CARBON DIOXIDE RECOVERY FROM GAS-FIRED POWER PLANTS

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Abstract. *Since 1996 the Brazilian electric sector has undergone a major restructuring. The aim of such change is to reduce the State's participation in the sector, and to induce the growth of private investments. In particular, this event created several opportunities for thermal power plant projects, leading to competition at the generation level. In this scenario of increased competition, the power plant efficiency becomes a key element for determining the feasibility and profitability of the project. Moreover, the utilization of the plant's own effluents as feedstock or as a source of additional revenue will impact positively in its economics. As an example, long-term additional revenues could be created by the sale of* CO_2 *extracted from the combustion products of thermal power plants. The production of* CO_2 *also contributes to mitigate the environmental impacts of the power plant project by significantly reducing its airborne emissions. This paper shows how a gas-fired power plant can extract and utilize* CO_2 *to generate additional revenue, contributing to a more competitive power plant.*

Keywords: *Combustion, Environmental Engineering, and Process & Energy Systems.*

1. CARBON DIOXIDE AS AN AIRBORNE POLLUTANT

Both the carbon oxides CO and CO_2 are found in the atmosphere. The concentration of CO_2 is much greater than that of CO due to the burning of organic material. Figure 1 shows the fast growth of the CO_2 concentration in the atmosphere in the past decades. The curve also shows that the rate of CO_2 concentration is increasing. If no actions are taken, catastrophic conditions would be expected.

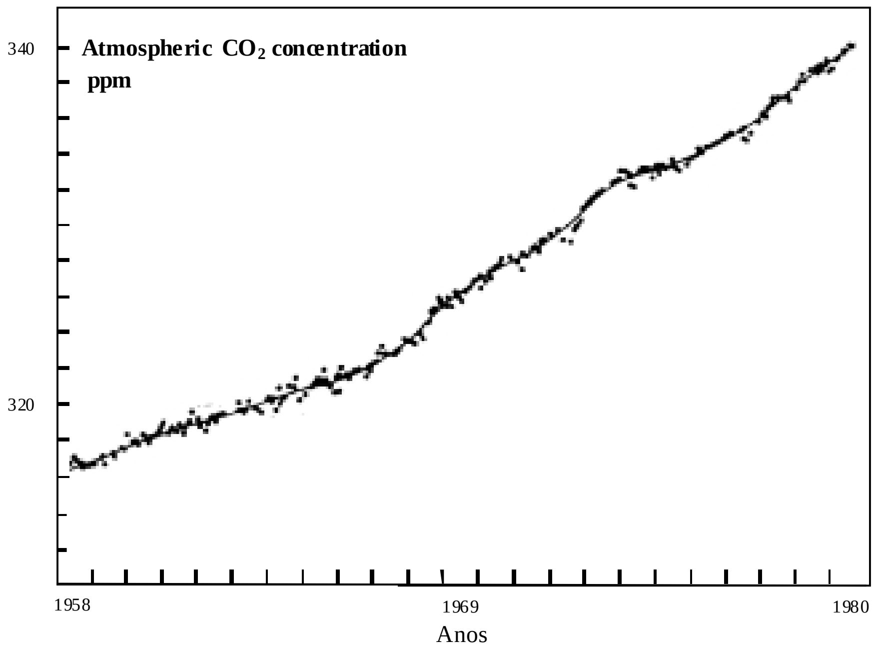
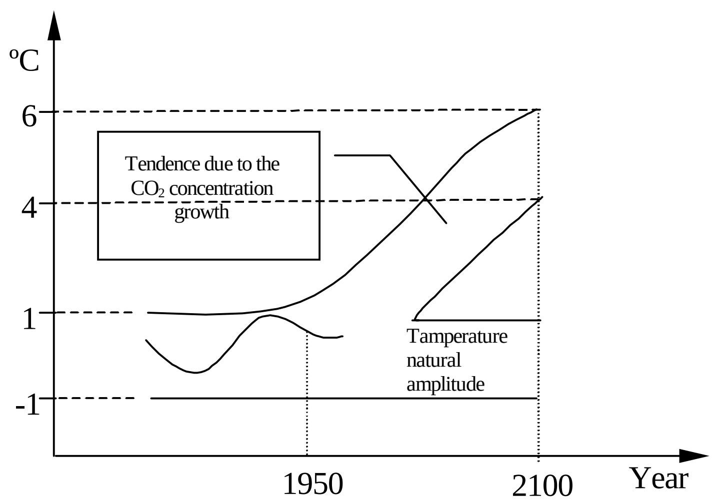


Figure 1: CO_2 concentration growth in the atmosphere - 1960's through 1980's. (El-Wakil, 1984)

The high concentrations of CO_2 in the atmosphere make it less transparent and cause it to retain more incoming solar radiant energy as well as more Earth radiant energy than would otherwise escape into space. This fact contributes to warm the lower part of atmosphere, the troposphere, creating a risk of serious damages to the environment throughout the world. This effect is called the green house effect. A graph with the forecast of the temperature increase on the planet is presented in the Figure 2. Based on Figure 2 we can observe that the average global temperature in the year 2010 shall rise by 4 to 6 ºC above the current level. Naturally this number reflects the current trend and assumes that no actions will be taken to mitigate these effects.



Source: Power Plant Technology, p. 719 (El-Wakil, 1984)

Figure 2. Global temperature increases forecasts considering the green house effect.

Carbon dioxide is mainly emitted by thermal power plants around the planet. It is formed inherently by both complete and incomplete combustion of fossil fuels. Its effects on human beings are felt only in high concentrations that are not found in the atmosphere nowadays.

Studies for CO_2 thermal machine emissions control have been the scientists and gas turbines engineers concern in the last decades. Energy efficiency programs are being conducted in almost all the developed and under developed countries. Besides, research is being carried out in a couple of power plant projects with carbon dioxide liquefaction, aiming at the reduction of the energy cost and generation of long-term revenues by either selling the combustion products to a CO_2 production company, or producing liquefied CO_2 and selling the final product directly to end-users.

2. CARBON DIOXIDE - COMMERCIAL ASPECTS

Carbon dioxide can be used basically in all three forms: as gas, as a liquid or as a solid. The versatility of CO_2 has stimulated its use in many industrial applications, from the beverage industry to the medical ones. The property to control fast cooling also makes the carbon dioxide a valuable tool in production processes and transportation. The inert properties of CO_2 make it an ideal agent and a pressure medium for many processes that cannot be performed by any other substance. The following are descriptions of some of the many applications for carbon dioxide.

2.1 Beverage and Food Industries

Its is perhaps one of the widest application of CO_2. The liquefied CO_2 can be used in packaging, tank counter pressure or carbonation. In the USA, industrial use of carbon dioxide is estimated to amount to 5,00,00 tons per year, of which approximately 70% are dedicated to the food and beverage industries. The cryogenic freezing processes alone use over 2,000,000 tons per year (Rushing, 1997). In such application the CO_2 can have a dual function either in the fast freezing and insuring longer shelf life, due to an anaerobic atmosphere created in a packaged product.

In this industry another growing segment is in pH reduction and water treatment applications. Specifically, in many processes the carbon dioxide is the safest and most easily controlled moderate acid, including pulp/paper, chemical, and effluent treatment.

2.2 Oil and Gas Industries

For oil and gas industries, carbon dioxide is utilized in enhanced oil recovery projects (EOR) (Rushing, 1997). For this kind of applications, in which it is used in very large volumes, CO_2 is often delivered without purification. That being so, if the power plant is strategic located near the wellhead, the CO_2 can also be delivered without undergoing the liquefaction process. The basic idea is to inject the CO_2 into the reservoir simultaneously with other treating fluids to obtain better oil and gas flows than that obtained from other stimulating techniques. This technique promotes faster clean up of wells, generally without the need to swab. On the oil and gas industry there are several other applications of carbon dioxide, even in solid forms. EOR is particularly applicable to onshore marginal fields with decayed production, such as those on northeast Brazil.

2.3 Agricultural

Since vegetables assimilate CO_2 in combination with sunlight, the presence of carbon dioxide is beneficial in the production of all forms of fruits and vegetables. Both yield and growth rates have been demonstrated improvement of as much as 40% in greenhouse tests under a controlled CO_2 atmosphere. In agriculture there are many other applications, namely: nursery produce, quick ripening of green fruits and vegetables for shelf storage in groceries and supermarkets, and controlled atmosphere for hops protection.

2.4 Freezing Systems

Liquefied CO_2 can be used as a refrigerant medium in chilling or freezing processes in tunnels or spiral systems. It is ideally suited for rapid production line chilling, crushing or freezing of meat patties, steaks, pastry items, chicken parts, fish fillets, etc. The latent heat absorption capability of liquid CO_2 flashed to a vapor phase at atmospheric pressure is utilized to rapidly extract heat from the product being processed. The effluent CO_2 vapor can be vented to the atmosphere or re-liquefied.

2.5 Other Uses

There are many other uses of carbon dioxide in its various forms and none are less important than the processes described above. Such additional processes include fire extinguishing, chemical industry, metals industry, plastic industry, pipelines, etc.

3. CO_2 RECOVERY FROM GAS-FIRED POWER PLANTS - COMMERCIAL AND TECHNICAL ASPECTS

3.1 Quantification of CO_2 Produced from Burnt Natural Gas

Hypothesis: (1) Natural Gas (NG) is composed by methane (CH_4) only; (2) complete combustion; (3) ambient temperature 25 ^oC, and (4) ambient pressure 101,3 kPa.

Results: Using the STP conditions and the hypothesis established above, it is possible to estimate that 1 m^3 of burnt natural gas produces 1,9643 kg_{CO2}. Applying the Ideal Gas Law, it is possible to estimate the production for 25 ^oC of ambient temperature, which reaches a figure of 1,7976 kg_{CO2}/ m^3_{NG}.

3.2 CO_2 Production in a 480 MW Gas-fired Power Plant

A 480 MW power plant at 25 ^oC ambient temperature typically uses 1,560 x 10^6 m^3_{NG}/day, considering an average capacity factor of 0,85. Burning such volume of natural gas this power plant will produce 2,804 x 10^6 kg_{CO2}/day. Being the factor that represents the mass relation between the CO_2 liquefied and the CO_2 generated about 0,10, the liquefied mass of CO_2 produced by such a power plant is about 280 ton_{CO2L}/day (Gaudernack & Lynunn, 1996).

3.3 Loss of Power

In terms of internal consumption and operating requirements for such CO_2 recovery from power plants, high-pressure average steam requirements is 2,5 ton_{steam} per ton of CO_2 recovered and the power consumption is about 1kW per ton of CO_2 recovered. Considering the 480 MW power plant, it could be assumed that 11% of the output is used to produce 280 ton_{CO2} per day. (Rushing, 1997)

4. CO_2 RECOVERY FROM GAS-FIRED POWER PLANTS - ECONOMIC ASPECTS

4.1 Business Structure

As the power plant operator usually has no expertise on the carbon dioxide market, it should associate to a commercial/industrial gas company to produce and sell the CO_2. In this partnership, the power plant would invest in its own facilities, leaving the purification and liquefaction investments to the commercial gas company, as shown in Figure 3.

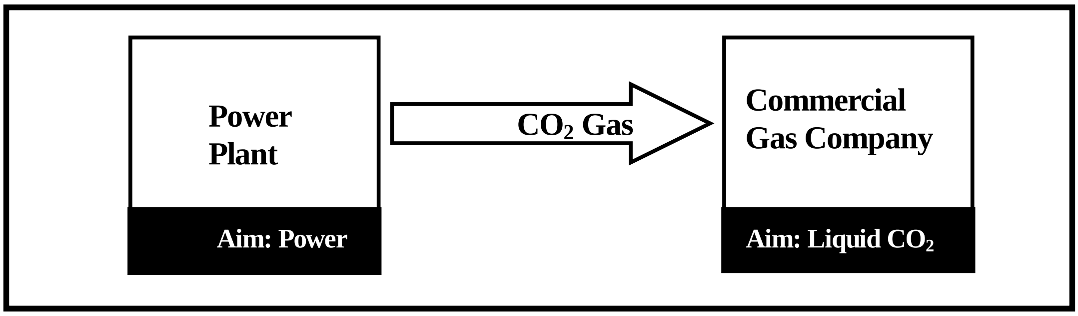


Figure 3. Proposed structure for CO_2 business.

4.2 CO_2 EOR Grade Estimated Price

The CO_2 without purification and liquefaction has its price estimated at about 25,04 US$/$ton_{CO2}$. This price refers only to the usable share of CO_2 gas.

4.3 Application of the Business Structure to a Finance Model of a 480 MW Gas-fired Power Plant

To demonstrate how much benefit a recovery CO_2 project might bring, a 480 MW gas-fired power plant in combined cycle was selected to be analyzed under two assumptions: a standard power plant and a power plant with a carbon dioxide recovery plant.

A conventional deterministic financial analysis was carried out and the Profit and Loss Account, of either the standard or the CO_2 recovery plant, were obtained. Table 1 and Table 2 show the results. The discount rate utilized to achieve the Net Present Value (Bradley & Mayers, 1992) was worth 21% per year. The discount rate at 21% per year was chosen to show that depending on the case, the recovery of CO_2 from a gas-fired power plant is the only way to make some projects feasible.

Table 1. Profit and Loss Account of a standard power plant operation (US$ 1,000,000)

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Case 1: Not Considering the CO2 Revenues ***Total Investment:*** ***300.00***

DRE		2000	2001	Year 1 2002	Year 2 2003	Year 3 2004	Year 4 2005	Year 5 2006	Year 6 2007	Year 7 2008	Year 8 2009	Year 9 2010	Year 10 2011	Year 11 2012	Year 12 2013
Power	480														
Capacity Factor	85%														
Loss of Power	0%														
Fiem Energy (MW)	408	-	-	408.00	408.00	408.00	408.00	408.00	408.00	408.00	408.00	408.00	408.00	408.00	408.00
Energy Price (US$/MWh)	35.00	-	-	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00
Energy Revenues:				125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09
CO2 Quantity (ton/dia)	0.00			-	-	-	-	-	-	-	-	-	-	-	-
CO2 Price (US$/ton)	0.00														
CO2 Revenues:				-	-	-	-	-	-	-	-	-	-	-	-
Gross Revenue		-	-	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09
Taxes		-	-	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42
PIS	0.65%	-	-	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
COFINS	2.00%	-	-	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
CPMF	0.38%	-	-	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
ANEEL Fiscaliza+C31t	0.50%	-	-	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Net Earnings		-	-	120.68	120.68	120.68	120.68	120.68	120.68	120.68	120.68	120.68	120.68	120.68	120.68
Opertional Expenses:		-	-	87.04	87.04	87.04	87.04	87.04	87.04	87.04	87.04	87.04	87.04	87.04	87.04
O&M (US$ Millions)	12.000	-	-	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
Depreciation	5.00%	-	-	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Fuel (US$/MWh)	16.80	-	-	60.04	60.04	60.04	60.04	60.04	60.04	60.04	60.04	60.04	60.04	60.04	60.04
Operating Revenue		-	-	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63	33.63
Operational Result		-	-	13.09	20.79	20.79	18.71	16.63	14.55	12.47	10.40	8.32	6.24	4.16	2.08
Interest	11.00%	-	-	13.09	20.79	20.79	18.71	16.63	14.55	12.47	10.40	8.32	6.24	4.16	2.08
(+) CPMF		-	-	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
EBIT		-	-	21.02	13.32	13.32	15.40	17.48	19.55	21.63	23.71	25.79	27.87	29.95	32.03
Income Tax	25.00%	-	-	5.23	3.31	3.31	3.83	4.34	4.86	5.38	5.90	6.42	6.94	7.46	7.98
Social Contribution	8.00%	-	-	1.68	1.07	1.07	1.23	1.40	1.56	1.73	1.90	2.06	2.23	2.40	2.56
Net Profit		-	-	14.11	8.95	8.95	10.34	11.73	13.13	14.52	15.91	17.30	18.70	20.09	21.48
Cash Flow		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Net Profit		-	-	14.11	8.95	8.95	10.34	11.73	13.13	14.52	15.91	17.30	18.70	20.09	21.48
(+) Depreciation		-	-	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
(-) Amortization		-	-	-	-	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90
(-) CPMF		-	-	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
(+) Loans		-	119.00	70.00	-	-	-	-	-	-	-	-	-	-	-
(-) Investments		30.00	170.00	100.00	-	-	-	-	-	-	-	-	-	-	-
Final Cash		(30.00)	(51.00)	(1.37)	23.47	4.57	5.96	7.36	8.75	10.14	11.54	12.93	14.32	15.72	17.11
IRR		13.93%													
NPV @ 21%		(29.58)													
Debit Balance		-	119.00	189.00	189.00	170.10	151.20	132.30	113.40	94.50	75.60	56.70	37.80	18.90	(0.00)

5. CONCLUSION

Carbon dioxide recovery from gas-fired power plants represents an effective strategy for CO_2 emission control and an effective way to create long-term revenue for thermal power plant.

When evaluating the profit and loss account, it was identified that the power plant with CO_2 recovery had its internal rate of return (IRR) increased by 11% when compared to the standard power plant. The net present value (NPV) calculated at 21% discount rate, which was negative (-US$ 29.8 million) in the standard power plant, became positive (US$ 16.4 million) with the CO_2 recovery power project.

As demonstrated in this paper, carbon dioxide recovery can effectively be used to enhance the economics of power generation projects. On extreme cases, it can be employed to make weak or marginal projects feasible.

This technology also has positive externality effects, as it contributes to reduce CO_2 emissions to the atmosphere and so mitigating one of the potential causes of global warming.

Table 2. Profit and Loss Account of a recovery CO_2 power plant operation (US$ 1,000,000)

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Case 2: Considering the CO2 Revenues ***Total Investment:*** ***300.00***

DRE		2000	2001	Year 1 2002	Year 2 2003	Year 3 2004	Year 4 2005	Year 5 2006	Year 6 2007	Year 7 2008	Year 8 2009	Year 9 2010	Year 10 2011	Year 11 2012	Year 12 2013
Power	480														
Capacity Factor	85%														
Loss of Power	11%														
Fiem Energy (MW)	363.12	-	-	363.12	363.12	363.12	363.12	363.12	363.12	363.12	363.12	363.12	363.12	363.12	363.12
Energy Price (U$/MWh)	35.00	-	-	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00
Energy Revenues:				111.33	111.33	111.33	111.33	111.33	111.33	111.33	111.33	111.33	111.33	111.33	111.33
CO2 Quantity (ton/dia)	280.40			0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
CO2 Price (U$/ton)	250.40														
CO2 Revenues:				25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63
Gross Revenue		-	-	136.96	136.96	136.96	136.96	136.96	136.96	136.96	136.96	136.96	136.96	136.96	136.96
Taxes		-	-	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83
PIS	0.65%	-	-	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
COFINS	2.00%	-	-	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74
CPMF	0.38%	-	-	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
ANEEL Fiscalization	0.50%	-	-	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Net Earnings		-	-	132.13	132.13	132.13	132.13	132.13	132.13	132.13	132.13	132.13	132.13	132.13	132.13
Opertional Expenses:		-	-	80.44	80.44	80.44	80.44	80.44	80.44	80.44	80.44	80.44	80.44	80.44	80.44
O&M (US$ Millions)	12.000	-	-	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
Depreciation	5.00%	-	-	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Fuel (US$/MWH)	16.80	-	-	53.44	53.44	53.44	53.44	53.44	53.44	53.44	53.44	53.44	53.44	53.44	53.44
Operating Revenue		-	-	51.69	51.69	51.69	51.69	51.69	51.69	51.69	51.69	51.69	51.69	51.69	51.69
Operational Result		-	-	13.09	20.79	20.79	18.71	16.63	14.55	12.47	10.40	8.32	6.24	4.16	2.08
Interest	11.00%	-	-	13.09	20.79	20.79	18.71	16.63	14.55	12.47	10.40	8.32	6.24	4.16	2.08
(+) CPMF		-	-	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
EBIT		-	-	39.12	31.42	31.42	33.50	35.57	37.65	39.73	41.81	43.89	45.97	48.05	50.13
Income Tax	25.00%	-	-	9.76	7.83	7.83	8.35	8.87	9.39	9.91	10.43	10.95	11.47	11.99	12.51
Social Contribution	8.00%	-	-	3.13	2.51	2.51	2.68	2.85	3.01	3.18	3.34	3.51	3.68	3.84	4.01
Net Profit		-	-	26.23	21.07	21.07	22.47	23.86	25.25	26.64	28.04	29.43	30.82	32.22	33.61

Cash Flow	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Net Profit	-	-	26.23	21.07	21.07	22.47	23.86	25.25	26.64	28.04	29.43	30.82	32.22	33.61
(+) Depreciation	-	-	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
(-) Amortization	-	-	-	-	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90
(-) CPMF	-	-	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
(+) Loans	-	119.00	70.00	-	-	-	-	-	-	-	-	-	-	-
(-) Investments	30.00	170.00	100.00	-	-	-	-	-	-	-	-	-	-	-
Final Cash	(30.00)	(51.00)	10.71	35.55	16.65	18.05	19.44	20.83	22.22	23.62	25.01	26.40	27.80	29.19
IRR	24.96%													
NPV @ 21%	16.43													
Debit Balance	-	119.00	189.00	189.00	170.10	151.20	132.30	113.40	94.50	75.60	56.70	37.80	18.90	(0.00)

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