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ANG STORAGE AS A TECHNOLOGICAL SOLUTION FOR THE "CHICKEN-AND-EGG" PROBLEM OF NGV REFUELING INFRASTRUCTURE DEVELOPMENT

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Abstract

The storage and transmission of natural gas (NG) without using pipelines poses known challenges. Due to a growing demand for non-pipeline uses of NG, the practical problems it raises have to be solved in the near future. Especially since motor vehicles - one of the applications of NG - become the biggest liquid fuel consumer in developed countries. Due to techno-economical and ecological factors, natural gas will remain the most important existing alternative to oil-based motor fuels in the foreseeable future.

Two methods are currently commercially applied for natural gas storage: either under extremely high pressure of 200-250 bars in gaseous form (CNG) or at a very low temperature (minus 161.5 degrees C) in liquefied form (LNG). CNG is applied mainly for Natural Gas Vehicles when LNG is applied mainly in big scale gas marine transportation.

The massive implementation of Compressed Natural Gas (CNG) vehicles in most markets is restrained by the need of grandiose refueling infrastructure and inconvenience and additional costs of on-board CNG tanks.

Adsorbed Natural Gas (ANG) technology stores natural gas in special micro-porous material placed inside the vessel. This material acts as a sponge to adsorb natural gas. ANG technology enables to store similar gas quantities as CNG under much lower pressure (40-50 bars) and decrease dramatically filling station capital and operation costs as well as reduces NG end-user cost. In addition this method opens new possibilities for non-cylindrical tanks application. Alternatively ANG in combination with higher pressure enables to increase the driving range of NGV or to reduce the size of NGV tank.

Till now commercialization of ANG method didn’t succeed due to unsolved technological problems. According to our evaluation AngStore project of MoreGasTech S.A.S. proposes the first commercially valuable ANG solution for vehicle.

Angstore develops two types of products: Low-pressure ANG tanks (40-65 bars) and High-pressure ANG tanks (100-200 bars).

Low-pressure ANG tanks providing cost-performance characteristics similar to CNG cut to 1/2 – 1/3 the refueling infrastructures capital and operation costs. This can enable much faster and efficient development of NGV infrastructure deployment in countries/regions without well-developed CNG stations network.

High-pressure ANG tanks enable 50% increase of NGV driving range in comparison with CNG. Otherwise they can reduce tank volume. This makes transition to gas attractive for some vehicle user groups including first of all those with high driving ranges or strict on-board space limitations.

TABLE OF CONTENT

1. Background

The storage and transmission of natural gas (NG) without using pipelines poses known challenges. Due to a growing demand for non-pipeline uses of NG, the practical problems it raises have to be solved in the near future. Especially since motor vehicles - one of the applications of NG - become the biggest fuel consumer in developed countries (1.). Due to techno-economical and ecological factors, natural gas will remain the most important existing alternative to oil-based motor fuels in the foreseeable future.

Therefore, massive implementation of Natural Gas Vehicles (NGV) is one of the main tools in the strategy of the EU for the use of alternative fuels for transportation. According to the EU Transportation Fuel Targets in 2020 natural gas should comprise 10% of the total automotive fuels consumption. The implementation of this program means:

- About 30 mil. NGVs in the EU
- NG consumption by vehicles - about 50 BCM per year - about 10% of current European NG consumption

Two methods are currently commercially applied for natural gas storage – LNG and CNG

a) LNG – Liquefied Natural Gas (minus 161.5 degrees C) proposes more volumetric efficient gas storage but involves a very distinct Economy of Scale. Therefore it is applied mainly in big scale gas marine transportation. In some niches it is also used for gas distribution. Because of this advantage of scale, on-board LNG storage technology could be competitive only for heavy vehicles. LNG tanks for cars have an unproportionally high cost and provide less volumetric efficiency than LNG tanks for big vehicles.

b) CNG – Compressed Natural Gas (200 or 250 bar) is applied mainly for on-board gas storage of NGVs and in some niches for gas distribution.

The massive implementation of Compressed Natural Gas (CNG) vehicles in most markets is restrained by the need to invest in grandiose refueling infrastructure, and the inconvenience and additional costs of on-board CNG tanks.

CNG vehicle refueling infrastructures deployment and operation is associated with the following problems:

- The capital investment for the construction of a CNG filling station is several times bigger than for a petrol/diesel station ($0.2-0.3 for small stations, $0.7-3 M for large stations)
- The operation of a CNG station requires high energy consumption and very expensive maintenance
- The price of CNG stations substantially increases NG cost for the vehicle user. Without significant tax preferences CNG price is not attractive enough compared with petrol and diesel
- “Chicken-and-Egg” Problem (a classic Market Failure case):
Gas companies don’t invest in costly stations network because there are not enough NGVs users. Users don’t buy NGVs due to a sparse stations network
- Large-scale implementation of NGV takes place in countries where government applies massive NGV subsidies and/or powerful administrative measures (at least for the initial development period)

On-board tanks of CNG vehicles involve some functional problems beside the substantial additional cost. CNG tanks generally:

- occupy twice the volume of petrol/diesel tanks (about 100 liters of geometric volume)
- allow for one-half the driving range of petrol fueled vehicle (about 300 km)

Thus, the low energy density of CNG storage limits NG fueling application for many potential users. This limit is especially important for vehicles with high driving range. Since fuel comprises a larger part of the cost of their transportation they could theoretically save more fuel costs using NG.

2. ANG Technology

2.1 Adsorbed NG Technology Introduction

Adsorbed Natural Gas (ANG) storage technology has quite a few promising advantages over both CNG and LNG. The core of this technology is gas storage tank filled with adsorbent material that acts as a sponge to adsorb natural gas.

ANG technology allows storing big amounts of natural gas at a relatively low pressure (40-60 bars) at room temperature in a relatively thin-walled tank filled with adsorbent. This level of pressure allows refueling the tank using simple and cheap equipment or sometimes refueling directly from NG pipelines.

The volumetric efficiency of ANG storage tanks is measured by volumetric ratio. LNG, being a lower-pressure liquid, is the most volume efficient natural gas storage option and has volumetric ratio about 615 V/V, i.e. 615 Normal cubic meters (liters, etc.) of gas are stored in one “geometrical” cubic meter (liters, etc.) of the storage tank. Compressed natural gas (CNG) has a volumetric ratio of 200 V/V. Generally the goal of ANG product developers is to achieve a similar volumetric ratio.

The combination of adsorption and higher pressure makes it possible to increase the volumetric storage ability of ANG and bring it even to higher levels than that of CNG.

In addition, low-pressure ANG tanks open new possibilities for tank designs of various forms and configurations instead of the cylindrical form of CNG high-pressure tanks. Thus, tanks could be tailored to fit odd spaces, similar to today’s gasoline/diesel tanks. A non-cylindrical tank gives a significant advantage for small vehicles from a volumetric efficiency standpoint. For example, rectangular shell gives an additional 25% volume (see also in Fig. 1 - the green is rectangular ANG tank whereas the red is CNG cylindrical tank).

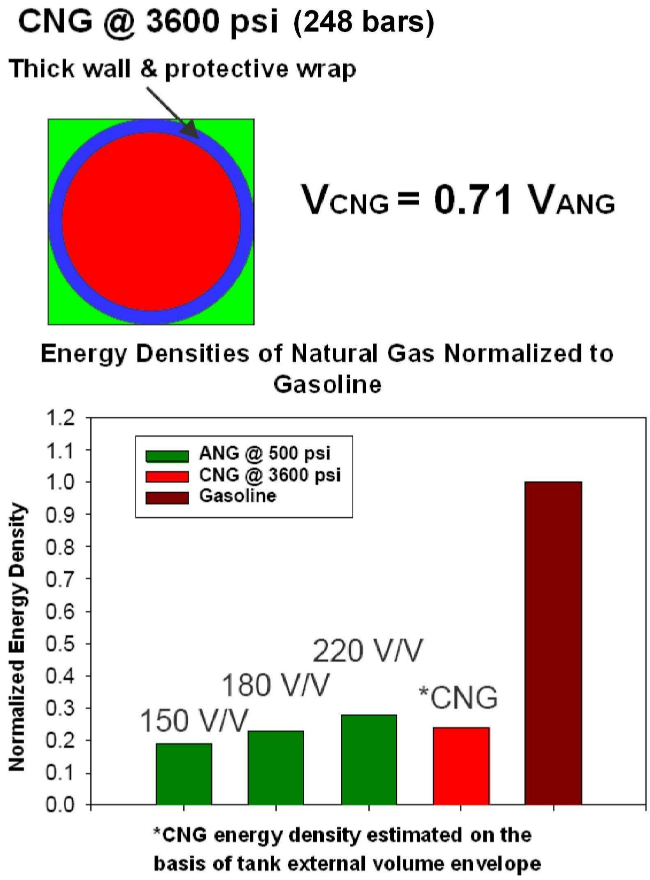

Fig. 1 ANG Tank Free-shape Potential Advantage (2.)

Up to now the commercialization of ANG method was hindered due to several unsolved technological problems. The main challenges of ANG storage products development are:

a) Sufficient volumetric storage ability that will be competitive with existing NG storage methods.

b) Efficient gas filling and release from ANG tank for automotive application require the control of thermo-dynamic processes.

c) ANG fueling system cost should be competitive with the cost of existing fueling systems.

2.2 ANG Storage Systems Development – State of the Art

Attempts to develop ANG automotive fuel system was done by several organizations during the last decade all over the world. Among them we would like to mention the following: AGLARG (Atlanta Gas Light Research Group), USA, Brazilian Gas Technology Center (CTGÁS), HONDA Research Company, Japan, LEVINGS, EU-FP5 funded project, Oak Ridge National Lab (ORNL), USA, Osaka Gas Company, Japan, University of Alicante, Spain, UNIVERSITY OF PETROLEUM, CHINA

PARAMETERS AND CONDITIONS	**AGLARG (Atlanta Gas Light Adsorbent Research Group)**	**EU FP5 LEVINGS program (coordination by FIAT)**	**OAK RIDGE NATION. LABO-RATORY (ORNL)**	**HONDA MOTORS**	**UNIVERSITY OF PETROLEUM CHINA (UPC)**		**Brazilian Gas Technology Center (CTGÁS)**
Years	1990-1999	1997-2000	? -2000	From 2000	1994-95		From 2000
Investigation method	Chrysler B-van, Dodge Dakota Truck	FIAT Marea, On-board, field testing	Laboratory Investiga-tions	Tank development Adsorbent - laboratory tests	Car XIALI 713IU On-board, field testing		Laboratory investigation on full-size prototype
Pressure, bar	35-40	35-40	35	35	50	125	35-40
Tank uptake V/V	150 in laboratory condition, 142 on-board	123	150	155	100-110	170-180	130-150
Tank delivery V/V (to engine)	135 (approx)	107	Not relevant	-	Un-known	Un-known	Unknown
Adsorbent presumed cost	Prohibitive	High, but about 10 times less than the AGLARG	Supposedly very high	Supposedly similar to AGLARG	Un-known	Un-known	Unknown
Vessel (tank) design features	Multicell of extruded aluminum	Multicell of steel tubes	Small laboratory vessel of volume 0,05 L.	Multicell	Un-known	Un-known	Cylindrical form with volume 30 liters

Table 1: Comparative characteristics of some ANG projects

Based on state of the art study the following short conclusion can be made:

1. Max. V/V reached up to the present is 150, with prohibitively high cost of sorbent.
2. Sorbents with more or less acceptable cost provide V/V=120-130.
3. All existing tanks were based on multicell concept that requires a sorbent block with high mechanical strength.
4. Due to the presence of buffer gas the volume of tank delivery is 15% less than tank uptake.
5. All tanks made up to the present do not include any active thermal management systems.
6. High-pressure ANG storage was researched much less than low-pressure ANG
7. The combination of adsorption and low-temperature storage was almost never researched.

The solutions to these problems can be grouped around two aspects:

- Adsorbent material with sufficient gas storage ability that is inexpensive enough to meet the requirements of automotive application
- Effective design of a pressure vessel including thermal management abilities

The first issue concerns with the maximization of the sorbent ability for gas uptake. The adsorption capacity per unit volume of adsorbent can be calculated by $V_v = (V_w)x(d)$, where V_w is the adsorption capacity per unit mass of adsorbent, and “d” is the density. All mentioned ANG projects considered activated carbon as the most suitable. Primarily it is supplied in powder or granules and needs to be compacted. By compacting the density d is increased, and so the adsorption capacity per unit volume V_v increases.

Direct packing of the adsorbent carbon into the vessel is a formidable task. Briquetting, or immobilizing, the carbon was considered as an alternative. Therefore, current tank design is based on multicell concept, where each cell serves as a vessel for gas storing, and at the same time as a carrying component for sorbent briquettes. This concept requires high mechanical strength of the sorbent blocks, which provides by using a binder. The binder, however, tends to block methane access to the carbon micropores resulting in reduced storage. Thus, a closed circle arises.

The second issue is that according to the thermodynamic laws, during the process of adsorption, the sorbent and gas temperature is increased, and methane uptake by the sorbent diminishes. Correspondingly, lowering the temperature during adsorption will reduce the vessel’s filling time and increase methane uptake.

During the gas desorption the sorbent temperature falls with a corresponding decrease of gas pressure and delivered gas flow. It means that heat is needed for effective gas desorption.

2.3 Angstore technology solution

AngStore project belongs to MoreGasTech S.A.S., French based company specializing in high-pressure gases equipment. Major R&D activities are performed in Israel.

To solve described above problems Angstore has developed innovative technology based on several new concepts.

- Novel method to process the adsorbent material and manufacture the gas adsorption structure having high volumetric storage ability and low cost.
- An efficient thermo-managing control system for cooling or heating the adsorbent material as required for controllable gas filling/discharging
- Development of a new design concept of combined tanks, which store either gas only, or liquid and gas, in the same tank of prismatic or free shape form. This allows additional increasing of the total volumetric storage ability of the tank.

Two laboratory prototypes were developed and tested using specially developed simulative bench with testing pressure range up to 100 bar.

First prototype – 1-liter multi-purpose vessel designed to be connected to external thermodynamic control system.
Second prototype - 8 liters vessel modeling the vehicle’s prismatic tank with installed thermodynamic control system.

Third prototype - 20 liters full-scale prototype of the cylindrical tank intended also for field trials – still not tested

Applying our technological innovations we have reached up to now the following achievements:

1. Volumetric ratio of V/V=155-195 at a pressure of 40-65 bars and ambient temperature with inexpensive adsorbent packages.

2. Volumetric ratio V/V=220-250 at a pressure of 70-100 bars and ambient temperature with the same adsorbent packages. Effective volumetric ratio of above 300 applying combined tank design concept.

3. 20% increase of the volumetric ratio by cooling of the system to minus 15-20 degrees C in experiments at low pressure.

Developing this technology will provide offer the following functional advantages as applied to automotive tank:

1. One-box tank having easy manufacturability and assembly properties.
2. Effective high-speed tank filling and discharging at constant rate of gas delivery under changes of the engine load.
3. Minimal heat (energy) losses and possibility to use different sources of energy, including exhaust gases, engine cooling liquid, etc.
4. Possibility to place the tank and heating/cooling device in different places, using several tanks.
5. Disposing of shape constraints and possibility to adapt the tank’s form to different vehicle body and frame components.

Planned advance of the ANG system development in the next period includes:

1. Pilot ANG vehicle operation
2. Increase in volumetric storage ability with further increase in storage pressure up-to 150 and possibly 200 bar. Expected volumetric ratio - 350 V/V and possibly more
3. Possible further improvement of adsorbent material properties
4. Exploration of low temperature ANG storage (below o^0 C)

3. Products Characterization

3.1 Low-pressure ANG tanks

These storage tanks are designed for operating pressure of 60-65 bar. This is the maximum allowed pressure for welded pressure vessels by existing standards. The welding option enable relatively low cost manufacturing of the ANG tank pressure envelope opens more possibilities for tank assembly methods and non-cylindrical form design.

These products target the decrease in refueling costs due to lower pressure at filling. Both centrifugal and screw compressors can be practical at this pressure level.

<u>Automotive cylindrical low-pressure ANG tanks</u>
This product provides for gas storage ability, weight and cost parameters similar to 200 bar CNG tanks of steel.

<u>Automotive non-cylindrical low-pressure ANG tanks</u>
This product aims at optimizing the volume utilization in light vehicles. Its “effective” volumetric efficiency could be at least 25% higher than CNG cylinder. However its could cost significantly more.

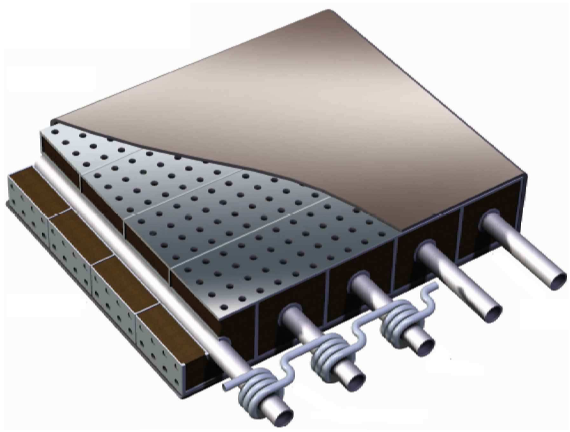

Figure 2. Conceptual Prismatic Automotive Tank Design

Gas distribution low-pressure ANG tanks - under market feasibility study

We study the application of low-pressure ANG cylinders for gas distribution in the framework non-pipeline gas supply projects. The attractive point in this application is the possibility of direct filling the tanks from transmission pipeline without any compressor.

3.2 High-pressure ANG tank

Cylindrical High-pressure ANG tank

These tanks will have an operating pressure of between 100 and 200 bars. They aim to maximize the gas storage ability and therefore vehicle driving distance using existing CNG refueling infrastructure.

Alternatively these tanks will provide the same driving range as the CNG tank with reduced tank volume for vehicle having especially high requirements for volume minimization (2-wheelers for example) or those who prefer to save costs on tank.

The estimated cost of these tanks will be 20-50% more than CNG steel cylinder of the same geometrical (water) volume.

Non-cylindrical High-pressure ANG tank

The design of these tanks represent complex engineering problem. We developed some innovative proprietary solution enabling design of tanks with prismatic or other form.

Based on our conducted investigations we develop currently a range of the products. Angstore product spectra and possible applications are illustrated in table 2.

Product Type Parameters		Automotive application				Gas Distribution/ Storage
		Cars, Vans, Pickups	Trucks	Scooters	3 - Wheelers	
Low pressure, 40-65 bar	Cylindr.	+	++	-	++	++
	Free shape	++	+	++	+	-
High pressure, 100-200 bar	Cylindr.	++	++	++	++	+
	Free shape	++	-	+	-	-

Table 2. ANG products application summary

4. ANG Technology Need and Value Proposition

4.1 General

Adsorbed Natural Gas technology enables to store the same volume of gas under much lower pressure (40-60 bar) than is currently used. This in turn substantially decreases filling station capital and operation costs and reduces NG end-user cost.

Alternatively ANG in higher pressure (between 100 and 200 bars) can increase the driving range of NGV or reduce the size of the NGV tank.

Thus ANG technology brings two types of products with different value propositions

A. Vehicle tanks with cost-performance characteristics similar to CNG enabling more cost efficient refueling infrastructure development and operation.

Here we analyze capital and operation costs and, thus, estimate the ANG cost advantage. The high level of required capital investment represents a separate problem in the case of NGV infrastructure. We demonstrate this problem with the example of the German Market.

B. Vehicle tanks with improved performance (extended storage capacity for given volume), which utilize the existing infrastructures

In order to evaluate and characterize the potential demand for these tanks we analyzed NGV use advantages-disadvantages for different vehicle groups. These groups were defined by their annual driving range (mileage) and characterized mainly by the level of cost benefits of transition to the gas.

4.2 Low-Pressure ANG Market Application

4.2.1 Investments required in CNG infrastructure – the German case

Germany initiated the biggest NGV program in Europe and maybe in the world. In order to reach the level of 6-7 mil. NGV (10% of the total park in 2020) the German government provides:

- Subsidy for a significant part of filling station capital investment for the construction of 1000 stations by the end of 2007
- 60-100 % subsidy of CNG vehicle conversion cost
- Long term obligation for preferential taxation, benefits in car insurance, etc.

However, according to our evaluation, even after completion of the current station deployment program Germany will be far from the needed total filling capacity to support the targeted NGVs numbers.

Station Type	Station filling capacity, Ncm per hour	Station filling capacity, mil. Ncm/year	NGVs per station	Germany - quantity of stations needed	Station cost, K Euro	Germany - needed investment, M Euro	EU - stations needed	EU - needed investment, M Euro
1	2,000	10.80	2,700	2,111	1,200	2,533	10,519	12,622
2	1,000	5.40	1,350	4,963	700	3,474	21,778	15,244
3	500	2.70	675	9,926	400	3,970	43,556	17,422
4	250	1.35	338	19,852	250	4,963	87,111	21,778

Table 3. NGV 2020 Target – Estimated Required CNG station quantities, gas filling capacities and costs

Average vehicle characteristics (3.):
Fuel consumption – 12.5 km/liter (8 liters per 100 km)
Annual driving mileage – 20,000 km per year
Annual fuel consumption – 1,600 liter = approx. 1,600 norm. CM of NG
Targeted Germany NGV park – 6.7 mil. vehicles
Targeted EU NGV park – 29.4 mil. vehicles

Station Types:
1 – analogous to big public filling station – simultaneous filling of up-to 8-12 light vehicles. Currently this type of station is very rare in world NGV markets.
2 – analogous to regular filling station - simultaneous filling of up-to 4-6 vehicles
3 - small station – up-to 4 CNG hoses - simultaneous filling of up-to 2-4 vehicles
4 –installation of one CNG dispenser (up-to 2 hoses) in existing petrol stations - simultaneous filling of 1-2 vehicles (1 – in peak hours)

Our definition of NGVs quantities per station are based on comparative analysis of Italian and Argentinean NGV markets statistics and our own analysis of CNG stations operation (4.). Needed installed compressor capacities take into account minimal requirements of peak-time filling, fast filling and emergency.

Most new station in Germany belong to type 3 and 4. It means that after completion of the current program the CNG station network could support about 10-15% of the 2020 target NGV fleet. Even now there are queue problem in peak hours in particular areas despite of the fact that 620 stations serve only 30,000 NGVs.

Currently there are about 10,000 petrol/diesel filling stations in Germany and their number is not expected to grow.

Capital investment needs described here don’t take into account land use considerations in different countries and areas.

Thus even in Germany the EU “Target 2020” completion is in doubt if based on existent mode of development and technology.

4.2.2 CNG Station Operation Expenses and Total Costs

CNG filling involves two additional significant cost components when we compare it with liquid fuel filling.

Energy Consumption
CNG compression consumes energy equivalent to 4-5 % of the filled gas quantity

Compressors Maintenance
CNG compressor operation involves high physical amortization. Maintenance costs reach 10% of the equipment purchase cost. Compressors are responsible for 40-60% of total station capital costs.

Total Cost of CNG and price differentials with liquid fuels
CNG costs excluding taxes in Europe were €0.4 – 0.5 in 2005. Average CNG cost excluding gas purchase from the network is around €0.2. Including taxes CNG price reaches €0.62 in European average in comparison with 1.2 for petrol and 1.05 for diesel (4., 5., 6.).

These price differentials don't allow a fast capital return (for vehicle conversion and station construction) with NGV users driving 20,000 km per year and less. Potential users who drive more face the problem of short driving range allowed by existent CNG tanks.

4.2.3 Value Preposition of Low-Pressure ANG Technology

ANG filling equipment
Gas compression from the level of distribution networks (1-16 bars) to the level of 200 bar (CNG) requires using multi-stage piston compressors. Gas compression from the level of distribution networks (1-16 bars) to the level of 60 bar (low-pressure ANG) requires simpler means, for example centrifugal compressors. These compressors have the following advantages over existing CNG compressors:

a. Substantially lower capital cost – about ½ of existing CNG. The bigger the station capacity, the bigger the cost reduction.
b. Lower physical amortization level and therefore substantially lower maintenance costs
c. Higher energy efficiency
d. Lower space requirements

Most other gas equipment components needed for low-pressure filling also cost significantly less (piping, control, dispensers, etc.).

ANG Station Operation Expenses and Total Fuel Cost

Due to the much lower compression level ANG refueling consumes about ¼ of the energy needed for CNG. Operation of centrifugal compressors, proposed for ANG, involve much less physical amortization. Annual rate of maintenance expenses is evaluated at 5% of equipment cost instead of 10% for CNG. Taking into account the lower cost of equipment - the total maintenance expenses will be about ¼ of CNG.

Required ANG station capital is at least ½ of CNG. Therefore the capital return component in ANG fuel cost will be ¼ of CNG (assuming capital return for 15 years and 5% of discount rate)

Total ANG cost will be between ½ and ¼ of CNG (excluding gas purchase cost). In current European conditions we estimate the ANG fuel cost saving to be about €0.1 per Ncm.

Summary of Low-pressure ANG application gains

- Reduction of capital cost for the gas seller

- Decrease in risks of big investment in public stations with uncertain gas demand by NGV users
- Possibility to change the pattern of NGV station deployment toward higher filling capacities: for example, to install “Type 1” capacities (or more) as the standard NGV station and “Type 3” capacities for addition of NG dispensers in petrol stations
- Improvement of profitability level of NGV station business that is currently a problem in many markets
- Improvement of the over-all economy and energy efficiency of NGV – especially important for political decision-makers in many countries

4.3 High-pressure ANG market application

4.3.1 NGV Cost Advantage for vehicle groups with different driving range

Conversion to CNG (or purchase of CNG vehicle) involves additional cost and provides fuel cost saving during the vehicle operation life. NG as automotive fuel has bigger advantage for vehicles using more fuel and therefore having more annual mileage. For vehicles with relatively low annual mileage the conversion to gas is not profitable.

We analyzed cost advantage of CNG light vehicles in comparison with gasoline and diesel fueled vehicles, divided according to annual driving range (mileage). This analysis is based on fuel prices differentials on the final consumer level.

	Vehicle annual driving range (km)					
	10,000	20,000	30,000	40,000	60,000	80,000
EU: **CNG saving versus diesel fuel** Average saving - $0.31 per gasoline liter equivalent. Additional cost of the vehicle - $1,500						
First year of profitable operation	8	4	3	2	2	1
Net cumulated saving after 7 years of operation, $	-8	1,484	2,977	4,469	7,453	10,438
Developing countries: **CNG saving versus gasoline** Average saving - $0.36 per gasoline liter equivalent. Cost of conversion to gas - $1,000						
First year of profitable operation	4	2	2	1	1	1
Net cumulated saving after 7 years of operation, $	540	2,081	4,243	5,161	8,242	11,323
USA: **CNG saving versus gasoline** Average saving - $0.14 per gasoline liter equivalent. Cost of conversion to gas - $4,000						
First year of profitable operation	-	-	-	8	5	4
Net cumulated saving after 7 years of operation, $	-3,038	-2,075	-1,113	-150	1,774	3,699

Table 4. Profitability of conversion to NG for vehicle users in different groups of countries

Fuel prices here are averages for each group of countries. EU group includes the data of 22 countries. Developing countries group includes the data of 26 countries (4.).

In Europe we compare diesel- fueled vehicle and CNG converted gasoline engine vehicle. In developing countries and USA we compare gasoline fueled and CNG converted gasoline engine vehicle.

4.3.2 High-pressure ANG technology solution for NGV driving range problems

In Europe significant cost advantage of NGV use begin for vehicles driving 30,000 km per year. CNG tank provides only 2 whole days of average driving (in particular days it will be not enough for 2 days).

For the group driving 40,000 km per year and more the NGV driving range is problematical: every-day refueling with limited stations availability and possible long queues in peak hours.

In USA NG use is marginally profitable and only for vehicles driving 60,000 km.a year. These users definitely need extended driving range. Of course in current NG-oil price differentials the economically motivated NGV use in USA almost doesn't exist.

High-pressure ANG tank combines the effect of adsorption and high-pressure. It could propose driving range extension up-to 450-500 km in comparison with 300 km of CNG tank of same volume. It enables to expand the NGV use for additional significant driver groups (3., 7.).

Existent CNG equipment can be used for high-pressure ANG tank filling with addition of some simple adjustments. In particular: a pressure reducer should be added in case, for example, that the operation pressure of 150 bar will be defined as the optimum for ANG.

In the developing world it is a less significant problem due to the profitability of CNG conversion even for vehicles driving 20,000 km and less as well as higher sensitivity to vehicle tank cost increase in the high-pressure ANG case.

This type of ANG tanks proposes also a possibility to reduce the volume of a tank providing the same driving range as CNG. Such product can be applicable for users, which are especially sensitive to the volume occupied by the tank as for example very small vehicles in Asia. The cost of this tank will be lower in proportion to its volume.

4.3.3 ANG on-board storage using the LNG based refueling

LNG transportation becomes the most significant trend in the world gas industry. Numerous receiving terminals planned on the coasts of many countries and further emergence of spot trade will open new possibilities for NGV fueling.

Currently we study the feasibility of two LNG applications for ANG:

1. Filling the above described ANG tanks using LNG
2. Special ANG tank combining effects of adsorption and low temperature

<u>First application</u>

ANG vehicle tanks obviously could be filled by the known method of L-CNG. The advantage of ANG is that low-pressure ANG tank filling requires simpler equipment than the high-temperature fast vaporization system used in L-CNG stations.

<u>Second option</u>

There is possibility to combine gas adsorption and cooling effects for increase of storage ability. Our first experiments demonstrated about 20% increase in the storage ability of ANG tank when the temperature is lowered to minus 15-20 degrees C. The insulation of such tank will be much simpler than needed for LNG on-board tanks. This provides promising option for small vehicles, which cannot apply economically LNG tanks. If low-temperature ANG tank is proven as economically feasible product it could bring the NGV driving range close to the gasoline tank.

5. Conclusions

The introduction of commercially valuable ANG vehicle tanks is feasible. Such tanks have functional and cost parameters competitive with present CNG tanks.

Low-pressure ANG tanks providing cost-performance characteristics similar to CNG cut to 1/2 – 1/3 the refueling infrastructures capital and operation costs. This can enable much faster and efficient development of NGV infrastructure deployment in countries/regions without well-developed CNG stations network.

High-pressure ANG tanks enable 50% increase of the NGV driving range in comparison with CNG. Correspondently they can reduce tank volume. This makes transition to gas attractive for some vehicle user groups including first of all those with high driving ranges or strict space limitations.

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