indigenously by the Member State ... may be deducted up to a maximum of 25 % of the said consumption” (EC 1998). The most conspicuous was that as ‘difficulty’ not just a physical shortfall, but also a significant increase in prices might be considered. “In 2006, Directive 2006/67/EC was promulgated, which was meant as a summary document of the previous directives ... in the interest of clarity, and therefore did not introduce any new provisions” (EC 2006; CEPS 2011).

The legislation currently in force in the EU concerning oil stocks is Council Directive 2009/11/EC of 14 September 2009 (hereinafter: Directive, or CSO Directive, where CSO is compulsory stocks obligation) replaced and covered the scope of the previous directives, achieving “a higher level of coherence with IEA standards and thus reduce bureaucratic procedures. It also aimed at harmonising emergency mechanisms among member states” (EC 2009; CEPS 2011). According to the Directive the *stockholding obligations are 90 days, based on net imports or 61 days of average daily inland consumption, whichever of the two quantities is greater*. Furthermore, the “Directive adds the obligation for each member state to have at least one-third of the reserves composed of oil products in proportions corresponding to the consumption patterns of the member state” (CEPS 2011).

“Member states have an obligation to ensure that stocks are available and physically accessible. In this regard, they are responsible for putting in place arrangements for the identification, accounting and control of these stocks. A register containing information on emergency stocks (the location of the depot, refinery or storage facility, the quantities involved, the owner of the stocks and their nature) should be established and continually updated. A summary copy of the register shall be sent to the European Commission once a year” (CEPS 2011).

“Additional powers are granted to the EU, such as reviewing and auditing stocks maintained by member states”. “The purpose of this measure is to enable the European Commission to coordinate an EU contribution in the event of IEA action” (CEPS 2011).

The Directive encourages “the setting up of *central stockholding entities (CSEs)* in the form of non-profit making bodies or services” (CEPS 2011). The main purpose of the CSE is to acquire, maintain and sell oil stocks for the purposes of the Directive or for the purpose of complying with international agreements concerning the maintenance of oil stocks.

“Under the conditions and limitations laid down by the Directive, CSEs and member states may delegate some aspects of the management of stocks to another member state with stocks on its territory, to the CSE set up by the said member state or to economic operators” (CEPS 2011).

According to the Directive the member states have to “ensure that they have procedures in place and take such measures as may be necessary, in order to enable their competent authorities to release quickly, effectively and transparently some or all of their emergency stocks... in the event of a major supply disruption, and to impose general or specific restrictions on consumption in line with the estimated shortages, inter alia by allocating petroleum products to certain groups of users on a priority basis” (CEPS 2011).

Although stock release has not been *activated* by the EU (in spite of its above mentioned initialisations)

“two kinds of situations are envisaged:

- If an international decision to release stocks affecting one or more member states has been taken (probably by the IEA), the member states can use their stocks and must notify the Commission... or the Commission can directly recommend to member states to release some of their stocks.
- If one member state experiences difficulties and no international decision has been taken, the Commission shall ... inform and coordinate with the IEA.

- ▶ If a major supply disruption is deemed to have occurred, the Commission shall authorise the release of some or all of the quantities of emergency stocks” (CEPS 2011).

According to the *Directive it had to be reviewed by the end of 2015*. The evaluation is an ongoing project where stakeholders of the member states (MS), CSEs and economic operators were involved.

During the surveys discrepancies, challenges were revealed experienced by the stakeholder and amendments are recommended in the following areas:

- ▶ The directive has largely widened the oil products that can count toward a MS's stockholding obligation. Instead of the 'main products' (gasoline, heating oil, road diesel, jet fuel, heavy fuel oil) of the past, using products such as petroleum cokes, vaseline, bitumen, etc. are allowed, which are not strategic products in case of a crisis. For credibility's sake, the products that can count toward the obligation should be reviewed and limited.
- ▶ Furthermore, in some countries, so called 'Any oil' is used in the stock ticket market, which means, that the type of product will be defined only in an emergency, until then it is unclear which product has been reserved. Such oil stocks make a poor contribution to energy security. Therefore it should be clear at any time which product is available to the market, e.g. subject to a ticket agreement.
- ▶ Plenty of cross-border tickets are used in order to fulfil national obligations, where the audit of these tickets is the task of the beneficiary. However, it is an impossible mission, as the beneficiary MS does not have an insight in the amount of stocks in a given storage facility, and is not able to check which stocks are labelled 'commercial' or used by operators to cover their own stockholding. Only the country where the stocks are stored can legally ensure that an operator provides him with all information needed to make inspection possible. Therefore, the depository state should be responsible for the control and can prevent double counting and abuse.
- ▶ There is also a discrepancy regarding the eligibility of certain feedstocks or products: some of them can be set against the obligation in one country but not in another. To avoid this inconsistency it is recommended to comprise an EU-wide unified table, linking CN codes of the eligible products, feedstocks (FuelsEurope 2015).
- ▶ Consistently with the IEA rules the directive considers 10% of the stocks as 'non-accessible'. The deduction of 10% has been imposed in order to compensate for stocks in the system not being available when a stock release comes into place. These might be stocks in tank bottoms. The 10% unavailability factor is based on relatively old studies of IEA which are probably out-of-date, or which are not publicly available, contrary to EU legislation practices. MSs are seeking a revision of the calculation methodology to remove this 10% tank bottom deduction on obligated industry and CSE stocks, or at least consider whether 10% is still an accurate figure and accordingly it should be reduced. However, consideration should be done alongside the IEA to ensure the regulations remain aligned.
- ▶ The EU methodology for calculating the stock levels states that crude oil stocks have to be reduced by 4%, 'which corresponds to the average naphtha yield.' Under the IEA methodology, the naphtha yield of 4% is deducted from 'crude oil, NGL (natural gas liquids) and feedstocks' i.e. the deduction is made not from crude oil alone but from crude oil, NGL and feedstocks. It is recommended that this discrepancy between the two methodologies shall be resolved.
- ▶ The naphtha treatment has a significant influence on obligation as well. The directive stipulates that MSs fall into different calculating methodologies depending on the average naphtha yield in the year. There is a 7% threshold: if the naphtha yield does not exceed it, a fixed deduction of 4% has to be applied, if the naphtha yield exceeds it, the actual naphtha yield can be deducted. This brings a severe problem for countries, whose average naphtha yield is in the proximity of 7%, because small changes from one year to another may imply very large differences in the stockholding obligation. Sudden differences in the stockholding obligation may represent unbearable costs for the CSEs, which are supposed to operate on a not-for-profit basis. The 7% is a very critical level for Hungary as well, which may cause jumps up or down in the obligation and it is difficult to manage taking into consideration the storage capacities and the renting practices, selling the surplus or buying the requested quantity.
- ▶ Regarding the 'naphtha issue' the economic operators complain that all naphtha stocks are explicitly excluded in the calculation of the stock, indifferent of its use. Therefore, also the naphtha used as feedstock for producing gasoline or used as a component in the gasoline blending cannot



be used for compulsory coverage. The obligated operators / refineries urge to allow the use of naphtha stocks for compulsory coverage when it is used for gasoline production (FuelsEurope 2015).

- “There is a difference in the biofuels definition between the CSO Directive and Directive 2009/28. In order to remain consistent there should be a single definition, allowing for maximum flexibility” (FuelsEurope 2015). (Directive 2009/28/EC deals with renewable energy sources.)

After the final evaluation of the Directive the necessary changes may be implemented or settled via the EU comitology procedure.

THE HUNGARIAN STOCKPILING SYSTEM

HISTORICAL BACKGROUND

The need for establishing emergency crude oil and oil products reserves became apparent after the first explosion of oil prices in the world's leading industrial countries, which were major oil importers. It became clear that the dependence of oil consuming countries on external supplies had to be decreased, and one tool to achieve this was the creation of emergency reserves within regulated and agreed conditions. The building of emergency reserves with the participation of the

industry, but in a non-competitive way, started in Western Europe, the United States and Japan in the mid of 70's after the formation of the IEA.

It was in 1990, after Hungary had started its transition toward market economy, when the necessity of creating market-based emergency reserves came up. In the structure of the Hungarian energy supply (see Figure 3), fossil fuels and crude oil in particular played and play nowadays also a decisive role.

Considering the economic and geographical position of the country, the high rate of oil import dependence (see Figure 4) and the existing supply system, first of all the Friendship pipelines which have crucial role in crude oil supply, there is a clear need for increasing supply security.

For the economic stability of the country, it was necessary for the Hungarian oil sector to catch up to the international requirements. The constitution of a safe level of reserves became possible after creating a framework of proper legal and physical requisites. The efforts made on the part of the industry, coupled with the necessary political will, made it possible for Parliament to adopt in 1993 the Act no. XLIX/1993 on the obligatory stockholding of imported oil and oil products which was based on the German stockpiling practice and which established the Association of Crude Oil and Oil Products Stockpiling, the legal predecessor of the today

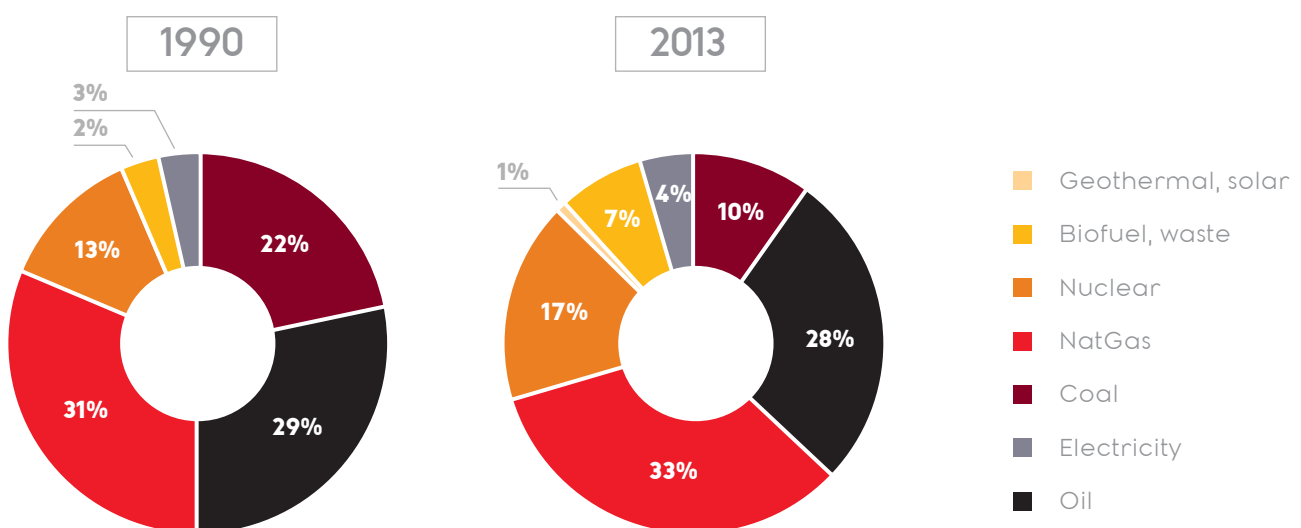


Fig. 3. Hungarian TPES (Total Primary Energy Supply)
(Based on <http://www.iea.org/statistics/statisticsearch/report/?country=HUNGARY=&product=balances&year=Select>)

called Hungarian Hydrocarbon Stockpiling Association (HUSA or Association) becoming responsible for building and maintaining emergency stocks.

With this act Hungary was the first among the former COMECON (Council for Mutual Economic Assistance) countries to meet the political and economic requirements to join the OECD in 1996, enabling full membership in the IEA the following year, 1997.

In February, 2006 the Hungarian Parliament approved the Act no. XXVI/2006 on strategic storage of natural gas ('Gas stockpiling act') with the purpose to manage eventually emerging gas supply crisis and to improve the security of natural gas supply of the household and communal consumers. 'Gas stockpiling act' has appointed the Association to establish and operate the natural gas strategic reserve as well. Since then HUSA has two chambers: Oil section and Gas section.

OPERATING POLICIES OF THE ASSOCIATION

HUSA operates within the framework and under the conditions stipulated by the overruled above mentioned act, by the Act no. XXIII/2013 on the obligatory stockholding of imported oil and oil products (Stockpiling act), by the 'Gas stockpiling act' and the Association's statutes adopted by the general meeting.

Association activities are controlled by the market players, as members and the government, through voting rights exercised at the general meeting and at board of directors' meetings (see Figure 5). The Association is under governmental control, exercised by the minister in charge of energy affairs who is also responsible for the approval of the statutes of HUSA.

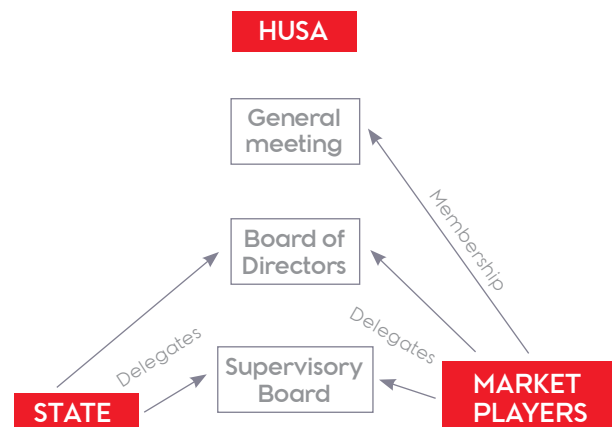


Fig. 5. Governance of HUSA

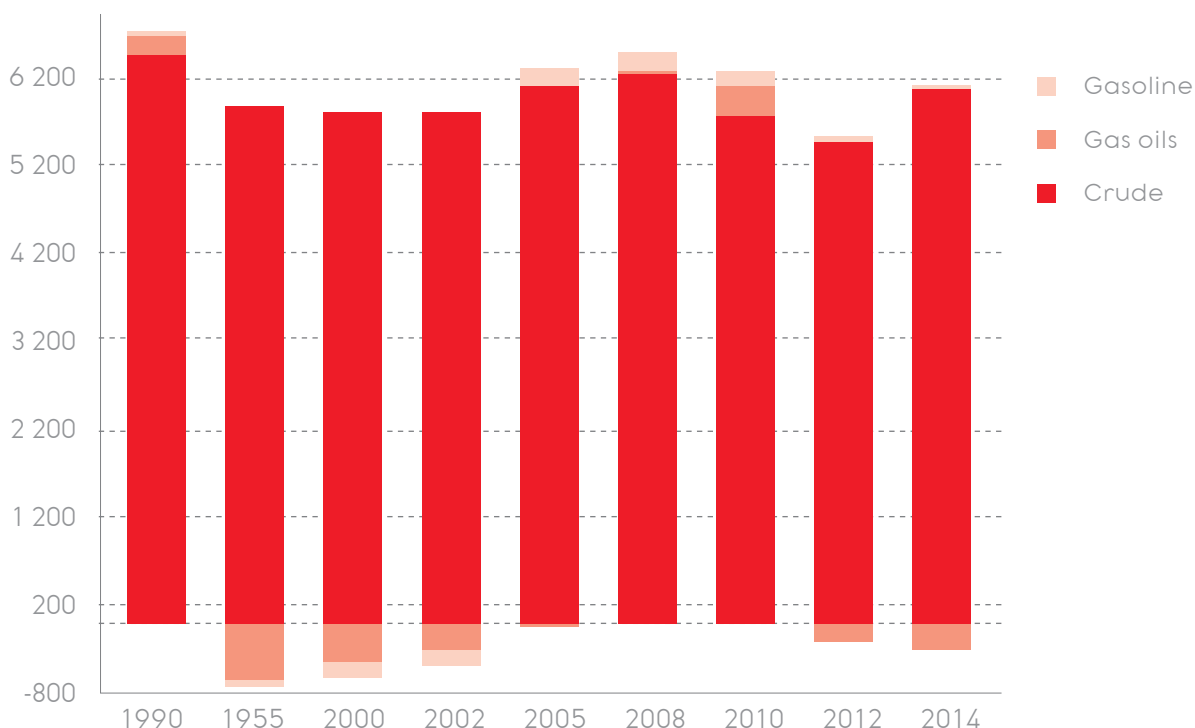


Fig. 4. Net imports of Hungary, thousand tonnes
(Based on: <http://www.iea.org/media/statistics/IEA_HeadlineEnergyData_2015.xlsx>)

The supreme decision-making body of the Association is the general meeting, which is composed of the representatives of its members. Under the stockpiling acts, all economic operators placing oil products and / or natural gas on the market automatically become members of the Association.

The board of directors is the strategic, non-executive management of the Association which is authorised to decide on conceptual and strategic issues. The board of directors comprises fourteen members. The general meeting elects six members from the Oil section, and four members from the Gas section. As for the other four members, two represent the minister in charge of energy affairs, one the minister in charge of public finances and one the Hungarian Energy and Public Utility Regulatory Authority.

The supervisory board controls the legality of the Association's activity and procedures. It is composed of seven members, two of whom are selected by the supervising minister, one is appointed by the minister in charge of public finances, one by the Hungarian Energy and Public Utility Regulatory Authority and three are delegated by the members companies (two from Oil section and one from Gas section). The Association's general manager and his deputy are elected by the general meeting. The general manager is the head of the executive management. After outsourcing of finance and IT in 2016, the current staff of the Association is eight full-time employees.

The Association operates according to its statutes and within the framework laid down in the annual budget, which is approved by the general meeting each December for the following year. The annual reports which are reviewed by the auditor and the supervisory board, are adopted at the general meeting convened in every May following the year in question.

The primary funding of the HUSA's activity is ensured from the member's contribution fees paid by the member companies in proportion to the actual volumes put on the market.

The Association owns the strategic stocks and finances them from borrowed funds. Until 2001, state-guaranteed loans were used. Taking into consideration that the activity of the Association and the stocks held by it provide sufficient coverage, financing banks have not required governmental assurance since 2002. The annual contribution fees provide a cover for the interest payable on loans, the storage costs, the expenses of stockholding in proper quality and quantity, as well the operating costs of the Association.

FULFILMENT OF STOCKHOLDING OBLIGATION

In accordance with the legal regulations the Association built up the 90 days' emergency reserves gradually between 1993 and 1998. It happened in a lucky period, before the long-term and dynamic oil price increase started at the beginning of 2000s.

Since the end of 1998 the volume of stocks satisfied the statutory obligations and the international requirements (see Figure 6). Both of the IEA's and the EU's regulation imposes an obligation for at least 90 days of inventory, however, originally the projection base was different. As it is written in the previous chapters the IEA describes the average daily net imports of the calendar year preceding the current year, while the EU were based on average daily internal consumption for the calendar year preceding the current year. In case of Hungary it was not a significant difference in the use of various projection, since a remarkable proportion of imports in domestic consumption. After harmonisation of the methodologies in 2009, the EU also switched to the net import calculation.

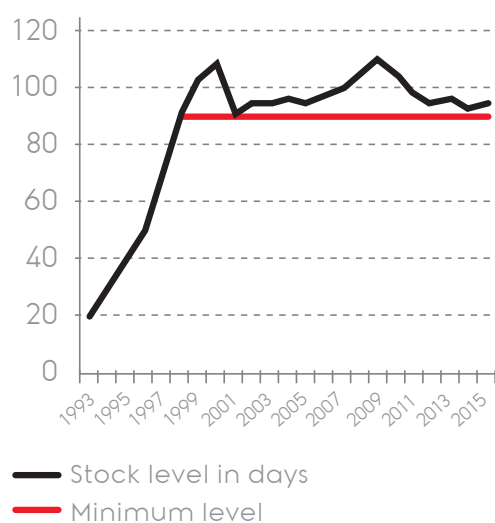


Fig. 6. Hungarian oil and oil product stocks in days

The Stockpiling act prescribes parallel to the Directive minimum one third of the stocks to be kept in the form of oil products. Ratio of crude oil and oil products held by the Association is 40:60 per cent, well above the legal requirement. The necessary or optimal volume of crude oil to be kept is determined by taking into consideration the need of the refinery and the time limit to find alternative source. Within the oil product stocks, the proportion of gasoil / diesel and gasoline follows the structure of domestic consumption. Compositions of HUSA's strategic stocks are shown by Figure 7.

One of the first tasks of the Association after its formation was to assess the availability of free storage capacities in the country, which satisfied the applicable environmental and technical requirements and ensured a connection through pipeline, rail or road for the drawing of stocks as it may become necessary. In the case of crude oil, the proximity of a refinery also had to be ensured. In the country, however, there was not enough free storage capacity which could have fulfilled the requirement of creating 90 days' stocks. The Association has invited several times public tenders for storage of crude oil and oil products which led to the first long-term

custody agreements, which were used to back up the loan agreements that provided the necessary funding for investments. For the implementation of the construction projects and the fulfilment of the storage tasks, new companies were formed which were then later acquired by the Association at the beginning of 2000s. Currently HUSA stores its stocks within the frame of custody agreements concluded with MOL Plc. for crude oil, with TT Plc. – which is co-owned by the Association – for oil products and with Opal Plc. – which is fully owned by HUSA – for both crude oil and oil products. The fully utilised capacities of these companies are shown in Table 2.

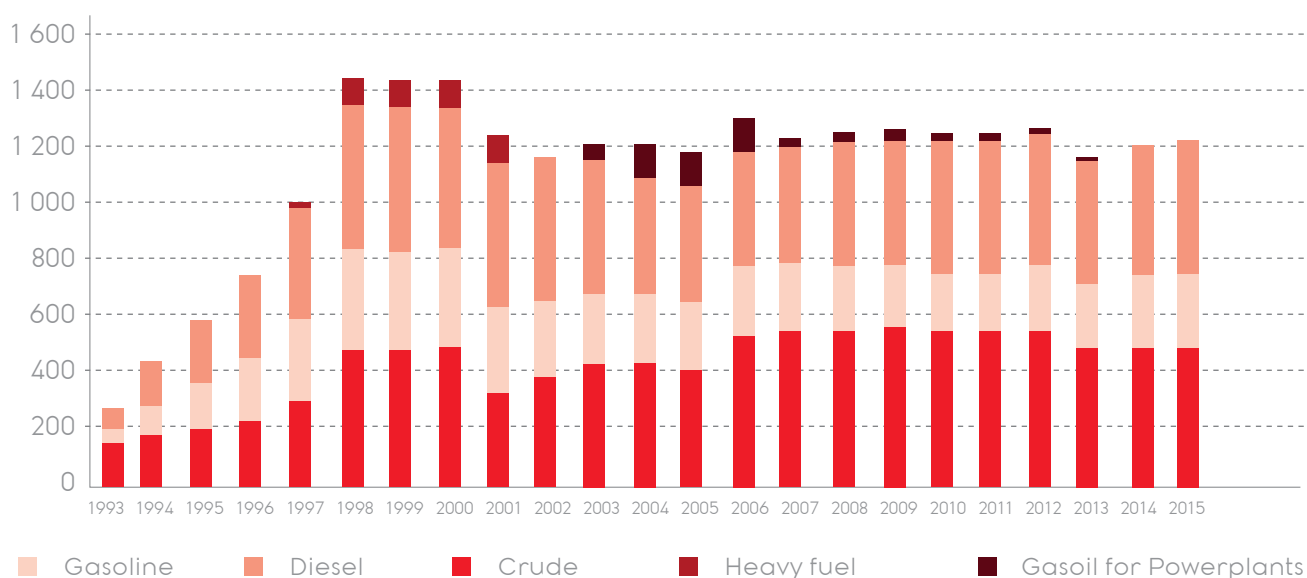


Fig. 7. Compositions of HUSA's strategic stocks, thousand tonnes

Contractual partner	Crude oil	Gasoline	Diesel	Total, m ³
Fully-owned – Opal Plc.	480 000	140 000	271 000	891 000
Co-owned – TT Plc.		190 000	300 000	490 000
Third party – MOL	115 000			115 000
Total, m³	595 000	330 000	571 000	1 496 000

Table 2. HUSA used storage capacities, 2015

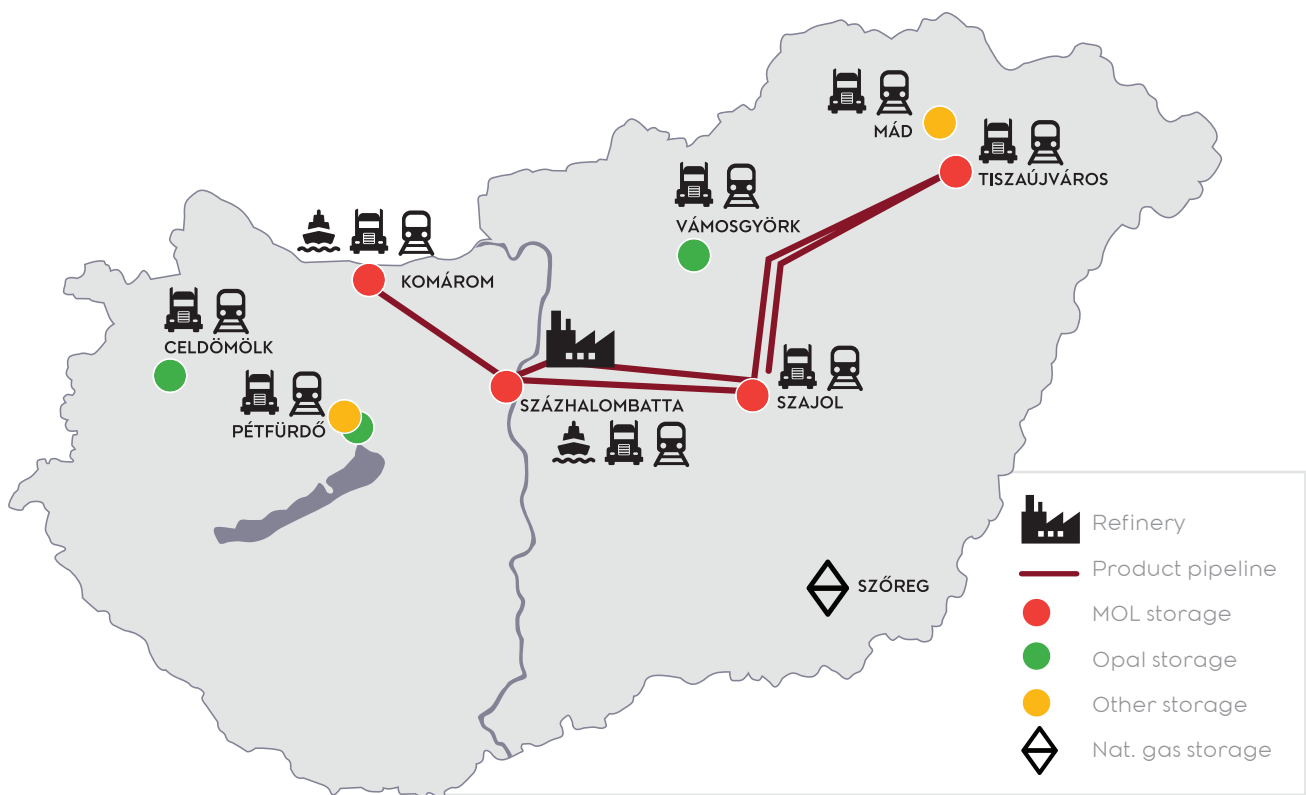


Fig. 8. Locations of HUSA used depots

Concerning the storage depots they are geographically well-diversified, modern facilities with rail, road and partly pipeline connections (see Figure 8) enabling appropriate access to the stocks. The on-line monitoring system introduced in 2011 allows HUSA to control the stocks at any time.

ECONOMIC AND FINANCING ACTIVITY

The Association has to pursue its activity on the basis of two fundamental considerations: full compliance with the statutory stockholding obligation and the performance of this task at a minimum level of costs.

Main guiding principles of HUSA's activities:

- Transparency: all important decisions are adopted by the general meeting
- Neutrality to competition: the Association has to ensure and consistently maintain equitable conditions for all market players
- No market distortion: in fulfilling its activities, the Association handles stocks of large volumes that could cause disruptions in the market if presented all at once. To avoid this, sales and purchases should be carried out in limited volumes at a time

and scheduled according to market processes

- Tendering: all contracts have to be concluded within the framework of open or selected tendering.

HUSA is a non-profit entity, incomes shall cover the expenditure of its activity. Concerning the cost structure of the Association there are three main elements:

- Storage costs
- Financing of bank loans, where only the interest shall be paid and
- Operating costs.

The Association's expenses are financed by the market players through contribution fees, which are passed on to consumers in retail prices. The unit cost of stockholding represents a marginal share in the fuel prices, it is less than 1 per cent. Figure 9 shows the fluctuation of the fee from 1994.

Other income of the Association is the dividends derived from the acquired storage companies.

Figure 10 shows the structure of incomes and expenses of the Association.

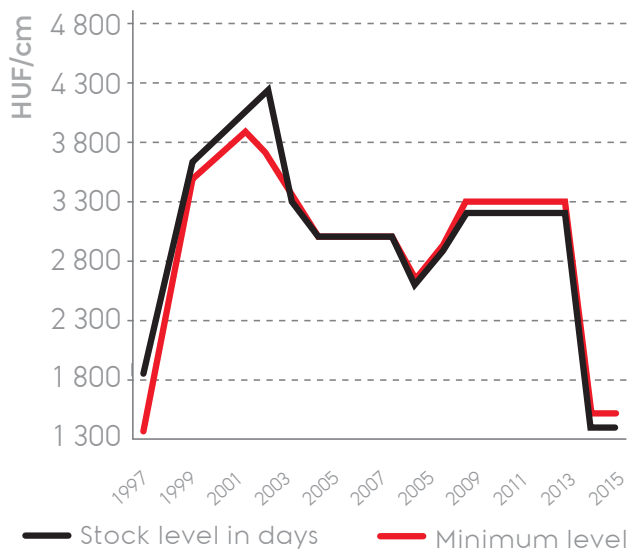


Fig. 9. Stockpiling contribution fees (payable by the consumers)

The success of the Association business and financial activity is also due to its active but conservative management of funds. The two guiding principles of this management are that liquid assets have to be kept at a minimum level and the short-term excess cash resulting from the monthly cash-flow fluctuations has to be invested into safe instruments. In its business relations, the Association is a reliable partner and a tough negotiator. The goodwill of HUSA is evident from the volume and favourable pricing of loans offered to it along with other banking services, and the fact that good conditions remain even after the ceasing of the state guarantee. Stocks purchased at lower prices in the 1990s now can assure the fulfilment of the minimum covenant level (1.0:1.40) required by the banks (see Figure 11).

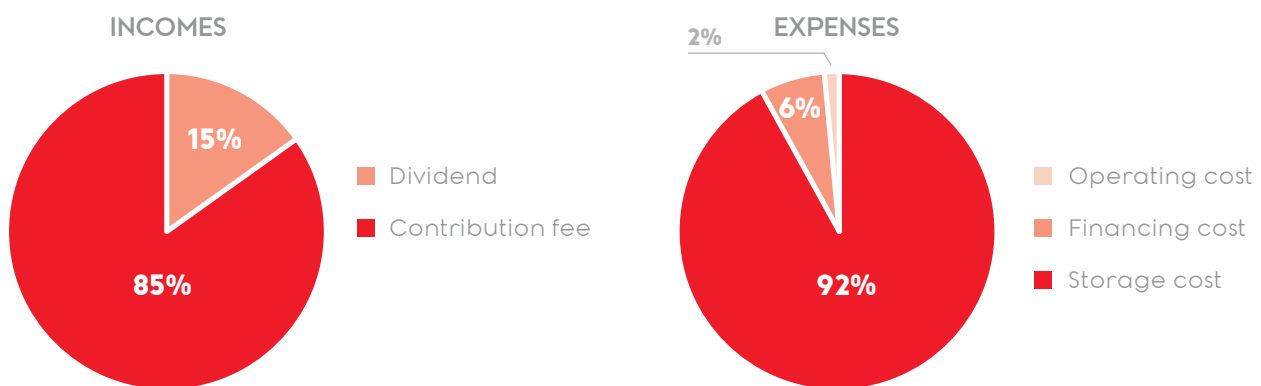


Fig. 10. Structure of HUSA's budget

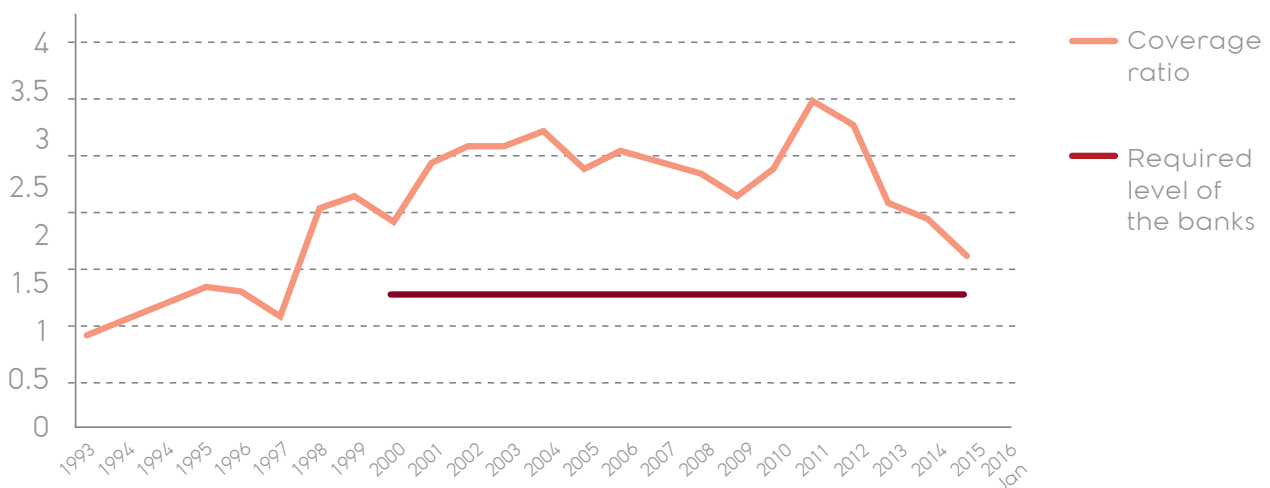


Fig. 11. Covenant of bank loans

Summarising the information about the Agency and the Hungarian stockpiling practice, following shall be highlighted:

- Hungary was the first among the former COMECON countries which introduced the strategic stockpile activity
- The Association is a 'central stockpiling entity', which is the most effective organisation form supported by EU as well
- It is an independent, self-governing, non-profit, statutory body
- It doesn't burden the state budget or the market players and
- It assures a tangible, accessible, physical available stock at any time.

The more than 20 years' activity of the Association fulfilled the expectations that had motivated its founding and is appreciated both by national and international institutions, as well as the oil market players.

CONCLUSION, RECOMMENDATION

Emergency oil stocks are a very powerful policy tool for mitigating short-term physical supply disruptions and for providing liquidity to allow market recovery, however, there are untapped fields in supply's security of our region.

Considering the Middle East European region's high dependency on crude oil import mainly from Russia, a regional cooperation would be welcomed in the field of strategic stockpile. The Russian-Ukrainian conflicts pose a threat to region's supply, to that response transport of crude oil could be arranged from alternative source, via the crude pipeline Friendship-1 reconstructed between Százhalombatta and Sahy (Péterfalvi, F & Szecskó, Z & Uitz, V 2015). Adria pipeline with its connection to pipeline Friendship-1 would be an alternative supply route for the countries in the region. In that way, crude oil from the Adriatic Sea can be transported from Croatia to the Czech Republic. Thus, in an oil supply crisis regional imbalances can be decreased with physical oil flow from the southern countries to the northern countries utilising even strategic oil stocks. Envisioned regional cooperation may need intergovernmental or interregional agreements initiated by the ministries in charge of energy policy.

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Reviewed by Béla Bártfai, Dr., CEO of HUSA and Lajos Alács, CEO, Mabanft Hungary Plc., member of HUSA's BoD



Anikó Lévai

joined HUSA in 2010. Previously she worked for MOL Group as sales expert. Anikó graduated as economist from Foreign Trade College of Budapest.



Crude oil storage park

NxDSP – Stepping-up efficiency

Kocsis Tamás (39)

Head of Business Support
MOL Group Downstream
TamKocsis@MOL.hu

ABSTRACT

In response to the global economic recession and depressed external downstream business environment since the 2008 financial crisis, the 'New Downstream Program' (NDSP), was launched for the 2012–2014 period. The initiative had the clear objective of returning MOL to Europe's top quartile in terms of operational efficiency and profitability by exploiting synergies in its integrated downstream operations. Given the positive results which NDSP achieved in three years and the fact that European refineries are still struggling to avoid closure due to a continuing weak external environment, MOL Group started a second wave of efficiency improvement programmes. The 'Next Downstream Program' (NxDSP) continues to focus on long-term sustainable improvement, boosting profitability and competitiveness in Central Eastern Europe (CEE). In addition, it addresses both external and internal challenges, and takes advantage of the experiences of the previous 'Program'.

ANTECEDENTS

Efficiency programmes with tangible results have always existed in different areas of MOL Group companies. Energy efficiency initiatives – such as the Energy Conservation Programme in MOL (2010–2012) – have always been an important tool for optimising production costs. INA expanded the scope of its efficiency programmes called OptINA1 and OptINA2 to the whole INA R&M. ZOOM was arguably one of the first comprehensive Group-wide activity-tracking system fed with information from all levels and organisations, focusing on projects planning, execution, and follow-up.

ORGANISATIONAL RESTRUCTURING

Growing cooperation within MOL Group and a Group-Local restructuring led to new programmes being managed from Group level that provided more benefits than the previous independent efficiency programmes. The new approach is in line with the multi-dimensional responsibility matrix, harmonising different local practices, enhancing overall transparency and promoting reuse of proven successful practices. In addition, it reduces the overall administrative burdens because the action level targets and results can be used for a variety of purposes, from setting different key performance indicators (KPIs), through organisational or divisional performance tracking, to external communication.

ECONOMIC ENVIRONMENT

Since the 2008 financial crisis, European oil downstream industry players have been struggling to survive in a depressed macroeconomic and burdening legislative environment.

The European oil industry has visibly declined, facing record low refinery capacity utilisation, in stark comparison to the global trend of increasing refinery utilisation. Downstream profitability was put under pressure by a number of factors including high crude and feedstock prices, volatile refinery and petrochemicals margins, low demand levels and increasing operational costs. European refineries are still failing to compete due to higher wages and tax regimes, plus the burdening European legislation compared to competitors in the Middle East and Asia-Pacific regions. For the European refining business the only way to survive is to focus on efficiency improvement in all elements of the value chain to achieve as efficient operation as possible. Recently the external environment became more favourable, even exceptional, for the downstream business, characterised by very low crude oil prices, and strong refining margins, mainly driven by widening gasoline crack spreads and the highest ever petrochemical margin. This gives us the opportunity to achieve positive results and capture additional benefits by closely monitoring our downstream performance

through the 'Next Downstream Program' lens. We recall the quote often attributed to professor Peter Drucker: "What gets measured gets improved".

'NEW DOWNSTREAM PROGRAM' (NDSP)

The NDSP, launched in 2012, was designed as a Group-wide initiative with the goal to improve internal operation and to present a response to our investors to the unfavourable external environment.

The 'Program' covered all downstream parent companies and subsidiaries of MOL Group, and every element of the integrated value chain from crude oil selection through refining and petrochemicals to wholesale and retail.

NDSP did not compete with other existing, well-known efficiency related initiatives like LEAN or EIFFEL. It encompassed all the internal efforts and organised them into sub-programmes. With the contribution of all business areas, over 300 individual actions were executed.

More than just cost cutting, the 'New Downstream Program' initiated a mind-set transformation to lean-thinking. Moreover, revenue maximisation was an equally essential part of the 'Program', requiring all levels of the organisation to identify new sources of profitability.

SETTING THE GOAL

At the beginning of both 'Programs', NDSP and NxDSP, responsible managers were trusted to collect executable actions from each area. These actions were quantified using a unified methodology following business rationale and controlling requirements. The estimated benefits of these actions were aggregated and set as a realistic target. On the same basis, external communication was started in order to introduce investors to MOL Group's desired financial improvement.

REACHING HARMONISATION

As mentioned, the NDSP required a change in approach from both the business and functions. Action owners responsible for the correct evaluation of achievements had to also consider the effects on other actions or on other organisations. Both business participants and controlling experts cooperated together to find the optimal measurement tools and practices of the given actions.

Setting up a well operating communication scheme that works both ways, from and to action owners, covering all areas and companies took time, but was achieved with minimum cost.

INVESTORS' RECEPTION

At the time NDSP was communicated to the public in early 2012, various market players and analysts cast doubt over whether such an ambitious plan to grow clean CCS-based (current cost of supply-based) EBITDA (earnings before tax, depreciation and amortisation) by USD 500 million by 2014 was achievable.

"This looks like a very ambitious program... Tracking will be not easy due to the constantly changing environment" (ING).

"...it is certainly positive that MOL is approaching the difficult R&M environment proactively and, instead of giving up it is aiming to keep this core business ... by improving its efficiency and profitability further. However, its numerical targets seem very ambitious..." (WOOD & Co.).

Despite the scepticism regarding the 'Program', over the years of the NDSP the Downstream financial indicators showed significant improvement (see Figure 1). MOL Group Downstream clearly outperformed the external environment.

The outstanding performance of Downstream was recognised internally by top management and externally, visible in stock price improvement (see Figure 2).

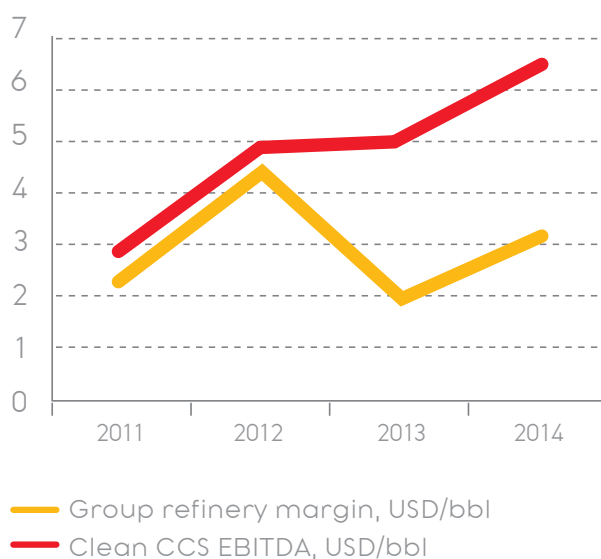
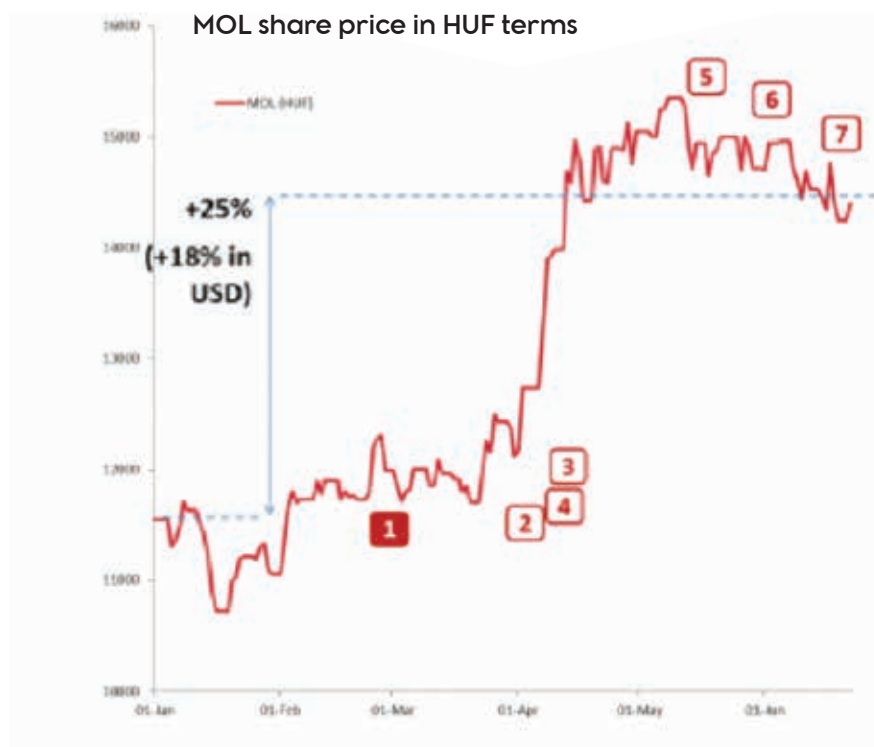


Fig. 1. MOL Downstream financial indicators (Group refinery margin indicates product and supply price difference at given yield structure)

2015: FINALLY MOL BROKE OUT FROM THE NARROW RANGE DUE TO BETTER CEE AND DOWNSTREAM SENTIMENT



KEY DRIVERS OF THE 25% YTD INCREASE

- 1 Announcement of NxDSP ... & mixed KRI news
- 2 S&P upgrade Hungary to BB+: more positive sentiment towards Hungarian stocks
- 3 Record high monthly MOL refinery margin
- 4 Downstream focused Equity Roadshow in Warsaw, followed by strong Polish trade flow
- 5 Q1 results: beat of consensus by ~10%
- 6 General profit taking in Europe and news that MSCI decreases MOL's weight in some indices
- 7 Increased worries over Greece effect CEE stocks

UNUSUALLY HIGH TRADE VOLUMES SINCE APRIL...partially from Poland

Fig. 2. MOL Group stock prices after closing NDSP and announcing NxDSP

PRODUCTION		SUPPLY & SALES			RETAIL	GROUP
REFINING	PETCHEM	SUPPLY & TRADING	SALES	LOGISTICS	RETAIL	STRATEGIC PROJECTS
ENERGY MANAGEMENT		CRUDE PROCUREMENT	DIRECT SALES	LOGISTICS SUPPLY DEVELOPEMENT	ASSET OPT. AND NETWORK EFFICIENCY	MANTOVA PROJECT
PRODUCTION FLEXIBILITY AND YIELD IMPROVEMENTS		FEEDSTOCK PROCUREMENT	COUNTRY CONCEPTS	LOGISTIC COST EFFICIENCY	DELIVER SOLID FUEL FLOW	BUTADIENE UNIT
MAINTANCE & AVAILABILITY		TRADE DEVELOPMENT	PETCHEM COMMERCIAL IMPROVEMENT	MAINTENANCE MANAGEMENT	STEP CHANGE IN NON-FUEL	LDPE4 UNIT
HYDROCARBON LOSS MANAGEMENT			CARD SALES	HC LOSS MANAGEMENT	OPEX OPTIMISATION	ATTILA & PAPRIKA PROJECT

Fig. 3. Structure of 'Next Downstream Program'

'NEXT DOWNSTREAM PROGRAM'

The NxDSP represents the second wave of efficiency programmes using a unified approach with the whole Downstream business in focus.

Planning for the NxDSP started in summer 2014, parallel with the updating of the Downstream strategy, and well ahead of its publication and official launch. The time spent with structuring programmes, processes and responsibilities provides the NxDSP with a solid foundation.

The 'Program' is an essential part of the MOL Group Downstream strategy for 2015–2017, serving as a measurement tool for the implementation of strategic goals.

NxDSP provides analysis / view on results from both directions of the matrix organisational structure, business line and local company wise. It focuses on internal performance by monitoring individual initiatives and also by accounting external effects separately. Benefit is expected not only from decreasing costs but also from increasing revenues.

STRUCTURE AND STAKEHOLDERS

NxDSP follows the three main profit centres which Downstream EBITDA builds upon: Production (crack spread + OPEX), Supply & Sales (sales margin and logistics costs) and Retail (retail fuel and non-fuel margin), and has a total of 11 main programmes. In addition, the most important strategic growth projects in MOL Group Downstream are also included in NxDSP (see [Figure 3](#)).

All initiatives of NxDSP belong to one of the three above mentioned business lines, sponsored by respective **business line managers** and supported by Downstream management. Every programme within the business line has its own **programme leader** who is responsible for its execution. Within every programme a number of actions were proposed which bring improvement in a specific area. Every action has an **action owner** who is responsible for its implementation and who is working closely with Controlling for monitoring and verifying the achieved benefit.

Production

More than one third of the whole NxDSP – 100 initiatives – belong to Production and are part of the following programmes: Energy management, Production flexibility and yield improvement, Maintenance and availability, and Hydrocarbon loss management. These programmes cover all our refining and petrochemical production sites.

The **Energy management** programme is based on increasing energy efficiency, and cost cutting in energy supply and distribution. NxDSP energy initiatives cover types of energy, fuels and industrial gases (electricity, natural gas, fuel gas, fuel oil, steam, water, nitrogen, hydrogen) and all affected processes (energy production, energy distribution, purchase, sales, and distribution).

The basis for target setting was the Solomon Associates' benchmark study from 2012 and energy related market information. The programme consists of crucial investment projects as well as more sophisticated, fine-tuning initiatives. Positive effects of this programme can also be seen in reduced environmental impact and CO₂ emissions.

Production flexibility and yield improvement is aiming to increase white product yields by +2.5% until 2017 by increasing conversion in our key units and more efficient crude distillation. This will result in lowering the bottom of the barrel, yield of undesirable black products. Increasing flexibility between fuel and petchem products, diesel and mogas ratio and different LPG routing will deliver higher value products. Since 98% of all EBITDA improvement programme is CAPEX-dependent, tracking actions / project execution through NxDSP gives early warning to management and also serves as an immediate measurement of implemented projects' performance.

Maintenance & availability or '**UpTime**' is focused on increasing the operational availability of our key processing units to sustain and enhance our competitiveness in the long term. The basis for target setting was the Solomon Associates' benchmark study from 2012 but the target set for 2018 is more ambitious than Solomon Associates suggested. The '**UpTime**' programme is designed to reduce unplanned downtime by using the best engineering tools to optimise turnaround duration and extend turnaround cycles, and to use efficiently planned downtime for investment realisation. Reliability awareness, a mindset change and ownership of the assets are essential for the success of the programme.

The **Hydrocarbon loss management programme** is based on improving monitoring and general loss management by standardising processes and methods, regular reporting, and more efficient startup and shutdown procedures of the units. Decreasing hydrocarbon emissions by leak detection and hydrocarbon recovery using flare gas and vapour recovery units is closely monitored through this programme.



Supply & Sales

Within the Supply & Sales part of NxDSP there are three main programmes: Develop market presence and improve net margins, Develop market access through trading, and Logistics. A special feature of these programmes is that they all have their sub-programmes which allow a more thorough monitoring of the actions.

Develop market presence and improve net margins

programme is consistent with the strategic direction of Supply and Sales division for continuous growth in the next three years. The programme has four action streams: Direct sales, Country concepts, Petchem sales, and Card sales that focus on:

- Achieving volume and commercial margin growth in Central & Eastern Europe by implementing country concepts
- Identifying new profitable sources for supplying the markets
Putting more focus on other products besides fuels (e.g. LPG, aromatics, black products)
- Improving commercial activity in Petchem by targeting more end-users, recovering lost market share, leveraging new products and
- Increasing card sales, improving card services and coverage of card products.

Complementary to the above programme and also part of the Sales strategy, **Develop market access through a trading** programme aims to facilitate entry into new markets by developing physical and derivative trading.

As an essential support for sales, the **Logistics** programme focuses on streamlining the logistics of supply and distribution in a cost efficient manner, at the same time reducing losses in logistic processes.

Retail

The Retail segment contributes to NxDSP through inorganic growth (see the next 'Strategic projects' chapter), but also by focusing on organic growth projects related to optimisation and enhancement of the daily business activities via four specific programmes: Asset optimisation and network efficiency programme, OPEX optimisation programme, Deliver solid fuel flow, Step change in non-fuel.

Asset optimisation and network efficiency

programme contribute to income generation through the better utilisation of current assets while the Retail P&L (profit and loss) will also be improved by applying a conscious approach on operating costs through **OPEX optimisation programme** as result of the adoption of the new Retail strategy.

Fuel related EBITDA will improve with the new Retail strategy implementation, targeting specific operation areas. **Deliver solid fuel flow** programmes' actions are identified to contribute in achieving 50% of own fuel production sold through the retail channel. Furthermore, significant investment in service stations appearance and additional products & services will result in premium fuel ratio improvement and increased fuel sales generated EBITDA via a new pricing strategy.

Through **Step change in non-fuel**, filling stations are converted into redesigned service stations to utilise current selling points to their best potential and to become the customers' first choice both in fuel and convenience retailing. The latter will not be anymore only a complementary service, but the main driver for attracting customers by selling fresh-made grocery products and high quality coffee, with the 'take away' option as well.

Strategic projects

Growth part of NxDSP consists of four strategic projects which are monitored separately, but use the same approach and methodology.

NxDSP follows the **conversion of IES refinery of Mantua** into a brand new logistic hub for trading activities which will serve the whole of Italy.

We enter into a new area of the petrochemicals' market and strengthen our competitiveness by starting up a new Butadiene extraction unit – **BDEU** – in Tiszaújváros (130 kt/year capacity).

A new Low density polyethylene – **LDPE4** – unit in SLOVNAFT Bratislava increases production capacity (to 220 kt/year), efficiency, production flexibility, and improves product quality and ensure higher naphtha off-take from the refinery.

The acquisition of ENI and Lukoil retail filling stations – **Attila & Paprika projects** – in Romania, the Czech Republic and Slovakia and converting them into redesigned service stations demonstrates the Groups' resolve to sow the seeds for future inorganic growth in the Retail sector, consolidate its leading position in the region, without putting all its faith in an improving macro environment and riding on the back of a cyclical recovery.

PROGRESS MONITORING

Tracking the execution of NxDSP is based on two main tools:

- Action monitoring sheet (AMS) and
- Central database (CDB).

Action monitoring sheet (AMS) is a comprehensive Excel file designed for the action owners and action controllers to store all the relevant information about an action in a standardised format. The action owner in cooperation with Controlling has to:

- ▶ Identify the action and set the targets of the action and
- ▶ Quarterly provide the fact benefit and forecasted benefit of the action.

The AMS also serves as a tool to separate the monitoring of internal performance from the effect of external factors and one-off events which have to be filtered out to ensure comparability between years. AMSs represent the data source for the Central database.

Central database (CDB) centralises the information from all the AMSs on a common platform, listing all the actions with their most relevant details. The CDB serves as the main information source for the stakeholders about Nx DSP execution. The content is grouped by business line / by programme / by company / by product line.

It is important to note that anytime during the Nx DSP lifespan it is possible to include new initiatives. Actually new ideas / projects are encouraged to counter projects that cannot be executed or initiatives that are not delivering their expected benefit.

METHODOLOGY

EBITDA was decided to be the primary indicator for measuring the performance of the 'Program' (see formula for calculating EBITDA below):

- ▶ $EBITDA = \text{Revenue} - \text{Expenses (excluding tax, interest, depreciation and amortisation)}$.

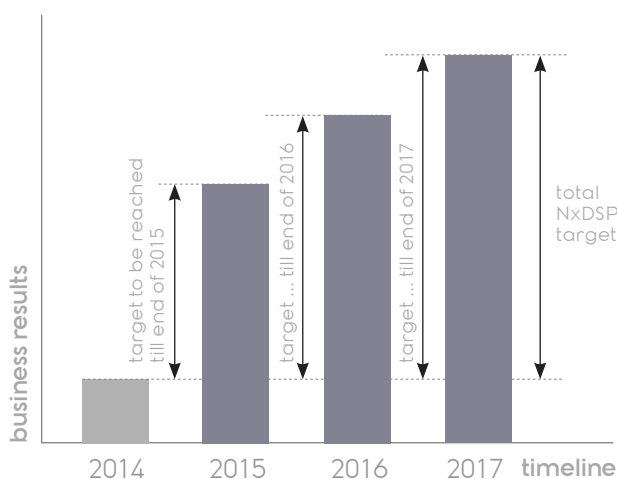
It is a financial measure calculated using a company's net earnings, before interest expenses, taxes, depreciation and amortisation are subtracted, indicating a company's current operating profitability (e.g. how much profit it makes with its present assets and its operations on the products it produces and sells). This helps eliminate the effects of financing and accounting decisions, allowing comparison between companies with different financing, different asset base with various ages.

Furthermore, the net income is corrected taking into account the changes in expenses (e.g. crude oil price) over the reporting period, allowing comparability between different periods of time.

All these point to EBITDA as the most proper indicator for assessing the performance of the initiatives within Nx DSP.

The base year used for setting the original targets of Nx DSP was 2014 and this shall be kept as the reference throughout the entire duration of the 'Next Downstream Program'.

TOP-DOWN TARGET SETTING (ON 2014 BASIS)



BOTTOM-UP TARGET SETTING AND BENEFIT TRACKING (YEAR ON YEAR METHODOLOGY)



Fig. 4. Year-on-year methodology



However, during the three years of the ‘Program,’ targets can be adjusted to reflect the changes in external / internal premises. Therefore at the beginning of each year, targets are revised on a year-on-year basis (vs. previous year) (see Figure 4).

For the benefit tracking, the year-on-year measurement is used (comparing the actual year’s figures with the previous year’s figures) to facilitate comparison between the revised targets and the facts. This comparison is done by defining the current year’s relevant EBITDA item and deducting the previous year’s matching EBITDA item.

E.g. in case of energy related actions the relevant EBITDA items can be costs of import energy, own consumption, CO₂ allowance, etc. If the energy cost of a unit in question in the current year is USD 10 000, and in the previous year it was USD 12 000, the benefit will be the difference of these two, namely USD 2 000 saving in cost of energy.

To ensure comparability between years, the effects of external factors and one-off events have to be filtered out. For this purpose the deviations in the actual results

vs. base have to be categorised as external or internal, following the methodology established by Group Downstream Controlling (see Figure 5). Stakeholders must be able to identify:

- ▶ *External effects*, which include all the elements of the business environment which have an effect on the actions, but are beyond the influence and control of MOL Group Downstream (e.g. international quotations, foreign exchange (FX) rates)
- ▶ *Internal effects* represent all the parameters of the business which can be influenced and controlled by MOL Group Downstream (e.g. production output, sales margins, filling station throughput)
- ▶ However, within the internal effects established by Controlling, at action level another effect can be identified. Even if one factor is determined by the company’s business decisions and evolution, from an action owner point of view it can be completely independent from his influence and efforts. These factors are called *independent factors*.

E.g. the production volume is an internal factor for the company, but for an action owner in Logistics, the volume he is required to store can be an independent factor over which he has no decision.

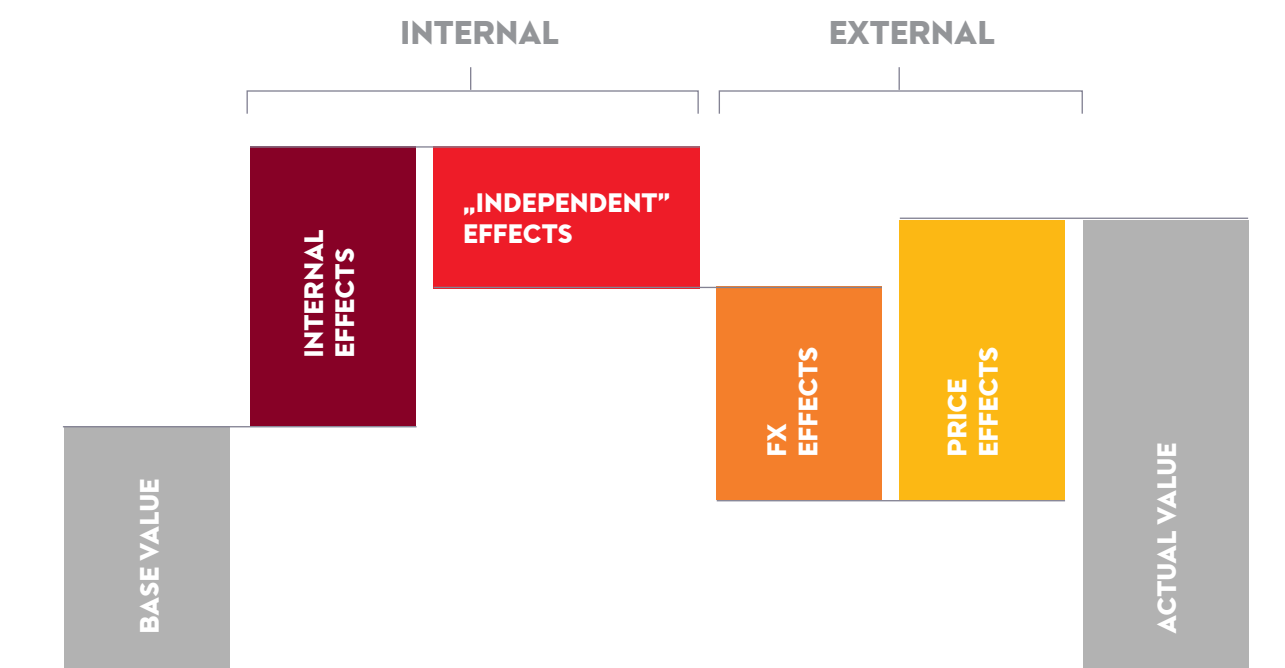


Fig. 5. EBITDA influencing factors

The aim of separating these effects is to offer the possibility to the stakeholders to analyse:

- ▶ Strictly the internal performance of the action owners and their initiatives
- ▶ Assess separately the impact of the external factors on the total benefit and
- ▶ Have an overview of the profit and loss (P&L) effect of the action (total benefit, including both internal and external factors).

E.g. in case an energy management action lowers a significant specific energy consumption (which is an effect of internal efforts), the overall energy costs will still depend on the turnover of the asset and on the price of energy. In this case, the energy price is an external factor, but after all the turnover volume is a decision of the business independent from the direct influence on the action owner.

Example:

$$E_{\text{energy}} = C \cdot V \cdot P$$

where E is expense, C is specific energy consumption, V is processed volume, P price of energy; the quantity of consumed energy is an internal factor, but the price of purchased energy highly depends on the market, beyond MOL Group's reach.

To correct the energy expense increase compared to the previous year in the calculation, the price and volume effect has to be separated. The price effect (based on Laspeyres price index) will be the price change on base year volume. The volume effect will be the volume change on current price. Internal, independent and Group level external effects can be calculated as follows.

Internal effect:

$$E_{\text{efficiency effect}} = \Delta C \cdot V^{\text{in base year}} \cdot P^{\text{in base year}}$$

Independent effect:

$$E_{\text{processed volume effect}} = C^{\text{in current year}} \cdot \Delta V \cdot P^{\text{in base year}}$$

External effect on Group level:

$$E_{\text{price effect}} = C^{\text{in current year}} \cdot V^{\text{in current year}} \cdot \Delta P$$

CONCLUSIONS

Eventually all these initiatives – having either binding targets or rewarding schemes – are successful thanks to the business experts behind them.

Soft aspects like motivated people and a supporting and promoting culture play an important role in the

long-term development of a company. In parallel with the creation of the new Downstream strategy and launching of the 'Next Downstream Program' the human component was addressed by putting emphasis on the values that the division possess and believes in. As with all cultural changes this is a long journey and it is not only about change but being conscious of our values.

NxDSP is a way to structure and encourage new business improvement activities. It gives consistency, comparability and transparency to all enrolled internal efforts.

ACKNOWLEDGEMENT

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Keywords: efficiency, downstream, EBITDA

Reviewed by David Pullan, SVP, MOL Group DS Technology & Development



Tamás Kocsis joined MOL Group in November 2012 during the Glocal project and was holding position of Group Energy Production manager till May 2014. Prior to joining MOL Group, he filled various positions in different business sectors, including logistics and banking. Between 2007 and 2010 he was chief of the cabinet to the CEO of MÁV, Hungarian State Railways. Afterwards, he joined the Ministry of National Development. Tamás holds a university degree in economics, from Oxford Brookes University.

Product yield improvement in the 'Next Downstream Program'

István Valkai (50)

Benchmarking & Standardisation manager
Technology & Development
MOL Group Downstream Production
IValakai@MOL.hu

ABSTRACT

Even in the favourable market environment and amid strengthening refining margins in 2015, MOL Group Downstream continued to pursue efficiency improvement and started the 'Next Downstream Program' (NxDSP), a new initiative along the whole value chain from production to retail. In the Group's refineries and petrochemical plants the 'Program' is targeting both revenue increase and cost saving, as well as higher operational availability of production assets. This article introduces two revenue oriented sub-programmes, Production flexibility and yield improvement and Hydrocarbon loss management. It discusses the main constraints and summarises the potential technical solutions, coordination and management methods applied to address the challenges.

INTRODUCTION

MOL Group launched the 'Next Downstream Program' (NxDSP) in 2015, immediately after the successful efficiency improvement campaign 'New Downstream Program' was completed (see the related article on pp. 70–77.). NxDSP also has an ambitious goal of improving clean CCS-based (current cost of supply-based) EBITDA (earnings before tax, depreciation and amortisation) by USD 500 million in three years compared to 2014 as the base year. DS Production contributes to the effort with several actions in four main streams:

- Production flexibility and yield improvement
- Energy management
- Maintenance and availability and
- Hydrocarbon loss management.

This article summarises the programmes of the Flexibility & yield improvement and Hydrocarbon loss management streams that both affect refining and petrochemical product yield, one of the most significant drivers of Downstream economics.

The main challenges as well as the key processes of the programme that will be introduced in more detail below are as follows:

- Idea management
- Knowledge sharing
- Motivation
- Project control and
- Monitoring.

Downstream has a well-established technology development organisation with dedicated expert teams in all of MOL Group's flagship companies where efficiency improvement has always been a continuous activity. The added value of the 'New Downstream Program' and NxDSP was to provide an additional incentive to make development quicker, more efficient and transparent. The programme includes, monitors and presents all actions and investment projects that deliver sustainable EBITDA improvement between 2015 and 2017 in one package. With five production sites involved in three countries this requires effective coordination.

IDEA MANAGEMENT

Product yield improvement in the refining and petrochemical industry requires process optimisation and modification of complex technology, often at significant cost. Engineers have always had good ideas about process development, although these sometimes failed the rigorous test of feasibility and economic evaluation.

In the early stage of efficiency programmes it is important to have a sizeable pool of ideas and to make sure that creative contributors are not discouraged. Brainstorming methodology ensures that no idea gets refused prematurely and screening is only carried out in further stages. In the first year of the programme several workshops were organised at the production sites to generate new ideas, where not only technical experts but also production planning, optimisation and product line management were involved. These events have become regular exercises.

NxDSP assigned all ideas from the initial pool to action owners who were the relevant technical experts in the area. The Yield improvement programme applied standard data templates (Process Data Sheets) that the experts filled in with their first estimation on the material and energy balance effect, expected change in capacity, feed rate and early indication of operating cost on a process unit level.

Controlling has been involved to calculate the business impact and validate the numbers on pre-defined Action Monitoring Sheets (AMS) that were the basis for an initial assessment of the programme's EBITDA target, and will also serve as result tracking tools.

As the production sites are a complex network of process units, and MOL Group takes advantage of cross border material transfers and synergies between the sites, in these programmes a further level of feasibility analysis was necessary. In the second stage of evaluation site level spreadsheet models were developed to determine the potential material balance effect at the refinery gate, in case all individual actions are implemented.

Finally, MOL Group level optimisation has been carried out on the selected actions, using linear programming models that confirmed the potential benefit of the programme. The original business goals were set and broken down to technical targets for operation on the basis of these calculations.

MAIN PROGRAMME OBJECTIVES AND ACTIONS

Figures 1 and 2 present the original targets and the typical technical solutions in three categories for both yield related programmes.

Both programmes forecast significant contributions to the NxDSP results, however most of the original actions require investment. Yield improvement has

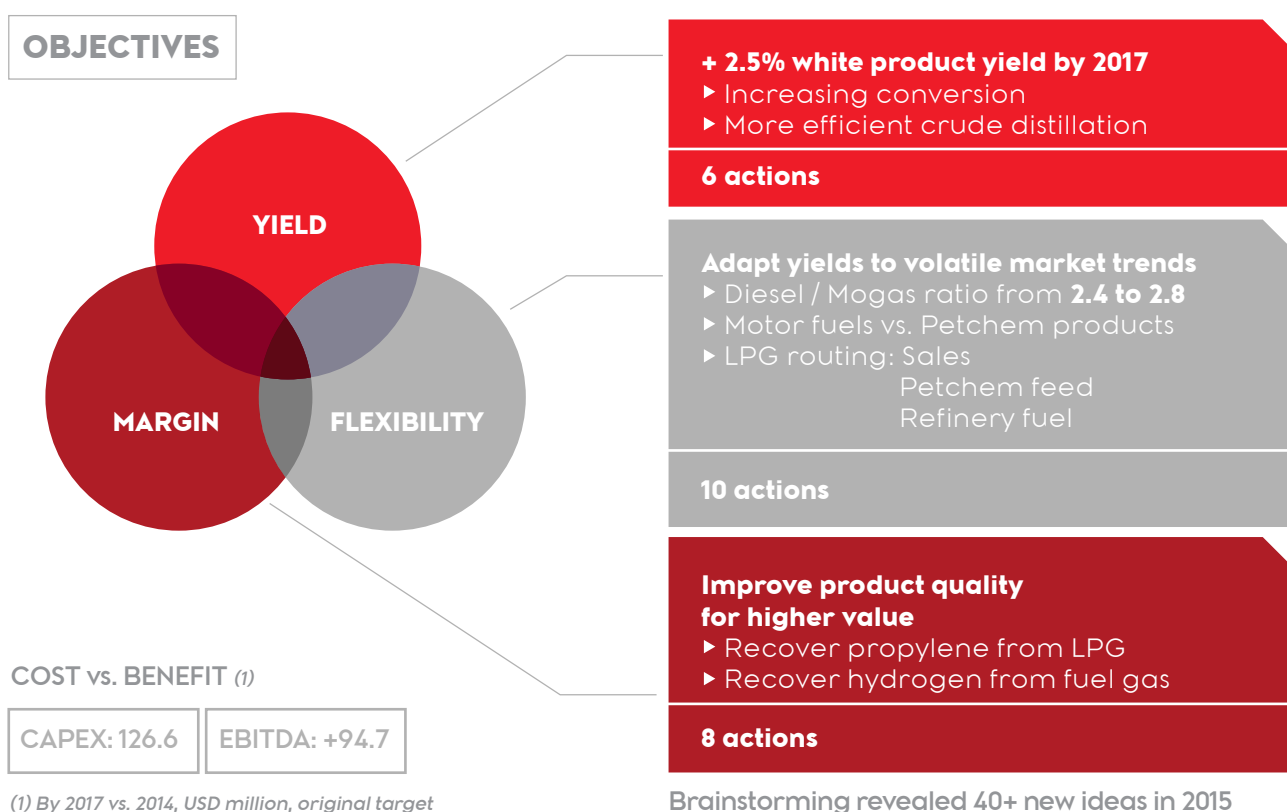


Fig. 1. Production flexibility & yield improvement programme objectives

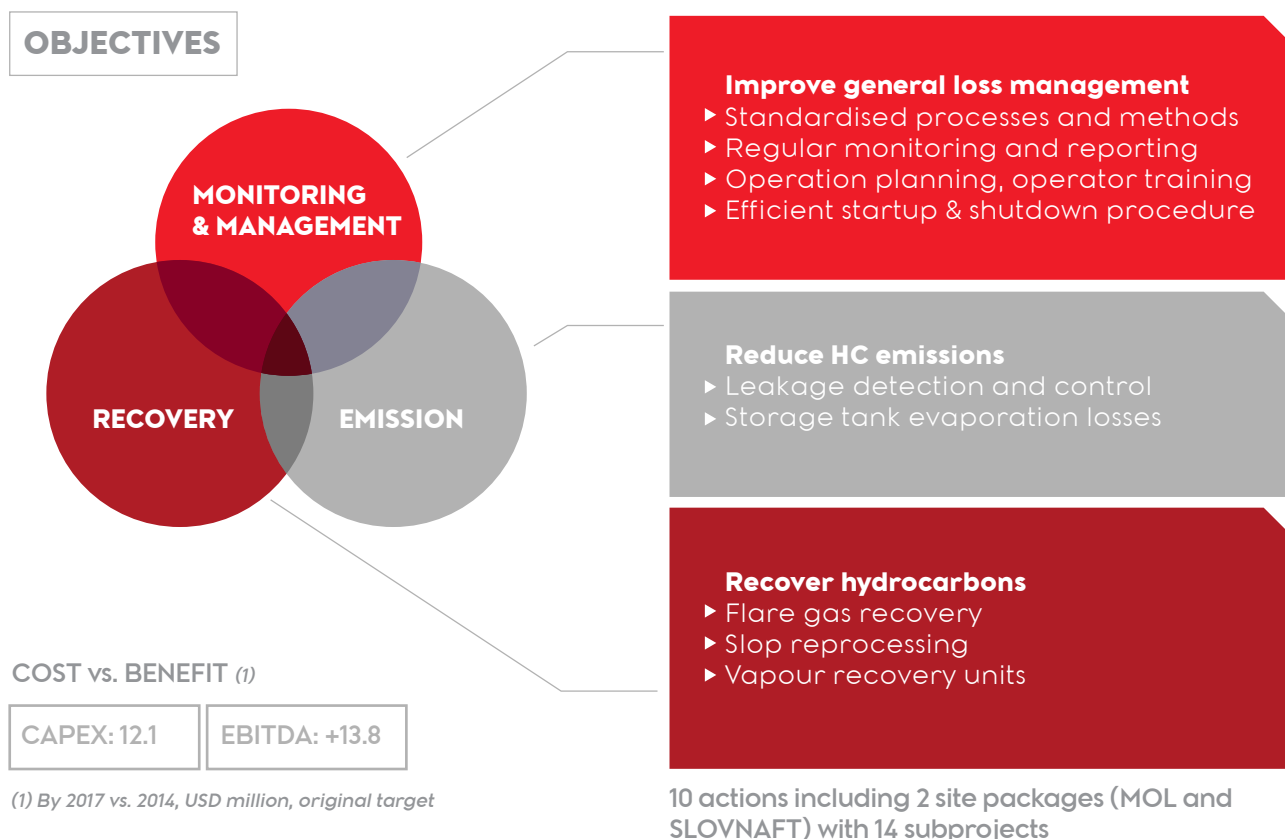


Fig. 2. Hydrocarbon loss management programme objectives

revenue increasing effect rather than cost cutting and the existing yield structure can be maintained after project implementation, if it is required by the market demand. This way the refinery flexibility will also be improved. These projects promise a short payback period, a few examples that have the highest impact are highlighted below:

- ▶ SLOVNAFT successfully implemented Headwater's HCAT® technology in their Residue hydrocracker (LC-FINING®) unit. The dispersed hydrocracking catalyst will greatly improve conversion and reduce the heavy fuel oil yield of the LC-FINING® process by 6 %wt
- ▶ MOL is revamping the Mild hydrocracker unit in Danube Refinery (Százhalombatta) to increase vacuum gasoil (VGO) conversion by more than 10%. The new technology will improve the diesel to motor gasoline ratio, eliminates certain capacity bottlenecks in the refinery and reduces VGO transfer costs within MOL Group
- ▶ The propane-propylene fraction produced in the Fluid catalytic cracker unit of INA's Rijeka Refinery is transported to other production sites

including SLOVNAFT and MOL Petrochemicals, where the high value propylene product will be recovered utilising the free distillation capacities. This is a good example of favourable synergies between MOL Group's production assets in different countries

- ▶ The material accounting and hydrocarbon loss management process is being improved and standardised on several production sites that will result more precise loss reporting and monitoring
- ▶ Flare gas recovery projects are being implemented by both MOL and INA that will have the highest impact on hydrocarbon loss reduction and will also result energy cost savings.

The three years duration of NxDSP sets a challenging time schedule for the typical refinery investment projects. The local development teams continue to work on additional ideas, however new actions focus on quick-win solutions like processing alternative crude oils and advanced optimisation methods, while leveraging further synergies between our refineries and petrochemical plants.

KNOWLEDGE SHARING

Experts at the local production sites and Downstream's global organisations provided valuable input in the brainstorming stage. For the effective utilisation of feasible ideas on every relevant site, knowledge sharing has been promoted as follows:

- ▶ All ideas generated on local workshops have been shared with all other sites in the form of a consolidated global database
- ▶ A number of general industry best practice solutions have been defined for consideration by all teams
- ▶ The proven Technology Development Networking forum was available for experts to discuss the technical challenges
- ▶ New actions have been introduced to both global and local production planning, optimisation and product line management teams, and
- ▶ Certain actions required intensive cooperation between several sites making use of shared resources like process modelling tools.

MOTIVATION

Intensive efficiency programmes like NxDSP require extra effort on top of the regular daily work from all contributors.

It proved to be challenging at the start to find new, quick and feasible development opportunities after the three years of the 'New Downstream Program' where 'low hanging fruits have all been picked'. While industry benchmarking studies and technical consultancy have also been used to support the programme, eventually most of the potential improvements have been identified in internal team work.

Downstream management has been involved and informed about the NxDSP status, the programme has been in focus from the beginning. There has been great emphasis on the involvement and motivation of local business and technical management who can mobilise local resources most effectively.

Cooperation between global and local programme coordinators and management teams continuously improved in the first year of the programme, ensuring that all participants are aligned with the main goals.

Maintaining these practices as well as the recognition and rewarding of active contributors shall be essential in the remaining period.

PROJECT CONTROL AND MONITORING

As soon as new ideas are recorded, the programme's success greatly depends on project management and

timely implementation. Capital projects enter the regular technical scoping and stage gate approval process, where decision making is based on the evaluation of project economics and risk analysis. NxDSP actions are no exception but receive additional attention and support from all management levels.

The status of technical definition is monitored by both the global and local programme leaders until ideas are developed into project proposals. The progress of engineering design and implementation of the key projects is reviewed on NxDSP workshops and apparent risks are immediately discussed with the project teams.

As NxDSP approaches its final year, the successful implementation of ongoing actions and projects, and delivering results in line with the target become more and more important. For this reason project performance needs to be measured right after implementation.

The financial results of each individual action are continuously monitored, action owners and programme leaders provide quarterly status reports, gap analysis and propose corrective actions when necessary.

NxDSP relies on coordination and cooperation of all participants, it challenges work methods and provides motivation to improve the development process. In addition to EBITDA improvement, these efficient methods will remain with us after the programme, delivering sustainable benefit for Downstream.

Keywords: refining, petrochemicals, efficiency, product yield

Reviewed by David Pullan, SVP, MOL Group Downstream Technology & Development



István Valkai joined MOL Plc. in 1995, developed refinery conversion and product separation technologies and continued as process engineer at Danube Refinery from 2002 to 2004. He was the head of Refinery Technology

Development within the integrated Downstream Development between 2004 and 2012. He worked as lead expert in MOL Group's Downstream Technology & Development from 2012 and has been the Benchmarking & Standardisation manager since 2014. István graduated from University of Veszprém in 1990 with an MSc degree in chemical engineering.

Improving process safety and operation efficiency of MOL DS Production via effective use of Plant Information (PI) and Opralog systems

Éva Hornyák (38)

Expert
MOL Process Information and Automation
EHornyak@MOL.hu

Gábor Mucsina (28)

Expert
MOL Process Information and Automation
GMucsina@MOL.hu

László Szabó (33)

APC Management senior engineer
MOL Process Information and Automation
LSzabosz@MOL.hu

Tibor Komróczki (46)

Manager
MOL Process Information and Automation
TKomroczi@MOL.hu

ABSTRACT

Between 2012–2014 MOL Group Downstream (Refining and Logistics) has implemented the ‘New Downstream Program’ (NDSP) targeting improvements in the key performance indicators (KPIs), including energy consumption reduction by 2%, operational availability improvement by 1.1%, hydrocarbon loss reduction by 30% and yield improvement by 5%.

MOL has been a long-time user of OSIsoft’s Plant Information (PI) System™, primarily as a ‘historian’ with heavy use of PI DataLink client tool and many individual Microsoft Excel workbooks. MOL realised that the use of Plant Information Asset Framework (PI AF) could provide fundamental support in its NDSP’s implementation and mind-set transformational journey. The article overviews the use of the PI System™ and in particular PI AF at Danube Refinery for the implementation of NDSP, the results of PI System™’s development in the direction of a strategic enterprise integration.

PLANT INFORMATION SYSTEM

Danube Refinery / Process Information and Automation organisation is responsible for management and operation of the OSIsoft’s Plant Information (PI) System™, which collects production, energy, maintenance, laboratory, and other related data from various data sources. PI System™ is in direct connection with the Distributed Control System (DCS) that provides snapshot operating data from plant level and linked to the REFIS (Refining Information System) software collection that includes several different programs such as – Opralog (Electronic logbook), SEMAFOR (System to Monitor Operational Performance, KPI) system and NICE framework (Natural Info Centre) applications.

Integration of the basic data sources of Danube Refinery results in a well-defined corporate information system – so called MES (Manufacturing Execution System), that can meet all of the business requirements (see [Figure 1](#)).

PI System™ of Danube Refinery is operating in high availability (HA) architecture, which means two virtual servers in geographically separated locations. Server virtualisation has led to reduced maintenance and hardware costs and increased system availability. Further advantage of the PI HA construction is the scalability due to system load distribution. Information are stored as PI tags in the database and processed, visualised via PI client tools (see [Figure 2](#)).

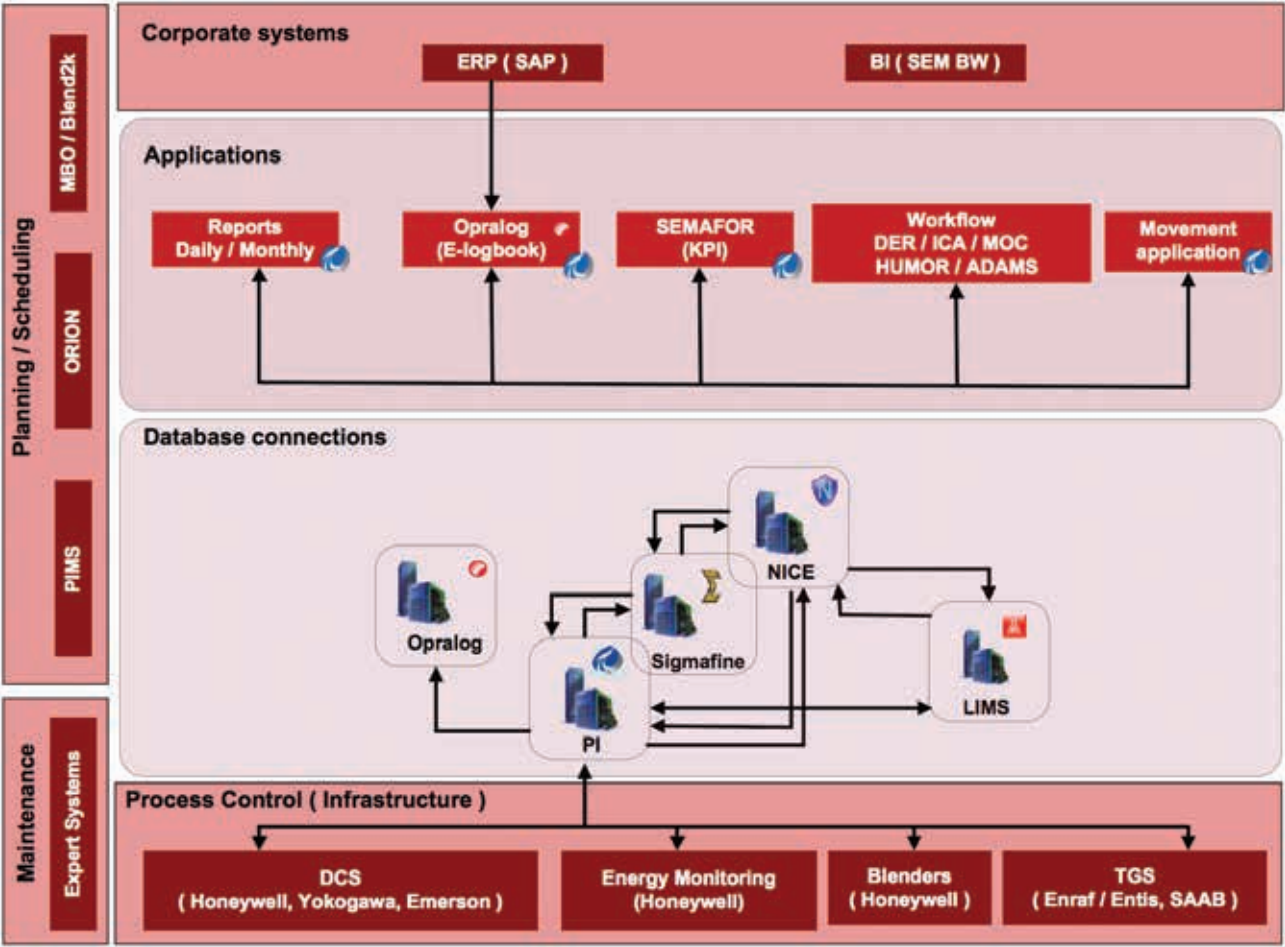


Fig. 1. Danube Refinery Manufacturing Execution System (MES) framework
MBO / Blend – Aspen Multi-Blend Optimizer (MBO™); ORION – Aspen Orion XT™ for seamless scheduling and optimisation of product blending; PIMS – Aspen PIMS™ Plant Information and Management System; ERP – Enterprise Resource Planning; BI (SEM BW) – Business Intelligence (Strategic Enterprise Management Business Warehouse); DER – Employee Comments; ICA -Investigations and Corrective Actions; MOC – Management of Change; HUMOR – Waste Monitoring System; ADAMS – Audit Design and Management System; Sigmafine – Pimsoft's Sigmafine® is data validation and reconciliation system; LIMS - Laboratory Information Management System; TGS – Tank Gauging System; Enraf® / Entis – Honeywell tank inventory system

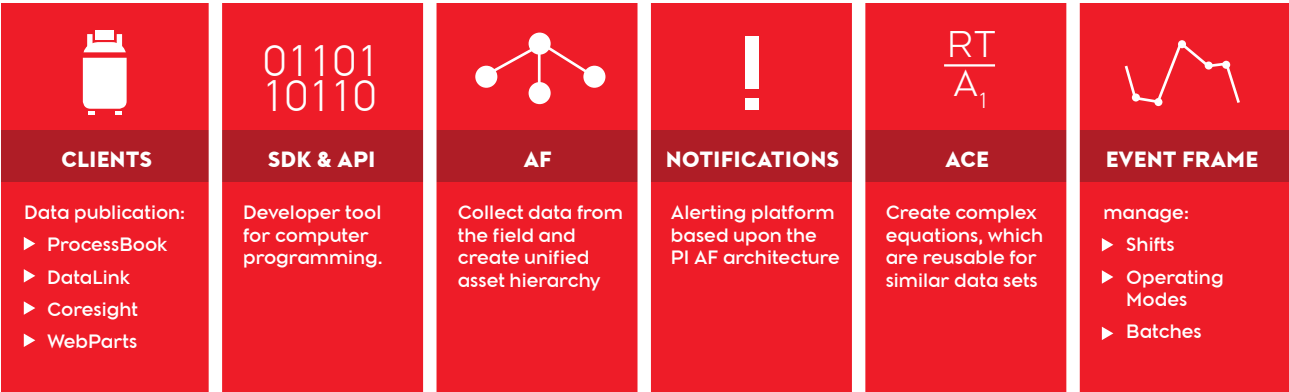


Fig. 2. PI System™ client applications
SDK – Software Development Kit; API – Application Programming Interface; AF – Asset Framework; ACE – OSIsoft's PI ACE supports complex calculation in Visual Studio environment



Generally, PI System™ helps the user to

- Close the gap between process control and business governance
- Provide real-time information for tighter control of operations
- Improve communication and information flow between units and organisations
- Ensure process safety management and data integrity, and
- Recognise operational anomalies.

PI ASSET FRAMEWORK (AF) & NOTIFICATION

PI System™ was implemented almost 20 years ago in Danube Refinery. The number of PI tags has already reached one hundred thousand due to the continuous system improvement. Realising the data complexity, PI Asset Framework (PI AF) was selected as an effective solution to establish a clear data structure, in 2010. Tree hierarchy of PI AF is based on predefined relationship declaration – according to the general parent / child connectivity. Each element of the structure has numerous attributes such as description, tag name, unit of measure to describe the assets (see Figure 3).

PI AF hierarchy and Notification function are integrated. In that way alerts can be ordered if limits are exceeded to ensure immediate interventions of the system users. Data visualisation and analysis are also supported because PI AF hierarchies (elements, attributes) are searchable from PI client tools (see Figure 4).

MOL DOWNSTREAM ASSET FRAMEWORK (AF)-BASED APPLICATIONS

The OT (Operational Technology) context infrastructure provided a configurable capability that MOL used to develop applications in the areas of energy management, environmental compliance, operational dashboards, asset integrity, model integration and asset reliability. MOL also leveraged the context infrastructure to enable IT / OT integration and a portfolio of various analytical methods including streaming, predictive, and ‘big data’.

To support the ‘New Downstream Program’, IT and OT integrated team chose a new infrastructure-based approach enabling organisational change based on collaboration, and proactive / predictive data based decisions. The approach used (Microsoft platform enabled) OSIsoft’s PI System™



Fig. 3. PI Asset Framework structure

DMHCK – Danube Mild hydrocracker; DFCCU – Danube Fluid catalytic cracker



Fig. 4. PI Asset Framework value

ProcessBook – OSIsoft’s ProcessBook™ helps access and visualize the real-time and historical PI System™ data; Coresight – OSIsoft’s PI Coresight helps to analyse data enterprise wide

as an OT context infrastructure to aggregate, normalise, validate, historise (both past and future data) and perform real-time analytics, create alerts and notifications to support metadata integration. In short, the OT context infrastructure provided an enterprise data object model that created the foundation for all calculations, analytics, and visualisation functionality.

Over the course of two years, MOL expanded the OT context infrastructure with new features and configured a wide range of applications covering energy and environmental management, asset reliability, and operational dashboards. The OT context infrastructure was also leveraged to integrate what MOL considered 'best of breed' solutions for Operator logbooks, planning and scheduling, yield accounting and maintenance management systems. Expanded features and configured applications include the following:

Safety and asset integrity

- ▶ Interlock (override switches) statuses
- ▶ Operating envelopes
- ▶ Corrosion control (high temperature hydrogen attack)
- ▶ Alarm management
- ▶ Control rooms' temperature (without operators supervision)

Energy

- ▶ Energy monitoring and management
- ▶ Energy KPI breakdown (6 tiers)
- ▶ Column energy efficiency dashboards
- ▶ Hydrogen, utilities, and energy balances
- ▶ Flaring

Yields

- ▶ Product quality
- ▶ Analyser reliability (Argus)

Operational optimisation

- ▶ NG (natural gas) and fuel gas demand forecasting
- ▶ Normal mode of control loops, and
- ▶ Advanced process control (APC) monitoring.

PI CLIENT SOFTWARE SOLUTIONS

REDUCING RESERVED DAILY NATURAL GAS CAPACITY

MOL wants to increase its operational efficiency through better production and energy forecasting techniques. To understand the business importance of the accurate energy planning, natural gas purchasing and contracting method clarification cannot be neglected.

As a large industrial consumer MOL has to pay for the consumed natural gas and for the daily natural gas capacity availability. The reserved daily natural gas capacity is practically a daily maximum amount which can be consumed by all MOL facilities in the country (Hungary). This, the so called *entry maximum*, has to be declared and fixed for a two years period. Any exceedance over the entry maximum results in a very high penalty, therefore the entry maximum should be high enough to handle every possible disturbance in the technology. On the other side, the entry maximum has a price. It means that the too high entry maximum is practically loss (see Figure 5).

MOL could have gained significant benefits by decreasing the reserved entry maximum. After the deep analysis of our natural gas consumption the Energy Programming Team could have determined a lower entry maximum which is high enough to handle the problems in the 99% of the time. The lower entry maximum is only sustainable with an accurate and effective prediction system, which is able to notify the responsible employees in case of possible exceedances. In MOL, natural gas prediction system has been implemented in 2014 using different PI components.

The input of the PI Asset Analytics calculation is the actual consumption data from different sites. The real-time consumption data, measured in various MOL locations across the country are stored in the PI Server. Computation is based on extrapolation technique through a continuous totalizer calculation which resets itself each day at 6 am. It practically integrates the summarised gas consumption and increases this amount with a predicted value for the rest of the day.



Fig. 5. Natural gas daily consumption vs. entry maximum consumption

Besides the calculations the user interfaces are also really important for the systems. The whole idea is a kind of IT system for failure management therefore during normal operation the system is not used regularly. PI ProcessBook was selected to create comprehensive and simple displays, final results were published on PI Coresight 2014.

Displays are very simple, users are alerted in case of any foreseen exceedances (see Figure 6). Navigation between the different displays is easy by the help of the buttons, so in an alarming situation users can find the information without struggling with the system usage. If the predicted daily consumption is too high, fast decision has to be made. There are possibilities to decrease the natural gas consumption, but the costs and the availabilities of the interventions could be totally different.

PI Notification is the last segment of the system operation. This component informs all of the decision makers if possible exceedance is detected. Notification e-mail contains also the most important data and hyperlink to the PI Coresight displays, therefore the conversation can be started immediately to find the proper solution.

It is not always easy to find a clear profit, a clear business benefit for an IT system. In this case it is quite clear. The calculations, displays, alerts implemented in PI System™ led to the entry maximum reduction, which means Euro 240 000 yearly saving for MOL. Based on this experience Process Information and Automation group of Danube Refinery is working on the implementation of a similar prediction system for the electricity consumption.

ENERGY AND QUALITY MANAGEMENT

The first step in reducing energy consumption is the analysis of the unit present conditions and the measurement of the quality and quantity of the utilised energy. The efficient operation ranges are usually close to operational constraints. The objective of the integrated Energy Monitoring System (EMS) is to provide a standard data reporting structure as the basis for analysis and decision making by the Energy Management System users.

Important indicators of oil refining technologies are the quality of the products usually specified in the appropriate Euronorms. In order to meet these specifications quality of the intermediates is to be controlled which could be supported by SQC (Statistical Quality Control) tools.

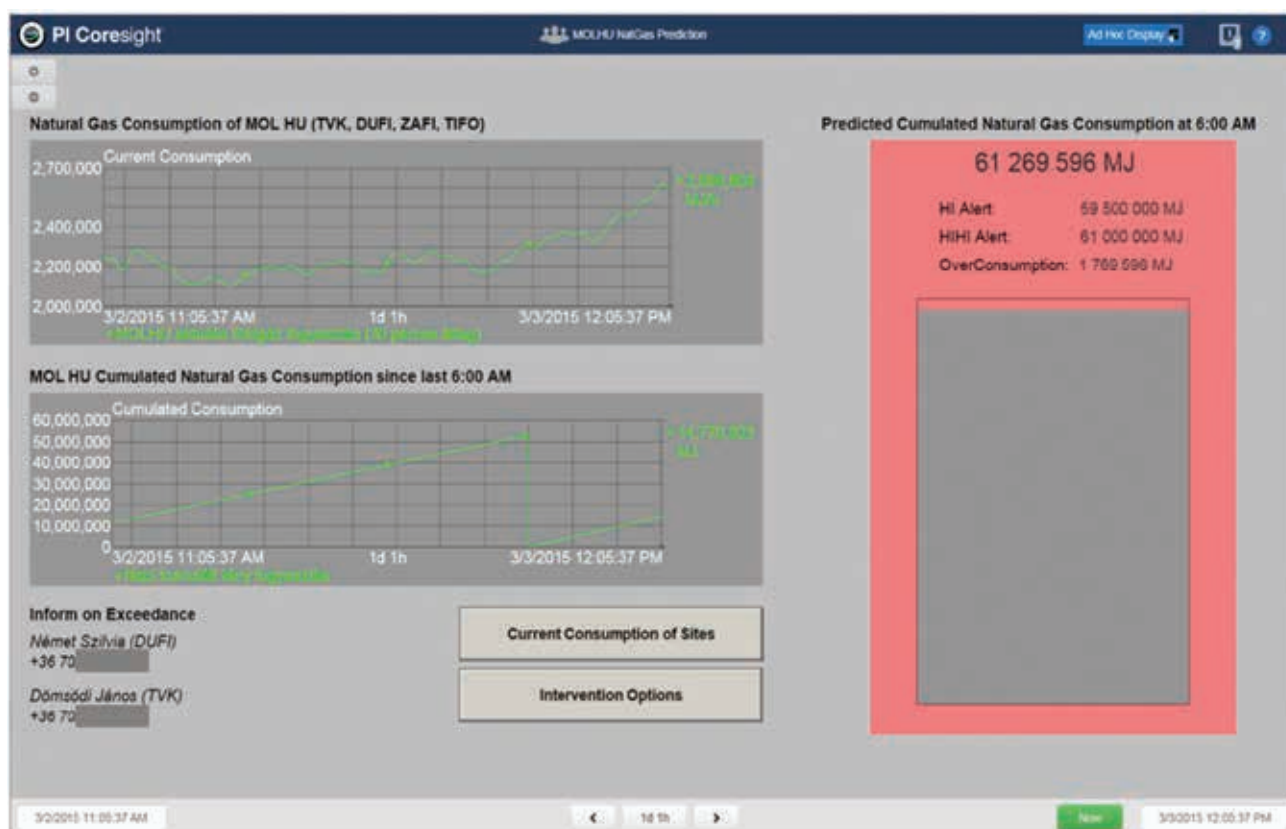


Fig. 6. Coresight display of natural gas consumption monitoring

Energy monitoring

Energy Monitoring System (EMS) is an effective hardware and software system to reduce energy waste, operational energy cost and environmental load by promoting energy efficient operation. The base of the monitoring calculations is a hierarchical KPI system, which is implemented in PI AF. With the help of PI AF elements energy wastes of units are identified and evaluated easily. EMS system calculates the optimal energy consumptions of the assets (Key performance indicator, KPI) and the optimal value of operational parameters that affect energy consumption (Key operating indicator, KOI). With the targeted KPIs and KOIs the system can help the operators to drive the unit closer to the optimal and energy-efficient working points (see Figure 7).

The Energy Monitoring System's new multi-level hierarchy is under continuous development. Future system will cover every area from high-level performance measures within the site manager's portfolio, cascading down through operational areas and structures to short-term control parameters at the plant operator level (e.g. boiler / furnace firing conditions). At all levels of performance measures frequency of review and appropriate corrective action loops need to be defined (see Figure 8).

DCS system

The first level of the EMS system would help unit operators at control screens. Energy Monitoring System (EMS) has a DCS level, where the calculated actual and target consumptions are displayed for the operators in real time to reduce the reaction time for corrective actions. To ensure this effect, DCS alerts are configured to indicate deviation from the economic operation.

Expert system

The upper level would be used by the experts to improve the efficiency of management workflow. These visualisation and reporting tools are implemented with PI client tools. The expert system contains online displays on the PI Coresight and Excel spreadsheets which evaluate wasted energy based on PI Event information. The data is obtained with PI DataLink.

Notifications

The system also includes a notification application (based on PI Notification) which informs the experts about deviations. The notification system has different levels and the application ranks the energy waste according to the cost. There are two types of events: one for the KOI limit-crossing and the other one for the overconsumption of the asset.

Unit energy consumption target = Actual energy consumptions—Deviations

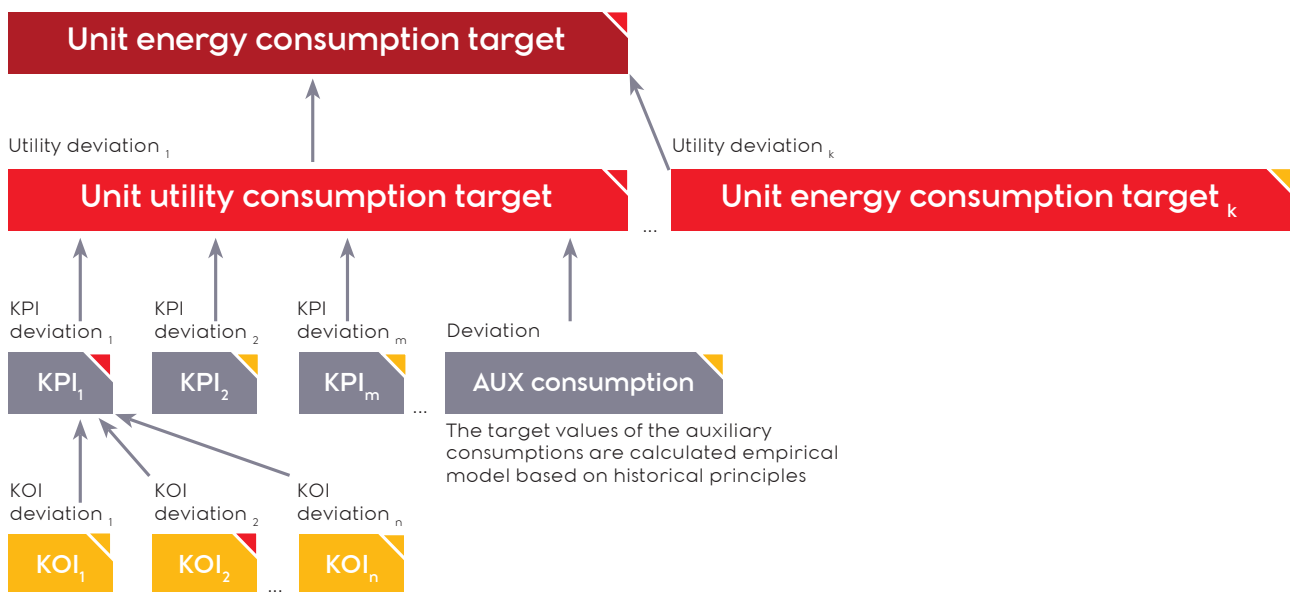


Fig. 7. Hierarchical structure of energy KPIs

Manager	Real-time trend SEMAFOR	Managerial summary	
Energy experts			
Experts			
Unit experts			
Shift leaders	Excel sheet whiteboard maker	Daily Opralog reports	
Operator	DCS screen	DCS SEMAFOR	DCS alarms
	Real-time trends	Reports	Notifications

PI Coresight
EMS screens

Excel BI reports for
drill down analysis

Asset Team Excel reports
for the economic analysis

Notifications from the
energy waste



Fig. 8. Planned energy monitoring tools of Danube Refinery

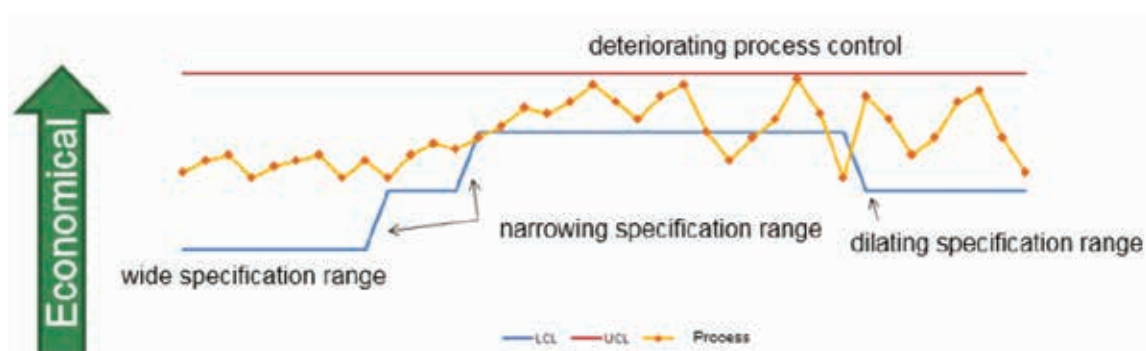


Fig. 9. Statistical Quality Control
LCL – lower control limit; UCL – upper control limit

Statistical Quality Control (SQC)

One of the most important initiatives of Danube Refinery Process Information and Automation group was the implementation of a statistical quality control system for operation, which can be used to reduce the variance of product qualities. Reduction of quality variance would increase production efficiency, because the production plants can keep the qualities closer to specification limits, thus reaching higher yields and lower energy consumption.

Quality control solution is based on the Western Electric Company (WE) process evaluation system. The solution is implemented in PI AF and evaluates measured process performance and calculates intervention suggestions based on WE rules (Western Electric Company 1956; Kemény, S & Papp, L & Deák, A 1998)]. System helps to manage specification limits dynamically increasing their flexibility. SQC requires on-line quality data therefore analyser or soft-sensor information is always necessary for calculation (see Figure 9).

SQC displays are created in PI ProcessBook to exploit the benefits of the PI client tool. Figures can be changed easily because of relative PI AF element specifications based on SQC operation cycle (see Figure 10).

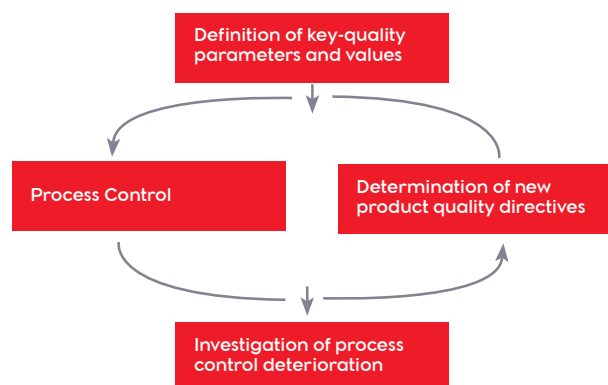


Fig. 10. SQC operation cycle

At the beginning of 2016 41 product quality parameters were monitored in 14 units through complex calculations performed by PI Asset Analytics. Computation is based on template attributes therefore complex calculations (e.g. time averaging and time-stamp calculations) can be implemented in different analysis.

INTEGRITY OPERATING WINDOW

Preventing high temperature hydrogen attack (HTHA) in DHPP1-2 (Danube Hydrogen production plants) units, PI AF system was complemented with new asset module in 2015. Integrity Operating Window (IOW) parameters covering the most potentially hazardous technological points are recorded in the system. The system links the parameters with process variables and limit settings. Attribute limit setting definition is based on Nelson curves references (API RP 941 2008) to define safe thresholds for parameters: f^k (metallurgy, temperature, hydrogen partial pressure (PP), length of exposure) (see Figure 11).

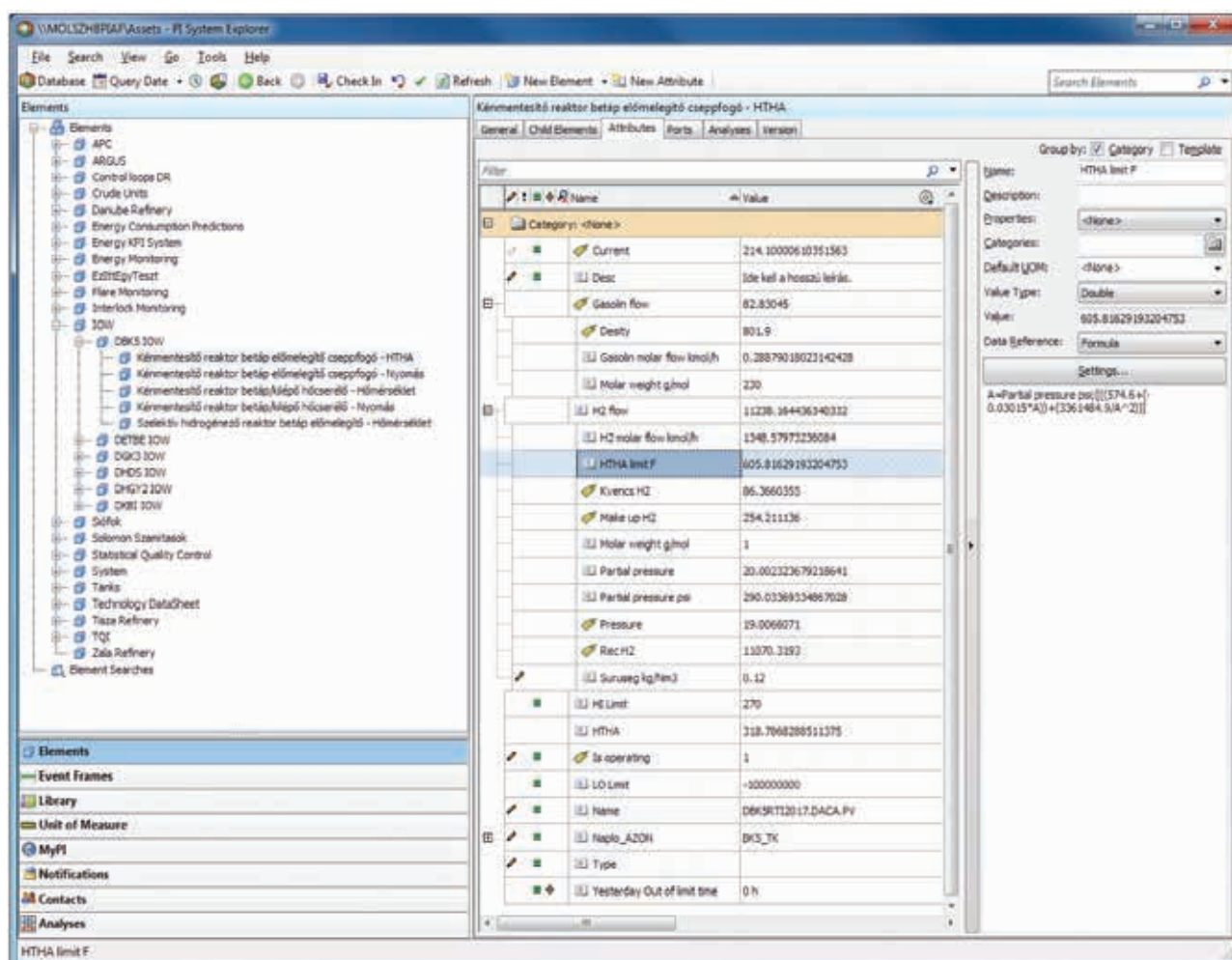


Fig. 11. PI AF - Integrity Operating Window template

Developed PI AF template covers

- Calculation of hydrogen partial pressure
- Attribute of pipe class
- Temperature and length of exposure limits, and
- Total time above temperature and partial pressure.

System has been tested and rolled out for six units (DNHT5 – Danube Naphta hydrotreating, DETBE – Danube Ethyl Tertiary Butyl Ether, DGHT3 – Danube Gasoil hydrotreating, DMHCK – Danube Mild hydrocracking, DLNIS – Danube Light naphta isomerisation, and DHPP2 – Danube Hydrogen production plant) with PI Notification functions. Extension of IOW system to other areas is continuous. The success of further developments mainly depends on the quality of the unit's instrumentation and the new limit setting definition progress.

OPRALOG SYSTEM DEVELOPMENTS

Opralog, the electronic logbook system allows the flow of information between shifts to improve and grants direct communication across the plant. Opralog system is widely used in Danube Refinery to record every process-related information in shift logs and publish the data via reports. Electronic logbook supports the administrators to integrate the software with other systems – like Plant Information, LIMS, NICE databases or SAP modules – to support the revision of the Danube Refinery's operation.

INTERLOCK STATUS CONTROL

Safety Instrumented Systems (SIS) statuses are crucial points of the refinery's safe operation. In special cases the Safety Instrumented Functions (SIF) are allowed to be overridden by using Maintenance Override Switches (MOSs). However, this overridden status shall be maintained only for a limited period of time just as long as the device maintenance is finished. The number of the disabled safety functions shall also be kept on the lowest possible level.

The most common problems with the previous old paper-based interlock monitoring were the lack of data (e.g. signatures, dates) and the irregular control method.

Now, MOS status information is stored in PI database, interlock elements, attributes and performance equation's calculations are available in the PI AF system. Each time when the interlock status has changed PI Notification triggers a subscription and sends a message to Opralog system's users to draw attention to the modifications (see [Figure 12](#)).

According to Opralog entries and reports the number of the disabled interlocks has reduced by about 23% in the last two years, resulting in Euro 700 000 saving on EDC (Solomon Associates Inc.'s equivalent distillation capacity) calculated loss.

'TECHNOLOGICAL CARD' PARAMETER'S DEVIATION MONITORING

Continuous monitoring of the process data is an essential safety action in the oil refinery, therefore 'technological card' (prescribed) parameters and their limits are one of the most important parts of the PI AF system structure. The deviation monitoring procedure is based on the following way: PI System™ collects all relevant process data, the unit states information and calculates dynamic limit settings for them; then PI AF transmits the results into the electronic logbook system.

After 24 hours of deviation PI Notification system sends an alert message to the Opralog system via web service, which creates an entry about the alert and informs the technologist and shift members about the problem via e-mail messages.

GAS FLARING SUPERVISION

Unnecessary flaring activity has serious effect on the environment beside its energy waste aspect. E-flare programme aims at detecting and documenting flaring activity with the help of Opralog system and PI client tools in order to reduce the losses by 90% between 2013 and 2018.

Workflow process of the flare activity monitoring can be described as it follows. PI Notification sends a warning note to Opralog system to draw the operators' and shift leader's attention to the on-going flaring activity, and after comments an investigation team examines the problem. In case of unnecessary flaring activity – as an outcome of the investigation – a proposal has to be made how the units could avoid these types of events in the future (see [Figure 13](#)). Preventing actions cover installation of flare gas recovery compressors or expansion tanks. Since the initialisation of the E-flare programme in 2013, volume of gas flared decreased significantly.

TANK QUALITY INTEGRATOR

Tank Quality Integration (TQI) application helps the refinery operators to reduce quality giveaway and prevent avoidable reprocessing. System operators can get online information about the product qualities in the tanks by the help of the application. Considering this information the operators can control the final product quality in the tanks, thus, can reduce quality giveaway.

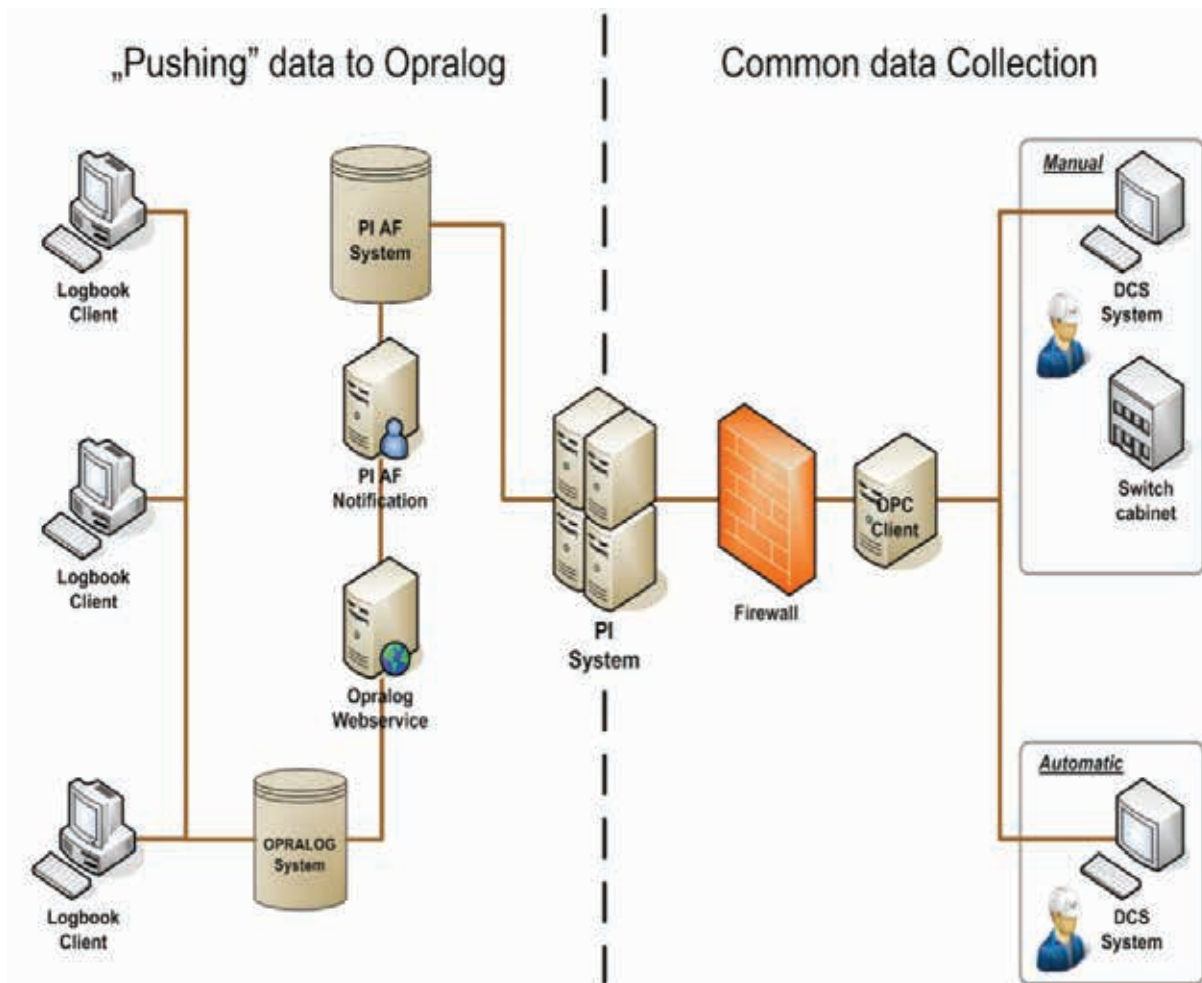


Fig. 12. Opralog Interlock System

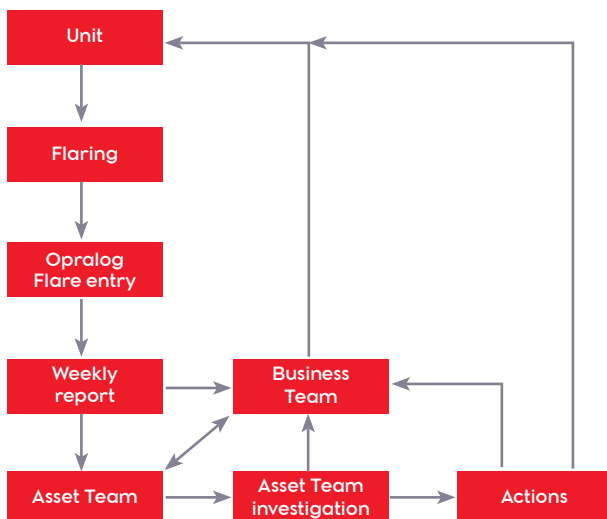


Fig. 13. Flare monitoring in Danube Refinery

TQI project was successfully closed in 2015; system displays were handed over to the users for training and operation purposes. After the implementation only several minor modifications were needed to make the calculations more robust. Now TQI is in operation and the calculated results are in line with the laboratory measurements.

TQI programme covers the Aromatic Recovery Unit and the propane-propylene system (in DDCKU, DFCCU) of Danube Refinery. In these cases quality giveaway cannot be reduced by blending, as these processes produce final products.

Due to changes in technology, and the relative inaccuracy of measurements in some processes the actual parameters are kept too far from the product specification limits to

avoid off-specification product flows. This is a quality giveaway; the product tank has a buffer capacity to balance the shorter quality limit exceedances.

To calculate the product quality in the tank, users need data from different sources. Calculations require online process data (flow rate, quality) from PI and data (movement, tank mass) from NICE (Natural Info Center) Movement Log application as well.

Tank Quality Integration system covers three main functions. It has a reliable and configurable calculation engine, collects the data needed for calculation and the results are made available for the operators via a user friendly interface.

Calculation engine

The main criteria for the calculation engine are the maintainability and the integration possibilities. As a conclusion of the pre-project investigation PI System™ / Analysis Add-In was selected to fulfil these

requirements, since it does not need IS development or contractors for maintenance, and it is integrated in REFIS (Refinery Information System) main process database. It also has the possibility to extend the calculations for other sites. This calculation engine has direct connection to the data stored in PI System™, therefore it is possible to read the input data and write the results in the PI Server.

Data channel

The connection between the PI Server and the DCS systems had been already used and widely tested in various applications. In order to send the results of the TQI calculations on the existing way from the PI to the DCS, we have to increase the tag capacity of the industrial PI Server.

The calculations are implemented in the PI System™. Some of the required information is currently stored in this database except for movement and online tank mass data. Previously the online tank mass was calculated only at the user's request, and the automatic calculation



Fig. 14. Tank Quality Integrator

method had to be developed. The results of these calculations are forwarded to the PI Server. Concerning the information channel, OSIsoft RDBMS (Relational DataBase Management System) interface offers a proven solution with official support. It also has the benefit of flexibility, thus it can be utilised by various reporting systems (e.g. for monthly white product report).

User interface

The user interface has to be easy to use for the operators. The main tools for the operators are the DCS stations, therefore TQI results are forwarded and visualised in DCS displays. New DCS displays were created by the DCS vendor (see Figure 14).

The key benefit is the quality giveaway reduction, which means increased energy efficiency in the Aromatic Recovery Unit and increased propylene yield in the DDCKU unit. In case of Aromatic Recovery Unit the expected qualities meet the specification of the end product.

The propylene product of the DDCKU unit is mixed with propylene from the DFCCU. Based on the current propylene quality in the DFCCU unit (1 700 ppm propane content) and the expected DDCKU operation (for increased propylene yield), propane content of the mixed final product meets the specification.

FUTURE PLANS

The establishment of a preventive maintenance system is included in the short-term strategy. The aim of the preventive maintenance is to keep the assets in continuous operation without unplanned unit shutdowns. These advanced maintenance strategies have to rely on the continuous monitoring of the assets through process (working hours, temperature, flows, etc.) and SAP PM Module data. A new project plan was initiated in 2015 to establish a condition-based maintenance system via a new PI-SAP interface.

MOL leveraged a wide range of Microsoft platform elements, including SQL (Structured Query Language – core element of the OT context infrastructure), SharePoint, Excel Services, and Power View. MOL is currently rolling out Microsoft Azure based Machine Learning (ML) technology to enable advanced analytics and business / enterprise intelligence. The demonstrated best practices can be best summarised by using an OT context infrastructure to enable IT / OT integration and organisational transformation.

Keywords: PI AF, PI Notification, PI Coresight, energy monitoring, Opralog, TQI, SQC, OSIsoft

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Reviewed by István Kovács (Group DS T&D Advanced Process Solution Manager)



Éva Hornyák joined the company in 2006 and participated in various projects. She is responsible for the development and administration of SEMAFOR KPI management system and the operation of several HSE applications. Ms. Hornyák holds a BSc in information technology in the field of technical management from Dennis Gabor College.



László Szabó works at MOL since 2013 in various areas dealing with process information and process simulation. He is responsible for the development and operation of the Energy Monitoring System and the implementation of the Energy KPI System™ in MOL. László holds an MSc in chemical engineering in the field of process engineering from University of Pannonia.



Gábor Mucsina joined MOL in 2012. His main role is to support the business with proper tools and solutions for planning, process optimisation or process safety management. Gábor holds an MSc in chemical engineering in the field of process automation from Budapest University of Technology and Economics.



Tibor Komróczki has been working for MOL since 1987. He started his carrier at DFCCU unit and was working in different roles. In 2001 he joined the Process Information team as an application developer. Since 2009 he leads the Process Information team and in 2013 he won the leader position of the integrated Information and Automation team in MOL Technology and Development department. Tibor holds an MSc in computer engineering - Specialist in Microsoft Business Application Development.

Cross-disciplinary subsurface data utilisation: a tool for improving efficiency in E&P

Dávid Havas (33)
E&P data manager
MOL Group
DHavas@MOL.hu

ABSTRACT

Oil companies who properly control and adequately utilise datasets derive the greatest benefit from the data they possess. Currently operation costs are scrutinised in greater detail and it is crucial to maximise the utilisation of the considerable amount of raw and generated subsurface data. The cross disciplinary subsurface data utilisation has a positive affect by mitigating risks, reducing costs, improving safety and speeding up professional work. Overall the ability of the E&P is enhanced to cope with the regular downturns of oil price. This paper gives an overview regarding the major subsurface data types used in E&P, the challenges and the actions that enables cross-disciplinary subsurface data utilisation.

BACKGROUND

From the early days of the oil industry, costly technical data was continuously being collected, interpreted and stored in high-volumes and variety. Big data which can be interpreted as “high-volume, high-velocity and / or high-variety information assets that demand cost-effective, innovative forms of information processing that enable enhanced insight, decision making, and process automation” (Gartner 2016) is living element of oil industry. The oil industry is historically one of the major data generators and data utilisers across wide range of industries. The amount of data which is dealt with on a daily basis can be compared to the aerospace industry and to that in pharmaceutical research. Considering the dynamics of data generation an appropriate solution has to be found to turn this data explosion into a business advantage.

MAJOR DATA TYPES

In the E&P value chain (exploration, appraisal, development, production and abandonment being the phases) geoscience and engineering take an active role to reach the ultimate goal to discover commercial oil and / or gas fields to develop, set up and sustain production always keeping health and safety as a priority. To achieve

this goal complex interactions are required on both an individual and team work basis supported by a wide range of technical applications. All these building blocks create the massive and cross relational data environment which can be described by the words of explorer John Muir: “When we try to pick out anything by itself, we find it hitched to everything else in the universe” (Muir, J 1911).

To dig deeper in the data world which is created and used in Upstream the data should be classified to get a better understanding of them. Data classification by source and origin and major connection points are shown in [Figure 1](#). This schema reflects the general data landscape and data connections in Upstream at a typical mid-size oil and gas company. Data is separated into three major groups by the nature of their source: *raw data, interpreted or processed data and integrated data*. Each group has key role in the E&P value creation procedure. However, much of the raw data gathered is unique in nature. In many cases it can only be acquired at a very high cost and often there is only one opportunity to gather the necessary raw data. As an example, a core can be only taken from the targeted geological formation during it is drilled through. Interpreted data might be regenerated using the same technical procedure although it could be very time-

consuming, for example in case of complex geological or reservoir models. Models may have to be reinterpreted if new data elements are made available such as new seismic lines or well data. These iterations continuously increase the size of datasets and the cohesion between the elements. Simultaneously the procedure also increases the understanding of the geological structure and data environment complexity. Interpreted data forms the basis for decisions regarding capital-intensive investments. This is why data is considered as one of the company's key assets.

CHALLENGES TO DEAL WITH IN DATA SHARING

A clear view on the required outcome makes changes executable and sustainable. So it happens in time of a data revolution that data is increasingly being considered as key asset of a company. It is generally known that knowledge means technical, commercial power. Knowledge is built from information and experience which can be preserved in data format. Data can be converted into information if it is structured and put into context and meaning.

Major data consumer and data generator companies have realised, that they are 'sitting on a pile of gold' which is actually the data that they possess. However this pile of gold is built up from small pieces like a puzzle whose elements are stored in different types and sizes of boxes. These boxes are eventually locked or opened and there is no master key to open all boxes at the same time. Moreover these boxes are stored in different places in terms of geographical and logical criteria. So the task is given that the elements have to be arranged to formulate a marketable golden piece. This example gives an overview of the current situation in many companies outside the oil industry and these are the challenges that have to be overcome in oil industry as well.

Irrespective of which major data generator industry is observed, the general view is that an expert could use between 40–80% of the working time looking for data and quality checking. This general assumption becomes more realistic in those working periods when it is necessary to apply new datasets into the ongoing or planned procedure. There is a clear need for efficiency improvement for companies and the opportunity to take an advantage against tough competition.

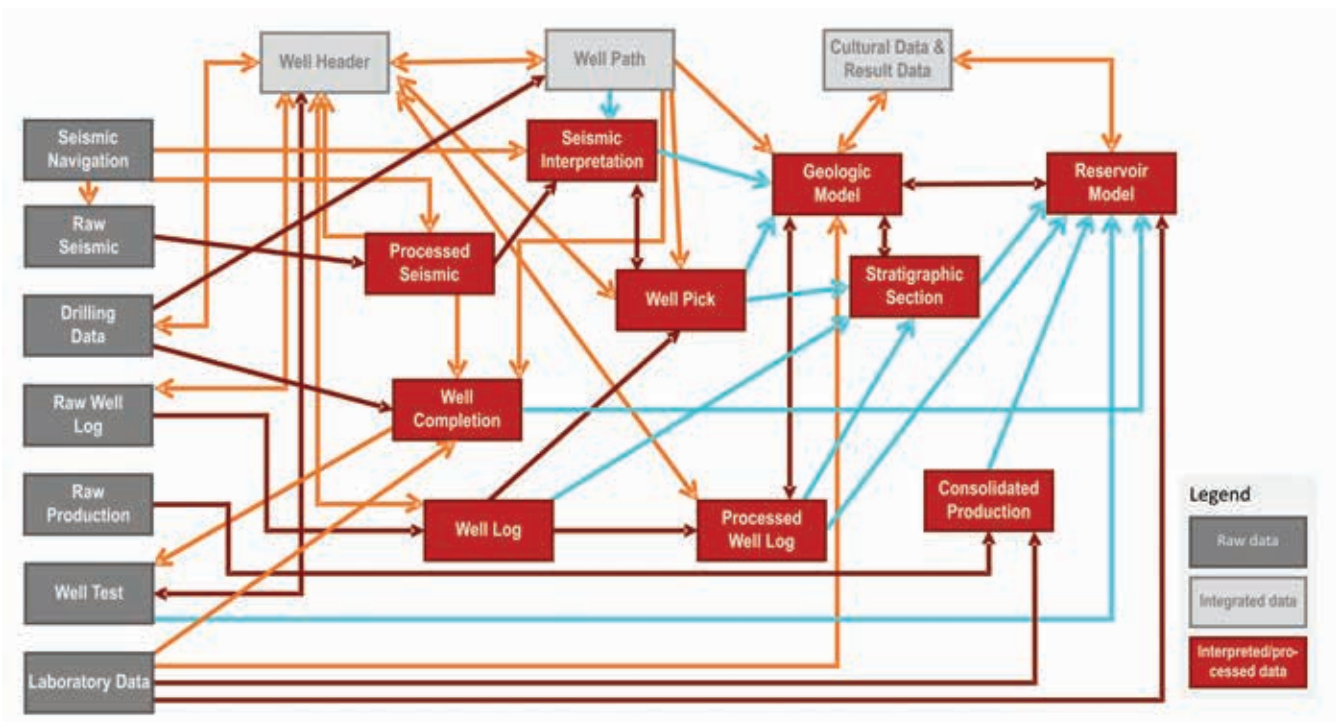


Fig. 1. Major data types in E&P value chain. Note the very complex interrelations between the disciplines in E&P

However, if it would be so easy to reorganise the whole data structure and data access process it might had already happened in all major data utiliser industries. There are many obstacles which could be listed over many pages, why data access is so time-consuming in many cases. The ones which are considered as majors are listed on **Figure 2** under Disablers. The diagram shows major enablers and disablers of a case when a set of data had started to be collected and organised into a standard data structure in a proper data environment from completely unstructured, outdated silos.

Silo thinking and data ‘mine’-ing are two areas which can be easily identified either at a clinical research company or at an exploration company. Silo thinking is a heritage of those ages when disciplines were rather working alone and not in a collaborative environment. At that time applications used in daily procedures were only focused on fulfilling the given discipline’s needs. It was enough that time and business environment was satisfied what they had. However, globalisation affects not only countries and industries, but it also has direct effect on the building elements of industries such as different domains of a science. To increase efficiency and stay in business

in a highly competing environment fundamental changes have happened in major industries. Clusters and alliances have been created among players in the market to enable them to compete with their rivals who might come from all over the world. This process has a direct effect on the collaboration between various departments of the companies as well. So alliances and collaboration must be continuously created and maintained between the different departments. This collaboration effect has created new needs towards applications used in the process workflows emphasising the importance of integration of different domains’ processes. And processes need to be fuelled by data, so data integration has become a crucial topic as well. Process efficiency improvements could have driven optimisation programmes which one may feel as direct threat to livelihood. Therefore applying the old quote from Sir Francis Bacon: “Knowledge itself is power” (“Ipsa scientia potestas est”) one may consider that data ‘mine’-ing is the key to maintaining the status quo in long run. However, a competitive collaborative environment requires frequent sharing of ideas and data so there is a continuously increasing forced change to open up bureaus and move to the integrated data environment.

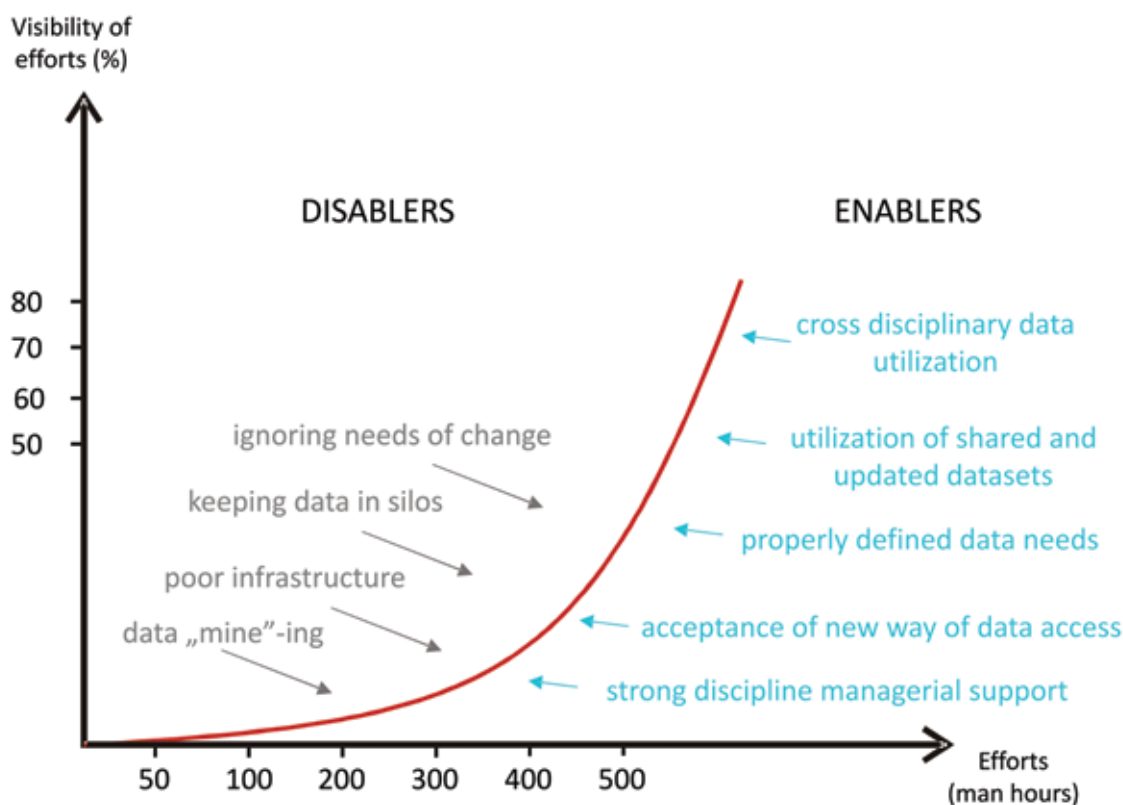


Fig. 2. Disablers and enablers in data management project

FUNDAMENTS OF ENHANCED DATA UTILISATION AND THE POSITIVE EFFECTS

The data landscape of E&P is the first element of increasing data utilisation. Data landscape is built up from identifying sole source of data, data ownership, data parameters, security, data connections and data exchange procedures. In a visualised format **Figure 1** and **Figure 3** show some elements of data landscape. In **Figure 1** the list of datasets and major connections are shown. In **Figure 3** the major E&P data types are sorted into data repositories.

Information can be extracted from data if it is properly structured and put into context and meaning. A powerful database with an open data model which would be the repository for all E&P data might provide an efficient solution to increase the speed and reduce the time to access the relevant data. However, it is hard to find this type of solutions among the ones available in the current market. There are some solutions which can cover multiple E&P data domains' needs, but definitely not on a full-scale basis. On the other hand special care has to be taken to the different needs of each domain. A drilling engineer needs the geological data in different details than a seismic interpreter and in contrast a seismic interpreter needs less detailed technical data of the well than a drilling engineer. Both of them need the same data types however in significantly different complexity. There is a common subset of the used data however there is sizeable subset which might be used only by one of the disciplines. There are some technical

initiatives to create database to store many types of E&P data in the same environment, but still the domain specific databases provide greatest efficiency. Application and database producers try to find solutions for the integration needs of the industries. There are clear signs in the market that disciplinary databases are being developed in order to be able to cover bigger and bigger stake of other domains' datasets. This is an opportunity for companies to choose one of the major databases and harmonise the number of data repositories and accelerate data access. In such a project the different types and details of data needs of disciplines have to be seriously considered.

Careful planning of data structure, continuous consistent data loading, precise monitoring and quality checking of data content are the pillars of properly working cross-disciplinary data utilisation. The properly established and maintained data environment and content formulate the solid fundament which empowers oil companies to improve the analytics capabilities as well. "Analytics was identified as one of the largest opportunity areas where digital can help transform oil and gas companies, yet most respondents felt their company did not have sufficiently mature analytics capabilities to realize the full value" – says the 2016 Upstream Oil and Gas Digital Trends Survey (Holsman, R & Richards, B 2016).

Data environment and data utilisation is effective and enhanced, if timely and trustworthy required data can be reached in shortest time for the authorised members of relevant disciplines. According to the data directive report of Economist Intelligence Unit there is a "strong

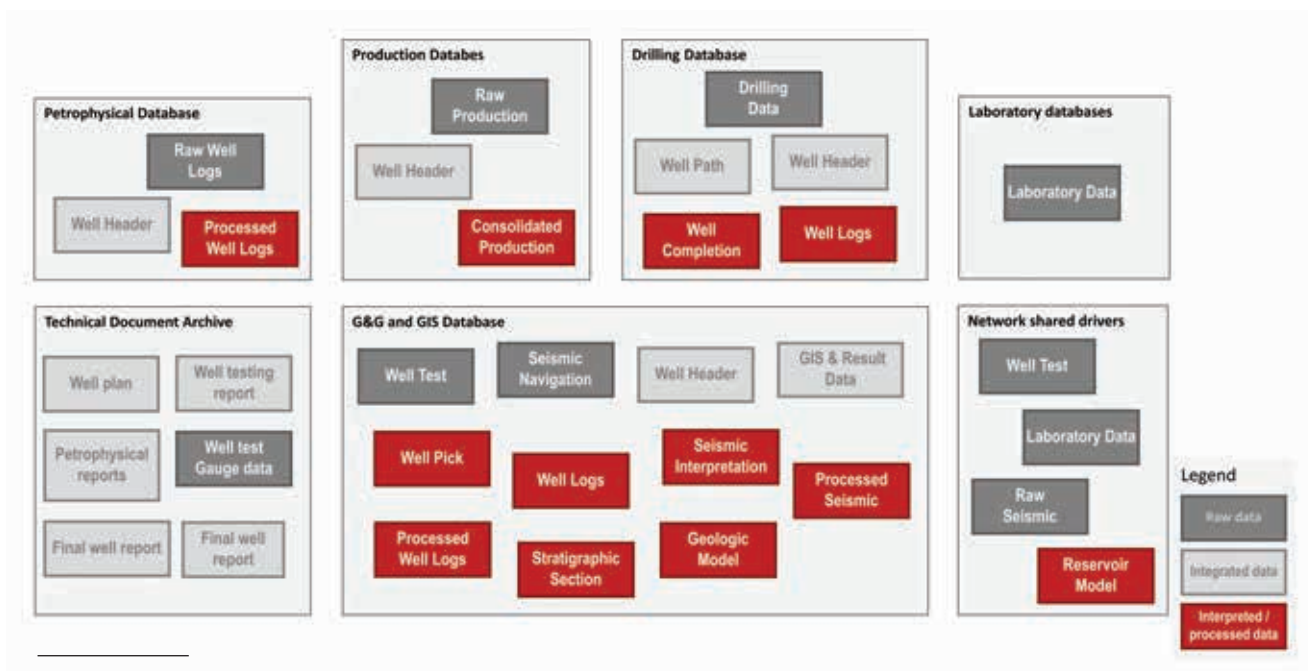


Fig. 3. A typical E&P Data landscape. Note that same type of data can be found in multiple repositories

relationship between earnings growth and strategic use of data... this study finds sharp differences between “high growth” firms, ... as compared to their “no growth” peers... even though both sets of firms collect lots of data, high-growth firms make far better use of it, while no-growth firms are more likely to find themselves swamped by the data they hold” (EIU 2013).

In some cases the same types of data can be found in multiple repositories, since the given discipline uses considerably more data types in its own processing workflow than the data consumers from other disciplines do. A petrophysical interpreter applies hundreds of logs during the processing workflow and the end users of interpreted well logs generally need

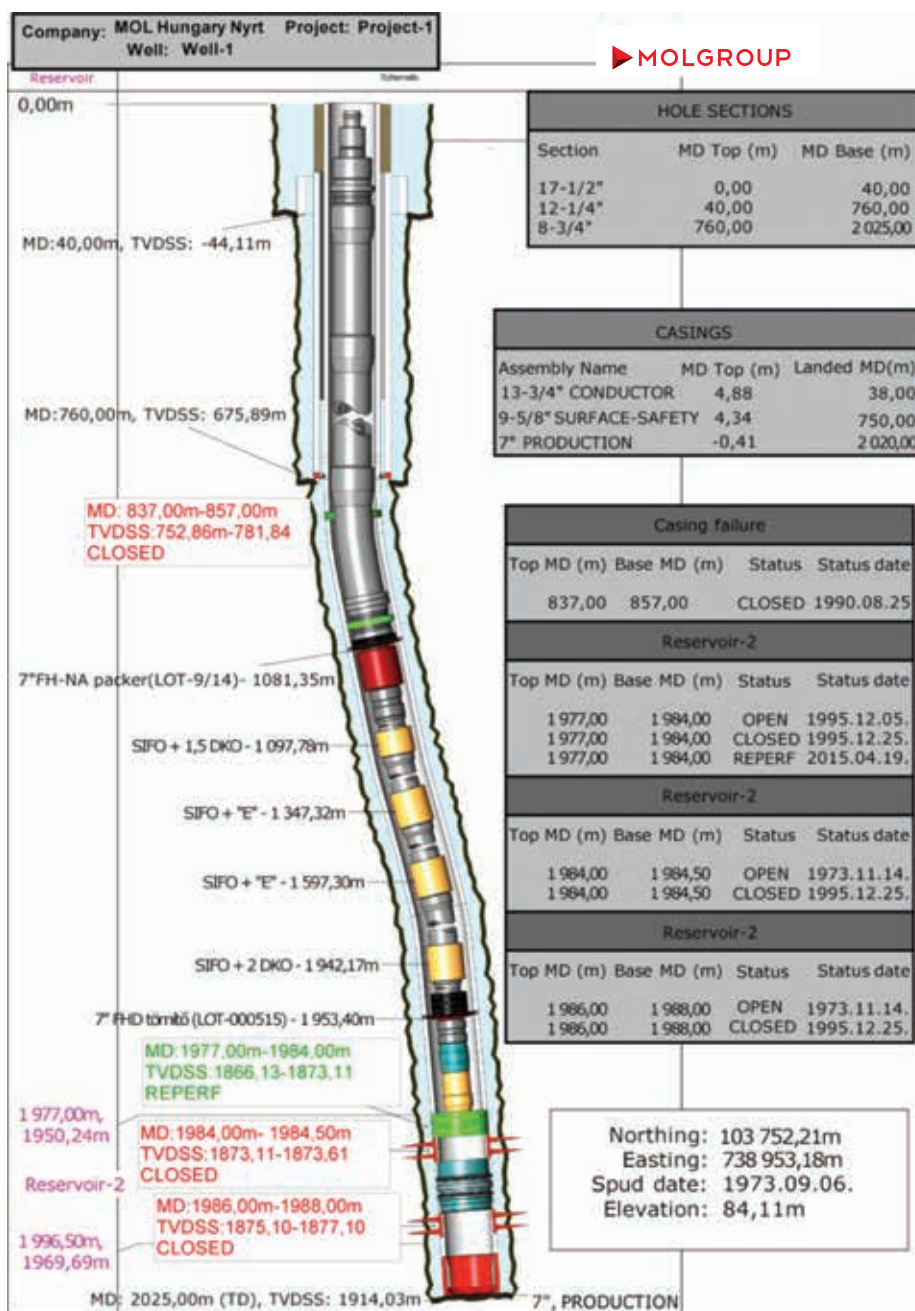


Fig. 4. An example of integrated well book (created by Zoltán Papócsi, Dániel Szabó and Data Management). Note, that well schematic shows geographical, technical and reservoir data
MD – measured depth; TVDSS – true vertical depth sub sea; SIFO – side pocket mandrel; DKO – valve or gas lift valve; FHD tömítő – seal assembly

less of them. However, it is necessary that all the logs are kept because these are the basis of calculations and enable the disciplines to dig deeper in complex cases. On the other hand the integrated subsurface database does not fully satisfy the level of details and data formats to cover full scale of raw and interpreted well logs (although it satisfies the end users' needs).

A data map gives answers to the 'where to find' questions. However, it does not give answer about the content, the quality and integrity of the content. It is obvious that a standard procedure has to be applied to ensure and maintain the availability and high quality of data sets and to increase the data access speed. These are fundamental issues for enhanced cross-disciplinary data utilisation. A valuable example of the visualised format of cross-disciplinary data utilisation is shown on **Figure 4**. All the data and elements are stored in the same repository and contain information which is important for multiple disciplines as reservoir geology, reservoir engineering, drilling and completion, and for projects such as a production intensification project.

As part of E&P data management strategy the data governance should give an optimal solution to ensure a trustworthy and timely data environment. To really reach this optimum, mutual and joint efforts of data management and disciplines have to be done in E&P companies.

As the data silos are opening up and collaborative working methods become a daily routine, more and more data is being shared with other disciplines and all of this data has to be structured and placed into the company's collaborative dataflow. This is a non-stop procedure and in order to successfully reach and maintain easy-access to high quality data, the data and the utilising procedures and the environment of geosciences and engineers have to be known and understood by data management.

The data revolution is ongoing and the new collaborative and open methods have to be embedded into the company working culture that wants to benefit from data assets and from cross-disciplinary data utilisation.

CONCLUSION

Oil industry is a major data generator and utiliser across wide range of industries. The marketable value of the subsurface datasets possessed by an E&P company is based on the level of data integrity and accessibility. Timely and trustworthy data environment, clarity about access of relevant data is essential to truly take advantage

of company data assets. To stay ahead of changing business environment, multidisciplinary team activities require fast access to each of their data sets which can be provided by continuously improving the subsurface database of the company.

ACKNOWLEDGEMENTS

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Keywords: data management, subsurface, integrity, utilisation

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Reviewed by Prof. Dr. István Bérczi



Dávid Havas has filled various positions and has lead international multidisciplinary projects within MOL Group since 2008, in Corporate Services and in E&P Data Management. Dávid is an economist, graduated at University of Pécs and he currently pursues electronic engineering at University of Applied Sciences Technikum, Vienna.

iCore – a unique approach to packing generation – Part 2

László Győry (50)
Laboratory manager
MOL Group E&P
LGyory@MOL.hu

ABSTRACT

A combined approach based on grain size distribution and microscopic investigation of grain shapes is applied to generate virtual packing of particles. Based on these sources of information a grain specific data structure has been created to support the formulation of a series of random particles. The created grains are always convex but vary on a wide scale from flat and angular to rounded and spherical through many in between but with the probability of occurrence described by the geologist. Packing consisting of grains created by randomness and probabilities come to their virtual existence through sedimentary, compaction and diagenetic steps. Process-based and biased random walk methods are combined with a collision detection algorithm of Gilbert-Johnson-Keerthi to create these virtual packs. Packing evolution through these steps is governed by target porosity and specific surface area values and finally the ready to use for modelling packs are fully porosity adjusted.

Part I that was published in MOL Group Professional Journal 2015/2 (pp. 90–99) is continued with the chapters and subjects below. Numbering of the figures and tables in the article are also continued to ensure unambiguous reference to them.

PERIODIC BOUNDARY CONDITIONS

Basically two sets of boundary conditions can be applied when packs are generated the way as we have discussed so far. The rigid wall conditions, that as the name suggests, refer to the walls as non-passable objects by the particles moved around in the computational cycles. It has a couple of advantages, first of all, the simple algorithm and faster run. Besides these no more advantages can be identified, but several disadvantages are certainly there. These disadvantages become obvious when we examine the pack and see the clear signs of the wall effects, which means, the pack near the rigid walls have a different local density from that of the pack inside. Another source of disadvantages can be identified when the dynamic flow modelling is carried out. One of them is to fail to construct a system free of surface effects at both the inlet and outlet faces of the virtual core specimen, which might be dominant and spread toward the interior of the pack if the virtual pack is small due to some other constraints. The other is the size of the system, which is constrained by the size of the pack itself. There is no chance for building larger units from packs created with rigid wall conditions and carry out flow experiments in these larger systems.

The periodic boundary conditions (PBC) can be classified according to the dimensions along which

they are applied. Fully periodic conditions in each three main directions are applied by Sain (Sain, R 2010). Since the technique applied so far and the nature of the basic approach to the problem together determine what PBC can be applied in our system. Maintaining the basic characteristics of the system, namely the gravitational movement of grains, we decided to use a set of horizontally PBC, which means that periodic conditions are applied in x and y directions only, but not in z-direction. That means that the vertical walls of the container are passable by particles, while the horizontal walls, the top and the bottom are non-passable, the particle will rebound from them.

For successful handling of the PBC case it is necessary to make the algorithm a bit more complicated since some of the particles being cut through by any of the vertical walls will cause the particle to appear at other boundaries as well, depending on the location of the original particle. It means that a particle as soon as starts to leave the container in one direction, it will appear right away on the opposite side of the container as a ghost particle. If it happens near a corner the real particle will create three ghost particles that shall be checked for collision against the real and other ghost particles. This phenomenon can be handled in at least two ways, one is the nearest image convention (Sain,

R 2010), the other was our approach followed the logic of the statistical mechanics course at coursera.org (Coursera). This created virtual images of the real particles, in a dynamic way, cut through by the vertical walls and these images were also taken into consideration at collision detection ensuring the overlapping-free edges of the particles' pack in the vicinity of the walls.

Figure 3a shows the result of the technique letting the thin sections be seen from above. The original thin section is marked with label (i, j) , and PBC ensures the flawless multiplication of the computational space, splicing the units one to another in both x and y directions. At the edges of the sections particles that are

cut through by the container walls are depicted with a combination of red and blue colours. Red shows the real particle, while blue shows the ghost equivalent of it. In the upper right corner of the sections there is a particle that consists of one red and three blue sections underlying the fact explained above that a particle leaving the container at a corner will create three other ghosts ensuring the non-overlapping case between the particles. Figure 3b shows the same packing from side view using the same colour convention for real and ghost particles. Figure 1 in first part of this article (MOL Group Professional Journal 2015/2, p. 97) depicts non-spherical particle packing including both the real and ghost grains. It shows well the effect of ghost particles on the real grain configuration of the packing.

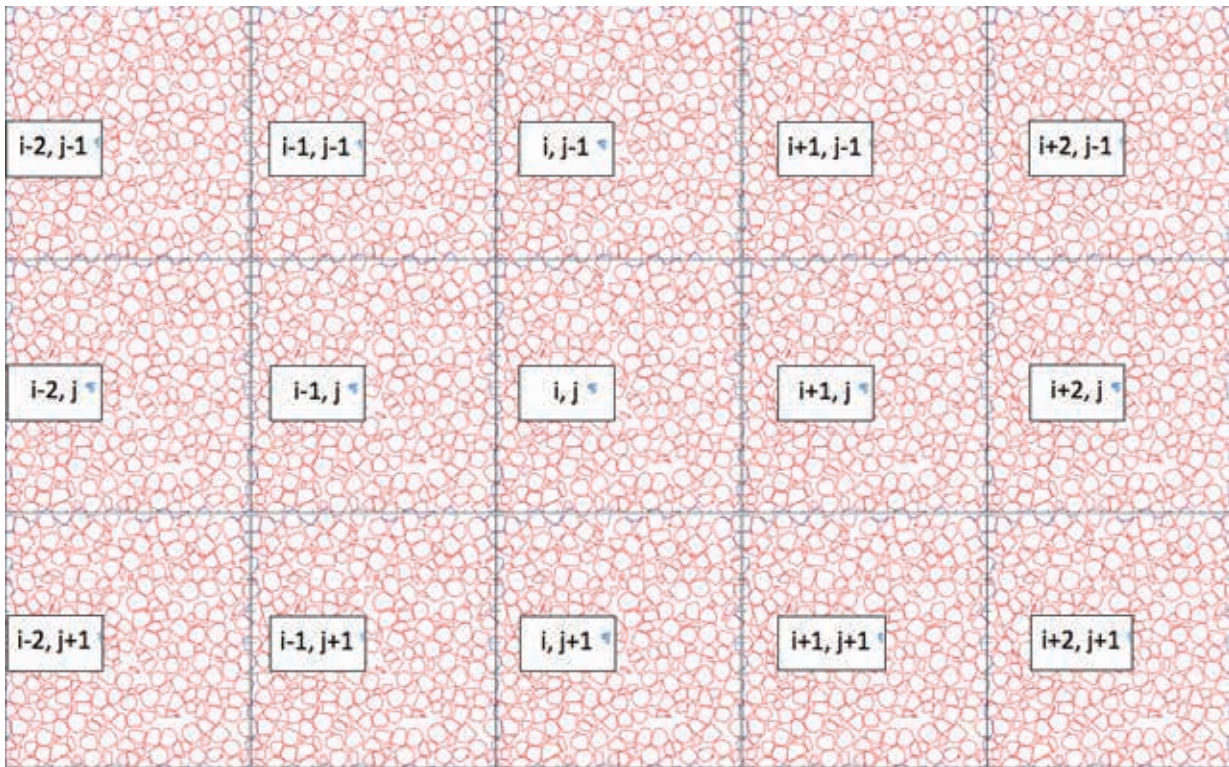


Fig. 3a. Building large artificial rock specimen from a basic unit (i, j) utilising the horizontal periodicity, depicted the x-y view of the sections

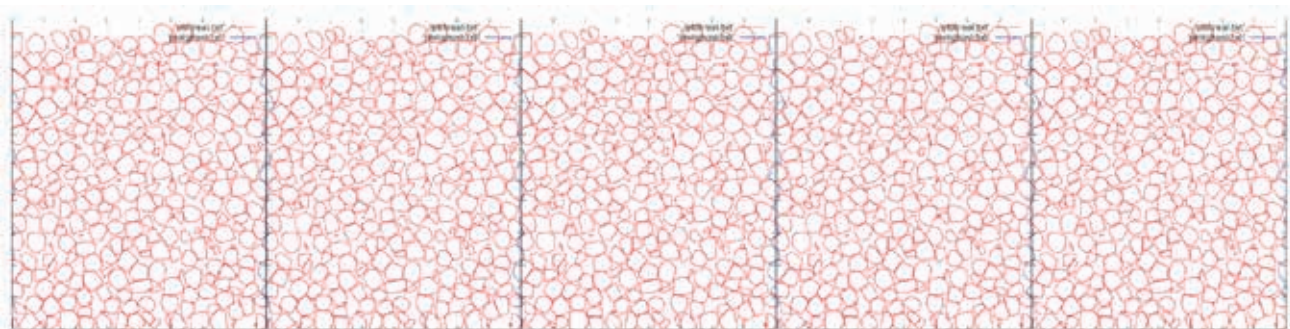


Fig. 3b. Building large artificial rock specimen from a basic unit utilising horizontal periodicity, depicted the x-z view of the sections

COLLISION DETECTION

Collision detection between particles is the most important part of the algorithm having a very direct effect on both the efficiency and packing quality. The whole process was designed to form a logically consistent system, therefore the basic data structures initiated and populated with elementary pieces of information satisfy the requirements of the methods applied throughout the process including

- Both the grain description and their depiction
- The grain movement by translation and rotation and
- The collision detection between particles and the depiction of the packs.

Throughout the whole process this logic follows the data handling from providing the inputs and dealing with the intermediate results and finally to the processing of the ready packs. No further tinkering with the structures and data is required to depict the packs for example.

The number of particles involved in the collision detection process has got a very obvious effect on the speed of the algorithm. A commonly applied technique is to pre-test the bodies, before launching the actual collision detection process. As already referred, the data structure in our case enables us to use the circumscribed sphere's radius to do the pre-test reducing all the computational demand to checking two spheres for collision each time. Spheres can be regarded as the most efficient geometric form to perform the pre-test, while using bounding boxes is more costly in the computational space. In case of a high number of particles it is still not enough, because there is still $N-1$ number of pre-tests that have to be performed for each particle when moved, where N is the number of particles. To eliminate the obviously unnecessary pre-tests for cases when the two bodies are far away from each other, a commonly applied technique is to divide the space into smaller units and do the pre-tests for bodies being in the sub-space only. With this the number of particles to be checked against one specific grain can be reduced considerably and a remarkable gain can be attained in speed.

An important issue is how much acceleration can be gained by subdivision? Instead of a general discussion of the topic only our case will be discussed here shortly. In the packs we model, the smallest sub-box size is determined by the largest grain being present. If the sample of grains is not well sorted, which means that the size distribution of grains is broad in the pack extending toward the tiny particles, it is easy to understand that there will be still a huge number of particles in the sub-boxes, therefore the attainable acceleration is less than

hoped. The other extreme situation is the uniform spheres case, where the sub-box size is in sync with the spheres size, therefore the sub-boxes contain a small number of spheres, and consequently the attainable acceleration is maximal. The idea of the above described minimum and maximum cut-off values applied on both sides of the GSD gains another noteworthy interpretation here. They regulate not only the segregation likelihood but the sub-boxing efficiency as well. Since the grain of the maximum size determines the sub-box size, not much chance is there for seeking any optima regarding the sub-boxing technique, but to exclude the particles still forming clusters and with this to reduce the maximum size of the grain in the pack. It follows that the sub-boxing optimisation can be done when the maximum and minimum cut-off values are applied on GSD in the preparation phase of the process. Since the sub-box size is aligned with the size of the largest grain in the pack, it can happen that considerable parts of the grain extend over the sub-box walls and into the neighbouring sub-boxes, where they might cause overlapping with other particles if not tested. Therefore in a 3D case not only the actual sub-box content is pre-tested for collisions but all the 26 neighbouring cells. To do so, a special walking around the actual cell sort of algorithm has to be constructed to perform all the necessary pre-tests not missing out any particles. It further complicates the algorithm, when horizontally periodic boundary conditions are applied, because in this case the neighbouring cell has got an extended meaning.

Sub-boxing can be enabled only if all the particles are linked to a specific sub-box and the allocation is redone at an appropriate frequency ensuring the flawless and unambiguous grain $\rightarrow$ box designation. Unambiguity is very important for linking the particles to sub-boxes. A program function does this based on the C standard library function, `qsort` (see <https://en.wikipedia.org/wiki/Qsort>). Since it takes 'long' to do the allocation, if there are lots of particles and sub-boxes, it is subject to logic and optimisation how frequently and when to call the function.

The close range collision detection, which is performed when the pre-test of the collision of the encompassing spheres is positive, is based on the Minkowski difference of the two convex solids. As it was already pointed out a couple of times, the data structures and the particle definition and generation all were shaped to enable us to use this feature of the convex bodies. In geometry, the Minkowski sum of two sets of position vectors A and B in the Euclidean space is formed by adding each vector in A to each vector in B . Analogously, the Minkowski difference is defined as $A - B = \{a - b \mid a \in A, b \in B\}$

(see https://en.wikipedia.org/wiki/Minkowski_addition). From our point of view it has two important consequences: one that the Minkowski difference of the convex bodies is also a convex body, the other is more important, namely, if two convex bodies are overlapping, then their Minkowski difference will contain the origin. To decide whether two convex bodies are occupying the same part of the space to whatever tiny degree, i.e. produce overlapping, can be reduced to the case of deciding whether the Minkowski difference of the two bodies contains the origin or not.

Based on the above described two characteristics of the Minkowski difference of two convex bodies at least two algorithms are worth being considered here to use them for close range collision detection purposes. One is the quick hull algorithm, that is very efficient in finding the fewest possible number of planes that can wrap up a convex solid and identify the points forming the hull's sides. As we know, in case of two convex bodies A and B, having vertices a and b, respectively, the difference of them will have points as many as $(a \times b)$. The origin shall be added to the $(a \times b)$ set of points, and the qhull algorithm is to be run. If the convex hull does not contain the origin, it means, it is inside the Minkowski difference, therefore the two convex bodies are overlapping. Since the number of points might be high, $(a \times b)$, in case of two solids of shape class 6, 19–20 vertices for each solid, $a \times b =$ close to 400 points) the qhull takes relatively long to complete and decide on the origin's position relative to the Minkowski difference.

The other method is the Gilbert, Johnson and Keerthi, or GJK for short (see http://realtimecollisiondetection.net/pubs/SIGGRAPH04_Ericson_GJK_notes.pdf). GJK algorithm is an iterative method, does not necessitate the storage of the Minkowski difference computed prior to the actual collision detection. It uses simplices of various dimensions from 0 to 3 and support functions and iterates over the point pairs of the two convex solids always seeking the opportunity to approach the origin. In 3D if a tetrahedron (simplex in 3 dimensions) can be found during the iteration that contains the origin, then there is a collision between the particles being checked. The convergence is reached very quickly, usually just a few steps therefore the GJK algorithm can be very effectively used for collision detection purposes. That is why we decided in favour of GJK after analysing the two possible algorithms. We implemented the GJK algorithm and developed our own code written in C that utilises the data structure created. We have developed the GPGPU (general purpose graphics processing unit) version of the code as well for parallelisation purposes and future tests. GJK lends itself well for GPGPU

applications, because it does not require dynamic memory allocation and is quite memory frugal. The convergence of the algorithm was studied by data gathered during the packing generations. We found that there was some difference between the collision and no-collision cases in the number of steps until convergence was reached. In case of no-collision, convergence was reached sooner, the peak of the distribution curve was at 2, while in case of collision it was at 3, but the statistically meaningful part of the curves was below 10 and 8, respectively. In less than 1% of the cases no convergence was reached at all, in these cases the algorithm quit at step 32, the maximum step allowed. The statistics was made on the basis of 5.44 billion GJK function calls.

During the numerous runs of the packing generator, overlapping between two particles has occurred only in a few cases, or as it turned out the suspicion of overlap could be raised a couple of times. The code reported of these cases and a visual inspection of the two grains each time took place. Two of these cases are shown by Figure 4, depicting the grains from the best or much telling perspective. If there is any overlap it is certainly tiny, and can be considered much like a false positive overlap alarm than a real one.

Collision detection is possible between more complex bodies as well, if they can be retraced to simple solids, either a set of spheres or convex solids. Concave and other objects can be built up from spheres of various sizes filling up the concave volume as well as possible, and then the series of spheres have to be checked one against other for collision. If the concave object can be subdivided into convex ones, then the above described collision detection method can be applied in these more complex cases.

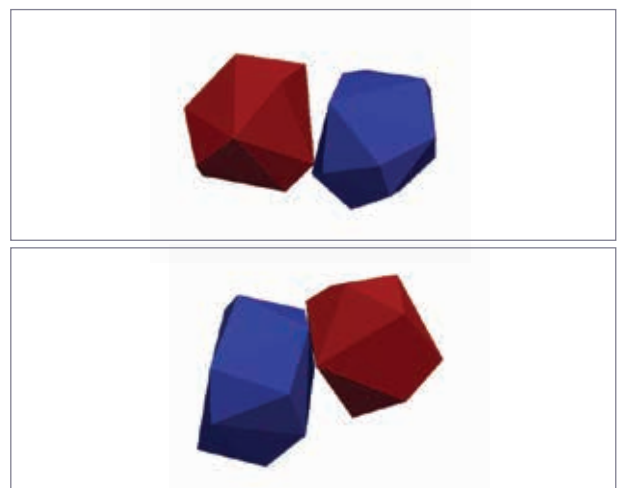


Fig. 4. False positive overlaps found at final checks of packing quality in ppt occurrences

CEMENT AND PORE FILLING MATERIAL

With all the above detailed steps we have arrived at the last phase of creating a virtual pack of grains, a model of a real sample reusable in an infinite number of tests, to study and investigate its properties and the characteristics of dynamic flow experiments. Let us sum up what we have at this stage of the process: a pack consisting of randomly shaped convex grain particulates, this pack has got a size distribution identical with that of the original sample in the size range that was used for creating the so called primary packing, between the two cut-off values and the pack has got an intermediate porosity. The final porosity can be reached by adding back the lost grain size ranges that can be expressed in grain volumes, caused by the cut-off values, to the primary packing. This make up for the loss can be done in two ways: putting on the cementing material and inserting the pore filling material. These two types of materials mean two different ways of handling.

In models like the one discussed in this article, cements are basically adheres to the grains in three ways: rim cement, contact cement and nucleation cement (Sain, R 2010). Algorithmically the rim cement is the easiest case, it can be implemented by moving the vertices of a particle in radial directions. Contact cement comes to existence between two or more grains and requires a more challenging solution, but not a difficult one. The third type, the nucleation cement is associated with crystalline overgrowth of particles that algorithmically means, in our solution, an additional point placement above one or more of the free, not contacting faces and the inclusion of these point(s) into the grain's data structure and all the consequences of it.

Pore filling materials can be classified as to their locations in the particulate packs. For algorithmic purposes we have created four classes of pore filling materials as to their locations of accumulation: pore wall lining, grain face centred accumulation, pore throat blocking and random pore filling materials. Filling up the pore space – where to place the pore filling material without causing inadmissible overlap between the primary structure and the new particles and between the new particles, too – is a real challenge regarding the quantity that is the attainable porosity reduction and the algorithmic efficiency. We have found that probably the most efficient solution to this problem of placement is a sort of Monte Carlo sampling technique. Similarly to the porosity estimation a huge number of points is shot into the primary structure, the points are randomised using an even probability distribution function, then points falling into the pore space are kept after testing them for collision with the primary structure, then in a second test run the new particle-particle interactions are

checked by using the randomly allocated radius to the points and those are kept that do not produce overlap with their neighbours. Since in this process spheres are used – using double precision number formats small polyhedrons can also be used – their total volume can be calculated quickly and with this a new porosity estimation can be done, and go on with this process in an iterative way until the target porosity is reached.

After placement, these new particles can be moved according to the strategy chosen, to which typical locations they can converge. This takes only a few hundreds or thousands of steps due to the much shorter distance they have to cover and though the number of particles is high it does not take long to direct them to their locations. The basic principle for moving them is the same, the biased random walk method, which was applied in the compaction phase, but this time with one considerable difference. This is the biased direction of movement that can be set as to the strategy of moving for each particle, instead of the gravity applied generally for the whole population of particles forming the primary structure. Figure 5 shows the case, in which the red coloured polyhedrons are surrounded by blue spheres. In an experiment, the chosen strategy was the grain face centred accumulation, using only one step of particle placement round, the intermediate porosity could be reduced from 0.425 down to 0.365.

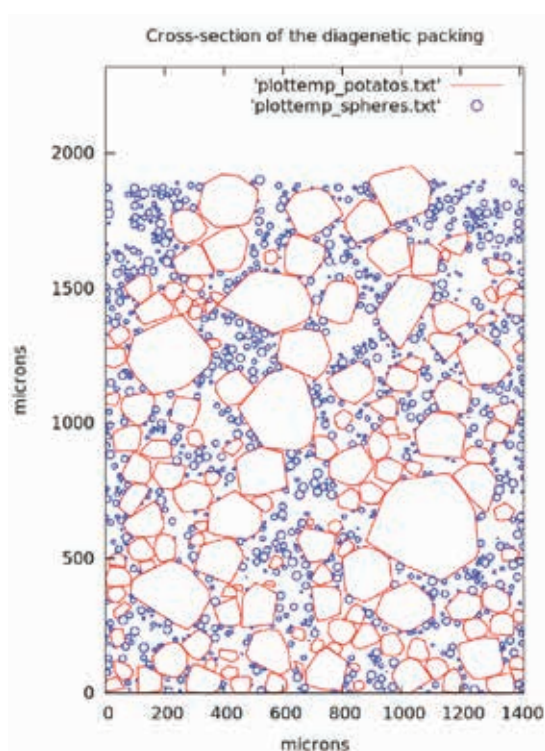


Fig. 5. Example sample of pore filling material in a pack of polyhedrons, accumulated in face centred positions

TESTING THE PACKS

Though the packs are not the goals, but the means in our project, their quality is very important from the point of view what can be achieved by doing experiments on these virtual packs. If these packs are a long way from the real samples in terms of any properties of the geologic samples, then the experiments are deemed a failure. Therefore it is vital to test these packs so that we can have a feedback in the process and the errors can be mitigated or even eliminated. Feedbacks are also important for another reasons, they help to shape the course of packing generation and the possible solutions to be applied.

The first test can be the visual evaluation of the pack, which can be done in both 3D and 2D depictions. For 2D cases we have already shown a number of pictures. First of all, the primary structure, the red polyhedrons and their arrangements can be analysed this way. Alignments and analysing a series of thin sections, the probability of their occurrence within the packing can be studied, and the prevailing arrangements can be compared to that of the real sample. 3D depictions of packs are shown in [Figure 6](#). The first picture shows a pack without its ghost particles, the counterpart of it shows the same pack with its ghost particles. The colouring was set for the best visibility. The deep red colour depicts the ghost particles covering the sides of the pack in the second figure.

The porosity of the packing is of great importance, since it is a basic way to compare the virtual packing to the real one, furthermore in case of quantitative analysis, e.g. absolute permeability estimations by the Carman-Kozeny method (Valdes-Parada, FJ & Ochoa-Tapia, JA & Alvarez-Ramirez, J 2009), porosity also plays an important role.

Specific surface area of a packing consisting of either polyhedrons only, or a combination of polyhedrons and spheres, can easily be calculated due to the grain definition applied. In case of the primary packing generation, in the phase of physical compaction, the C code contains a function that calculates the total volume and surface of the grain pack. Providing that the primary pack's grains are mainly sand, a density value of 2.65 g/cm^3 can be used to calculate the mass of the packing and following that the specific surface area of the material. In case of an artificially set of grains, having the same size distributions but consisting of grains belonging to basically different shape classes, the effect of grain shape on the specific surface area can be studied. [Table 2](#) shows the values we found in various experiments. The last row of the table contains data for spheres only with the same size characteristics and provides a reference value for showing the effect of the grain shape on the specific surface area.

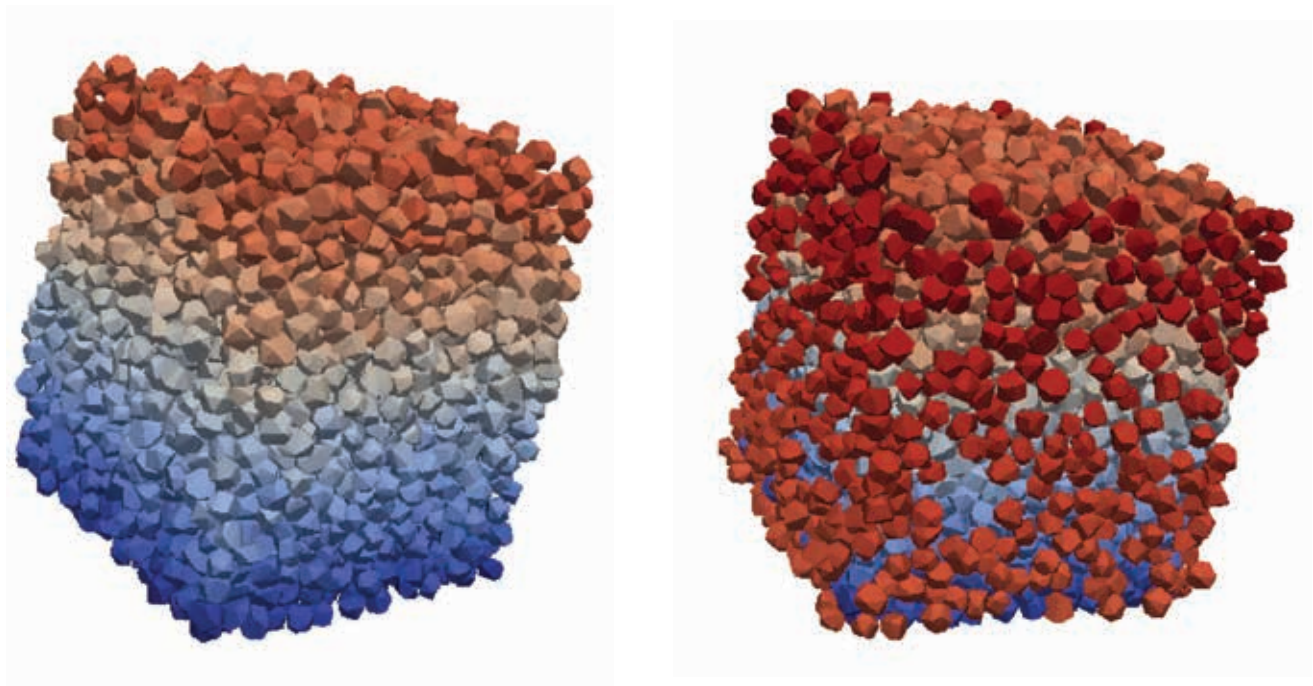


Fig. 6. 3D depictions of virtual packs without (left) and with (right) ghost particles created with horizontal PBC



Sample ID	Surface area, mm ²	Specific surface area, cm ² /g	Porosity	Shape class of grains
arti_f_21	50.96	505.5	0.3892	2
arti_p_21	44.47	441.1	0.3581	4
arti_s_21	44.07	437.1	0.3606	6
Spheres only	40.12	397.7	-	-

Table 2. The effect of grain shapes on the specific surface area

Particle	Effective diameter, cm	Mass, g	Area, cm ²	Specific surface area, cm ² /g
Gravel	2×10^{-1}	1.13×10^{-2}	1.3×10^{-1}	11.1
Sand	5×10^{-3}	1.77×10^{-7}	7.9×10^{-5}	444.4
Silt	2×10^{-4}	1.13×10^{-11}	1.3×10^{-7}	11.1×10^4
Clay ^a	2×10^{-4}	8.48×10^{-15}	6.3×10^{-8}	7.4×10^6

^aThickness = 10^{-7} cm

Table 3. An example for specific surface area data
(see <http://lawr.ucdavis.edu/classes/ssc107/SSC107Syllabus/chapter1-00.pdf>)

The so far applied approach regarding the primary structure of the packing and the specific surface area of the grains of this kind are in good agreement with the sand's relevant data in Table 3. However the real samples have much higher specific surface area, these realistic values, that can be generated by a linear combination of the values in Table 3 as a function of the composition, cannot be set in a virtual pack consisting of the sand grains only. This is in sync with the real samples, the realistic specific surface area values can be mainly attributed to the silt and clay content of the real samples. From this point of view, including the cement and pore filling material in the final stage of the process can be justified and as a result of this step a more precise model can be built.

We have already seen that the above described methods and their application might ensure the creation of a packing that is close to realistic samples with regard to the grain size distribution characteristics, prevailing shapes, porosity and specific surface area. It takes only time and computational performance and capacity

to generate packs that might satisfy the modelling requirements. These steps alone though, as we have already referred to it, are not the aim, but the means, so they much rather have to serve the purposes of the subsequent static characterisations and dynamic experiments. It means that the packs have to fulfil certain requirements like the resolution of the space when voxelization takes place therefore at this stage of the development some sensible balance has to be stricken. The satisfactorily fine resolution for lattice Boltzmann is very capacity demanding, actually impossible to achieve because no computer has that amount of memory. It follows that very fine details cannot be resolved therefore they remain hidden behind the relatively raw voxelization. That applies to other modelling as well, like pore size distribution and capillary pressure curve calculations. Research is currently being done how to surmount these problems and constraints so that the fine details can also be revealed and all these modelling can be made considerably more efficient.

CONCLUSIONS

We have presented the series of steps that bear logic consistency throughout these stages and lead up to the creation of virtual packs that consist of randomly shaped convex solids. The combination of methods, boundary conditions and solutions chosen is in alignment with the packs to be modelled and fits well to the basic characteristics of these packs of real clastic rock samples. The size of packs is constrained to the range below the probability of any macroscopic pattern appearance, within the homogeneous layer of particles that can be attributed to one sedimentation event. Replacing spheres by random polyhedrons serves multiple purposes: to create pore structures that are closer to the real ones, to instil the concept of anisotropy of real packs caused by aspherical grain occurrences into their virtual equivalents and to make the virtual packs have more fidelity to real packs in the visual appearances. Applying external conditions throughout the steps help us keep the process anchored to the real samples and their properties. Including the shape characteristics in the formulation of virtual grains resulted in more realistic particles that resemble the prevailing grain morphologies of real samples. Introducing the horizontally periodic conditions eliminated the wall effects, resulted in denser packs and made infinite systems possible to be built up using one single basic unit. Numerical characteristics like porosity and specific surface area are also included as external conditions or target values that help to characterise the virtual packs and check the quality of what we get by the end of the process. The order of steps and the methods applied are adjusted to the real sample's characteristics and the way they came into existence. Though a real MCMC (Markov chain Monte Carlo) method would eliminate the vertical heterogeneity problem of the packs during evolution and enables us to apply 3D PBC, that would raise other questions like how to handle anisotropy caused by flat particles with definite orientation and the position of pore filling material relative to the grains forming the primary structure, or the backbone of the packing. These questions are subject to future research in this area. We have shown that besides porosity the specific surface area adjustment is also of great importance, because it plays a crucial role in permeability estimation. The target porosity can be reached by applying sand grains only that form the backbone of the packing, the inclusion of pore filling material is essential to further improve the fidelity of any virtual packs to the real ones. Actually the transition from spheres to convex polyhedrons already improved the quality, having greater specific surface area than spheres, but the conscious application of fine particles to adjust the porosity and specific surface area values together cannot be disregarded. The packs are subject of further experiments, both static and dynamic,

in which the resolution of the 3D space, the finer the better the results are, might be a serious constraint due to immense computational requirements. Intensive research is currently being done in this area how to surmount the constraints and deliver more telling results.

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Keywords: virtual particle packs, clastic rocks, modelling, random walk, Monte Carlo, porosity, specific surface area, convex polyhedron, periodic boundary conditions, collision detection

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Reviewed by János Geiger, PhD



László Győry started his career in the fluid technology lab and dealt with technological problems and their solutions, while running an accredited elemental analyses unit, as well. Since 2008 he has been the head of the Exploration Laboratory. He holds an MSc degree in chemical engineering from Budapest University of Technology and Economics and a business diploma from Modern Business and Administration College Budapest.

Analytical determination of the perforation design's effect on the productivity¹

Ádám Viktor Pásztor (25)
MSc student
University of Miskolc
padamv91@gmail.com

Vera Magdolna Schultz (20)
BSc student
University of Miskolc
sverus95@gmail.com

ABSTRACT

The knowledge of the inflow performance relationship of a producing well is essential for an optimal production. It establishes the link between the applied pressure drawdown and the inflow rate at the bottom of the well. In a cased and perforated well, the reservoir fluid flows through the perforation channels before it enters the well, thus the perforation parameters have a large effect on the inflow performance relationship. There are two methods which are widely used for calculating the effect of the perforation design on the inflow performance. However, in these equations some of the important parameters are neglected, or such simplifications were applied which involved significant loss of accuracy. We aim to develop a model which gives realistic predictions, taking into consideration that both the laminar and transient skin factors depend on the phase angle. The final equation gives more realistic results.

INTRODUCTION

PERFORATION DESIGN

Steel casings are set to prevent ground water contamination and the fracturing of subsurface layers during the drilling of a well. If the reservoir rock can withstand the stress resulting from the pressure differential which develops during the production, then the reservoir fluid can be produced from the open hole. This is the so called open hole completion. However, in most cases the reservoir cannot tolerate large stresses; therefore the application of a production casing – which must be perforated – is inevitable. In this case, the produced fluid flows through the perforation channels before entering the well. This is why the investigation of the effect of perforation parameters on a given well's productivity is very important. Perforations are created with an instrument usually referred to as perforating gun filled with explosives. After positioning and activating the gun at the desired depth, holes are punched in the casing or liner of a well.

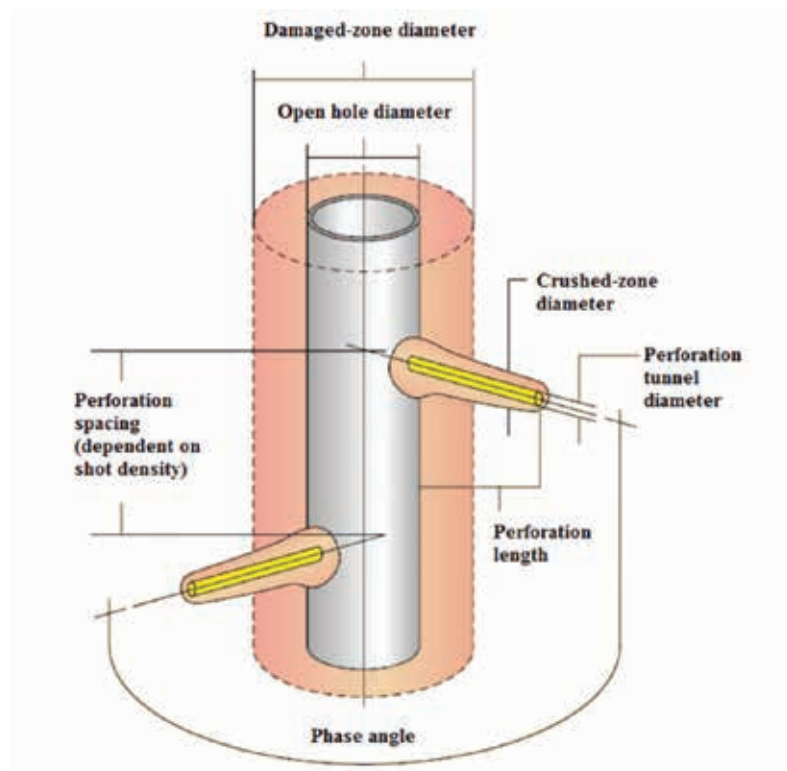
The amount of the explosive, which can be used in the perforating gun, is limited. Thus the volume of the perforation channels is limited as well.

The parameters of the perforation geometry are illustrated in **Figure 1**. The parameters with their notations used in this study are the following: perforation channel length (L_p), radius of the perforation channel (r_p), radius of the crushed zone (r_c), shot density (shots per linear foot; ns), phase angle (Θ). The crushed zone, a thin layer around the perforation channel with decreased permeability, is formed during the perforating process.

SKIN FACTOR

The skin factor (s) represents the pressure difference between the ideal and actual flowing wellbore pressure, i.e. the additional pressure drop in the near-wellbore region (Δp_s), due to the formation damage and other flow restrictions at the inlet of the well (see **Figure 2**).

¹ Extended and revised version of the authors' presentation delivered at the SPE Hungarian Section Conference, Visegrád, Hungary, 19th November, 2015



INFLOW PERFORMANCE RELATIONSHIP (IPR)

It is assumed that the primary function of the well is to connect the reservoir to the surface. The accurate physical description of a well is very important. For optimal production (the production which yields maximum return on investment) the well design requires some complex engineering considerations. The flow of the reservoir fluids into the well from the formation is governed by the difference between the reservoir pressure and the pressure at the bottom of the well. The equations which describe the inflow in function of the pressure difference are usually referred to as inflow performance relationships (IPRs). IPR curves illustrate the experimental relationships between the flow rate and the pressure difference. There are several different methods in the literature for calculating IPR of a well. In this study we rely on the method of Jones, LG and his colleagues (Jones, LG & Blount, EM & Glaze, OH 1967), because it can be used both in oil and gas production, furthermore it can be used to derive the absolute open flow potential (AOF). AOF is the theoretical maximum flow rate of a well which corresponds to atmospheric bottom hole pressure.

Fig. 1. Perforation parameters (viewed 13 August, 2014, http://www.halliburton.com/public/lp/contents/Books_and_Catalogs/web/TCPCatalog/2005TCPcatalog/PerforatingSolutions_catalog.pdf.)

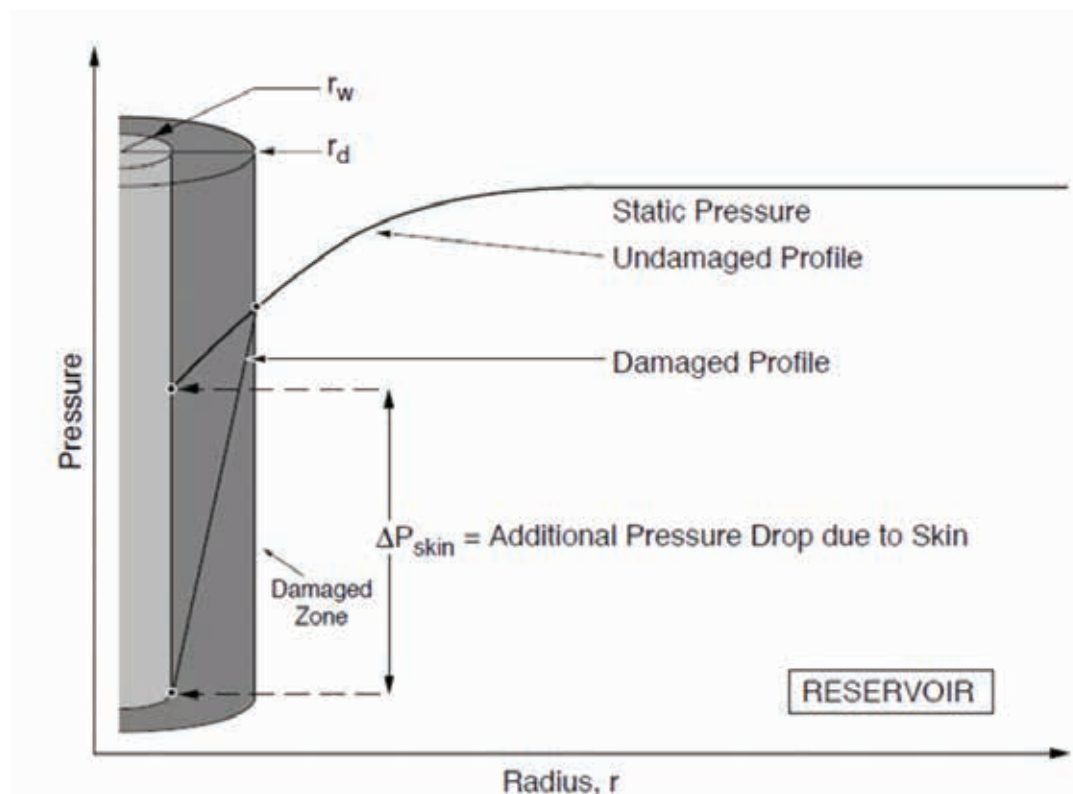


Fig. 2. Pressure profiles of damaged and undamaged vertical well (viewed 22 April, 2016, <http://blog.delphianballistics.com/2014/05/the-perforators-guide-to-formation-damage-part-1-measuring-formation-damage-as-total-skin/>.)

Different wells can be compared by using their AOFPs or IPR curves. The equations are the following (Jones, LG & Blount, EM & Glaze, OH 1967):
for oil wells:

$$p_r - p_{wfs} = Aq_o^2 + Bq_o, \quad (1)$$

$$A = \frac{2.30 \times 10^{-14} \times \beta B_o^2 \rho}{h^2} \left(\frac{1}{r_w} - \frac{1}{r_e} \right) \quad (2)$$

$$B = \frac{141.2 \times \mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + s_t \right]}{k_o h} \quad (3)$$

for gas wells:

$$p_r^2 - p_{wfs}^2 = Aq_g^2 + Bq_g \quad (4)$$

$$A = \frac{3.16 \times 10^{-12} \times \beta \gamma_g T z}{h^2} \left(\frac{1}{r_w} - \frac{1}{r_e} \right) \quad (5)$$

$$B = \frac{1.424 \times 10^3 \mu_g T z \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + s_t \right]}{k_g h} \quad (6)$$

where

p_r – average reservoir pressure, psi (1 psi = 6.895 kPa)

p_{wfs} – flowing bottom hole pressure at sandface, psi

A – turbulent term

B – Darcy flow term

q_o – oil flow rate, STB/d (1 STB/d = 0.16 m³/d)

β – turbulence coefficient

γ_g – gas relative density

B_o – formation volume factor of oil, bbl/STB

(it relates the volume of oil at storage tank conditions to the volume of oil in the reservoir)

ρ – fluid density, lb/cf (1 lb/cf = 16.02 kg/m³)

μ_o – viscosity of oil, cP

h – net thickness of formation, ft

r_w – wellbore radius, ft

r_e – drainage radius, ft

s_t – total skin

k_o – effective permeability of oil, mD

q_g – gas flow rate, Mscf/d
(1 Mscf/d = 1 000 scf/d = 28.32 m³/d)

μ_g – viscosity of gas, cP

T – reservoir temperature, °R (630 °R = 76.85 °C)

z – compressibility factor at reservoir pressure and temperature.

According to (Tek, MR & Coats, KH & Katz, DL 1962) the value of turbulence coefficient (β) can be calculated as:

$$\beta = \frac{2.33 \times 10^{10}}{k^{1.201}}. \quad (7)$$

From here on terms A and B will be used in the following forms:

$$A = C_1 \times \frac{1}{h^2} \left(\frac{1}{r_w} - \frac{1}{r_e} \right) \quad (8)$$

$$B = C_2 \times \frac{\ln \left(0.472 \left(\frac{r_e}{r_w} \right) \right) + S}{h}. \quad (9)$$

Constants C_1 and C_2 for oil wells:

$$C_1 = 5.359 \times 10^{-4} \frac{B_o^2 \rho}{k^{1.201}} \quad (10)$$

$$C_2 = 141.24 \times \frac{\mu_o B_o}{k}. \quad (11)$$

Constants C_1 and C_2 for gas wells:

$$C_1 = 7.3628 \times 10^{-2} \frac{\gamma_g T z}{k^{1.201}} \quad (12)$$

$$C_2 = 1424 \times \frac{\mu_g T z}{h}. \quad (13)$$

OLDER IPR METHODS FOR PERFORATED WELLS

The most commonly used methods for calculating the perforation design's effect on the inflow performance were developed by McLeod (McLeod, OH Jr 1983) and by Karakas and Tariq (Karakas, M & Tariq, SM 1988). In this section the behaviour of these models will be examined with the use of theoretical wells. Parameters of the theoretical wells are presented in Table 1. Our theoretical IPR method is based on the results of these investigations.

METHOD OF MCLEOD

McLeod assumed that perforations are small wells in the reservoir and used the 'Jones method' (Jones, LG & Blount, EM & Glaze, OH 1967) to calculate the pressure drop across them. Figures 3 and 4 represent IPR curves created for the theoretical oil and gas wells, respectively. The IPR curves in case of open hole completions are also plotted in order to show the impact of the perforation design on the productivity according to McLeod (McLeod, OH Jr 1983).

METHOD OF KARAKAS AND TARIQ

Karakas and Tariq presented a semi-analytical solution for the skin calculation in perforated completions. They quantified the wellbore and vertical-flow effects by finite-element simulations. They showed that the skin effect which is caused by perforations (s_p) is a combination of four different effects as follows: horizontal skin (s_H),

Perforation parameters						
l_p , ft	ns, spf	α	h_p , ft	θ , °	r_p , ft	r_c , ft
1	5	0.3	25	0	0.015	0.056666667
Reservoir parameters					Well parameters	
k , mD	r_e , ft	P_r , psi	k_H , mD	k_v , mD	r_w , ft	h , ft
Oil properties			Gas properties			
API gravity	μ_o , cP	B_o , bbl/STB	T , °R	z	μ_g , cP	γ_g
45.375	0.751	1.16	630	1	0.019329562	0.64

Table 1. Parameters of the theoretical wells (Pásztor, Á & Schultz, V 2015)

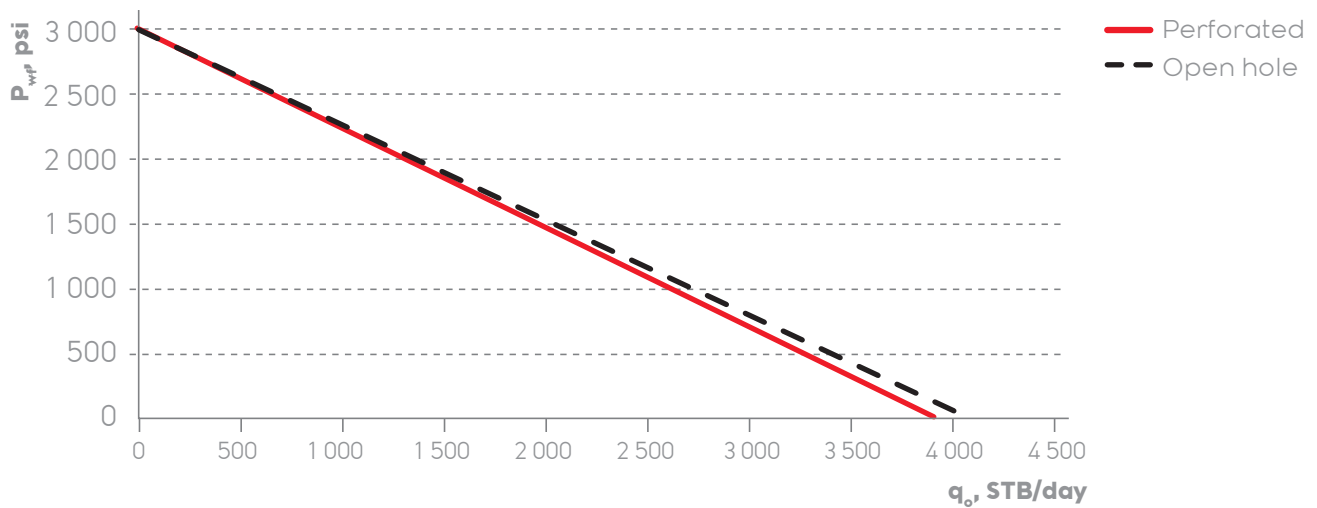


Fig. 3. IPR curves for the theoretical oil wells (McLeod) (Pásztor, Á & Schultz, V 2015)

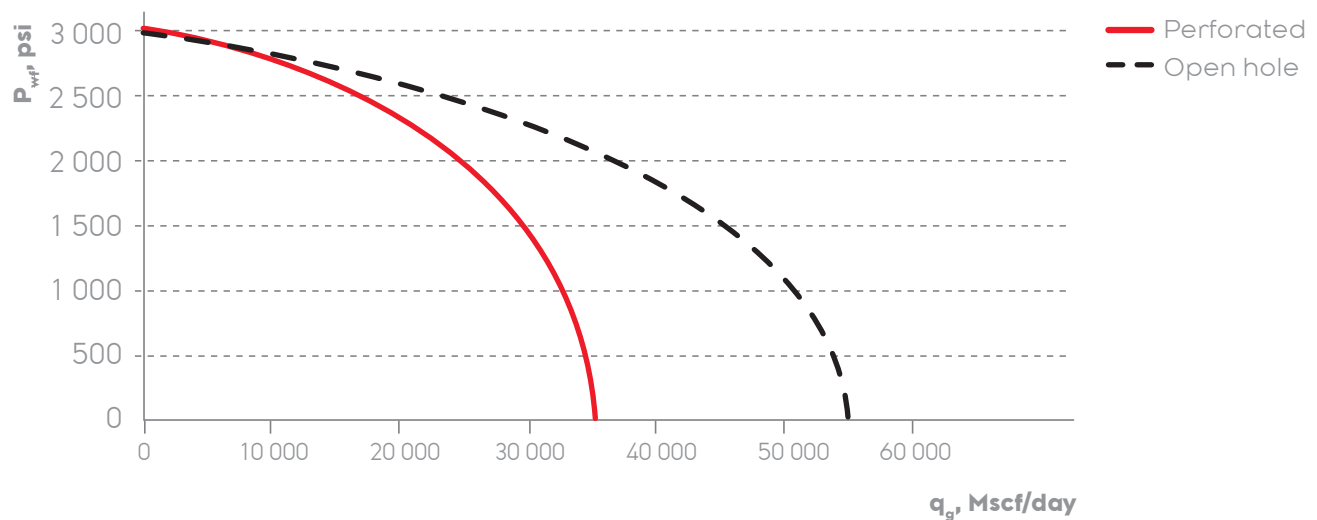


Fig. 4. IPR curve for the theoretical gas wells (McLeod) (Pásztor, Á & Schultz, V 2015)

vertical skin (s_v), wellbore skin (s_{wb}), and crushed zone-effects (s_c). Figures 5 and 6 represent IPR curves created for the theoretical oil and gas wells, respectively. The IPR curves in case of open hole completions are also plotted in order to show the impact of the perforation design on the productivity according to Karakas and Tariq (Karakas, M & Tariq, SM 1988).

PROBLEMS WITH THE METHODS

After the examination of the presented methods the following conclusions can be drawn:

- According to McLeod's method the perforation design has a negligible effect on the productivity of oil wells. On the other hand the method of Karakas and Tariq behaves inversely
- The equations which are used to calculate the s_h , s_v and s_{wb} values are originated from a 2D finite element model, based on semi-analytical fundamentals. Because of this their behavior cannot be explained.

DERIVATION OF THE ANALYTICAL MODEL

BASE CONCEPT

McLeod's concept – the assumption that the perforation channels are small wells – is a good starting point to get an analytical solution for the pressure drop calculation. So the first question that needs to be answered is that why the pressure drop is not affected by the perforation phase angle, according to McLeod. The answer lies in the drainage area of the perforations. McLeod sets the boundary of the perforations' drainage area at the boundary of the crushed zone. If we assume that the boundaries of the drainage areas are the drainage areas of other perforations, then it is easy to see that phase angle has a serious effect. With

this modification it is possible to achieve an equation which also expresses dependence on the phase angle of the perforations. According to this consideration two separate flows can be described. Firstly, the reservoir fluids flow perpendicular to the wellbore, and at some point the direction of the flow changes perpendicularly to the perforation channels. It is hard to say where the flow direction of a certain particle changes, but we can make an assumption about the 'average' particle. The change of the flow direction can happen anywhere in the drainage volume of a perforation channel. Assuming normal distribution, the average particle will start to flow perpendicularly to the perforation channel at the distance from the centre of the wellbore which halves the drainage volume (Pásztor, Á & Schultz, V 2015). Figure 7 represents the change of the flow direction.

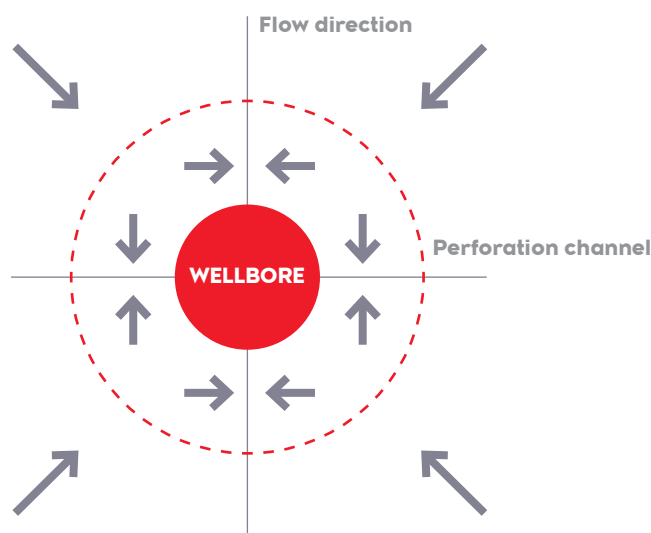


Fig. 7. Change of the flow direction (Pásztor, Á & Schultz, V 2015)

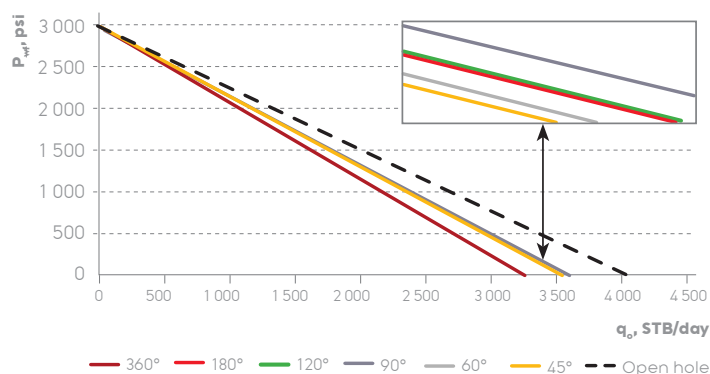


Fig. 5. IPR curves for the theoretical oil wells (Karakas & Tariq) (based on Pásztor, Á & Schultz, V 2015)

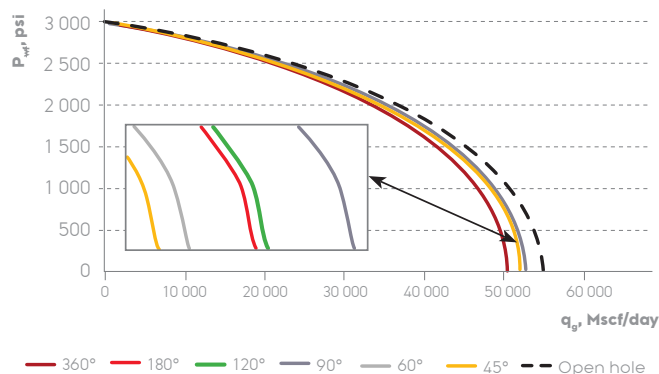


Fig. 6. IPR curves for the theoretical gas wells (Karakas & Tariq) (based on Pásztor, Á & Schultz, V 2015)

From the above mentioned statements the final theoretical inflow performance relationship is the superposition of the perforation channels' IPR and the IPR of the zone where the flow changes direction.

IPR OF THE PERFORATION CHANNELS

By assuming that the skin is caused by the permeability decrement in the vicinity of the well

$$S = \left(\frac{k}{k_s} - 1 \right) \ln \left(\frac{r_s}{r_w} \right) \quad (14)$$

and by making the following changes:

- ▶ $L_p \rightarrow h/h_p$
- ▶ $r_p \rightarrow r_w$
- ▶ $r_{pe} \rightarrow r_c$
- ▶ $k_c \rightarrow k_s$
- ▶ $r_c \rightarrow r_s$

the turbulent and Darcy terms of a perforation channel's inflow equation are:

$$A_p = C_1 \times \frac{\frac{1}{r_p} - \frac{1}{r_{ep}}}{L_p^2} \quad (15)$$

$$B_p = C_2 \times \frac{\ln \left(0.472 \frac{r_{ep}}{r_p} \times \left(\frac{r_c}{r_p} \right)^{\frac{1-\alpha}{\alpha}} \right)}{L_p} \quad (16)$$

where

r_p – radius of the perforation channel, ft

r_{ep} – radius of the perforation channel's drainage area, ft

L_p – length of the perforation channel, ft

r_c – radius of the crushed zone, ft

$$\alpha = \frac{k_c}{k}$$

k_c – permeability of the crushed zone, mD.

For the calculation of r_{ep} we must know the shape of the perforation channels' drainage volume. When the phase angle is less than 180°, the drainage volumes of the perforation channels restrict each other. Figure 8 shows the case of 60° phase angle.

In the case of 180° and 360° phase angles the perforation channels limit each other's drainage space only in the vertical direction. The horizontal boundary of their drainage space is located where the flow direction will change from perpendicular to the wellbore's axis to perpendicular to the perforation channels. The shape of these drainage volumes can be approximated as ellipsoids.

The radius of the perforation channel's drainage area is changing along and around the perforation channel because of its elliptical shape. In the calculations an average value must be used for which the concept of 'equivalent cylinder' is applied (Pásztor, A & Kosztin, B 2015).

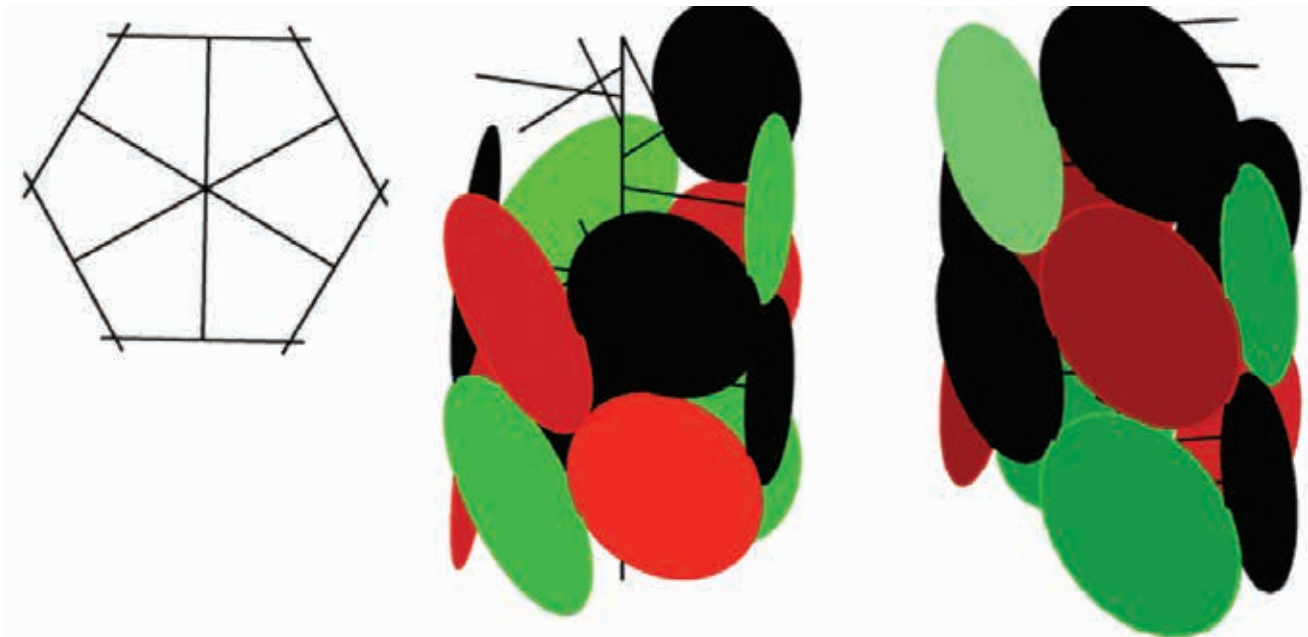


Fig. 8. Drainage area of perforation channels at their toe ($\Theta=60^\circ$) (Pásztor, Á & Schultz, V 2015)

For $\Theta < 180^\circ$

The flow changes direction at the distance of r_{ewb} from the axis of the wellbore. The periphery of the ellipse at that distance (shape of the perforation channel's drainage area on the plane which is perpendicular to the perforation channel) is (Pásztor, Á & Schultz, V 2015):

$$P_1 = \left(\frac{1}{ns}\right)^2 \left(\left(\frac{360}{\Theta}\right)^2 - \frac{360}{\Theta} + 1 \right) + \left(2r_{ewb} \tan\left(\frac{\Theta}{2}\right) \right)^2 \quad (17)$$

$$P_2 = 12 \left(r_{ewb} \tan\left(\frac{\Theta}{2}\right) \left(\frac{1}{ns}\right) \left(\frac{360}{\Theta}\right) \right)^2 \quad (18)$$

$$a_{ep} = \sqrt{\frac{P_1 + \sqrt{P_1^2 - P_2}}{6}} \quad (19)$$

$$K_{ep} = \pi \left(\frac{3}{2} \left(a_{ep} + \frac{r_{ewb} \tan\left(\frac{\Theta}{2}\right) \left(\frac{360}{\Theta}\right) \left(\frac{1}{ns}\right)}{a_{ep} \sqrt{3}} \right) + \sqrt{\frac{r_{ewb} \tan\left(\frac{\Theta}{2}\right) \left(\frac{360}{\Theta}\right) \left(\frac{1}{ns}\right)}{\sqrt{3}}} \right) \quad (20)$$

$$r_{ep} = \frac{K_{ep}}{2\pi} \quad (21)$$

where

P_1 – auxiliary variable, ft²

P_2 – auxiliary variable, ft⁴

a_{ep} – major axis of the ellipse, ft

K_{ep} – periphery of the ellipse, ft.

For $\Theta > 120^\circ$

As it was stated before, the shape of the perforation channels' drainage space can be approximated as ellipsoids, with the axis lengths of $\frac{L_p}{2}$, r_{ewb} distance from the axis of the wellbore and $\frac{1}{2ns} \frac{360}{\Theta}$.

The area of an ellipsoid:

$$A_{pdrain} = 4\pi \left(\frac{\left(\frac{1}{2ns} \frac{360}{\Theta} \frac{L_p}{2} \right)^{1.6} + \left(\frac{1}{2ns} \frac{360}{\Theta} r_{ewb} \right)^{1.6} + \left(\frac{L_p}{2} r_{ewb} \right)^{1.6}}{3} \right)^{0.625} \quad (22)$$

$$r_{ep} = \frac{A_{pdrain}}{\pi L_p} \quad (23)$$

where

A_{pdrain} – area of ellipsoid, ft²

r_{ep} – radius of the perforation channel's drainage area, ft.

IPR OF THE EXTENDED WELLBORE

The flow changes direction from perpendicular to the axis of the well to perpendicular to the perforation channels between the wellbore and the end of the perforation channels. Until the point of direction change the flow can be assumed to be like a flow to a well with an extended wellbore, with the radius of r_{ewb} . The IPR equation of a well with this extended wellbore is the following (Pásztor, Á & Schultz, V 2015):

$$A_{ewb} = C_1 \times \frac{1}{h_p^2} \left(\frac{1}{r_w} \right) \lambda_{ewb} \quad (24)$$

$$B_{ewb} = C_2 \times \frac{\ln \left(0.472 \left(\frac{r_e}{r_w} \right) \right) + S_{ewb}}{h} \quad (25)$$

$$\lambda_{ewb} = \frac{r_w}{r_{ewb}} \quad (26)$$

$$S_{ewb} = \ln \left(\frac{r_w}{r_{ewb}} \right) \quad (27)$$

where

A_{ewb} – turbulent term of the extended wellbore

B_{ewb} – laminar term of the extended wellbore

λ_{ewb} – turbulent effect of the extended wellbore

S_{ewb} – skin factor of the extended wellbore.

In case of $\Theta < 180^\circ$:

$$r_{ewb} = \sqrt{\frac{r_w^2 + (L_p + r_w)^2}{2}} \quad (28)$$

For $\Theta = 180^\circ$:

$$r_{ewb} = \frac{r_{dc}}{\sqrt{2}} = \frac{\frac{L_p}{2} + \frac{L_p}{\pi} + \frac{2r_w}{\pi}}{\sqrt{2}} \quad (29)$$

For $\Theta = 360^\circ$:

$$r_{ewb} = \frac{\frac{L_p}{2} - \arctan\left(\frac{r_w}{\frac{L_p}{2} + r_w}\right) \frac{L_p}{2\pi}}{\sqrt{2}} \quad (30)$$

FINAL FORM

With the superposition of the previously explained effects, the final form:

for oil production:

$$p_r - p_{wfs} = A q_o^2 + B q_o \quad (31)$$

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho}{k^{1.201}} \times \frac{1}{h_p^2} \left(\frac{1}{r_w} \right) (\lambda_{ewb} + \lambda_p) \quad (32)$$

$$B = 141.24 \times \frac{\mu_o B_o}{k} \times \frac{\ln \left(0.472 \left(\frac{r_e}{r_w} \right) \right) + S_{ewb} + S_p}{h} \quad (33)$$

for gas production:

$$p_r^2 - p_{wfs}^2 = A q_g^2 + B q_g \quad (34)$$

$$A = 7.3628 \times 10^{-2} \frac{\gamma_g T z}{k^{1.201}} \times \frac{1}{h_p^2} \left(\frac{1}{r_w} \right) (\lambda_{ewb} + \lambda_p) \quad (35)$$

$$B = 1424 \times \frac{\mu_g T z}{h} \times \frac{\ln \left(0.472 \left(\frac{r_e}{r_w} \right) \right) + S_{ewb} + S_p}{h} \quad (36)$$

where

$$\lambda_{ewb} = \frac{r_w}{r_{ewb}} \quad (37)$$

$$S_{ewb} = \ln \left(\frac{r_w}{r_{ewb}} \right) \quad (38)$$

$$\lambda_p = \frac{\frac{r_w}{r_{pe}} - \frac{r_w}{r_{ep}}}{L_p^2 ns^2} \quad (39)$$

$$S_p = \frac{\ln \left(0.472 \frac{r_{ep}}{r_{pe}} \times \left(\frac{r_{ce}}{r_{pe}} \right)^{\frac{1-\alpha}{\alpha}} \right)}{L_p ns h_p} \times h. \quad (40)$$

In the equations r'_{pe} and r'_{ce} refer to the perforation channels' radius and the radius of the crushed zone modified according to Pásztor and Kosztin (Pásztor, Á & Kosztin, B 2015).

BEHAVIOUR OF THE ANALYTICAL MODEL

In this section the behavior of the theoretical IPR equation will be presented. First the IPR curves will be shown and compared to the previously calculated ones. After that the effect of perforation parameters on the rate-dependent and independent skins will be investigated by running sensitivity tests. The rate-independent skin values calculated with the theoretical equation will be compared to the values calculated with the method of Karakas and Tariq, and the sensitivity tests as well. Finally the effect of perforation parameters on the productivity will be presented. Table 2 shows the starting and end values used in the sensitivity tests.

Variable	Starting value	End value
Shot density (ns), spf	2	8
Perforation length (L_p), ft	0.3	3
Perforation channel radius (r_p), in	0.09	0.36

Table 2. Variable parameters of the perforations (Pásztor, Á & Schultz, V 2015)

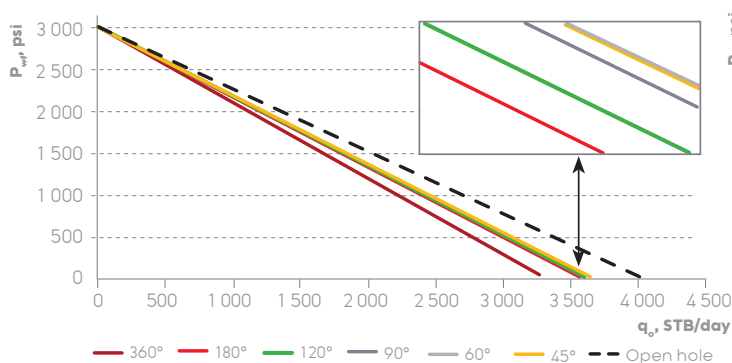


Fig. 9. IPR curves for the theoretical oil wells (analytical model) (based on Pásztor, Á & Schultz, V 2015)

IPR CURVES

Figures 9 and 10 represent the IPR curves calculated for the theoretical wells with the theoretical equation (IPR calculated for open hole completion is indicated with dashed line). Comparing these curves with the previously presented ones the followings can be stated:

- ▶ In case of oil production the IPR curves calculated with the theoretical equation and the equation of Karakas and Tariq are quite similar
- ▶ In case of gas production the IPR curve calculated with the theoretical equation for 360° phase angle is almost the same as the IPR curve calculated with the equation of McLeod, however the impact of the phase angle is greater than in the other models.

INVESTIGATION OF THE SKIN FACTOR

The comparison of the rate-independent skins calculated with the theoretical model ($S_{\text{analytical}}$) and the model of Karakas and Tariq ($S_{K\&T}$) is shown in Figure 11. On the graph the ΔS values ($S_{K\&T} - S_{\text{analytical}}$) are presented in function of the variable perforation parameter.

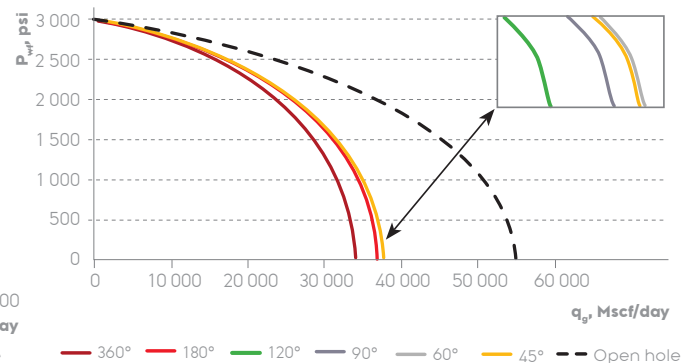


Fig. 10. IPR curves for the theoretical gas wells (analytical model) (based on Pásztor, Á & Schultz, V 2015)

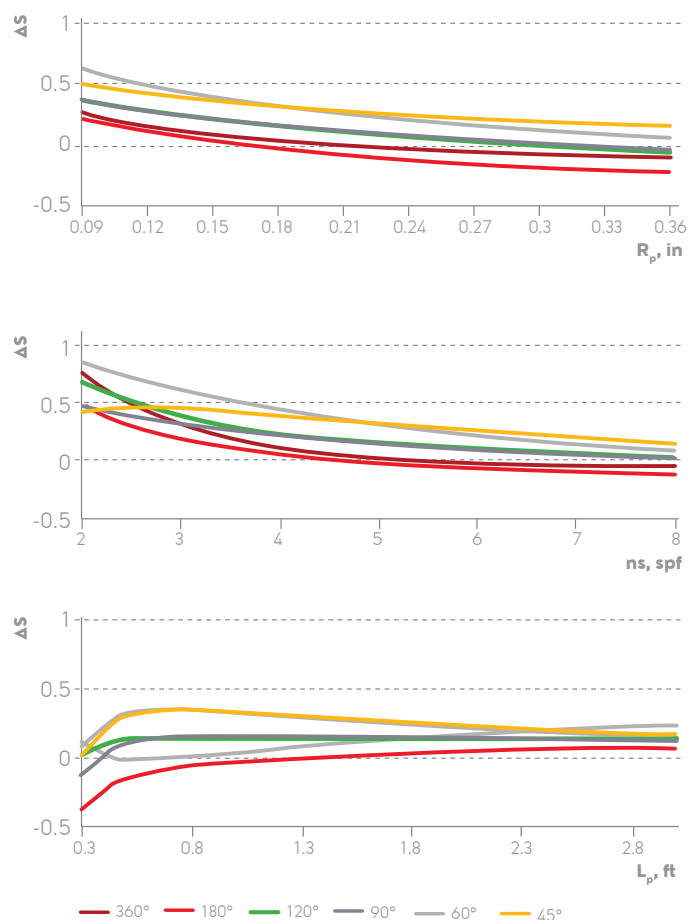


Fig. 11. Comparison of rate-independent skin (Pásztor, Á & Schultz, V 2015)

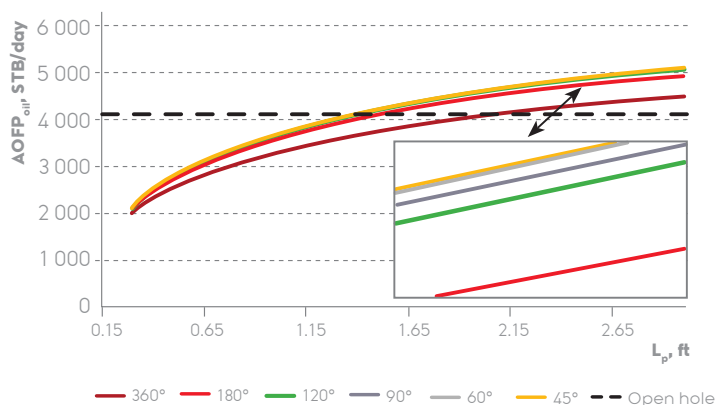


Fig. 12. Effect of perforation channel length on the productivity of oil wells (based on Pásztor, Á & Schultz, V 2015)

It can be seen, that the difference between the values of the two skins is low and the trend of this difference change with the variable parameters for the different phase angles is similar. This means that the theoretical model describes the results which Karakas and Tariq got from their finite element simulations quite well.

EFFECT OF PERFORATION PARAMETERS ON THE PRODUCTIVITY

For the investigation of the effect of perforation parameters on the productivity the absolute open flow potentials (AOFs) of the wells were calculated for each variable parameter value. Here the cases when the variable parameter was the perforation channels' length are presented (Figures 12 and 13). The graphs represent the absolute open flow potential in case of open hole completion with dashed line.

From the Figures 12 and 13 the following can be concluded:

- The perforation channel length has the greatest, and according to the other sensitivity tests, the perforation channel radius has the smallest impact on the productivity
- With a proper perforation design the productivity of a perforated well can be better than that of a well with open hole completion (curves go over the dashed line)
- In case of gas production it is more difficult to achieve a better productivity than in the case of open hole completed wells (e.g. longer perforation channels are needed in case of gas wells to reach the AOF of open hole completion)
- The best perforation angles in case of both oil and gas productions are 60° and 45° (with marginal difference).

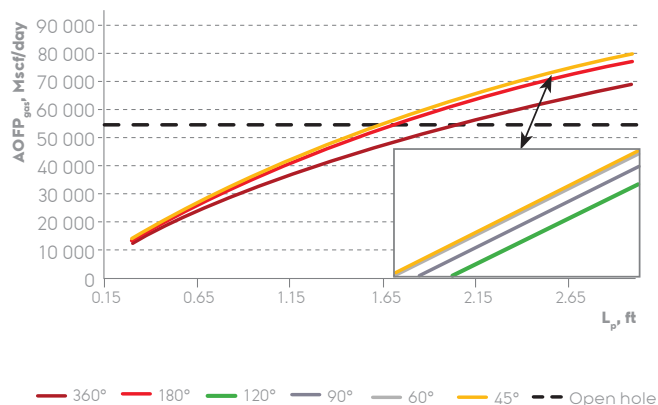


Fig. 13. Effect of perforation channel length on the productivity of gas wells (based on Pásztor, Á & Schultz, V 2015)

CONCLUSION

While examining the methods previously used for pressure drop calculation for perforated hydrocarbon wells the following criteria were set for creating a new theoretical model:

- ▶ It should have a pure analytical derivation
- ▶ The phase angle must be taken into consideration
- ▶ It must be usable for both oil and gas flow, so it must modify both the non-Darcy and Darcy terms.

With the splitting of the flow into two sections and considering the shape of the perforation channels' drainage space it was possible to create a model that met the first and second criteria. During the investigation of the theoretical model's behavior two important conclusions could be drawn about the calculated skin factors:

- ▶ The theoretical model describes the results which Karakas and Tariq got from their finite element simulations for the rate-independent skin quite well. This means that the results of the theoretical model are reliable
- ▶ The rate-dependent skin changes with the phase angle, so the third criterion is met as well.

The examination of the effect of perforation parameters on the productivity gave very important results for perforation design optimisation:

- ▶ The best perforation angles in case of both oil and gas production are 60° and 45° (with marginal difference)
- ▶ The perforation channel length has the greatest effect on the productivity and the perforation channel radius has the smallest. This result is very important because the volume of the perforation channel depends on the volume of the used explosive, which is limited, so increasing the perforation channel's length must be the top priority
- ▶ With a proper perforation design the productivity of a perforated well can be better than that of a well with an open hole completion
- ▶ In case of gas production it is more difficult to achieve a better productivity than in the case of open hole completed wells due to the rate-dependent skin.

Keywords: perforation design, inflow performance relationship, skin factor

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Reviewed by Zoltán Turzó, PhD, director of Institute of Petroleum and Natural Gas, University of Miskolc



Ádám Viktor Pásztor is an MSc student at University of Miskolc. During his studies he achieved first place in the MOL FRESHHH competition in 2012 and 2nd and 9th place in the MOL UPPP competition in 2014 and 2015. He

has the scholarship of MOL since the September of 2011 and the SPE's Star Fellowship since 2015.



Vera Magdolna Schultz started her BSc studies in the Faculty of Earth Science and Engineering at the University of Miskolc in 2013, and chose the specialisation of oil and gas engineering. In 2015 she achieved 9th place in the MOL UPPP competition.

Analysis of temperature-dependent circulation pressure loss calculation procedures for high temperature wells

Ádám Koncz (28)
assistant lecturer
University of Miskolc
oljkoncz@uni-miskolc.hu

Attila Nagy (29)
BSc student
University of Miskolc
attilanagy.1986@gmail.com

László Kis (28)
assistant lecturer
University of Miskolc
oljkisl@uni-miskolc.hu

Zsolt K. Szepesi (23)
BSc student
University of Miskolc
szepesi.zsolt.k@gmail.com

ABSTRACT

When drilling into more and more challenging reservoirs the otherwise not very significant technological factors may become much more important. The hydraulic optimisation and design of the drilling procedure is a crucial task but the many available solutions and field experience make the necessary calculation procedure a routine task for normal conditions. Special drilling- and geological conditions, however, can increase the importance of hydraulics and the need for improved accuracy arises. Sometimes special requirements – like in case of drilling a high temperature geothermal well – have to be met when performing hydraulic calculations. Temperature affects the mud's rheological behaviour and the normal procedures to determine the actual pressure conditions in the well may turn out to be inadequate. Determination of the actual pressure distribution is very important in sensitive or problematic formations or when the torque produced by a mud motor is calculated. This paper proves the importance of temperature-dependent pressure loss calculations and a proper practice is shown to fulfil the increased accuracy requirements. The proposed solution method can be used later for more accurate equivalent circulating density (ECD) calculation for drilling fluid mud at the weak formation or for mud motor's torque estimation from standpipe pressure.

INTRODUCTION

Drilling high temperature wells became a daily routine in the drilling industry in the last decade. Geothermal energy and usage is becoming even more popular and attractive for companies interested in the energy industry. The drilling industry is forced to find the best solutions for challenging formations, especially for weak formations or for high temperature wells. Both conditions can occur in a geothermal well because the stakeholder will be satisfied only with high temperature fluid in the well but the temperature can cause several problems for the drilling technology. The technology

used to drill those wells is very similar to that used to drill hydrocarbon wells. The technological inventions of the last decade can give more accurate, safer and more cost-effective solutions. However, some open questions still remained. Pressure conditions in the borehole become very important when problematic formations are drilled or special service equipment are used. For example, the conventional mud motor's torque cannot be determined precisely because the motor's pressure loss is unknown. This paper tries to show the best available calculation and measuring procedures to overcome the challenge just mentioned.

The pressure distribution determination in the borehole needs the exact knowledge of the rheological properties of the applied mud. The first section of this paper presents the proper practice for the temperature-dependent rheological analysis of the mud. The analysis will deliver the rheological parameters ready for later parts of the work. The determination of temperature distribution in a circulated well is not completely solved and approximate solutions are available only. In this paper a recently published method is used with some practical modification by the present authors. Then the pressure losses were calculated for the given sections by numerical methods using the proposed temperature model. The practical pressure loss equations were adopted from previous works. Pressure losses were calculated using the conventional method as well.

RHEOLOGICAL PROPERTIES OF THE MUD

The rheological properties of the mud determine its flow behaviour. Basic rheological measurements are done regularly at the rig site by the mud engineer according to the API recommended practice (RP) 13 series for testing of drilling fluids. The basic drilling mud measurements include the following:

- ▶ Measurement of mud weight (mud balance)
- ▶ Filtration test (filter press)
- ▶ Viscosity, yield, gel measurement (rotational viscometer)
- ▶ Solid content (retort test)
- ▶ Clay content (methylene blue test – MBT test) and
- ▶ Other chemical properties (chloride, etc.).

These measurements can be done using basic, engineering equipment. Mud density, viscosity and yield parameters are the main factors affecting hydraulic calculations. Rheological parameters change with temperature. For a correct and accurate standpipe pressure evaluation method the temperature effect should be taken into account (API 2010). Another important factor is the rheology model to be used. The calculations were carried out using the basic and most common rheological models applied in the oil industry (Bourgoyne, AT Jr et al. 1986): the Bingham-plastic model, the power law (or Ostwald) model and the yield power law (or Herschel-Bulkley) model. Each fluid model has a special basic function to describe the fluid's behaviour. The basic equation for the Bingham-plastic model (Gabolde, G & Nguyen, J-P 2013):

$$\tau = YP + PV \cdot \gamma \quad (1)$$

where

τ – shear stress, lb/100 sqft (1 lb/100 sqft = 47.88 Pa)

YP – yield value, lb/100 sqft

PV – plastic viscosity, cP (1 cP = 1 mPa·s), and

γ – shear rate, 1/s.

The parameters figuring in Eq. 1 can be calculated as follows:

$$PV = \theta_{600} - \theta_{300} \quad (2)$$

$$YP = 2 \cdot \theta_{300} - \theta_{600} \quad (3)$$

where

θ_{600} – viscometer dial reading at 600 rpm, and

θ_{300} – iscometer dial reading at 300 rpm.

The power law model assumes pseudoplastic behaviour for drilling mud ($n < 1$) according to the following equation (Gabolde, G & Nguyen, J-P 2013):

$$\tau = K \cdot \gamma^n \quad (4)$$

where

K – consistency index, lb_f·sⁿ/100 sqft, and

n – flow behaviour index (dimensionless)

and

$$n = 3.32 \cdot \log \frac{\theta_{600}}{\theta_{300}} \quad (5)$$

$$K = \frac{\theta_{300}}{511^n} \quad (6).$$

The Herschel-Bulkley (HB) model is the most complicated model. The basic flow equation is the following (API 2010):

$$\tau = \tau_y + K \cdot \gamma^m \quad (7)$$

where

τ_y – HB model yield value, lb/100 sqft, and

m – HB model flow behavior index (dimensionless)

$$\tau_y = 2 \cdot \theta_3 - \theta_6 \quad (8)$$

$$m = 3.32 \cdot \log \frac{\theta_{600} - \tau_y}{\theta_{300} - \tau_y} \quad (9)$$

$$K = \frac{\theta_{300} - \tau_y}{511^n} \quad (10).$$

The practical pressure loss equations for the Herschel-Bulkley model are not always included in basic drilling engineering books but the API RP 13D (API 2010) publishes one solution.

The factors of the just mentioned models can be determined only by measurements. A mud sample



was prepared for the measurement procedure from the example well drilling process. It was a water-based clay inhibitive mud used for HTHP (high temperature high pressure) conditions. As indicated earlier, the basic equipment available at the rig does not allow scientifically accepted measurements. The mud analysis was carried out in the Drilling Fluid Laboratory of the University of Miskolc (Hungary) using a laboratory standard HT rotational viscometer. Rotational viscometers work using two concentric cylinders. The annular space between the cylinders is filled with the measured fluid. The outer cylinder can be rotated by an electric motor while the other stays stationary. A force is generated by the fluid on the inner cylinder commonly referred as the bob. The generated torque which is proportional to the shear stress occurring in the fluid is measured. The shear rate depends on the rotational speed and equipment geometry which are normally known. Hence the fluid's viscosity can be calculated because all necessary factors were determined. The industry standard rotational speeds are 3, 6, 100, 200, 300, 600 min^{-1} .

The lab viscometer lets the operator to perform fully automatic measurements under downhole pressure and temperature conditions up to 3 000 psig (20.684 MPa) and 260 °C (Fann 2009). The machine is software-controlled thus the standardised specific measuring procedure can be repeated several times without any changes in the parameters. This is important because one full measurement cycle needs more than one day for wide temperature range. In order to get more accurate flow curves, in addition to the standard speeds some extra

speeds were also included. Shear stress was measured at 11 different speeds and 10 measurement points were sensed for each speed. One speed was measured for 2 minutes to obtain fully developed steady-state conditions. Only the temperature was changed because it was observed after several measurements at different pressures that the pressure effect can be neglected for the investigated water-based mud. The temperature-dependent flow curves are shown in Figure 1.

To avoid time consuming unnecessary measurements the investigated temperature range was designated to cover the expected temperature range in the example well. A slight anomaly can be detected on the slow shear rate regions. It is normal for such muds and has no unexpected effects on the predictions accuracy. The temperature effect on mud viscosity and on the actual rheological model's parameter set was obtained in two different ways and these results are listed in the conclusion section as well. The first method applied is based on Figure 2.

Fitting method 1 is the following. Two curves were fitted on the $\Theta 300$ and $\Theta 600$ values measured at different temperatures. The curve fitting was excellent for a 3rd order polynomial, as can be seen in Figure 2. The yield and viscosity parameters were calculated using these two fitted curves in the first case according to equations 2, 3, 5, 6, 8, 9, 10. In the second case – *fitting method 2* –, the original full flow curves (see Figure 1) were used to adjust PV, YP, n , m and τ_y parameters according to the temperature. Hence in the second case equations 2, 3, 5, 6, 8, 9, 10 were not used.

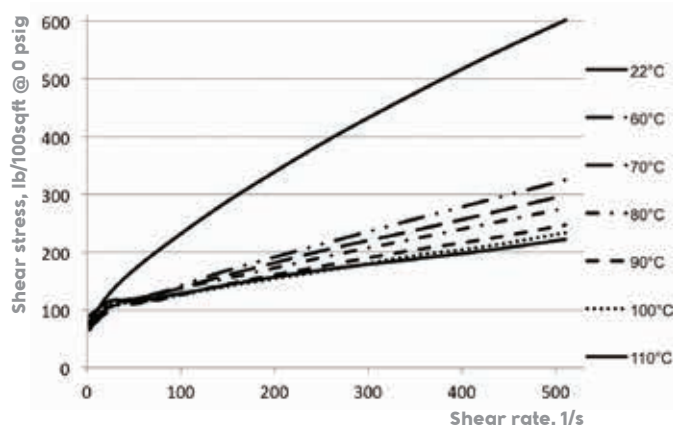


Fig. 1. Flow curves of the investigated mud

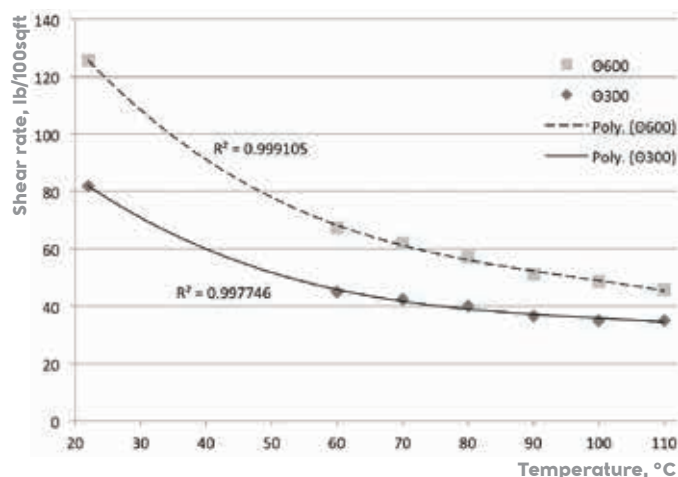


Fig. 2. Temperature effect on $\Theta 300$ and $\Theta 600$

TEMPERATURE DISTRIBUTION OF THE CIRCULATED MUD

Temperature distribution of the circulating mud during the drilling operation was calculated with the method proposed by Bobok and Szarka (Bobok, E & Szarka, Z 2012) adjusted with the API recommendations (API 2010). The API method suggests using linear temperature distribution in the well between the surface temperature and the bottom hole circulating temperature which is only a rough approximation. But the API's bottom hole circulating temperature can be used to improve the accuracy of Bobok's method. This new approach was used in this paper.

The calculation procedure requires the knowledge of the well configuration, the properties of the drilling fluid and the thermal parameters of the rock formations as input parameters. The method is based on solving three differential equations that represent the conservation of energy in the flowing liquid and in the surrounding rock. The temperature traverse in the drillpipe and in the annulus can be determined using the following equations, where the coefficients depend on the borehole (A) and drillpipe (B) performance state coefficients:

$$T_D = C_1 \cdot e^{(\lambda_1 \cdot z)} + C_2 \cdot e^{(\lambda_2 \cdot z)} + T_0 + \gamma \cdot z - B \cdot \gamma \quad (11)$$

where

- T_D – drilling fluid temperature in the drillpipe, °C
- C_1, C_2 – constants of integration, °C
- λ_1, λ_2 – root of the characteristic equation, m^{-1}
- z – depth, m
- T_0 – surface temperature, °C
- γ – geothermal gradient, °C/m, and
- B – drillpipe performance state coefficient, m,

$$T_A = C_1 \cdot (1 + B \cdot \lambda_1) \cdot e^{(\lambda_1 \cdot z)} + C_2 \cdot (1 + B \cdot \lambda_2) \cdot e^{(\lambda_2 \cdot z)} + T_0 + \gamma \cdot z \quad (12)$$

and

T_A – drilling fluid temperature in the annulus, °C.

The coefficients take into account the flow rate, the time and the overall heat transfer coefficients. Calculated results for the example hole can be seen in Figure 3.

PRACTICAL HYDRAULIC CALCULATIONS

Hydromechanics is a widely studied and popular discipline however different authors suggest different practical hydraulic equations (Bourgoyne, AT Jr et al. 1986; Gabolde, G & Nguyen, J-P 2013; Rabia, H 2001; API 2010). Still there are some common solutions:

- ▶ Laminar flow is described normally by mechanistic way. That means that a pipe roughness is assumed and the calculation is done using that value. Hence laminar flow calculation results are similar for each approach
- ▶ Turbulent flow is described by empirical correlations. Different authors use different correlations. For a normal circulation rate in a conventional drillstring the pipe flow is normally turbulent or is close to the turbulent region.

The understanding of flow regimes needs a small theoretical background. A good overview can be found in the reference (Bourgoyne, AT Jr et al. 1986) focused only on drilling hydraulics, here the most important conclusions are mentioned only. There are two basic flow regimes in pipes or annuli: laminar and turbulent flow.

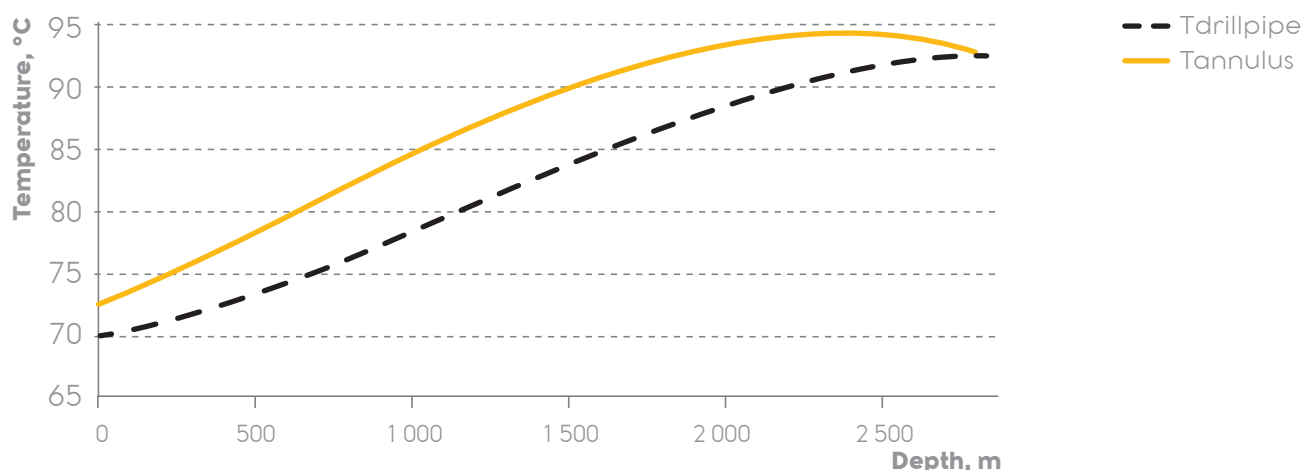


Fig. 3. Temperature distribution in the circulated well

The flow is fully developed and the flow streams are regularised for laminar flow. However the movement of fluid particles is totally chaotic for turbulent flow. A transition flow occurs between these two flow regimes, where the flow regimes cannot be separated: there exists a region where the flow is not totally chaotic but not fully developed. The Reynolds number is widely used to segregate those flow regimes. The Reynolds number can be written in the following form:

$$N_{Re} = \frac{ID \cdot \bar{v} \cdot \rho}{\mu} \quad (13)$$

where

N_{Re} – Reynolds number (dimensionless)

ID – inside diameter of the pipe, m

$\bar{v}$ – fluid average velocity in the pipe, m/s

ρ – fluid density, kg/m³, and

μ – fluid viscosity, Pa·s.

If the Reynolds number is greater than 2 100 (the critical Reynolds number) the flow is turbulent, if it is smaller, then the flow is laminar. As mentioned before, there exists a transition zone close to the critical Reynolds number where it is hard to decide on the flow regime. For power law and Herschel-Bulkley fluid models a second equation was invented to eliminate the effect of the uncertainty on flow regimes; an exact critical Reynolds number can be calculated where the transitional flow begins:

$$N_{Cre} = 3470 - 1370 \cdot n \quad (14)$$

However, to describe the flow regimes not only the Reynolds number can be used. Moreover, the drilling hydraulics calculations do not use normally the Reynolds number concept. Other, equivalent solution was invented to make easier the solution path: the

critical velocity concept. The idea is the same as for the Reynolds number, but instead of the dimensionless similarity invariant, a critical velocity is used which depends on the geometry and fluid properties. The flow is laminar below the critical velocity and turbulent above it.

Both flow regimes exist normally in a rotary drilling system. The pipe flow is mostly turbulent (may be laminar in the pipe, but turbulent in the bottom hole assembly – BHA) and the annular flow is commonly laminar. The pressure losses occurring in the system are much higher in the pipe than in the annulus because the flowing area in the annulus is normally bigger. These facts are the direct reason why so many practical hydraulic equations can be found in the literature: laminar equations are similar with small differences. However turbulent flow is not described by the mechanistic way yet. Only empirical correlations are available and many researches tried to create the overall best equation. We have to keep in our mind when speaking about drilling rig hydraulics, that the most important pressure losses (in the drillstring and in the nozzles) are turbulent flow pressure losses. Hence the calculation results depend on the correlation applied.

The hydraulic calculation was performed using the most commonly used methods for the example hole, for two different BHA configurations. Table 1 contains the drillstring data of the example well.

When performing such calculations adopted from real situations there are always some uncertainties. In our case, there was some extra equipment in the string which could not be included in the normal calculation procedure. There were a mud motor, a basic measurement-while-drilling (MWD) system, and a float sub installed in

Drillstring 1		Drillstring 2	
Name	Length, m	Name	Length, m
Bit (4x20/32" nozzle)	0.32	Bit (3x20/32" nozzle)	0.29
Mud motor	8.24	X/O	0.81
Stabiliser	2.44	Stabiliser	2.44
NonMag DC	9.89	DC	9.31
Float Sub	0.98	Stabiliser	2.45
X/O	0.93	DC	8.94
DC	54.14	X/O	0.93
HWDP	55.83	DC	54.14
Drilling Jar	10.1	HWDP	55.83
HWDP	140.95	Drilling Jar	10.1
DP	2 552.18	HWDP	140.95
		DP	2 549.81

Table 1. Drillstrings' configurations

(NonMag DC – non-magnetic drill collar; X/O – crossover sub; DC – drill collar; HWDP – heavy weight drill pipe; DP – drill pipe)

Drillstring 1. There are no exact calculation methods for such elements. The mud motor's pressure loss has the most important effect on the final results. It was assumed – based on the performance curve of the motor and on the flowrate – that the pressure loss equals 38 bar (550 psi) in the mud motor. Moreover, there is no information available about the MWD system and float sub. It was assumed that 7 bar (100 psi) is the cumulative pressure loss in these components.

Pressure loss calculation procedures follow the same way: individual pressure losses in the circulating path are determined separately and then they are summed. The following individual pressure losses should be defined:

- ▶ Surface connection pressure losses (from the pressure gauge on the standpipe to the upwards drillpipe)
- ▶ Drillstring pressure losses (to the bit)
- ▶ Pressure losses at the bit (the useful hydraulic power consumption) and
- ▶ Annular pressure losses (the pressure at the bell nipple is atmospheric).

The drilling rig was equipped with large diameter surface connection lines and surface equipment that produces the least pressure losses at the surface. A 5" drillpipe was used with a 6" DC stack in a 12 ¼" open hole, where the previous casing had an outside diameter of 13 3/8". The calculation was done using all important

available pressure loss calculation equations (Bourgoyne, AT Jr et al. 1986; Rabia, H 2001, Gabolde, G & Nguyen, J-P 2013; API 2010) applying the temperature-dependent rheological parameters proposed in the 'Rheological properties of the mud' section. The equations are not represented here; the reader is advised to see the references.

The following numerical solution was chosen: the entire hole was parted into 100 m long subsections or one drillstring component was one subsection. The temperature was calculated exactly for the component's depth using the temperature model. The pressure losses were then calculated in the whole well using the actual yield, viscosity, consistency, flow behaviour index valid at the given temperature. Then the pressure losses were added and the total pressure loss (or standpipe pressure) was determined. The cuttings effect in the annulus was included by the increased density and increased hydrostatic head of the annular mud column.

CALCULATION RESULTS

Calculation result matrix is summarised in Table 2. Heading contains the equations' authors. The measured standpipe pressure varied between 245 and 250 bar for Drillstring 1 and between 215 and 220 bar for Drillstring 2. The calculation results of the conventional method are shown in Table 2 as well.

	Rabia, H 2001	Bourgoyne, AT Jr et al. 1986	Gabolde, G & Nguyen, J-P 2013	API 2010
Drillstring 1. Bingham-plastic model FM1	227 (7.9%)	225 (8.86 %)	236 (4.47%)	-
Drillstring 1. Power law model FM1	218 (11.87%)	217 (12.16%)	-	-
Drillstring 1. Herschel-Bulkley model FM2	-	-	-	191 (22.52%)
Drillstring 1. Power law model FM2	129 (47.88%)	122 (50.62%)	-	-
Drillstring 2. Bingham-plastic model FM1	209 (3.89%)	201 (7.24%)	215 (1.15%)	-
Drillstring 2. Power law model FM1	195 (10.21%)	195 (10.15%)	-	-
Drillstring 2. Herschel-Bulkley model FM2	-	-	-	168 (22.49%)
Drillstring 1. Bingham-plastic model conventional	269 (8.76%)	272 (10.31%)	275 (11.2%)	-
Drillstring 1. Power law model conventional	250 (1.12%)	257 (3.87%)	-	-
Drillstring 2. Bingham-plastic model conventional	256 (17.79%)	252 (15.98%)	255 (17.57%)	-
Drillstring 2. Power law model conventional	229 (5.43%)	237 (9.12%)	-	-

Table 2. Temperature-dependent and conventional circulation pressure loss calculation results (relative errors are indicated in brackets) (FM1 – fitting method 1, FM2 – fitting method 2)



The conventional solution uses the original rheological parameters measured at +20 °C and taken from the daily drilling report. Relative errors (points of reference are the mean pressure of 247 and 217 bar, respectively) are indicated in the brackets.

In temperature-dependent calculations fitting method 1 (FM1) produced definitely more reliable results than fitting method 2 (FM2). Fitting method 2 with power law model had as high error as 50%. There were many measured points at low shear rates which made the curve fitting more sensitive for the low shear rate values. The power law model, however, predicts inaccurate at low shear rates for a plastic mud. Hence fitting method 1 should be used for muds having a special resistance against to initiate the flow, i.e. having a yield value.

The temperature-dependent calculations produced lower pressure losses than it was observed. The uncertainty factors were more important for Drillstring 1 than for Drillstring 2, namely the parasitic and not calculable pressure losses were larger than they were assumed. The average error of the conventional model calculations in case of Drillstring 1 (each author's all fluid model) was 7.05% and the temperature-dependent calculations (for Fitting model 1) error was (without HB model) 9.05%. Probably the pressure losses were higher than the assumed 7 bar in the unknown equipment. Otherwise for the stable Drillstring 2 (without the motor) the calculation results of the proposed method are better. The greatest error is only about 7% for the Bingham-plastic model but the other results are very close to the measured value. The importance of the rheology model to be used is easily recognisable from the results. The use of the Bingham-plastic model causes normally higher pressure losses than the use of the power law model. The Herschel-Bulkley model suggested by the API RP 13D (API 2010) uses the friction factor for the pressure loss calculation. That friction factor for turbulent flow is hard to determine and this phenomenon can be seen in the results.

The temperature-dependent calculation procedure produces better results when every piece of the drillstring can be accurately modelled like for Drillstring 2. However, when the data are insufficient the use of the conventional models can be more advantageous because they overestimate the pressure losses. Hence if there are any additional pressure losses in the system which cannot be calculated the results will be more accurate like for Drillstring 1. There is an easy and cheap way to obtain correct and reasonable information about a drillstring containing additional pressure loss elements.

When an MWD tool is run in the hole, the normal procedure contains a near-surface MWD test. This test should be performed so that the needed P-Q (pressure-flow rate) information can be collected. Then the commonly used pressure loss factor can help to get the exact pressure loss on the additional elements, according to (API 2010):

$$P_{\text{loss}} = C_{\text{dt}} \cdot Q^{1.86} \quad (15)$$

where

P_{loss} – pressure loss on the given element, bar
 C_{dt} – pressure loss constant of the given element, and
 Q – flow rate, l/min.

The experimentally determined C_{dt} can be used to improve calculation accuracy and reduce the effect of the uncertainties.

CONCLUSION

A proper way was shown in this paper to build a good temperature-dependent rheological model for pressure loss calculation. However, there exists no best solution for calculating pressure losses in a drilled hole because there are many uncertain factors. The actual solution should be matched to our needs. However, where more accurate results are needed the temperature effect of the circulated mud should be taken into account. The laboratory analysis for such usage is more difficult and expensive as well but can lead to much more accurate results.

The case study results proved that the presented calculation procedure has benefits when there are sufficient data available about the drillstring. For that case for the Drillstring 2 the average error of the proposed model (for all correlations, without HB model) was 6.52% while the conventional method has 13.18%. In that case the improved calculation accuracy can be used for pressure analysis at the weak formations or can be used for real-time torque analysis of a mud motor driven drillstring. The latter mentioned monitoring would have important positive effect in the whole drilling procedure because normally that torque can be not measured. Moreover, torque is a basic drilling parameter which is continuously monitored in a conventional drilling procedure hence the continuous monitoring for mud motor driven bit would help to collect more information about the whole drilling procedure.

Keywords: practical rig hydraulics, temperature distribution in circulated drilling mud, pressure loss calculation

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**Reviewed by professor Gábor Takács, DSc,
Petroleum Engineering Department, University
of Miskolc**



Ádám Konecz currently is working as an assistant lecturer in the Petroleum and Natural Gas Institute in University of Miskolc. His researches focus on the investigation of the energy flow in the sucker-rod pumping units, drilling hydraulics and well control.

He is SPE and OMBKE member as well. Ádám graduated as an electrical engineer (BSc) and later as a petroleum and natural gas engineer (MSc), both from University of Miskolc.



László Kis currently is working as an assistant lecturer in the Petroleum and Natural Gas Institute in University of Miskolc. His researches focus on the investigation of the operating parameters of the sucker-rod pumping units. He is SPE and OMBKE member as well. László graduated as a petroleum and natural gas engineer from the University of Miskolc.



Attila Nagy is currently pursuing a BSc degree in Earth Science and Engineering in Oil and Gas Engineering specialisation at University of Miskolc. He is especially interested in drilling fluids engineering. Attila acts as the secretary of the AAPG Miskolc Student Chapter and also is a member of the SPE

Miskolc Student Chapter. He worked as an intern at Rotary Drilling Company Ltd. Attila won first award as a co-author at the research contest of the Faculty of Earth Sciences (University of Miskolc).



Zsolt Kornél Szepesi has started BSc course in petroleum engineering at University of Miskolc in 2013. Since he has been an active member of SPE and AAPG student organisations, participated in field trips and international conferences. He also acts as president of AAPG Miskolc Student

Chapter from 2015. He worked as a trainee at Geoinform Limited. Zsolt Kornél won first award as a co-author at the research paper contest of the Faculty of Earth Sciences at University of Miskolc.

György Mosonyi received Manager of the Year Lifetime Achievement Award

In February 2016, the Managers' Hungarian National Association recognised György Mosonyi, Chairman of the Supervisory Board of MOL Group, with the Manager of the Year Lifetime Achievement Award. It is the most prestigious recognition that can be given to executives, who have been demonstrating exceptional leadership and have become a role model for others.

György Mosonyi graduated in 1972 at the Chemical University of Veszprém. From 1974, he worked for Shell International Petroleum Co. (SIPC) in Hungary as a sales representative, and from 1986 he oversaw the oil and petrochemical business as commercial director. In 1991 he worked at the Shell Centre in London. Here he learned: "the corporate culture is crucial for a company's success." From 1994 until 1999, he was President and CEO of Shell Hungary Plc. In 1997 he was appointed Chairman of Shell's Central and Eastern European Region, and in 1998 he became the CEO of Shell in the Czech Republic, as well. This was the period when Shell changed towards an open culture company, from the former hierarchical structure.

In 1999 János Csák, Chairman of MOL, invited him to the CEO function at the Company. This position was held by him until 2011, and during this period he was a member of the Board of Directors of MOL. "When I started my job here, I met a company that had achieved practically everything in the country. However, it had a very uncertain vision on future. The most important task was the transformation of the company's strategy and culture". During a conversation he said: I started in a very difficult year, in 2000, when the company faced a number of unanticipated internal and external difficulties, as well. The Chairman János Csák resigned and the Board elected Zsolt Hernádi with whom we shared the same vision on the future of MOL.

"In this work, I was not alone. In a series of workshops we succeeded to turn large part of the middle level managers to our side and to find a common language." The fact that György Mosonyi arrived to head MOL from the same industrial branch awoke trust in him. In addition, credibility was an important factor: "We had to say frankly what we're planning to do and to continue a dialogue on it." Important parts of the cultural change were the transformation of the organisation, the establishing of a matrix system, the essence of which is that understanding their roles and responsibilities, everybody works for each other. A cultural change is an ongoing activity: over the past decade and a half, it had several waves, and certainly it will not cease in the future, either.

The development of a new strategy started in a critical period. "At that time one could see a very clear trend in Central-Eastern Europe: the oil companies previously operating in isolationwere privatised and deregulation of markets has occurred. Thus, an opportunity opened up for MOL Plc. to purchase oil companies operating in other Central-European countries. So we were able to buy SLOVNAFT, and later we succeeded to purchase 25% of INA in Croatia." However, it (the regional expansion of the downstream) also meant that we were forced to retreat from some (upstream) exploration areas where we did not have too much chance to be able to finance the process until we produce oil."

The natural gas was an important field in the portfolio management. Already before the huge natural gas price losses, at the end of 1999 and beginning of 2000, György Mosonyi represented the view that MOL should exit from the gas business. "The gas that came into the country and the customers were in the hands of some highly powerful companies. One could see that sooner or later we would be squeezed out from the value chain."

A further strategic foundation was that in the businesses MOL was involved in, the Company had to achieve the efficiency of the top 25% of oil industry competitors. To achieve this, appropriate organisational skills were necessary, as well as a new management style, „... executives who show direction to colleagues under their lead and can motivate them to the best possible performance.”

“...I gave special importance to the enforcement of the value chain in the downstream philosophy. ... This was the reason that we had to purchase TVK ...”

“We declared in our new strategy announced in 2005 that the main driver to (further) development could be the growth in upstream production, which required exploration development and acquisition.” However, given the size of the company, our options are limited in the upstream area – he stressed.

Due to the hostile takeover attempts by OMV in 2007, previous focus of the management and activities of the company had to change. “We succeeded to fend off the attack. The management stuck together, politicians – from the side of all parties – were supportive, and the general public was also with us.” According to György Mosonyi, preservation of the company’s independence was the greatest achievement of that period.

The global financial and economic crisis, that started in September 2008, made it necessary to put into effect significant changes in the life of MOL. “... Due to the drastic fall in oil and oil product prices and the weakened Hungarian Forint..., we need to review our plans for the next year. 2009 will be a year of crisis, therefore, it is now mandatory for MOL to stay in a robust financial position... The goal is that MOL has strong reserves by the end of the crisis, making also further growth possible”, – said György Mosonyi in November 2008, in an interview. For him, keeping financial stability has been a top priority at all times.

György Mosonyi is committed to sustainable development. “...The profit is the basis for everything else, but that’s not all....In my view, the company has important doings in three very important areas: the economic performance, the environmental protection and the social responsibility must be looked at together, and represented in a holistic approach. The issue should be brought from the theoretical level into practice.” Between 2006 and 2011 György Mosonyi was Chairman of the Board Commission on Sustainable Development.



In addition to achieving good business results throughout the realisation of strategy, György Mosonyi also considers it success that "...the company got attractive to young people, who are continuously joining us....Compared to the past, employee team spirit has changed dramatically. It has become much more open, having ears to the world and is able to respond to everything. This is the secret of global success. "

In May 2011 György Mosonyi changed the CEO chair to that of the Supervisory Board's president. He was re-elected in 2016. He holds that the most important of the Board's activities is to supervise how the management operates internal controls (especially the system of internal audits, compliance, Ethics Council, anti-corruption measures). The Supervisory Board liaises with the Group's external auditors as well. György Mosonyi has been, from 1 September 2015, the Chairman of the Supervisory Board of MOL Petrochemicals Plc.

He judges the future of the industry in a positive way: in his opinion fossil fuels will play an important role in the future in meeting the world's demand through the professional carrier of several generations, while share of renewables will increase. Natural gas is a good alternative to coal in reducing carbon emissions. Regarding the future activities of the MOL Group he suggests "we do what we are familiar with, we should not wander away."

Outside MOL Group, György Mosonyi also occupied senior positions in number of other organisations in Hungary:

- 1992–1999 – Vice President at the Hungarian Petroleum Association and at the Hungarian Crude oil and Petroleum Products Stockpiling Association (today Hungarian Hydrocarbon Stockpiling Association)
 - 1995–1999 – Chairman of the Joint Venture Association and board member of the Hungarian Association of International Companies
 - From 1998 to 1st of May 1999 – Co-Chairman of the Investor Council and Chairman of the Hungarian EU Enlargement Council, the local organisation of the European Round Table of Industrialists
 - Between 2000 and 2009 – President, then Honorary President of the Hungarian Joint Venture Association, thereafter, until 2015 Member of the Board at the Association
 - 2002–2005 – Board Member of the American Chamber of Commerce
 - From April 2008 until 2012 – Vice President of the Confederation of the Hungarian Employers and Industrialists
 - Until 2015 – President of the World Petroleum Council Hungarian National Committee
 - Until 2016 – Vice President of the Hungarian Chamber of Commerce and Industry
 - From 2012 – Member of the Board of Directors at Hungarian Telekom.
- As a recognition of his outstanding technical and managerial work he was awarded on several occasions:
- In 1995, his activity was recognised with the Eötvös Loránd Award of the Ministry of Industry and Trade
 - In 2007, the National Association of Managers honoured him with the Manager of the Year Award for 2006
 - In 2010, for his decades of outstanding economic activities and his professional career he was honoured with the Officer's Cross of the Order of Merit of the Hungarian Republic
 - In 2010, he received the Honorary Citizen of the University of Pannonia Award
 - In 2016 the National Association of Managers honoured him with the Manager of the Year – Lifetime Achievement Award.

That's worth knowing

GENERAL

Measurement of 42-gallon oil barrel is 150 years old.

Following the early oil boom in Pennsylvania (USA) in the 1860s the oil producers realised that oil supply in the available variety of containers (incl. 40-, 42- and 45-gallon barrels) leads to distrust at customers. They decided to apply “a standard unit of measure to convince buyers that they were getting a fair volume for their money, and settled on the standard wine tierce which was two gallons larger than the standard 40-gallon whisky barrel. We, therefore, mutually agree and bind ourselves that from this date” (31 August, 1866) „we will sell no crude by the barrel or package, but by the gallon only. An allowance of two gallons will be made on the gauge of each and every 40 gallons in favor of the buyer.” It seemed to be a reasonable etalon since „when filled with crude oil, a 42-gallon tierce weighed ... about as much as a man could reasonably wrestle. Twenty would fit on a typical barge or railroad flatcar. Bigger casks were unmanageable and smaller were less profitable”. The 42-gallon standard oil barrel was officially adopted by the US Petroleum Producers Association in 1872 and by the US Geological Survey and the U.S. Bureau of Mines in 1882. More info is available at <http://aoghs.org/news/history-of-the-42-gallon-oil-barrel/>; [https://en.wikipedia.org/wiki/Barrel_\(unit\)](https://en.wikipedia.org/wiki/Barrel_(unit)) (March, 2016).

The International Oil and Gas Industry Association for Environmental and Social Issues (IPIECA) has published guidance documents ('good practices') on 'biodiversity and ecosystems services (BES) fundamentals', 'local content in relation to oil and gas project', and 'health impact assessment (HIA)'. The documents are downloadable at http://www.ipieca.org/library?tid_1%5B%5D=12&date_filter%5Bvalue%5D%5Byear%5D=&k (May, 2016).

GAS

In April, 2016 Cedigas released the first estimates for 2015. According to the publication, „2015 experienced a mixed growth in gas demand again. Trends in gas market fundamentals varied widely across the regions:

- Natural gas demand grew by 1.6% in 2015, after having stagnated in 2014. However, this performance was strongly tied to a weather driven recovery in the EU and was concentrated within a small number of countries, especially the United States.
- Production continued to grow strongly in North America and also increased significantly in Asia-Oceania and the Middle East. Reversely,

it stagnated in Latin America and dwindled in Europe, the CIS and Africa.

- In 2015, international gas trade (net of LNG re-exports) recorded a buoyant expansion, up 2.8% to 1 036 bcm, fuelled by both pipeline gas trade (+2.9%) and LNG flows (+2.8%)” (<http://www.cedigaz.org/news.aspx>) (May, 2016).

The European Biogas Association (EBA) has published its 2015 biomethane and biogas report in December, 2015. According to a summary of the report, available at <http://european-biogas.eu/2015/12/16/biogasreport2015/> in 2014 in the EU, number of biogas plants has increased by 18%, and of biomethane plants by 23%, compared to the previous year (May, 2016). More than 60% of the biogas plants in the EU have been erected in Germany.

REFINING AND MARKETING

According to a Concawe Review published in December 2015, cumulative cost impact of the most important EU legislative measures (Emission trading scheme, Industrial emissions directive, REACH, Renewable energy directive, Marine fuels directive) on EU refineries in 2020 is estimated at 9–11 USD/bbl crude oil intake (<https://www.concawe.eu/uploads/Modules/Publications/concawe-review-24.2.pdf>).

PETROCHEMICALS

The European Chemical Industry Facts and Figures 2016 report has been issued by CEFIC. The 59-pages document provides information on the profile, trade, competitiveness, employment, energy, capital and R&D spending and environmental performance of the European chemical industry and is available at <http://fr.zone-secure.net/13451/186036/#page=1> (May, 2016).

In 2015 the European Petrochemical Association (EPCA) with the support of McKinsey commissioned a survey of its 19 member companies on diversity and gender inclusion “to gain a better picture of the current status, progress and best practices across the European Petrochemicals industry”. Key findings published in a brochure in February 2016 are available at <https://epca.eu/media.../EPCA%20Brochure%20Why%20Diversity%20Matters.pdf> (May, 2016).

EPCA 50th anniversary Annual Meeting is to be held in Budapest, from 1 to 4 October, 2016 (<https://epca.eu/annual-meeting-workshop>).

Gyula (Jule) Rabó, Dr.

(1925-2016)

'Eminence Rabo' as he was called by many of his fellow zeolite catalysis scientists passed away on 1st March, 2016 at his home in Armonk, NY, USA. Born in Budapest in 1925, he became a widely recognised and respected zeolite and catalysis scientist around the world and was a generous colleague and teacher of younger generations.

Rabó graduated at Budapest University of Technology and Economics as a chemical engineer in 1946 and earned his doctorate degree in 1949. At the invitation of Professor József Varga, head of Chemical Technology Department he taught chemical engineering at the University, then, from 1951 he served as deputy director of the newly established High Pressure Research Institute (NAKI) focusing on research of cracking of heavy oils.

After the 1956 Hungarian Revolution he left Hungary. In 1957 he was invited to the USA by Robert Milton, inventor of synthetic zeolites and research director of Union Carbide to find new industrial applications for synthetic zeolites. Here, over three years he made great discoveries in zeolite catalysis. In 1958 Rabó and his colleagues discovered the strong acid Y zeolite compositions exhibiting greater activity and selectivity in cracking of hydrocarbons than the previous catalysts. In 1959 three key US patent applications were filed covering the conversion of hydrocarbons on crystalline zeolites. In 1959 Rabó with colleagues developed a new Y zeolite based hydrocracking catalyst which became the basis of the jointly developed Unocal-Union Carbide hydrocracking process. However, existence of Y zeolites could be disclosed only in 1960.

Dr. Rabó continued his research in zeolites and catalysis at Union Carbide and from 1988 at UOP (a joint venture of Union Carbide and Allied Signal). Dr. Rabó, with Professor Schomaker spent decades studying atomic structure of zeolites, their chemistry and reaction mechanisms. In order to maintain trade secrets their achievements were only partially published. Dr. Rabó retired in 1990 and continued consulting for UOP for several years.

Today, strong acid Y zeolite catalysts discovered by Dr. Rabó are widely used in crude oil conversion processes around the world and at MOL Group, as catalytic cracking and hydrocracking catalysts. Their use helped to increase white products' yield in crude oil processing thus significantly reduce crude oil demand.

Dr. Rabó was the key inventor of 60+ US patents and authored several dozen scientific articles, studies and books. He enthusiastically taught catalysis and encouraged colleagues to make new chemical inventions. Dr. Rabó frequently travelled to his motherland and enjoyed meetings with his former Hungarian colleagues from the Academia and oil industry. He was external member of the Hungarian Academy of Sciences and honorary doctor of his alma mater and University of Pannonia.

Dr. Rabó was widely recognised for his discoveries. In 1953 he received the Hungarian Kossuth Prize for the processing of high sulphur content indigenous crude oil. He was the first recipient of the of the New York Catalysis Society's Award for excellence in Catalysis, the E.V. Murphee Award from the American Chemical Society in 1988, and the Eugene J. Houdry Award from the American Catalysis Society in 1989. A year later he received the Humboldt Foundation Award (Germany). In 1991 he was the first recipient of Varga József Memorial Medal from the Hungarian Academy of Sciences. In 1993 he received the Chemical Pioneer Award from the American Institute of Chemists for pioneering discoveries in zeolite catalysis. He was nominated for the Nobel Prize in chemistry multiply times. In 2011 he received the Hungarian Commander's Cross of the Order of Merit for lifetime achievements.

He is survived by his wife and two sons; his two daughters have earlier passed away.

We remember him as 'Eminence Rabó' for his breakthrough discoveries, for his kindness and generosity.
Rest in peace!

Acknowledgement

The Editorial Board is grateful to Dr. Edith M. Flanigen and Dr. László Németh, long-time colleagues of Dr. Rabó at UOP for the information



Gyula Szekér, DSc

(1925–2015)

Former Hungarian minister of heavy industry and deputy prime minister has passed away at the age of 90 in December 2015. Between 1960 and 1986 he has played a decisive role in shaping the transformation of the Hungarian chemical and energy industries and sectors, including the establishment and development of Danube Refinery (Százhalombatta) and TVK (Tiszaújváros) (presently both belonging to MOL Group).

Gyula Szekér has been born in September 1925 in Celldömölk. After finishing secondary school in Pápa he graduated as a chemist at Péter Pázmány University, Budapest in 1949. In 1971 he has received his degree of ‘doctor of chemical sciences’ and later has become an honorary professor of Budapest Technical University (today Budapest University of Technology and Economics).

He has started his professional carrier in the Hungarian aluminium industry as a laboratory researcher. Between 1954 and 1956 he has filled the position of the head of the aluminium industry. From 1957 to 1975 he has worked in the Ministry of Heavy Industry as deputy minister and from 1971 as the minister. Between 1975 and 1980 he has served as the deputy prime minister, from 1980 to 1983 as the president of the Hungarian National Committee on Technological Development (OMFB), and between 1984 and 1989 (until his retirement) as the president of the Hungarian Standards Institution (MSZH).

“Modern chemical industry is a necessary condition for technical development” he wrote in one of his books in 1970. He was able to get this statement across to the decision-makers of that period. Between 1960 and 1986 as an industrial top manager he has been involved in the decision-making and implementation of a dozen of industrial enterprises and more than one hundred industrial installations. A large number of developments of high importance are closely connected to his name in the energy industry (as implementation of the Hungarian crude oil, natural gas and electricity networks, of Nuclear Power Plant in town Paks). He has promoted developments for import substitution and export expansion in the Hungarian pharmaceutical, oil refining, petrochemical, plastic, resin, synthetic fibre, chemical fertilizer, and aluminium sectors of the chemical industry. One of his outstanding achievements is the establishment of the Hungarian petrochemical industry at the sixties of the last century. Among others, he is the founder of the Museum

of Chemistry and Chemical Industry located in Várpalota. Portrait of the 81 year old dr. Szekér prepared by famous painter Ernő Csonka and exhibited in the Museum has been inserted here by the courtesy of the Museum.

As a pensioner, he has retained his passionate interest in the chemical industry. He has regarded the production facilities as own children. He was glad to see the new developments (in the locations) and frequently made critical comments against the attempts thought to be hurting the national interest.

His achievements have been recognised by Hungarian professional and civic organisations. The Hungarian Chemical Industry Association in 2003 has awarded him ‘Gold Medal for the XXI. Century’s Chemical Industry’. In 2004, his hometown, Celldömölk has bestowed honorary citizenship on him. In 2005, minister of Economy and Transport has decorated him with the medal ‘For the Hungarian Economy’. In October, 2015 the local government of Paks granted him the Pro Urbe prize for the development of the town.

Dr. Szekér’s enduring achievements and the grateful posterity will keep his memory green. Rest in peace!



