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Project Summary

Fired Heaters: Nitrogen Oxides Emissions and Controls

S. Anwar Shareef, Carol L. Jamgochian, and Lawrence E. Keller

The petroleum refining and chemical manufacturing industries account for most of the fired heater energy use. An estimated 4,600 fired heaters are in operation in these two industries, Nitrogen oxides (NO_X) are formed in fired heaters by two mechanisms: thermal NO_X and fuel NO_X. This study briefly describes the design and operation of fired heaters. Descriptions of the two major industries with fired heaters and the various heater applications are presented. An estimate is made of the growth in fired heater energy demand and the number of new fired heaters to be built in the next 5 years in these industries. The factors affecting NO_X emissions from fired heaters are discussed and quantitative relationships are presented, where available. Combustion modifications and flue gas treatment controls for NO_X emissions are described. Low excess air (LEA) operation and low-NO_X burners are discussed in detail. Long-term continuous NO_X emissions data for 12 petroleum refinery heaters are presented. Results of a regression model to predict the effect of stack oxygen level on NO_X emissions are used to evaluate LEA performance. This study also presents capital and annualized costs for LEA and low-NO_X burner controls.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The purpose of this study is to characterize NO_X emissions form fired heaters, identify applicable control techniques, and present the costs associated with these control techniques. A fired heater is a heat transfer device in which heat liberated by the combustion of fuels is transferred to fluids contained in tubes. The major applications of fired heaters are in the petroleum refining and chemical manufacturing industries. There are two basic functional categories of fired heaters applications: (1) the simplest are heaters designed to increase the temperature of a feedstock stream prior to additional processing (e.g., distillation column feed preheaters and reboilers); and (2) fired reactors in which high-temperature chemical reactions are carried out in the heater tubes (e.g., steam-hydrocarbon reformers used in ammonia and methanol manufacturing, and pyrolysis furnaces used in ethylene manufacturing). The fuels used for fired heaters include natural gas, refinery gas, and various grades of fuel oil.

NO_X is formed in fired heaters by two mechanisms: thermal NO_X formation and fuel NO_X formation. Thermal NO_X is the result of the reaction between atmospheric nitrogen and oxygen, while fuel

NO_x is the result of the reaction between fuel-bound nitrogen and oxygen. The various heater designs and operating parameters that affect NO_x emissions are described in this study. When available, quantitative data are presented from previous studies showing the relationship between these parameters and NO_x emissions

This study also summarizes short-term (1-2 hour) NO_x emissions data for about 150 fired heaters in various applications. While most of these data were collected and reported in previous studies, some were obtained directly form various plants specifically for this study In addition, continuous long-term NO_x emissions data were obtained in this study for 12 heaters at three petroleum refineries, two of which continuously monitor NO_x emissions for regulatory compliance purposes. Data on one heater at the third refinery were collected over a 45-day period in a previous EPA study Table 1 describes the heaters in the continous long-term data base.

The continuous data included from about 540 to 3,400 hourly data points for each heater. The hourly measurements included NO_x emission rates, stack oxygen levels, fuel firing rate, fuel gas hydrogen content, and the energy basis ratio of gas to oil (where applicable). Table 2 presents a summary of the long-term data. These data were analyzed statistically to quantify the effect of stack oxygen level on NO_x emissions. A multiplicative functional form based on the Zeldovich mechanism for thermal NO_x formation was found to adequately correlate the data.

The basic form of the model used is:

$$E = C_1 L^{C_2} A^{C_3} (1+R)^{C_4} (1+H)^{C_5}$$

where:

E = NO_x emissions (lb/MM Btu)

L = fuel firing rate expressed as a fraction of the design thermal energy release

$$\left(L = \frac{\text{Fuel firing rate, Btu/hr}}{\text{design thermal capacity, Btu/hr}}\right)$$

A = stack oxygen (volume fraction of O_2)

R = oil fraction, ratio of oil-fired heat release to total fuel-fired heat release. When no oil is fired, R = O and model parameter C_4 has no meaningful value.

H = fuel gas hydrogen content (volume fraction of H_2). When no fuel gas hydrogen data are available, model parameter C_5 is assigned a value of zero.

C_1, C_2, C_3, C_4, and C_5 = model coefficients that indicate the effect of the corresponding variables on NO_x emissions.

The model coefficients were fit to the NO_x emissions data using a statistical procedure known as autocorrelative regression. The autoregressive model accounts for any effects on the coefficients of autocorrelation associated with the sequential nature of the data. Using the results of the regression analysis, NO levels were predicted for the 12 heaters at various oxygen levels. This allowed for a determination of the effectiveness of low excess air (LEA) operation on NO_x emissions as well as for a comparison of NO_x emissions from different heater/burner types at the same stack oxygen level.

The two major combustion modification control techniques discussed in this report were LEA operation and low-NO_x burners. LEA operation of fired heaters can be achieved by (1) manual damper control systems based on oxygen monitoring and increased operator attention,and (2) automatic damper control systems based on oxygen monitoring (and/or other process monitoring) and microprocessor control. Low-NO_x burners can be used alone or in combination with LEA operation. The major type of low-NO_x burner is the staged air burner which employs staged air addition to the fuel stream. A more recent type of low-NO_x burner is the staged fuel burner which also uses staged combustion to reduce NO_x formation, but with reversed staging.

Cost estimates were made for LEA and low-NO_x burner controls. The energy credits associated with LEA operation were also estimated

Conclusions

The following conclusions were derived from this study:

- The petroleum refining and petrochemical industries account for the major fired heater use. The estimated fired heater energy consumption in the petroleum refining industry in 1985 is approximately 2.2 x 10^{14} Btu/yr.* The 1985 chemical industry fired heater energy consumption is estimated to be 6.8 x 10^{14} Btu/yr.
- The annual increase in fired heater energy consumption in the petroleum refinery industry is estimated to be 14.6 x 10^{12} Btu/hr. It is projected that approximately 80 new fired heaters will be built in the petroleum refining industry over the next 5 years.
- The annual increase in fired heater energy consumption in the chemical industry is estimated to be about 14.7 x 10^{12} Btu/hr. About 100 fired heaters are projected to be built in the chemical industry over the next 5 years.
- Almost 100 percent of the fired heater applications in the petroleum refining industry are low and medium temperature heaters. About 81 percent (energy basis) of the fired heater applications in the chemical industry are high temperature heaters (ethylene pyrolysis furnaces and steam hydrocarbon reformers).
- The major heater design parameters affecting NO_x emissions are fuel type (i.e., N_2 content of the fuel), burner type, use of combustion preheat, and firebox temperature.
- The major heater operating parameters affecting NO_x emissions are excess air level, degree of combustion air preheat, and oil/gas ratio for heaters firing combined fuel.
- The control techniques that have been used on fired heaters in commercial applications include low excess air (LEA) operation, low-NO_x burners staged air lances, flue gas recirculation selective catalytic reduction, and selective noncatalytic reduction.
- LEA control systems are applicable to all fired heaters. Manual and automatic damper control systems designed to reduce excess air levels can be used with natural or mechanical draft and with gas, oil, or gas/oil combination burners.
- At least 55 fired heaters use automatic LEA control systems and many others use manual LEA control systems based on oxygen monitoring.
- The target stack oxygen level for most heaters operating with LEA is 2-3%. The lowest long-term average oxygen level for heaters in the data base was 2%.
- The average stack oxygen level for about 180 heaters for which data were obtained in this study was 5.5%.

*To convert to metric 1 Btu = 1054 3 J or 0 252 Kcal

- Statistical analysis of continuous long-term NO_x emissions data for 12 petroleum refinery heaters indicated an average of 9% reduction in NO_x emissions per 1% reduction in stack oxygen level. The individual reduction in NO_x emissions ranged from 4.4 to 16.4%. Table 3 shows the predicted variation in NO_x at 100% load and varying stack oxygen levels.
- No effect of burner or draft type was found on the NO_x/O_2 relationship.
- Two major burner vendors have indicated that about 50 to 65% of their new burner sales are low-NO_x burners.
- No conclusion about the performance of low-NO_x burners could be derived from the continuous monitoring data because other design differences between heaters obscure the effect of low-NO_x burners
- Test-scale data from burner vendors indicate that NO_x emission reduction with the use of staged *air* burners ranges from 38 to 40% compared to conventional burners NO_x emission reduction associated with the use of staged *fuel* burners ranges from 70 to 72% compared to conventional burners
- Staged combustion air lances have been demonstrated for 15 days on a natural-gas-fired, natural draft heater. The same heater was retrofitted with forced draft and tests were conducted for 30 days with staged air lances
- Regression modeling results showed that at a fixed stack oxygen level, natural draft air lances reduced NO_x emissions by 50 to 60% relative to baseline (without staged air lances). Forced draft air lances further reduced emissions by 30 to 50% relative to natural draft air lances.

Table 1 *Description of Heaters in the Long Term Continuous Monitoring NO_x Emissions Data Base*

Heater Code	Water/Burner[a] Classification	Plant Heater Designation	Heater Designation	Heater Capacity (MMBtu/hr)	Number of Burners	Burner Manufacturer	Burner Model No.	Data Source[b]
A	G - RGB - ND	F-20	Vacuum Crude	28 7	6	National Airoil	#30 FA VHESP	1
B	G - RGB - ND	F-603	Naphtha Desulfurizer	9.8	1	John Zink	VYD-PC-22	1
C	G - PMB - ND	F-601	Naphtha Reformer	70 8	70	John Zink	VPM-12	1
D	G - PMB - ND	F-602	Desulfurizer	18.4	4	John Zink	VDPM-18	1
E	G - PMB - ND	F-602	Gas-Oil	18.4	4	John Zink	VDPM-18	1
F	G - SAB - ND	9H1-9H4 (common stock)	Reformer Charge	87.0	15	John Zink	DBA[c]	2
G	G - SAB - ND	12 - H1	Light Ends	39.6	8	John Zink	LN-PC-14	2
H	G - SAB - ND	–	Atmospheric Crude	18	3	John Zink	LNC-16	3
I	G - SAB - ND	F-1	Atmospheric Crude	86.3	8	John Zink	MA-PC-16[d]	1
					1		MA-PC-20[d]	1
J	G - RGB - MD/PH	F-603	Naphtha Desulfurizer	9.8	1	John Zink	PLNV-50	1
K	O/G - SAB - ND	10 - H1	Atmospheric Crude	110.6	8	John Zink	LN-PC-18	2
L	O/G - SAB - ND	11 - H1	Atmospheric Crude	37.0	4	John Zink	LN-PC-16	2

[a] Fuel Type - burner type - draft type/preheat.
Notation G = gas-fired, O/G = combination of oil and gas fired, RGB = conventional raw gas burner; PMB = conventional premix burner; SAB = staged air burner; ND = natural draft, MD = mechanical draft, PH = combustion air preheat.

[b] Data Source Key
1 = USA Petrochem refinery in Ventura, CA.
2 = Getty Refining and Marketing Company refinery in Bakersfield, CA.
3 = Report EPA/600/7-83/010 (NTIS PB 83-168 633).

[c] Modified with steam injection for lower NOx production.

[d] Modified with air staging for lower NOx production

[e] To convert to metric. MMBtu/hr (10^6 Btu/hr) = 0.2929 MW_t.

Table 2. Summary of Data in the Long Term Continuous Monitoring NO_x Emissions Data Base

Heater Code	Water/Burner[a] Classification	Test Period	Parameter	Number[c] Data Points	Average	Range	Standard Deviation
A	G - RGB - ND	11/81 to 4/82	Stack O_2 (%)	3448	5.06	0.3-12.3	1.92
			Fuel Firing Rate (MMBtu/hr)[d]	3445	23.6	13.2-40.4	6.94
			NO_x Emissions (lb/MMBtu)[d]	3445	0.11	0.03-0.24	0.042
B	G - RGB - ND	11/81 to 12/81	Stack O_2 (%)	1399	8.76	1.4-15.7	3.10
			Fuel Firing Rate (MMBtu/hr)	1401	5.6	2.1-7.1	0.45
			NO_x Emissions (lb/MMBtu)	1399	0 10	0.03-0.17	0.026
C	G - PMB - ND	7/78 to 12/78	Stack O_2 (%)	2096	3.15	0.1-17.0	1.43
			Fuel Firing Rate (MMBtu/hr)	3095	48.9	13.0-65.0	6.4
			NO_x Emissions (lb/MMBtu)	3095	0.09	0-0.28	0.033
		11/81 to 4/82	Stack O_2 (%)	3321	3.81	0.3-12.9	1.75
			Fuel Firing Rate (MMBtu/hr)	3321	32.0	18.0-43.1	2.8
			NO_x Emissions (lb/MMBtu)	3321	0.10	0 01-0.27	0.03
D	G - PMB - ND	7/78 to 12/78	Stack O_2 (%)	3088	2.85	0.2-16.5	1.65
			Fuel Firing Rate (MMBtu/hr)	3096	7.6	0.5-12.3	1.5
			NO_x Emissions (lb/MMBtu)	3084	0.10	0.004-0.29	0.028
E	G - PMB - ND	11/81 to 4/82	Stack O_2 (%)	3035	8.52	1.7-16.0	3.19
			Fuel Firing Rate (MMBtu/hr)	3034	8.1	4.7-13.2	1 4
			NO_x Emissions (lb/MMBtu)	3030	0.13	0.005-0.26	0.046
F	G - SAB - ND	2/81 to 10/81	Stack O_2 (%)	1079	5.5	2.7-8.4	1.4
			Fuel Firing Rate (MMBtu/hr)	1084	71.3	4.7-83.8	5.9
			Gas Fuel H_2, Content (%)	1149	39.1	30.1-49.6	6.6
			NO_x Emissions (lb/MMBtu)	1076	0.10	0.05-0.16	0.02
		3/82 to 4/82	Stack O_2 (%)	547	7.3	3.7-9.1	1.8
			Fuel Firing Rate (MMBtu/hr)	546	72.1	12.7-96.3	2.8
			Gas Fuel H_2, Content (%)	712	45.0	40.1-50.5	3.7
			NO_x Emissions (lb/MMBtu)	533	0.12	0.09-0.17	0.03
G	G - SAB - ND	3/82 to 4/82	Stack O_2 (%)	544	4.4	1.6-12.4	1.2
			Fuel Firing Rate (MMBtu/hr)	544	35.4	6.0-77 6	5.6
			Gas Fuel H_2, Content (%)	712	45.0	40.1-50.5	3.7
			NO_x Emissions (lb/MMBtu)	544	0.13	0.07-0.18	0.02
H	G - SAB - ND	7/81 to 9/81	Stack O_2 (%)	2786	5.85	0.80-14.0	1.9
			Fuel Firing Rate (MMBtu/hr)	2827	14.16	0.0-16.83	1.6
			NO_x Emissions (lb/MMBtu)	2786	0.103	0.003-0.133	0.012

Table 2. (Continued)

Heater Code	Water/Burner[a] Classification	Test Period	Parameter	Number[c] Data Points	Average	Range	Standard Deviation
I	G - SAB - ND	7/78 to 12/78	Stack O_2 (%)	2987	2.11	0.1-19.0	2.09
			Fuel Firing Rate (MMBtu/hr)[b]	2997	56.0	6.9-69.3	7.7
			NO_x Emissions (lb/MMBtu)	2987	0.08	0.008-0.16	0.021
J	G - RGB - MD/PH	1/82 to 4/82	Stack O_2 (%)	1887	9.04	0.6-17.8	3.61
			Fuel Firing Rate (MMBtu/hr)	1888	3.9	2.6-6.3	0.51
			NO_x Emissions (lb/MMBtu)	1877	0.22	0.07-0.37	0.049
		7/84 to 8/84	Stack O_2 (%)	721	5.77	1.1-11.0	1.85
			Fuel Firing Rate (MMBtu/hr)	721	4.05	2.67-6.19	1.07
			NO_x Emissions (lb/MMBtu)	721	0.180	0.046-0.309	0.045
K	O/G - SAB - ND	2/81 to 10/81	Stack O_2 (%)	933	3.5	1.0-9.0	1.5
			Fuel Firing Rate (MMBtu/hr)	934	122.1	19.8-136.7	10.5
			Gas Fuel H_2, Content (%)	1090	43.4	6.6-61.7	18.7
			Oil: Gas Ratio (%)	934	31.0	20.0-45.0	4.0
			NO_x Emissions (lb/MMBtu)	933	0.12	0.07-0.16	0.02
		3/82 to 4/82	Stack O_2 (%)	541	4.1	1.1-9.3	0.8
			Fuel Firing Rate (MMBtu/hr)	414	96.4	45.8-171.0	9.3
			Gas Fuel H_2, Content (%)	712	45.0	40.1-50.5	3.7
			Oil: Gas Ratio (%)	414	18.3	2.2-51.4	6.6
			NO_x Emissions (lb/MMBtu)	392	0.14	0.10-0.18	0.02
L	O/G - SAB - ND	2/81 to 10/81	Stack O_2 (%)	757	3.9	0.9-11.4	1.6
			Fuel Firing Rate (MMBtu/hr)	758	27.3	19.8-44.5	4.1
			Gas Fuel H_2, Content (%)	935	41.2	6.6-61.7	20.3
			Oil: Gas Ratio (%)	758	6.0	0.0-40.0	8.0
			NO_x Emissions (lb/MMBtu)	757	0.07	0.04-0.12	0.01
		3/82 to 4/82	Stack O_2 (%)	541	3.9	0.4-12.1	1.2
			Fuel Firing Rate (MMBtu/hr)	541	19.0	3.6-36.1	3.3
			Gas Fuel H_2, Content (%)	712	45.0	40.1-50.5	3.7
			Oil: Gas Ratio (%)	541	13.2	0.02-45.4	10.9
			NO_x Emissions (lb/MMBtu)	541	0.10	0.06-0.21	0.02

[a] See Table 1, footnote (a) for explanation of notation.
[b] Based on fuel gas meter reading and assuming 1000 Btu/scf.
[c] Number of hourly averages.
[d] For conversion to metric: MMBtu/hr (10^6 Btu/hr) = 0.2929 MW_t, and 1 lb/MMBtu (1 lb/10^6 Btu) = 430 ng/J.

Table 3. *Variation of NO_x Emissions with Stack Oxygen for Heaters in the Long Term Continuous Monitoring NO_x Emissions Data Base*

Heater Code	Heater/Burner Classification[a]	Test Period	Predicted NO_x Emissions at Full Load and Varying Stack Oxygen Levels, (lb/MMBtu)[b]				
			2% O_2	3% O_2	4% O_2	5% O_2	5.5% O_2
A	G - RGB - ND	11/81 to 4/82 First Part	0.091 (0.086, 0.096)	0 107 (0 102, 0 113)	0.121 (0.115, 0.127)	0.133 (0.126, 0.140)	0.140 (0.133, 0.147)
		Second Part	0 049 (0.048, 0.051)	0.062 (0.059, 0.064)	0.072 (0.070, 0.075)	0.082 (0.079, 0.084)	0.085 (0.082, 0.087)
B	G - RGB - ND	11/81 to 12/81	0 065 (0.060, 0.070)	0.073 (0.068, 0.078)	0.079 (0.074, 0.084)	0.084 (0.079, 0.089)	0.089 (0.084, 0.094)
C	G - PMB - ND	7/78 to 12/78	0 074 (0.069, 0.079)	0.089 (0.083, 0.095)	0.101 (0.094, 0.108)	0.111 (0.104, 0.119)	0.117 (0.109, 0.125)
		11/81 to 4/82 First Part	0.061 (0.051, 0 073)	0.082 (0.069, 0.098)	0.101 (0.085, 0 122)	0.120 (0.100, 0.143)	0.130 (0.110, 0.150)
		Second Part	0 076 (0.073, 0 080)	0.111 (0.105, 0.166)	0.144 (0.137, 0.152)	0.177 (0.168, 0.187)	0.193 (0.183, 0.203)
D	G - PMB - ND	7/78 to 12/78	0.097 (0 093, 0.100)	0.208 (0.104, 0.122)	0.117 (0.113, 0.122)	0.125 (0.120, 0.130)	0.129 (0.124, 0.134)
E	G - PMB - ND	11/81 to 4/82 First Part	0 081 (0 070, 0.093)	0 092 (0.081, 0.104)	0 100 (0 090, 0 112)	0.108 (0.097, 0.119)	0.110 (0.099, 0.121)
		Second Part	0 036 (0.031, 0 042)	0.054 (0.046, 0 062)	0.071 (0.061, 0.082)	0.088 (0.076, 0.101)	0.096 (0.083, 0.154)
F	G - SAB - ND	2/81 to 10/81 First Part (H_2 = 37 4%)	0 060 (0 050, 0 073)	0 77 (0 068, 0.088)	0.092 (0 085, 0.100)	0.105 (0.100, 0.111)	0.113 (0.107, 0.119)
		Second Part (H_2 = 39.8%)	0 046 (0 043, 0.048)	0 060 (0 058, 0 063)	0.074 (0 072, 0.076)	0.086 (0.084, 0.088)	0.091 (0.089, 0.093)
		3 82 to 4 82	0 083 (0 074, 0 092)	0 093 (0 086, 0 100)	0.101 (0 095, 0 106)	0.107 (0 103, 0 112)	0.111 (0 106, 0.116)

Table 3. *(Continued)*

Heater Code	Heater/Burner Classification[a]	Test Period	Predicted NO_x Emissions at Full Load and Varying Stack Oxygen Levels, (lb/MMBtu)[b]				
			2% O_2	3% O_2	4% O_2	5% O_2	5.5% O_2
G	G - SAB - ND	3/82 to 4/82	0.093 (0.091, 0.096)	0.109 (0.106, 0.111)	0.121 (0.118, 0.124)	0.131 (0.128, 0.135)	0.137 (0.133, 0.141)
H	G - SAB - ND	8/81 to 9/81	0.093 (0.064, 0.122)	0.100 (0.071, 0.129)	0.106 (0.078, 0.134)	0.110 (0.082, 0.138)	0.112 (0.084, 0.140)
I	G - SAB - ND	7/78 to 12/78	0.104 (0.099, 0.109)	0.111 (0.105, 0.116)	0.116 (0.110, 0.122)	0.119 (0.113, 0.126)	0.123 (0.116, 0.130)
J	G - RGB - MD/PH	1/82 to 4/82	0.125 (0.115, 0.136)	0.150 (0.139, 0.163)	0.172 (0.159, 0.186)	0.190 (0.176, 0.206)	0.198 (0.182, 0.214)
		7/84 to 8/84	0.136	0.173	0.205	0.234	0.247
K	O/G - SAB - ND	2/81 to 10/81 (H_2 = 43.4%) (Oil = 31.0%) (%N = 0.63)	0.099 (0.093, 0.104)	0.111 (0.105, 0.177)	0.120 (0.114, 0.127)	0.128 (0.121, 0.136)	0.131 (0.123, 0.139)
		3/82 to 4/82 (H_2 = 46.6%) (Oil = 17%) (%N = 0.63)	0.112 (0.107, 0.117)	0.127 (0.124, 0.131)	0.140 (0.137, 0.143)	0.150 (0.147, 0.154)	0.157 (0.153, 0.161)
L	O/G - SAB - ND	2/81 to 10/81 First Part (Oil = 3%) (%N = 0.63)	0.051 (0.046, 0.057)	0.057 (0.051, 0.064)	0.062 (0.055, 0.069)	0.065 (0.058, 0.073)	0.068 (0.060, 0.076)
		Second Part (Oil = 7%) (%N = 0.63)	0.051 (0.049, 0.054)	0.058 (0.055, 0.061)	0.063 (0.059, 0.066)	0.067 (0.063, 0.071)	0.068 (0.064, 0.072)
		3/82 to 4/82 (Oil = 13%) (%N = 0.63)	0.086 (0.083, 0.089)	0.100 (0.097, 0.103)	0.111 (0.107, 0.115)	0.120 (0.116, 0.124)	0.124 (0.120, 0.128)

[a]See Table 1, footnote (a) for explanation of notation.
[b]The confidence interval for each predicted value is given in parentheses.

S. A. Shareef, C. L. Jamgochian, and L. E. Keller are with Radian Corp., Research Triangle Park, NC 27709.
***John H. Wasser** is the EPA Project Officer (see below).*
The complete report, entitled "Fired Heaters: Nitrogen Oxides Emissions and Controls," (Order No. PB 88-245 741/AS; Cost: $21.95, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
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