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ACTIVATED CARBON BASED NATURAL GAS RECOVERY SYSTEM

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Abstract

High pressure natural gas contained in compressor casings is frequently blown off to atmosphere when a compressor station is shutdown not-to-restart. Previous work indicated that activated carbon could be used to capture this blowdown gas and re-use it later [1]. The performance of an activated carbon module was measured during a simulated blowdown of a natural gas centrifugal compressor casing. Further experiments were performed on an activated carbon module to determine a full temperature- and pressure-dependent storage isotherm. Results from the simulated blowdown testing and isotherm testing were then used to validate a transient numerical model to predict the performance and mass storage of a full-scale activated carbon based natural gas recovery system.

An economic analysis was performed to estimate the cost per unit mass of natural gas captured. The analysis is based on a full-scale module used to capture blowdown gas from an industrial size centrifugal compressor casing. A potential system for recovering natural gas and using the gas on site at a typical compressor station was conceptualized.

Contents

1 Introduction

Activated carbon continues to receive attention as a means of storing natural gas. For instance, commercial activated carbon modules are being manufactured and distributed as a safe and efficient means of storing and transporting natural gas for use with welding equipment [1]. Major manufacturers of activated carbon are beginning to produce carbon products optimized for storing natural gas [2]. Furthermore, government tax incentives for heat recovery systems, and the increasing cost of greenhouse gases continue to increase the economic feasibility of natural gas sequestration and storage systems [3].

Several times a year, the natural gas in centrifugal compressor casings must be vented to perform regular maintenance. Not only is this gas a commodity with value but it is primarily composed of methane, a greenhouse gas. The harmful effects of the gas can be mitigated by burning the natural gas in a flare but the commodity is lost. An activated carbon based natural gas recovery system would both capture the natural gas and eliminate the harmful greenhouse gas emissions.

The performance of an activated carbon module in this type of application was measured during a simulated blowdown of a centrifugal compressor casing at the TransCanada Didsbury Gas Dynamics Test Facility (GDTF). Further laboratory experiments were performed on an activated carbon module to determine a full temperature- and pressure-dependent storage isotherm. A numerical model was then developed for the activated carbon module that allowed for the estimation of several key scale independent properties of the carbon. Once the numerical model was calibrated to the experimental results, the performance and economic feasibility of a full-scale activated carbon compressor casing blowdown system were estimated. Options for use of the stored natural gas at a typical compressor station are also discussed.

2 Experimental Setup

2.1 Simulated Blowdown

A simulated blowdown was performed at the Didsbury GDTF. The goal of this experiment was to isolate a volume of pressurized natural gas and blowdown the volume into an activated carbon module. The volume of isolated natural gas was chosen such that the ratio of activated carbon to natural gas blowdown volume was 15.6%. In a previous investigation, it was determined that a ratio of approximately 10–15% is appropriate for maintaining a high storage pressure and percentage of gas capture [4]. Details of the activated carbon storage module used in experiments are shown in Table 1. The activated carbon found in the storage module can be described as granular. Similar storage modules are often charged with activated carbon in a monolithic form where the powdered or granular activated carbon is combined with a thermal binder and compressed to reduce the pore volume. Activated carbon in monolithic form has a higher storage capacity; however, monolithic activated carbon has a much lower permeability, making it harder to charge with natural gas.

The discharge tubing, shown in Figure 1, includes an isolation valve, a high-flow coefficient (low pressure-drop) regulator, and a small vent. The tubing and natural gas regulator between the blowdown volume and the activated carbon module were sized to ensure that the dominating resistance during blowdown would be the permeability of the activated carbon. A flexible tube was used for the connection between the activated carbon module and relief tubing so that the activated carbon

Table 1: Activated Carbon Module Properties

Void fraction	0.73
Carbon density	2400 kg/m^3
Carbon mass	16.2 kg
Module length	0.763 m
Module diameter	0.203 m
Module volume	25 L

module could be placed on a scale to measure mass storage.

The activated carbon module was insulated with a custom cylinder blanket. Two thermocouples (TC) were adhered to the outside surface of the module at different heights to monitor temperature. This is to assist with parametric estimation of heat of adsorption (generated heat) by removing the effect of convection from the external walls. Pressure measurements were taken on the isolation volume sufficiently far from the discharge tubing to ensure that static pressure was measured.

A second test was performed with a constant pressure blowdown source at the maximum pressure of the module (270 psi). This test was conducted without insulation to determine the maximum storage capacity and minimum storage time required to completely fill the module. Allowing the module to cool during the charging phase results in a greater mass storage because the storage capacity of the module is inversely proportional to temperature. These tests were also used to determine the reduction in storage capacity as the activated carbon module became contaminated with heavier hydrocarbons present in the natural gas stream. Further details regarding degradation of the activated carbon module and the key components of an adsorbed natural gas system can be found in [5].

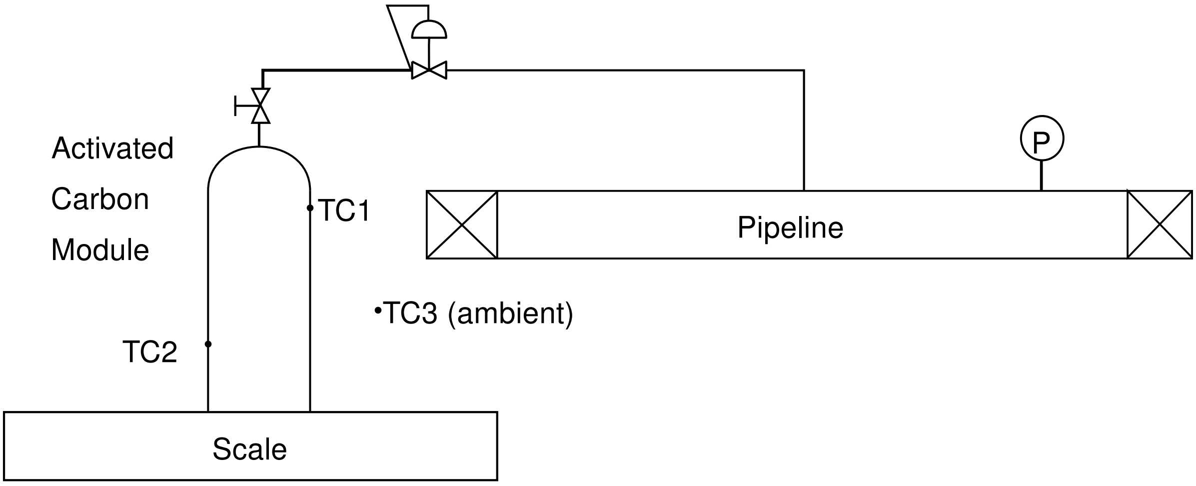

Figure 1: Simulated Blowdown Experimental Setup

2.2 Adsorption Isotherm Testing

In order to develop a transient numerical model of the activated carbon module, a full temperature- and pressure-dependent storage isotherm is required for the activated carbon. A series of experiments were conducted to determine the storage isotherm by filling the activated carbon module with natural gas and measuring the pressure response at 20°C to 60°C.

The activated carbon module was first filled with natural gas in the pipeline at its maximum storage capacity. With the mass of natural gas in the activated carbon module held constant, the temperature of the module was controlled with a temperature bath as shown in Figure 2. The activated carbon module was held at constant bath temperature for approximately three hours to reach thermal equilibrium before a pressure measurement was taken. After the pressure measurements were taken for temperatures between 20 and 60°C ,a small amount of natural gas was released from the module before taking further pressure measurements. This data was then used to determine a natural gas storage capacity equation, which is discussed further in Section 4.2.

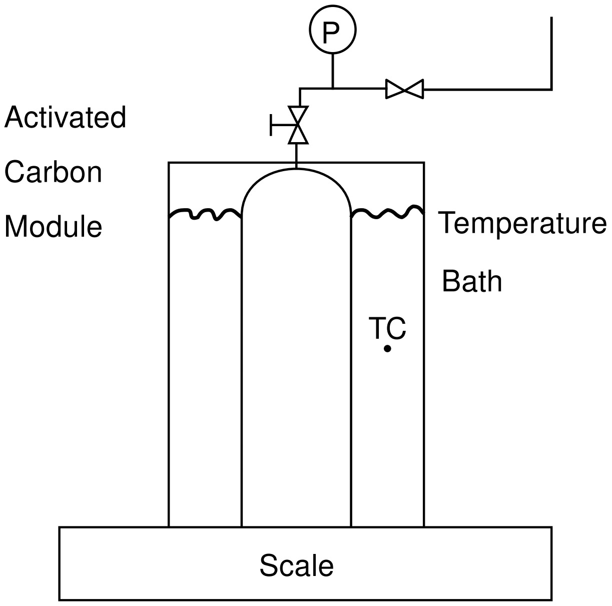

Figure 2: Adsorption Isotherm Experimental Setup

3 Numerical Model

The following section describes a transient numerical model, taken from literature [6] and modified for a one-dimensional Cartesian porous flow. The set of partial differential equations is standard for porous flow with the additions of a storage capacity term, C, in Equation (1) to account for the adsorbed natural gas and a heat generation term in Equation (3) to account for heat of adsorption.

Conservation of mass:

$$\frac{\partial}{\partial t}\left[\epsilon\rho + (1-\epsilon)\rho_c C\right] + \nabla \rho V = 0 \tag{1}$$

Conservation of momentum:

$$\frac{1}{\epsilon}\frac{\partial}{\partial t}(\rho V) + \frac{V}{\epsilon^2}\nabla \rho V = -\nabla P - \frac{\mu}{K}V \tag{2}$$

Conservation of energy:

$$\begin{aligned}\epsilon C_{vg}\frac{\partial}{\partial t}(\rho T) + (1-\epsilon)C_{ps}\frac{\partial}{\partial t}(\rho_c T) + (1-\epsilon)C_{vg}\frac{\partial}{\partial t}(\rho_c C T) = \\ \lambda_{\text{eff}}\nabla^2 T + \frac{\partial C}{\partial t}\Delta H(1-\epsilon)\rho_c\end{aligned} \tag{3}$$

The continuity equation (1) contains two storage terms: one for the compressed natural gas in the void porous volume, and one for the adsorbed natural gas. The storage capacity, C, of the activated carbon is defined as the mass of natural gas stored per mass of activated carbon. The pressure of the module is determine from the density, ρ, and temperature, T, of the non-adsorbed gas.

The second term in the conservation of momentum equation (2) is shown for completeness but has been neglected in the numerical model because it is between 5 and 10 orders of magnitude smaller than the other terms. The conservation of momentum equation is used to determine the velocity of the natural gas from the pressure gradient in the activated carbon and the porous resistance to flow. The resistance to flow, in turn, is determined from the permeability, K, and follows Darcy's Law:

$$Q = -\frac{-KA}{\mu}\frac{\Delta P}{L} \tag{4}$$

Darcy's law was originally formulated from experiments on water flow through sand beds and is used extensively in earth sciences [7]. This relationship is valid for slow creeping flows below a particle Reynolds Number, Re, of 10:

$$Re = \frac{\rho V d_{30}}{\mu} \tag{5}$$

where d_{30} is the 30% passing grain diameter for the porous media. Since the permeability of the activated carbon module is so low, Darcy's Law is valid. If however, the particle Reynolds Number were above 10, Equation (2) would require a resistance term for the turbulent regime. The Ergun equation (Equations (6)–(8)) is used for porous flow in both the laminar and turbulent regime [7].

$$f_p = \frac{150}{Gr_p} + 1.75 \tag{6}$$

$$f_p = \frac{\Delta P}{L}\frac{D_p}{\rho V^2}\left(\frac{\epsilon^3}{1-\epsilon}\right) \tag{7}$$

$$Gr_p = \frac{D_p V \rho}{(1-\epsilon)\mu} \tag{8}$$

Energy stored in the activated carbon module is distributed between the natural gas compressed in the pore void volume, gas stored in the adsorbed phase in the activated carbon and in the solid activated carbon. It is assumed for the following calculations that the gas and carbon are in thermal equilibrium.

The effective thermal conductivity is a measure of the linear heat transfer through the activated carbon bed from the conductivity of carbon and the stored natural gas. The empirical relation, shown in Equation (9) is valid below temperatures of 800 K and pressures of 3.5 MPa [8].

$$\begin{aligned}\lambda_{\text{eff}} = 0.04696 + \left(5.6475 \cdot 10^{-4}\right) T \\ - \left(1.3245 \cdot 10^{-6}\right) T^2 + \left(1.725 \cdot 10^{-9}\right) T^3 - \left(5.471 \cdot 10^{-13}\right) T^4\end{aligned} \tag{9}$$

The heat of adsorption, ΔH, and permeability of the porous media, K, were estimated by comparing the output of the numerical model to the pressure, temperature, and mass storage in the activated carbon module during simulated blowdown testing. These properties are scale-independent, and can be used in future calculations to determine the performance of a much larger vessel of any geometry.

All thermal and transport properties used in the numerical model are evaluated at the gas state defined by the temperature and density in each discrete node. Properties are calculated with the AGA8 equation of state at the gas chromatography composition measured during testing. The mixture composition of the natural gas stream is given in Table 2.

Table 2: Natural Gas Composition

Component	Mole Fraction (%)
methane	93.18
ethane	4.32
propane	0.98
i-butane	0.11
n-butane	0.13
i-pentane	0.03
n-pentane	0.02
hexane	0.03
nitrogen	0.5
carbon dioxide	0.7

4 Results and Discussion

4.1 Simulated Blowdown Results

The results of the simulated blowdown test are shown in Figures 3 to 5. For these tests, the activated carbon module (volume = 25L) is connected to the blowdown volume (volume = 110L) as shown in Figure 1. Prior to starting the test, the blowdown volume is at a pressure of 1850 kPag (270 psig) and the activated carbon module is at atmospheric pressure. The isolation valve between the activated carbon module and blowdown volume is then opened, allowing the two volumes to reach equilibrium. The mass measurements taken from the scale are susceptible to systematic error. Even though the module is connected to the pipeline with a flexible line it is difficult to maintain an accurate scale reading at the beginning of the charge stage. The total mass storage in the vessel was calculated most accurately from the final pressure in the pipeline with a high accuracy equation of state. The scale mass measurements can be used to double check the amount of mass stored.

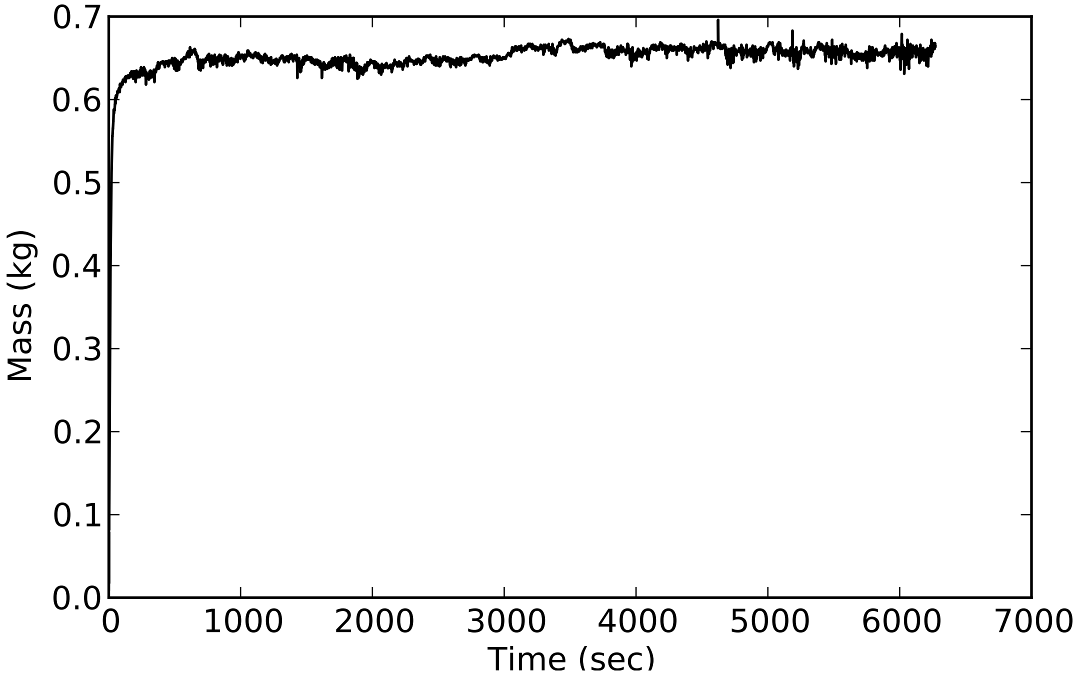

Figure 3: Experimental Activated Carbon Module Mass Storage

The surface temperature measurements from thermocouples 1 and 2 (Figure 4) show approximately the same temperature profile. If the permeability of the activated carbon were lower, the gas would propagate more slowly through the vessel and the temperature at the bottom of the activated carbon module would lag behind the temperature at the top of the module. Both temperature measurements begin to asymptote to a value of approximately 40°C. This value was used in the parametric estimation of heat of adsorption (ΔH) in Equation (3) and Equation (11).

Pressure in the natural gas blowdown volume is shown in Figure 5. The final pressure in the reservoir is reached at approximately 1000 sec which for a geometrically similar vessel gives a good estimate of fill times for full scale application. As the gas flows out of the reservoir, the temperature in the reservoir decreases due to isentropic expansion. This causes the pressure in the reservoir to

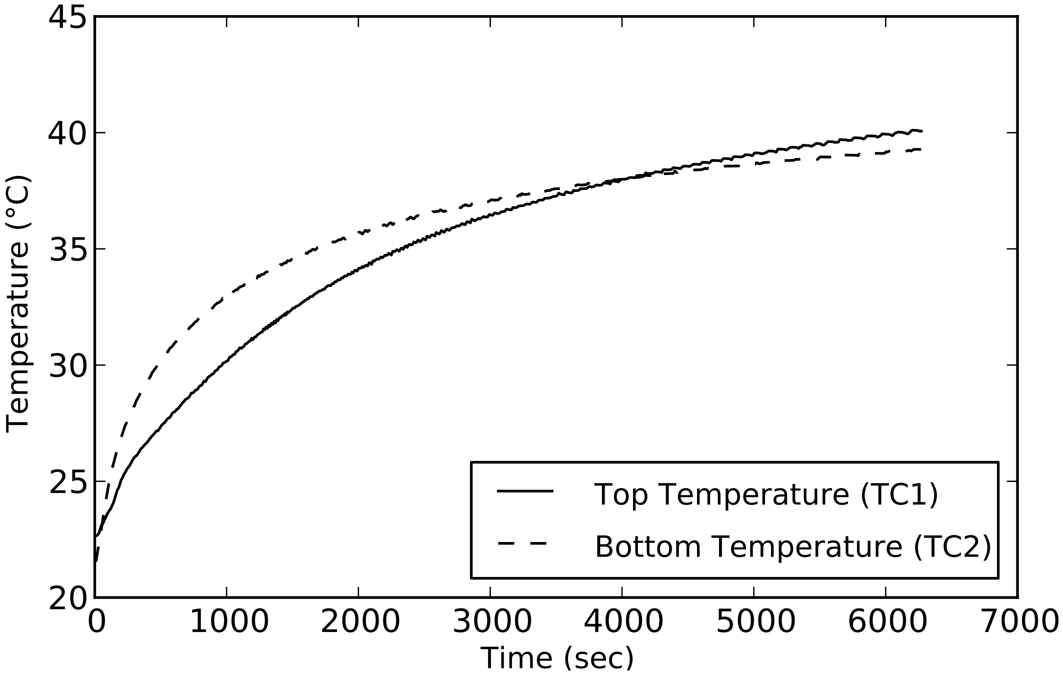

Figure 4: Experimental Activated Carbon Module Surface Temperature

decrease below the final asymptotic value of 1275 Pa until the temperature is recovered by conduction through the pipe walls.

4.2 Isotherm Results

As shown in Equation (10), C is the mass of natural gas adsorbed per mass of activated carbon in the storage module. Equation (10), a numerical best fit the the experimental laboratory isotherm data, has been used to produce Figure 6 which illustrates the temperature and pressure dependent storage isotherm of the activated carbon used in the module. This property of the activated carbon is scale independent but specific to storage of natural gas on the particular activated carbon used in the module. A comparison between the numerically fit equation for storage capacity, C, and the experimental data is shown in Figure 7.

$$C = \frac{a + bP + cP^2 + dP^3 + e\ln(T)}{1 + fP + gP^2 + h\ln(T) + i\big(\ln(T)\big)^2} \tag{10}$$

The results from Equation (10) are consistent with the results from the simulated blowdown testing with a final pressure of 270 psi and a temperature of 20°C. Equation (10) predicts a final mass storage of 0.899 kg while the experimental result ranged between 0.80 and 0.93 kg (Table 4).

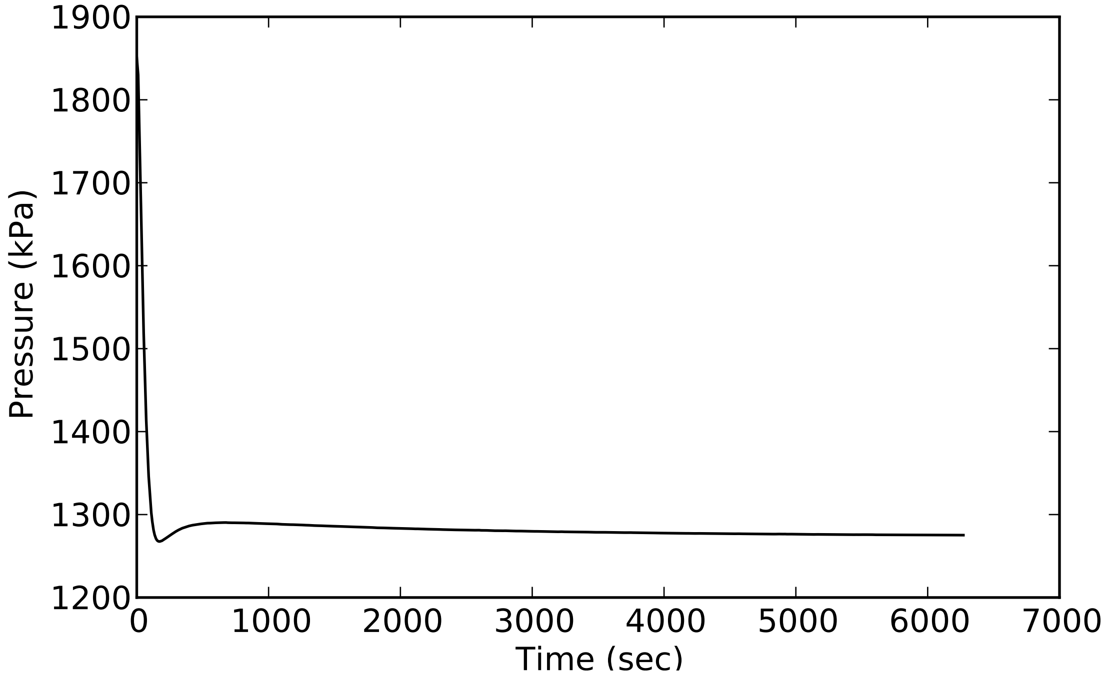

Figure 5: Experimental Reservoir Pressure

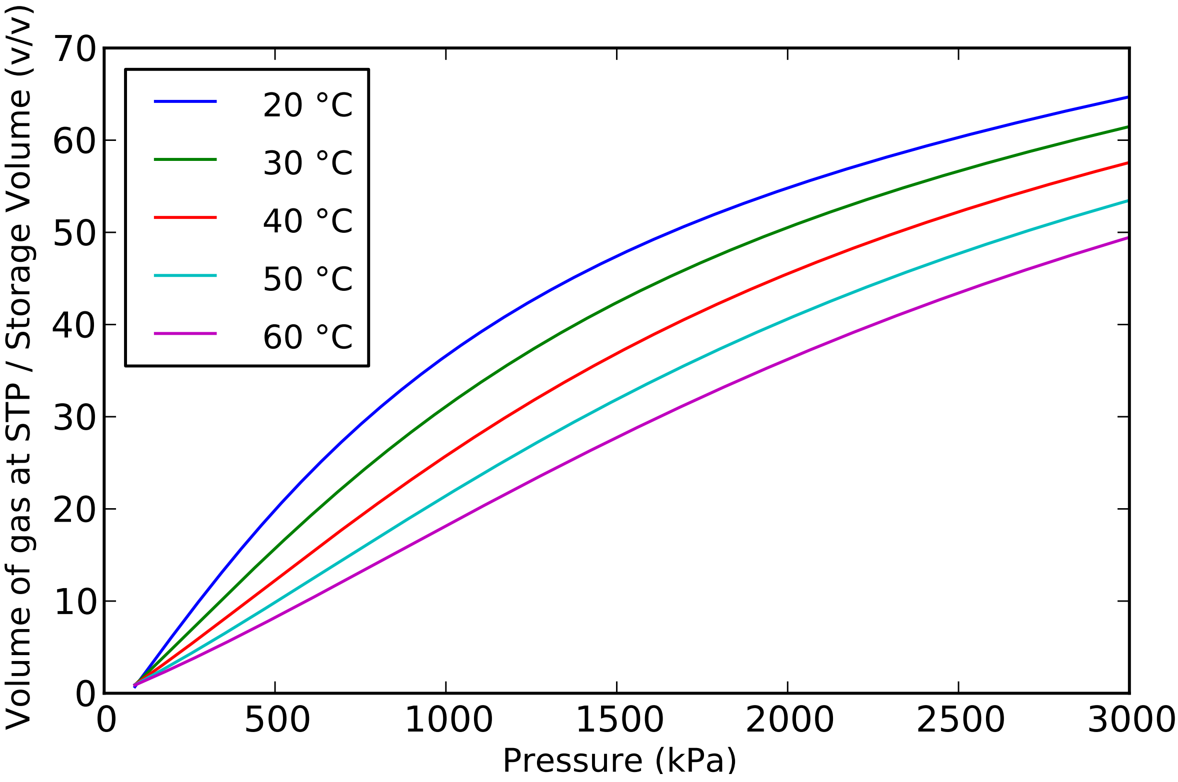

Figure 6: Activated Carbon Experimental Isotherms

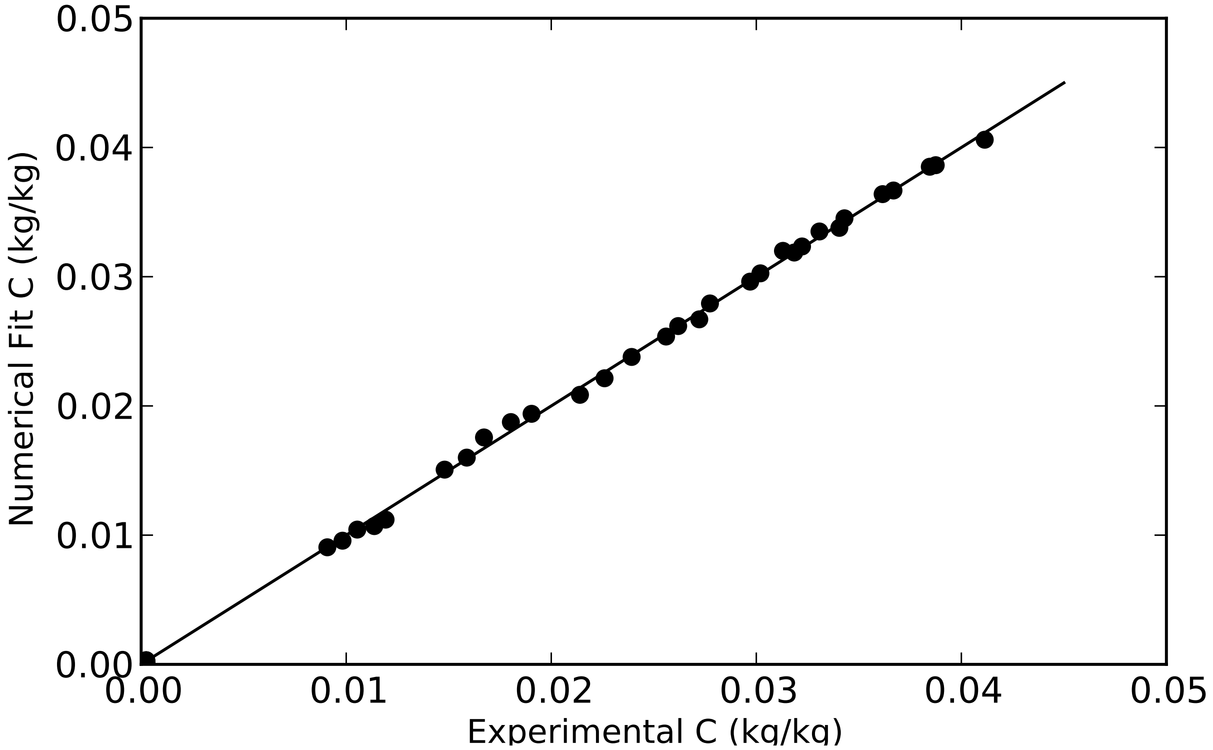

Figure 7: Comparison of Numerically Equation to Experimental Data

Table 3: Adsorption Isotherm Parameters

a	-1.51E-05
b	9.03E-09
c	8.89E-12
d	-7.12E-16
e	2.50E-06
f	1.75E-07
g	1.42E-10
h	-3.55E-01
i	3.14E-02

4.3 Parameter Estimation

The numerical model described in Section 3 includes several parameters specific to the activated carbon used in the natural gas recovery system. These values are, C, the storage capacity of the activate carbon, K, the permeability of the activated carbon, and ΔH, the heat of adsorption of the activated carbon. The effect of raising and lowering the permeability and heat of adsorption of the activated carbon bed on numerical results is shown in Figures 8 and 9. The values of permeability and heat of adsorption can be estimated from the results of the simulated blowdown experiments. The storage capacity of the activated carbon is a pressure and temperature dependent property that was measured with the isotherm testing.

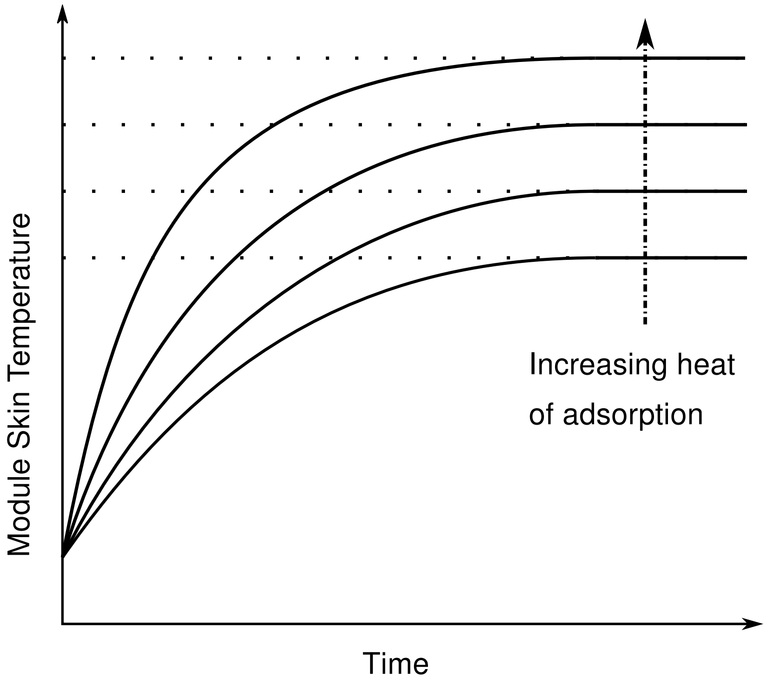

Figure 8: Effects of Heat of Adsorption

Results from the numerical model after parameter estimation from experiment data (Figure 4–5) is shown in Figure 10–11.

The heat of adsorption can be calculated from the maximum temperature reached in the activated carbon module during blowdown (Figure 4). The final temperature is related to the heat of adsorption according to Equation (11), which takes into account the isentropic compression of blowdown gas into the activated carbon module.

$$\Delta H = \frac{(T_2 - T_1)\left[\epsilon C_{vg}\rho g + (1-\epsilon)C_{ps}\rho_s + (1-\epsilon)C_{vg}\rho_s C\right] - C_{pg} m_{\text{in}} T}{C(1-\epsilon)\rho_s} \tag{11}$$

Prior to including the heat of adsorption in the numerical model developed in Section 3, the temperature increase due to isentropic compression was enough to account for the increase in temperature of the module during experimental testing. This indicates that the heat of adsorption of the activated carbon was negligible compared to the heat of compression in the module. The heat of adsorption was left as zero for further numerical simulations.

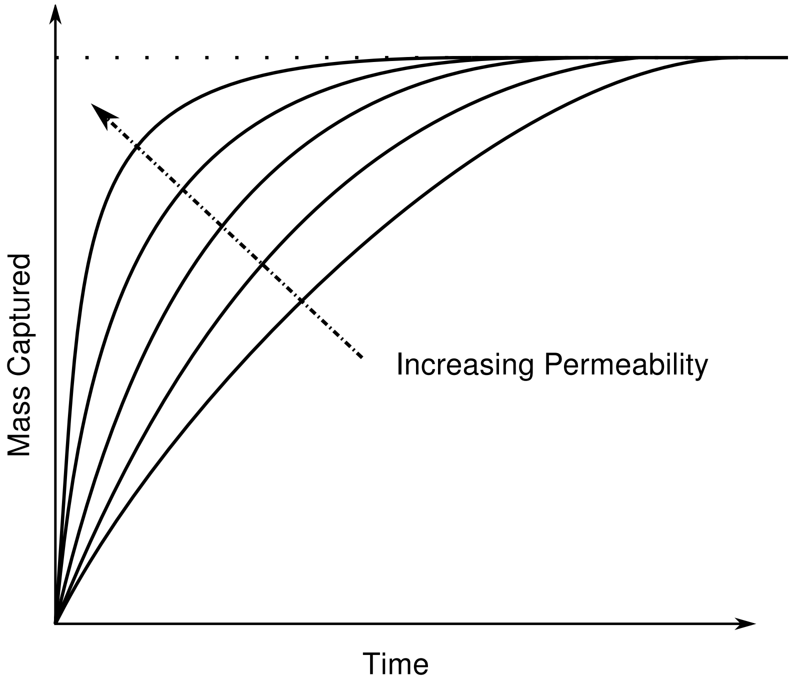

Figure 9: Effects of Permeability

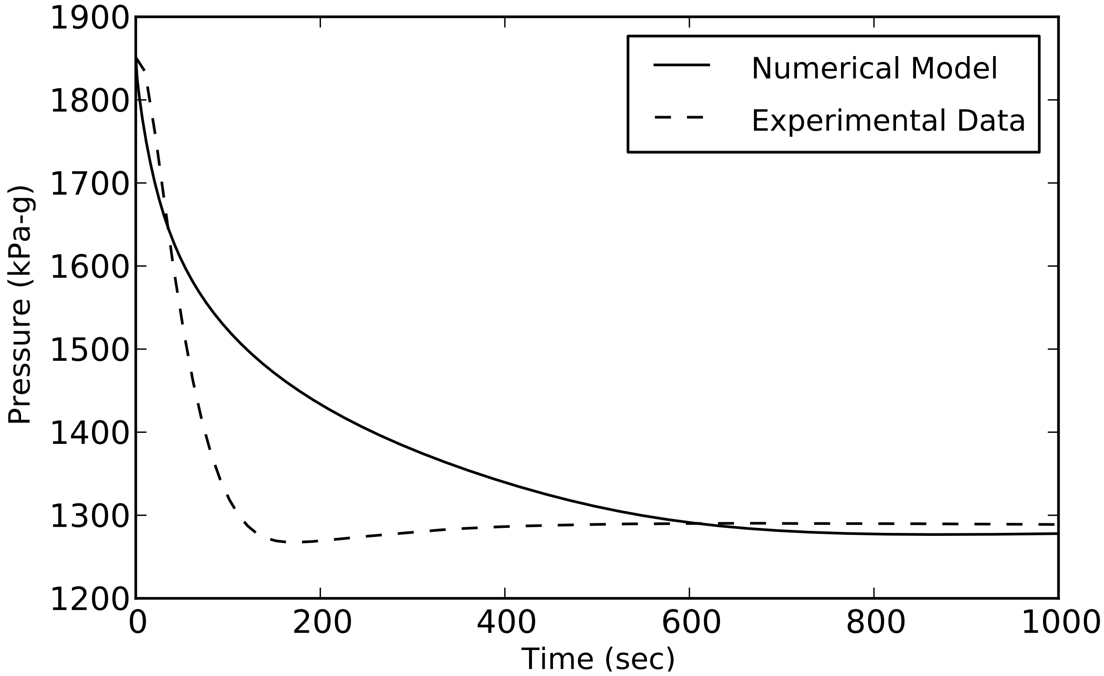

Figure 10: Reservoir Pressure

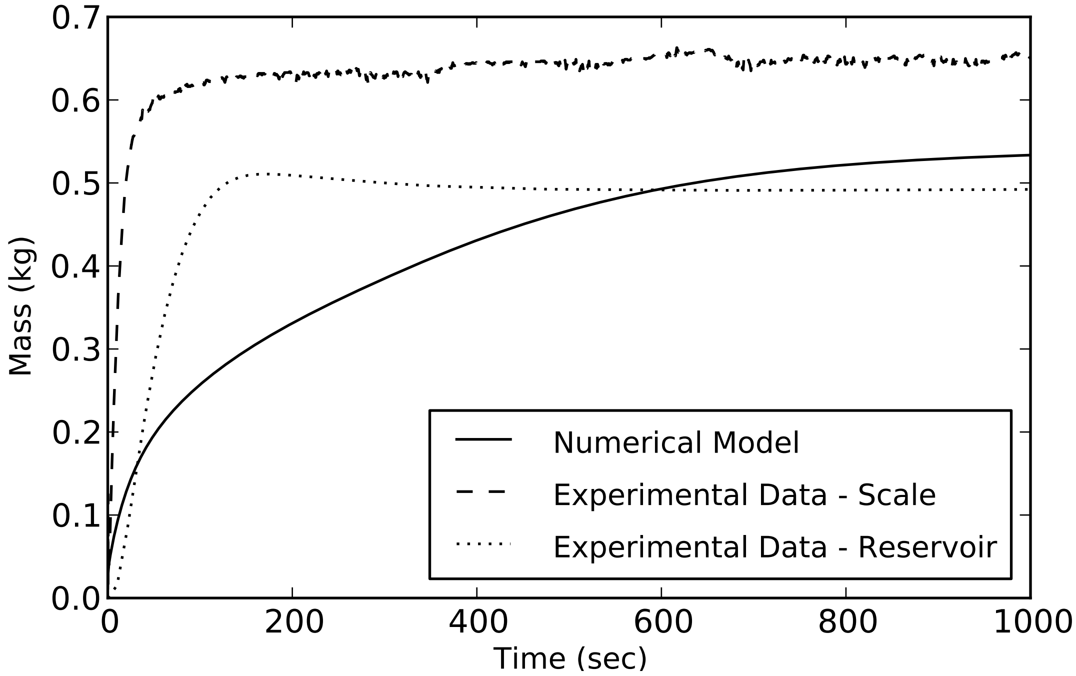

Figure 11: Numerical and Experimental Activated Carbon Mass Storage

The numerically calculated reservoir pressure is plotted with the experimental reservoir pressure in Figure 10. The mass storage, shown in Figure 11, is comparable to the mass calculated from the reservoir pressure. It was determined during testing that the scale was extremely susceptible to systemic error from environmental conditions or the initial influx of gas when the experiment was initiated.

4.4 Mass Storage and Degradation

The activated carbon module was subjected to a series of charge cycles with a maximum pressure of 270 psi. Each charge cycle lasted a duration of 2 hours (7200 sec), followed by a discharge to atmosphere of 2 hours. The initial and final mass of the vessel were recorded before and after each cycle in order to determine the maximum storage capacity and the degradation of the storage capacity. effects of degradation. The initial and final mass of the vessel as well as the calculated, v/v, storage capacity (ratio of volume of natural gas at STP to module volume) are shown in Table 4. In this Table, efficiency is defined as % of mass stored compared to first charge cycle. The results of storage capacity are nearly identical to those measured during 2010 testing [5]. For comparison, compressed natural gas at a pressure of 270 psi has a much smaller, v/v, storage capacity of 18.6.

The average decrease in storage capacity for charge cycle 11–17 was calculated to be approximately -1.29% efficiency per storage cycle. The literature results shown in Figure 12 (at charge cycle 15) showed a decrease in efficiency of approximately -0.53% efficiency per storage cycle. This indicates that the degradation rate of the activated carbon module tested was approximately twice that reported in literature [9]. This could be due to a larger fraction of heavy hydrocarbons in the Didsbury gas stream; however, the exact composition of natural gas in the literature degradation study is unknown.

Table 4: Experimental Efficiency as a function of cycle number

	Cycle Number						
	11	12	13	14	15	16	17
Initial mass (kg)	32.49	32.65	32.67	32.79	32.82	33.01	33.01
Final mass (kg)	33.42	33.51	33.52	33.62	33.64	33.81	33.81
Mass In (kg)	0.93	0.86	0.85	0.83	0.82	0.80	0.80
v/v storage	51.0	47.1	46.6	45.5	45.0	43.9	43.9
Efficiency	0.867	0.802	0.792	0.774	0.764	0.746	0.746

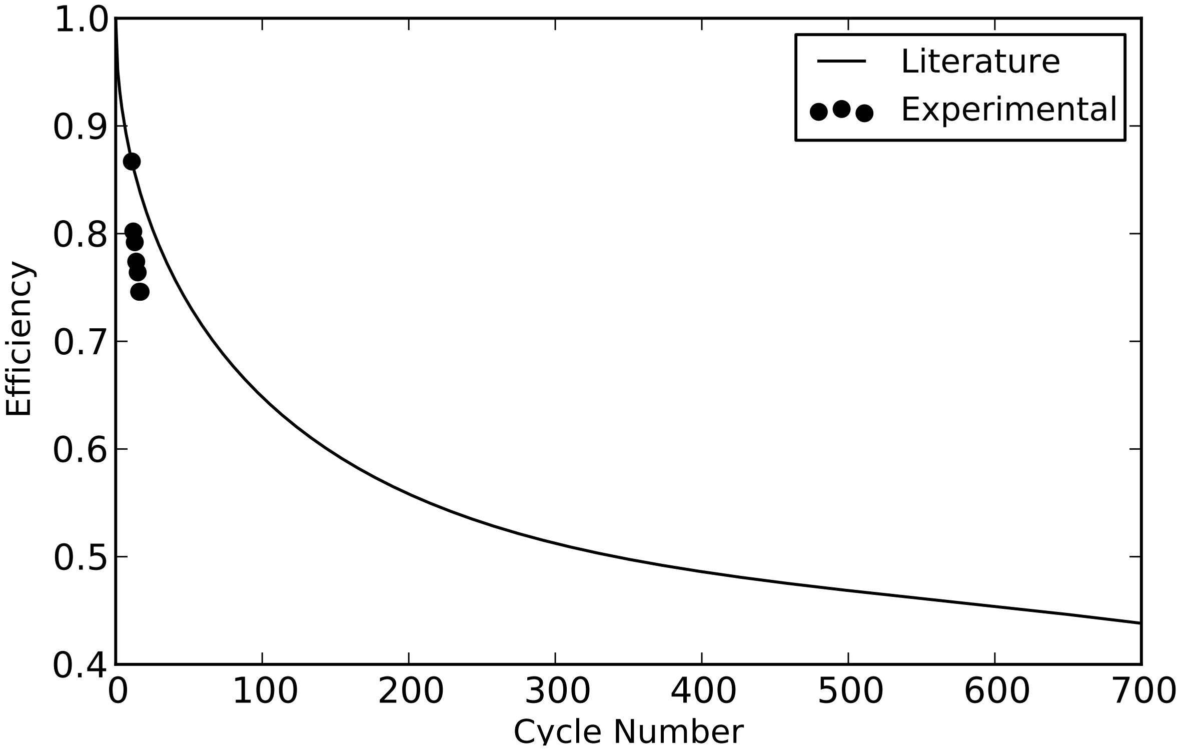

Figure 12: Experimental efficiency as a function of cycle number [9]

The v/v storage capacity of the activated carbon shown in Table 4 can also be compared to results of mass storage show in literature [10] (Figure 13). The activated carbon found in the experimentally tested module can described as granular.

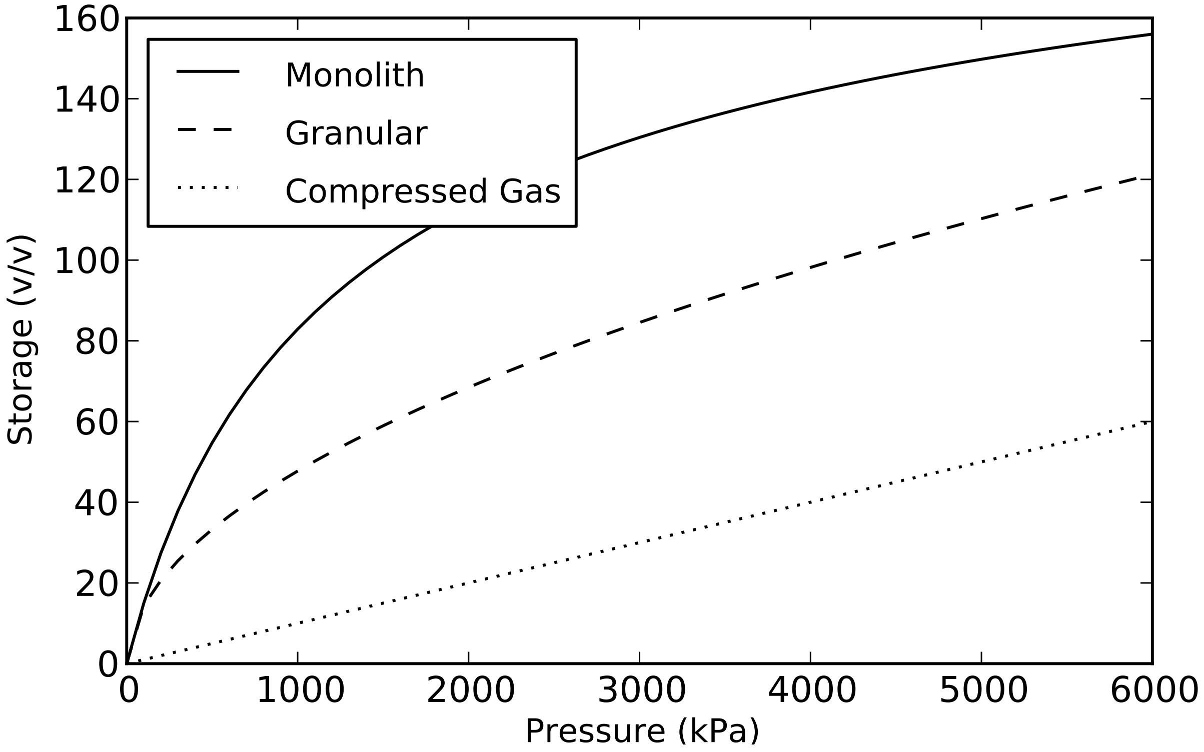

Figure 13: Advantica Isotherm Results [10]

5 Natural Gas Use Options

Recovery of natural gas from compressor casing blowdown becomes practical only if there are options to reclaim the natural gas after storage. If compression is required to feed the captured natural gas back onto the distribution network, or transportation to a facility with a low-pressure natural gas demand is required, recovering the natural gas becomes impractical.

Typical compressor stations have a number of systems that require a source of low-pressure natural gas. These systems include the central heating boiler, hot water tank, makeup air unit, and the alternate power unit. Natural gas required for these systems is supplied from the main pipline at a pressure of 800 psig where it undergoes two pressure cuts to 30 psig and 1 psig. This low-pressure gas demand can be supplied with gas recovered in activated carbon modules. A potential recovery system, shown in Figure 14, employs an activated carbon module, two hand valves, and a natural gas regulator. This system could be used to store gas during blowdown and slowly feed gas to the domestic gas systems after the modules are charged. The activated carbon module would be connected after the 30 psig pressure cut at a slightly higher feed pressure than the gas supply from the main pipeline. This would ensure that demand is first supplied with recovered compressor casing gas rather than gas from the main pipeline. A relatively small amount of gas would remain in the module at a pressure of 30 psig after desorption is complete.

6 Economic Analysis

An analysis for the installation of one activated carbon based natural gas recovery system installed at a TransCanada PipeLine Ltd. compressor station has been performed. The numerical model presented in the previous sections has been used to determine the final pressure of the compressor casing after blowdown and the total mass stored in the activated carbon module. The example recovery system used for this economic analysis has an activated carbon to blowdown volume ratio of approximately 10%. This recovery system is comprised of 4 activated carbon modules identical to the ones used in the simulated blowdown testing, as well as associated piping, valves and a regulator as required for the blowdown system shown in Figure 14. The estimated system component costs are shown in Table 5.

Table 5: Estimated System Costs

Component	Cost
Carbon Modules	$1770
Valves	$285
Regulator	$400
Piping	$500
Total Cost	**$2955**

Results from the numerical simulation indicate that this system will capture a total of 10.4 kg of natural gas at a pressure of 523 psig. This captured mass accounts for 25% of the mass of natural gas in the compressor casing assuming a compressor casing volume of 1 m^3 and an initial pressure of 750 psig. There are several reasons why only a small amount of natural from the compressor

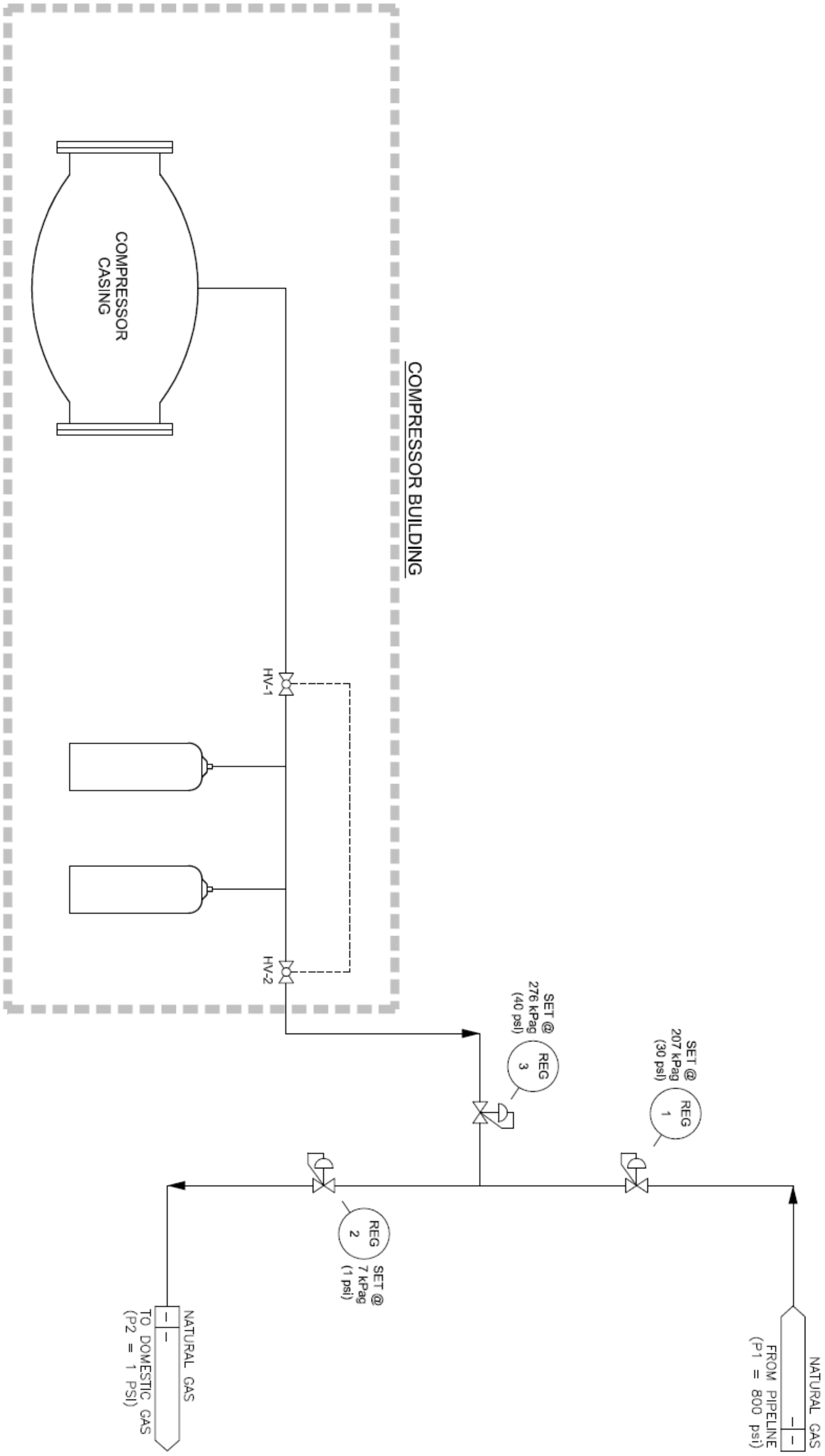

Figure 14: Natural Gas Use Option

casing is captured. An activated carbon to blowdown volume ratio of approximately 10% was chosen in order to keep the storage pressure in the activated carbon high. This takes advantage of the increased storage capacity of the activated carbon; however, a small activated carbon module stores less gas overall. A larger activated carbon module would capture more gas at a lower pressure but would also increase the cost of the system. More gas may be captured if a small pulldown compressor is used to compress gas into the module but the cost to buy one for this application would be prohibitive.

Assuming an average compressor casing blowdown frequency of four times per year, 41.6 kg of natural gas could be recovered annually. Methane emissions are considered to have 21 times the global warming potential of CO_2, therefore the equivalent CO_2 emissions (CO_2e) that could be abated with an adsorption recovery system would be 873.6 kg per year. At an average cost of \$3.24/GJ natural gas and \$15/tonne of CO_2e, this results in a cost savings of \$20.35/year per compressor unit.

Table 6 details the economic factors used for the analysis of one activated carbon natural gas storage system. A capital cost allowance (CCA) factor for Class 43.1: Capital Expenditures has been used. This class includes cogeneration and specified-waste fuelled electrical generation systems, active solar systems, and heat recovery systems. The discount rate and corporate tax rate have been specified for TransCanada capital projects.

Table 6: Economic Analysis Factors

	Name	Value	Units
Project Life	NY	30	years
Discount Rate	DR	12	(percent)
Corporate Tax Rate	X	29	(percent)
Equity	EQ	2955	$
Cost per GJ of Natural Gas	FCOST	3.24	$/GJ
Fuel Savings	FUEL	2.24	GJ/(a)
Cost per tonne of CO2e	CO2COST	15	$/tonne
Flow Rate of CO2	CO2	0.8736	(tonne CO2)/a
Total Revenue	TR	20.35	$/(a)
Maintenance, Repair and Overhaul (% of CAPEX)	MRO	10	(percent)
Capital Cost Allowance	CCA2	30	(percent)
Capital Expenditure	CAPEX	2955	$
Inflation Rate	INFR	4	(percent)
Inflation Rate (MRO, Fuel)	INFO	2	(percent)

In order to break even at the end of a 30-year project life, assuming no change in the cost of CO_2, the cost for recovered natural gas would have to be approximately \$101.16 per GJ. The current cost of recovered natural gas is \$3.24 per GJ, therefore a natural gas recovery system is not commercially viable at this time for this application.

7 Conclusions

Experimental testing was used to simulate a compressor casing blowdown. Further laboratory experiments were completed to produce a temperature and pressure dependent storage isotherm. Results from the simulated blowdown testing and isotherm testing were then used to produce a transient numerical model to predict the performance and mass storage of a full scale activated carbon based natural gas recovery system.

A complete economic analysis was performed to estimate the cost per kilogram of natural gas required to make a full-scale unit economical for compressor casing blowdowns. A potential system for recovering natural gas and using the gas on site at a typical compressor station was conceptualized for an estimate of the capital cost.

It has been concluded that an activated carbon based natural gas recovery system for compressor casing blowdowns is not currently commercially viable. In order for this system to be viable, there would have to be an increase in the cost of natural gas and/or greenhouse gas emissions or an application that requires a more frequent use of the technology. If an application was discovered where a system requires blowdown approximately 100 times per year with a nearby demand of low pressure natural gas this technology may be commercially viable.

8 Acknowledgements

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9 Nomenclature

A	Area (m^2)
C	Storage capacity (kg of gas/kg of activated carbon)
C_{pg}	Constant pressure heat capacity of gas (J/kg·K)
C_{ps}	Heat capacity of solid carbon (J/kg·K)
C_{vg}	Constant volume heat capacity of gas (J/kg·K)
d_{30}	30% sieve passing diameter of activated carbon material (m)
D_p	Particle diameter (m)
f_p	Ergun equation constant
Gr_p	Ergun equation constant
K	Permeability (m^2)
L	Length (m)
P	Pressure (Pa)
Q	Volumetric flow rate (m^3/s)
Re	Reynolds Number
T	Temperature (K)
V	Superficial velocity (m/s)
v/v	Ratio of volume of natural gas at STP to storage volume
ΔH	Heat of adsorption (J/kg)
ϵ	Void fraction of activated carbon
λ_{eff}	Effective thermal conductivity of activated carbon module (W/m·K)
μ	Viscosity (Pa·s)
ρ	Gas density (kg/m^3)
ρ_c	Carbon density (kg/m^3)

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