Steel fragilization due to emergency depressurization to protect gas compressor: real-scale experiment and modelling

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GRTgaz operates the largest transmission network in Europe with 33 700 km of pipelines, thousands of sectioning and delivery stations and 32 compressor stations. In these compressor stations, buildings for gas turbine compressors or for electric motor driven compressors are equipped with gas detectors. In case of confirmed gas detection, a fast depressurization can be launched automatically or remotely. This safety measure, through reducing indoor gas build-up, could protect compressors from damages caused by an enclosed explosion.

However, due to the fast depressurization, the released gas will cool down the steel pipes from the buildings to the vent stacks. Although no issue was reported in the past, GRTgaz was required by local authorities to assess the risk of steel fragilization associated with this fast depressurization. The objective is to verify whether the pipe failure and hence an uncontrolled release can be caused by this phenomenon.

To address this issue, GRTgaz has organized a real-scale test to measure steel temperature decrease during a depressurization and to validate modelling techniques. Through this experiment, GRTgaz is confident that these results can be extrapolated to different vent stack designs by using this validated model.

The modelling part was conducted by the Research and Innovation Centre for Energy (RICE) of GRTgaz. After a state-of-the-art review, RICE chose SYMMETRY, a software developed by VMG (Schlumberger Group), to perform the simulation. This 1D modelling tool simulates fluid thermodynamics for oil and gas processes and networks. One key function of this software is to simulate flaring and purging.

This article outlines the experimental set-up and makes a comparison of the measured temperatures and the calculated results. It can be concluded that, for the studied case, a steel brittle fracture is unlikely to be expected during a fast depressurization. The paper also discusses the accuracy of SYMMETRY in this kind of configuration and provides the main set-up options that can be used to obtain satisfactory results.

This article may help Hazards delegates to answer to similar questions from authorities or to model similar phenomena with SYMMETRY or equivalent software.

Introduction

GRTgaz activities and depressurization operations

GRTgaz operates the largest transmission network in Europe with 33 700 km of pipelines, thousands of sectioning and delivery stations and 32 compressor stations. GRTgaz is also strongly involved in the new challenges linked with the energy transition and aim to adapt its network for the new gases such as hydrogen. The company also acts for reducing CO_2 emissions and energy consumption.

In 2019, methane emissions accounted for 45% of scope 1 and scope 2 greenhouse gas emissions by GRTgaz. The company has set the ambitious target of reducing these emissions by a factor of three between 2016 and 2020. In 2019, this reduction was already 57% compared to 2016. At the same time, GRTgaz is committed to reducing energy consumption and emissions linked to gas compression.

Also, while pipe cutting is essential to carrying out work on the pipelines, GRTgaz uses “Gas booster” technology that empties pipeline sections by re-injecting the gas into the neighbouring pipeline, thus avoiding any atmospheric emissions. Over 90% of gas is currently recovered in this way. GRTgaz has ISO 14001 environment certification for all its compressor stations, and ISO 50001 certification for its energy performance and consumption. Apart from normal operations, methane releases still occur for safety purpose. Gas compressors are equipped with emergency depressurization systems which are automatically or manually activated after a confirmed gas detection inside a compressor hall.

Emergency depressurization purges gas lines connected to a gas compressor through a dedicated vent line. This system minimizes the risk of confined explosions that would damage the building and cause injury or fatality. This depressurization from several tens of bars to ambient pressure will cool down the released gas and, at the same time, the pipe walls. Local authorities asked GRTgaz to demonstrate that pipe wall temperature may not be lower than the limit allowed for steel integrity. The aim is to avoid a steel fragilization that could cause an uncontrolled gas release along the feed gas and vent lines.

Temperature range for pipeline design and temperature drop due to depressurization

Eurocode 3 standard recommends considering a temperature difference of more or less 35°C with the temperature of assembly. This temperature range must be between -40°C and +60°C. GRTgaz uses a slightly different rule which considers that the maximal difference between the temperature of assembly and the operating temperature is +/- 40°C. For a mean temperature of assembly of 20°C, the acceptable range temperature is between -20°C and +60°C which is consistent with climate in metropolitan France.

In case of emergency depressurization, it is necessary to calculate the temperature drop to identify cases where the steel temperature may exit from the allowed temperature range. A well-known rule of thumb consists in considering a gas temperature decrease of 0.5°C per bar drop. Another common assumption used for similar studies is to consider that the temperature drop of steel pipe is of the same magnitude of gas temperature drop. This assumption may conduct to specify stringent requirements on steel resilience or resilience test at unusually low temperatures.

To challenge this approach, GRTgaz conducted several experimental and theoretical works on steel fragilization. In 2021, GRTgaz performed a real-scale depressurization test to measure temperature decrease on pipe work close to the vent. The collected measures were then compared to calculations with the SYMMETRY © software. This article details the results of this work.

Experimental trials

Experimental set-up

GRTgaz chose to organize the trials at the compressor station of Etrez, about 100km north from Lyon (Southwest of France). The compressor station is close to an underground storage operated by Storengy (Engie Group), also located in Etrez.

The compressor station is equipped with electric-driven compressors and connects 8 pipelines (diameter from 450 to 120mm) at a maximal operating pressure of 67.7 or 80bar (g.).

The experiments organised in May 2021 consists in measuring temperature decrease during the depressurization of the vent lines. The length of the main pipeline of 600mm diameter is about 800m. With secondary pipes, the total purged length is about 2070m. The final line to the vent stacks is about 300m long with a 100mm diameter. The initial pressure is 49 bar (g.). The vent stacks are equipped with silencers (*Figure 1*), which diameters are 400mm.

Four thermocouples are placed on the 100mm vent line, 2 are near the silencer and 2 are located about 1 meter upstream. The temperature measurement is doubled at each location for a good robustness of results. Two thermocouples and a pressure transducer are also located close the emergency shutdown valves located in a pit. The thermocouples are PT100 probes and are attached on the external pipe wall with clamps.

Temperature probes used for process operations near compressors and air-cooling system are also recorded. Gas composition is also analysed during the test period.

The measurement records started 3 minutes before the opening of the safety valves and lasted after the complete depressurization to get both cool-down due to gas and final warm-up due to ambient air.

Figure 1 : Photography of the vent stacks

Figure 2 : Photography of the ESD pit

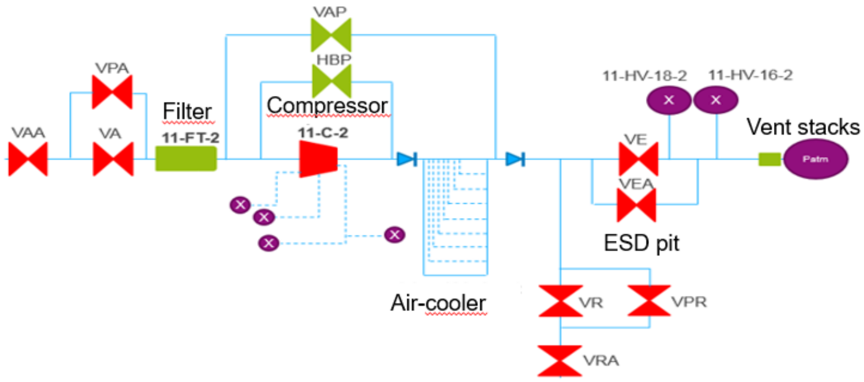

Figure 3 : Schematic view of the vented system

Experimental results

The depressurization drops from 49 bar(g) to ambient pressure in about 30 min as shown in Figure 4 and Figure 5. The minimal temperature recorded by the thermal probes are between -6°C to 1.2 °C depending on the location. For an initial temperature between 10 to 15°C, the temperature drop is about -14 to -17°C (Table 1).

Table 1 : Main experimental results from temperature probes

Probes	Initial temperature (°C)	Minimal temperature (°C)	Temperature drop (°C)
TIT35 (upstream compressor)	15.1	-1.6	-16.6
TIT76 (downstream compressor)	15.1	1.2	-13.9
TIT74 (upstream aircooler)	10.3	-6.1	-16.4
PT100-1 / PT100-2 (upper vent)	7.9 / 7.8	-7.3 / -8.5	-15.2 / -16.3
PT100-3 / PT100-4 (lower vent)	9.1 / 9.5	1 / 0.4	-8.1 / -9.1
TC 1/ TC 2 (ESD pit)	9.5 / 10.3	-4.3 / -4.1	-13.8 / -14.4

These results show that the measured temperature drop is less severe than the -25°C expected according to the rule of thumb of 0.5°C per bar loss.

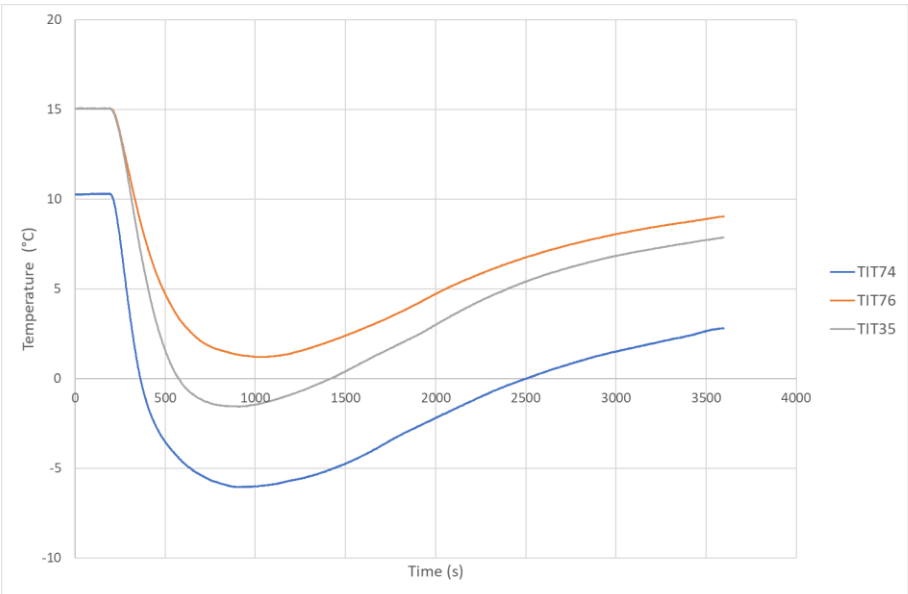

Figure 4: Temperature measurements during the depressurization test (process probes)

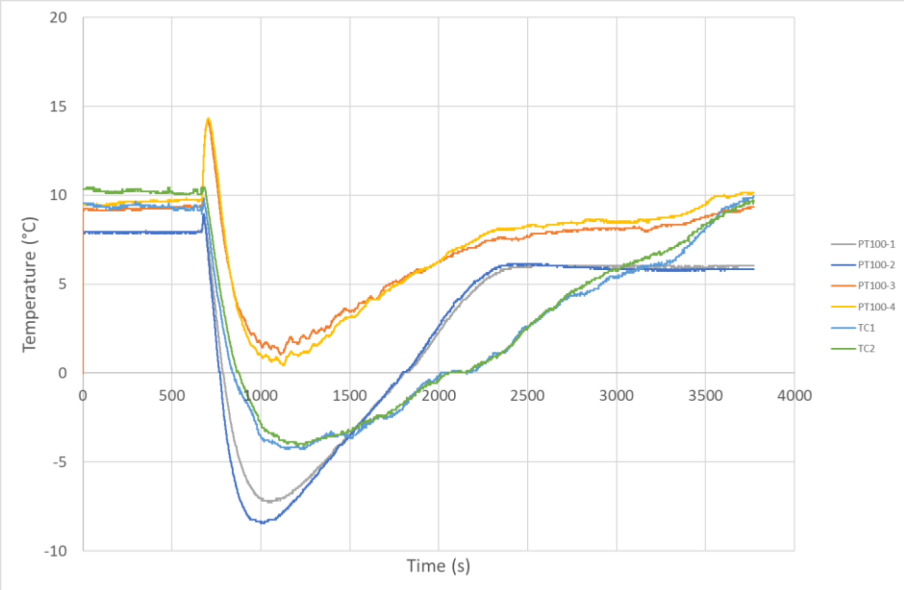

Figure 5: Temperature measurement during the depressurization test (test probes)

Depressurization simulations with SYMMETRY

The SYMMETRY software is developed by VMG, a Schlumberger group affiliate. It enables multiple process calculations for sizing and flow assurance. SYMMETRY models the facility with simple elements such as pipes, valves, compressors, etc.

In the dynamic mode, SYMMETRY can simulate vessel and/or networks depressurization by considering heat transfer and fluid dynamics. It couples several 1D models for each phenomenon, with a large panel of options and submodels to adjust accuracy and computational time.

Simulation set-up

To set up the calculations, RICE tested several sets of parameters and discussed with SYMMETRY developers. The first step of the case definition is to enter the fluid composition. Based on the chromatography measurements performed during the test, the following composition is defined in *Table 2*.

Table 2 : Gas composition used in SYMMETRY simulations

Gas compounds	Mole fraction
Methane	0.949
Nitrogen	0.0035
Carbon dioxide	0.0024
Ethane	0.039
Propane	0.0042
Isobutane	0.0009
n-Butane	0.0006
Isopentane	0.0002
n-Pentane	0.0001
n-Hexane	0.0001

The thermodynamical properties of the fluid are calculated with the “Advanded Peng Robinson Natural Gas 2” model, the most advanced option for natural gas flow modelling.

Then, the full geometry of the venting system is defined by indicating position and characteristics of the different pipelines, valves and fittings. The aim is to simulate the flow with a system as close as possible to the real geometry in order to ensure a correct pressure drop simulation. For fittings and valves, SYMMETRY proposes three methods to calculate the pressure drop. The default method is the Crane model [1], which estimates the pressure loss from a K factor given by an extensive database. As it is considered as a state-of-the-art technic, no comparison with the other methods has been performed. For the pressure drop due to friction along the pipeline, the Colebrook model [2] is used:

$$\Delta P = F\frac{L}{D}\rho v^2$$

$$\frac{1}{\sqrt{F}} = -2\,log\left(\frac{\varepsilon/_D}{3.7} + \frac{2.51}{R_e\sqrt{F}}\right)$$

With :
ΔP : pressure drop due to friction along the pipeline (Pa)
F : friction factor
L : pipe length (m)
D : pipe diameter (m)
ρ : gas density (kg/m^3)
V : gas velocity (m/s)
ε : pipeline roughness (m)
Re : Reynolds number

The pipeline roughness is chosen as 40 µm, which is a representative value for steel pipes after several years of operation.

Steel characteristics, wall thickness and ambient conditions are defined to calculate heat transfer between steel pipe and ambient air or ground. The model chosen for buried pipes is the Ground-T based, which is recommended for fully buried pipe. The ground temperature is set at 20°C, with a conduction constant of 1.5 W.m^{-1}.K^{-1}.

For above ground pipes, heat transfer with ambient air by natural convection is calculated by considering a constant heat transfer coefficient and ambient temperature (10°C). More detailed heat transfer models are available and will be tested. The inner convection is calculated with the *HTube mix* model based on Dittus-Boelter correlations [3].

Then, initial conditions in the components and streams are defined. The initial pressure is set homogeneously in the network and an exit pressure of 0 bar(g) is forced after the vent exhaust.

For this case, the dynamic solver is used. It proposes to choose different models to have detailed results for transient calculations. Based on developers' recommendations, the full *Do Pipe Transient DP Calc* model is selected to obtain more accurate results.

Finally, one of the main difficulty for this simulation is to model the silencer at vent exit. Interior of the silencer is neglected, even though it may affect pressure drop. Moreover, between the 100mm diameter vent line and the 400mm diameter silencer, there is a pipe reduction of 40mm diameter. This reduction create a sudden change in the flow, so SYMMETRY have difficulties to handle it. It creates numerical unstability after a relatively large simulation time.

Simulations results

The SYMMETRY simulation perfectly estimates the pressure decrease measured during the test. This way, it ensures that the exposure of pipes to the cold gas is correctly reproduced.

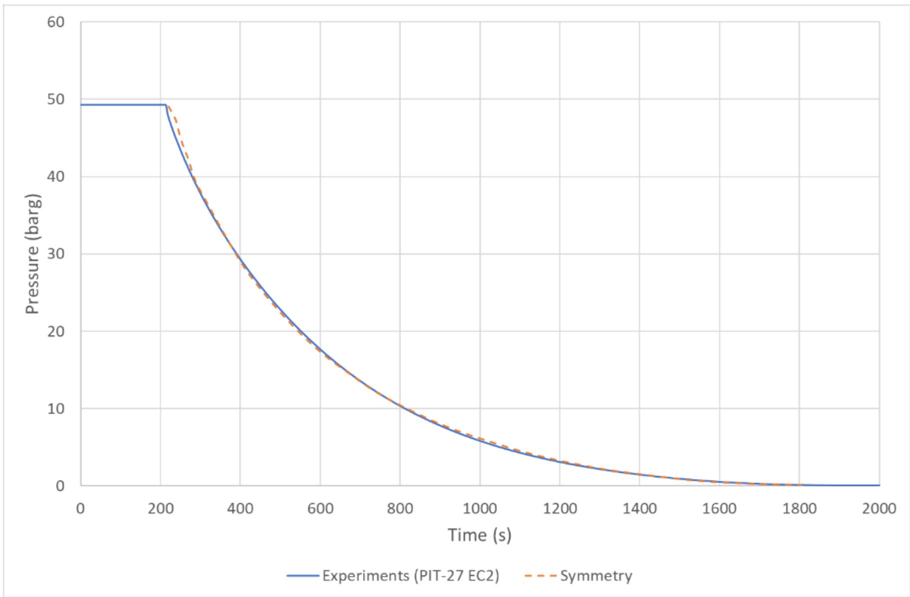

Figure 6: Pressure decreases measured and calculated with SYMMETRY

Figure 7, *Figure 8* and *Figure 9* illustrate the good prediction of the minimal temperature with SYMMETRY with a deviation of less than 2°C. The slope of temperature decrease is also very similar with the measurements.

For probes at the vent, the deviation of SYMMETRY with experiments is in the same order of magnitude of the deviation between the temperature probes. For the thermocouples in the ESD pit, SYMMETRY slightly overpredicts the temperature drop.

The temperature increase after the depressurisation is not as accurate, but it is still acceptable for the simulation since the main objective is to calculate the minimal temperature.

Figure 7 shows, at the end of SYMMETRY curve (see smaller dot area), a possible numerical unstability due to the 40mm diameter reduction. Without this reduction, the temperature drop is less accurate, but the temperature profile is still smooth during the temperature increase.

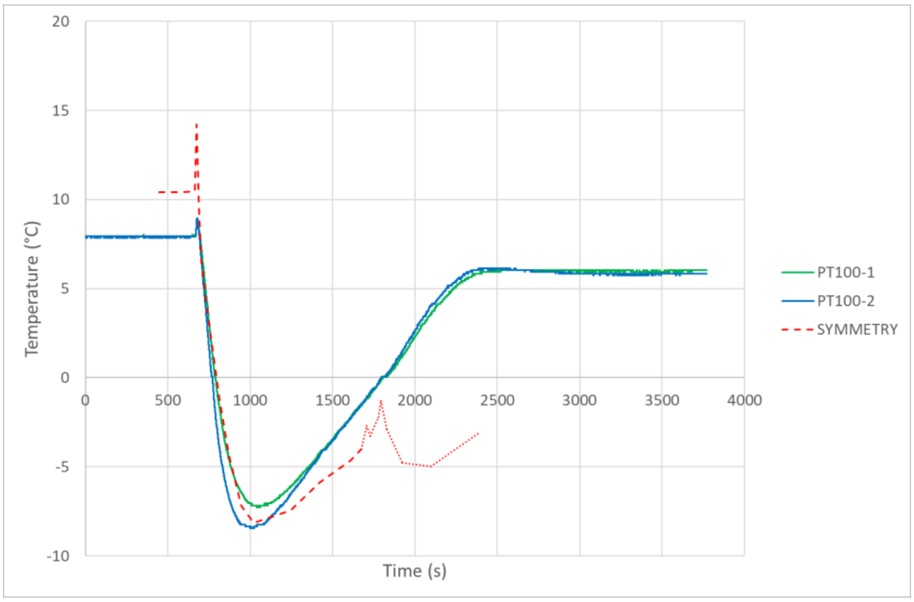

Figure 7: Comparison of calculated temperature and measured temperature at upper vent

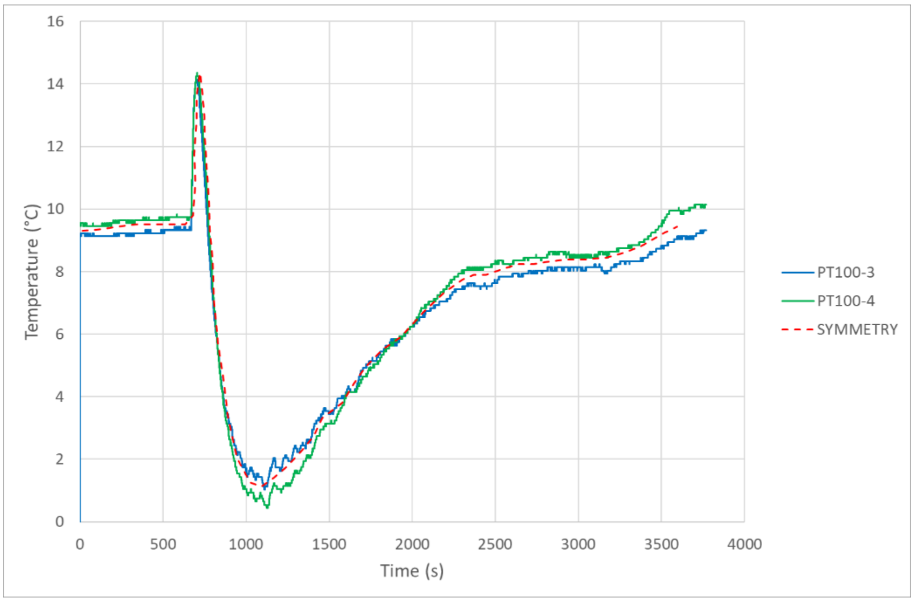

Figure 8: Comparison of calculated temperature and measured temperature at lower vent

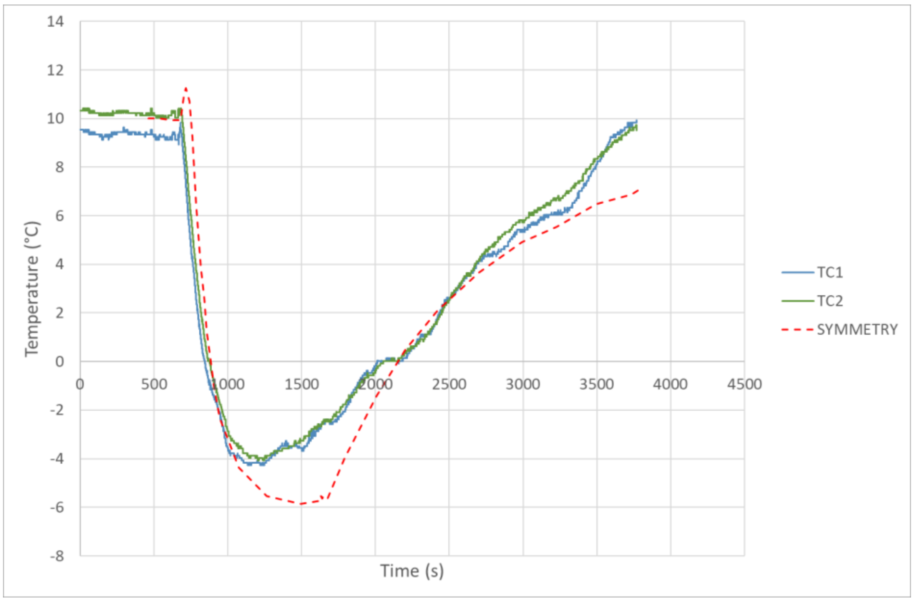

Figure 9: Comparison of calculated temperature and measured temperature in the ESD pit (TC1 / TC2)

Conclusions

The experimental trials of Etrez give valuable data about the pipe temperature decrease during an emergency depressurization. The temperature drop is about -8 to -17 °C, under the tested conditions. These values enable to build an argument to justify the choice of steel grades and explain that no damage or unusual fatigue are expected after this kind of depressurization.

The comparison of SYMMETRY with these data helps estimation of the accuracy of simulation to predict similar depressurization. The comparison indicates a very good agreement with pressure and temperature measurements. Consequently, with the validated setup, it is possible to simulate depressurization with different pipe geometries and different initial conditions to estimate the risk due to cold gas. Such simulations are ongoing for depressurization at sectioning stations.

References

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[3]. Peters, M.S. and Timmerhaus, K.D. , Plant Design and Economics for Chemical Engineers. International Edition, McGraw-Hill, New York, 1991.