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Miravalles Unit 3 Single-Flash Plant, Guanacaste, Costa Rica: Technical and Environmental Performance Assessment

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ABSTRACT

Since it was first visited by a United Nations scientific delegation in 1963, the Miravalles geothermal field in Costa Rica has developed into one of the most productive and reliable geothermal power complexes in the world. Currently five power units are in operation with a total installed capacity of 163 MW. This paper deals with power plant Unit 3, the only one that is not owned by the Instituto Costarricense de Electricidad (the Costa Rican Electricity Authority), known by its Spanish acronym ICE.

This paper provides a brief summary and overview of the current Miravalles operation including a layout of the field showing the locations of power units, wells, and Satellite No.7 and its gathering and reinjection system pipelines. The type of power units and their installed capacities are given along with some performance data including electrical generation, as well as capacity, load and utilization factors.

The history of the development of the single-flash 27.5 MW Unit 3 which began operating in 2000 is presented. The power plant occupies its own facility in the area of the field known as Las Mesas, approximately 2.5 km to the north-northeast of Units 1 and 2 at Miravalles. ICE is the owner and operator of the other four Miravalles units, as well as the field developer and steam supplier. However, Unit 3, the first and only Build-Operate-Transfer (BOT) power unit at Miravalles, presented specific problems for ICE which has the obligation to supply the steam to the unit as well as to purchase the energy generated by the unit from its owner and operator Geoenergia de Guanacaste (GdG). The conditions under which the steam must arrive at the fence of the unit are precisely defined in the BOT power purchase agreement (PPA). Since the steam conditions from the producing wells changed over the course of operation, ICE had to undertake certain actions to guarantee that they did not default on that obligation.

The unique design aspects of the plant are presented and discussed. The performance of Unit 3 is given in terms of its thermodynamic design and its actual operating conditions. State diagrams are used to show the processes followed by the steam in the plant; state-point property tables are given for design and typical operating conditions; actual performance data are analyzed in terms of power generation, parasitic power requirements, utilization efficiency, specific steam consumption, and specific brine consumption. Also examined are how the plant performance and steam supply conditions have changed over the plant lifetime, and how ICE has managed the field to meet its contractual requirements.

The paper includes a look into the environmental aspects of the unit. Although it is difficult to isolate the effects of one unit among a complex of five units, several possible impacts are examined including acid rain, air pollution and pollution of ground waters.

1. INTRODUCTION

Costa Rica is located in Central America. The country has an area of 51,000 km^2 and has a population of about 4.5 million. Back in the early 70s, Costa Rica used to satisfy its electricity demand, producing hydroelectric energy (70%) and fossil fuel (thermal) energy (30%); Moya (2006).

Because of the oil crisis (1973), thermal energy became very expensive for the country, and therefore, new ways to produce electricity were studied, including geothermal energy. The slopes of three volcanoes (Miravalles, Rincón de la Vieja and Tenorio) were identified as areas of possible geothermal interest. From these three areas, the Miravalles geothermal area was chosen mainly because of its road access; at that time roads were not very good for any of the selected areas, but the Miravalles geothermal area had slightly better conditions; Moya and Yock (2007). Currently, there are five generation units at the Miravalles geothermal field. Their start-up dates, power and owner are indicated in Table 1.

Table 1: Power units at Miravalles geothermal field. Abbreviations: ICE-Instituto Costarricense de Electricidad; CFE-Comisión Federal de Electricidad (Mexico); WHU-Wellhead Unit; and BOT-Build-Operate-Transfer.

Plant name	Power (MW)	Owner	Start-up date	Shut-down date
Unit 1	55	ICE	3/1994	
WHU-1	5	ICE	1/1995	
WHU-2	5	CFE	9/1996	4/1999
WHU-3	5	CFE	2/1997	4/1998
Unit 2	55	ICE	8/1998	
Unit 3	29	ICE (BOT)	3/2000	
Unit 5	19	ICE	1/2004	

During the same year of the commissioning of Unit 1, the feasibility Study for Units 3 and 4 in Miravalles was initiated. The study began at the end of 1994, was finished with a final report in 1995, and was carried out by ELC-Electroconsult. The main conclusions of the study were: a) “the installation of an additional 25-30 MW plant (Unit 3) in Las Mesas area is feasible from the perspective of resource availability. However, this will provoke a noticeable drop in the reservoir pressure of this marginal zone of the field, making it necessary, in extreme cases, to lower operating pressures in the long term (15-20 years). The uncertainties about effective reservoir conditions, and particularly the extension of the reservoir towards the north, make it impossible to determine the feasibility of adding further units in this zone, regardless of the highly positive outlook", and b) "the Cuipilapa sector (Unit 4) is very promising as an area for future field expansion, regardless of the fact that it is very near the anticipated re-injection area in the southern part of the field. If the existing wells (PGM-50, PGM-51 and PGM-52) are found to be good injection wells, then it will be possible to use wells PGM-28 and PGM-29 for production and begin the development of this sector with a 25-30 MW plant. Even though the potential seems to be greater, the current state of knowledge suggests that the expansion of installed capacity should be limited for the moment, particularly since it is still necessary to define the content of noncondensable gases and the possible direct connection of this area with the planned re-injection zone"; Moya and Yock (2007).

Despite the conclusion of the feasibility study (i.e., it is impossible to determine the feasibility of adding further units in this zone), ICE decided to build Unit 3 and wait longer for the construction of Unit 4. At that time (1995), ICE had already drilled wells PGM-02 (1979), PGM-11 (1984) and PGM-14 (1994). Later ICE drilled wells PGM-07 (1998), PGM-60 (1999), PGM-06 (1999) and PGM-62 (1999) to complete the steam required for Unit 3, a single-flash plant of 27.5 MW.

The previous generation units at Miravalles geothermal field (Unit 1, WHU-1 and Unit 2) were all financed by the Interamerican Development Bank (IDB), but for Unit 3, it was decided that the finance scheme would be a BOT (Build-Operate-Transfer) power purchase agreement. The current owner of Unit 3 is called "Geoenergía de Guanacaste" (GdG). As mentioned before, there is a power purchase agreement (PPA) between ICE and Geoenergía de Guanacaste, where ICE supplies and sells the required steam for Unit 3 to GdG and GdG sells the electricity to ICE. The PPA began in March, 2000 and it will last for 15 years (until 2015).

2. UNIT 3 CHARACTERISTICS

As mentioned in the previous section, the production wells that could feed Unit 3 are: PGM-02, PGM-06, PGM-07, PGM-11, PGM-14, PGM-60 and PGM-62. These wells, when connected to the gathering system, supply their two-phase flow to Separation Station No. 7 (also called Satellite 7). From this station, the steam goes to Unit 3 and the brine goes to one of the main brine collectors, to then be utilized at the binary plant (Unit 5) and finally to be injected in the southern part of the production zone. The well field is shown in Figure 1.

The gathering system associated with Satellite 7 is shown in Figure 2. Normally, wells PGM-02, PGM-07, PGM-11, PGM-14 and PGM-60 are the wells supplying the two-phase flow to Satellite 7. Wells PGM-06 and PGM.62 are spare production wells that could be incorporated into the system when required.

Wells PGM-11, PGM-14, PGM-60 and PGM-62 produce neutral fluids and use the calcite inhibition system described in Moya, Nietzen and Yock (2005). Wells PGM-02, PGM-06 and PGM-07 produce acid fluids and use the acid neutralization system described in Moya, Nietzen and Sánchez (2005).

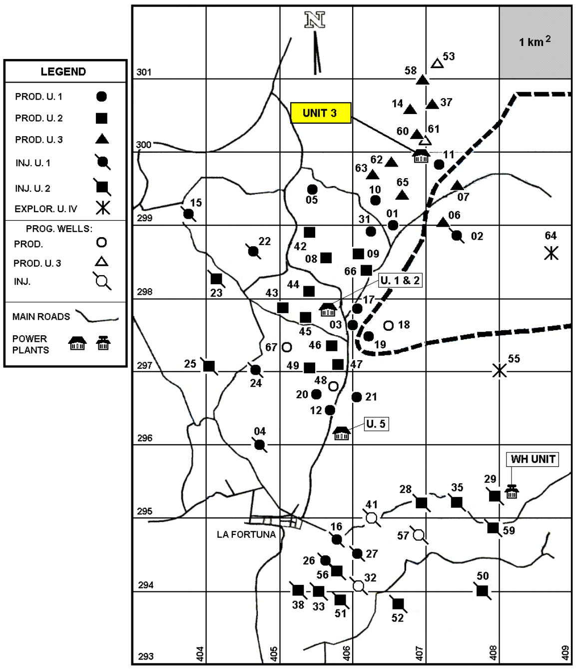

Figure 1: Miravalles well field.

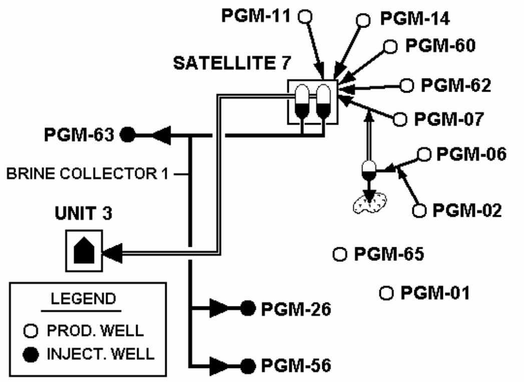

Figure 2: Unit 3 wells and gathering system.

Satellite 7 has a capacity to separate 60 kg/s of steam, and its monthly mass flow rates since the start-up are shown in Figure 3.

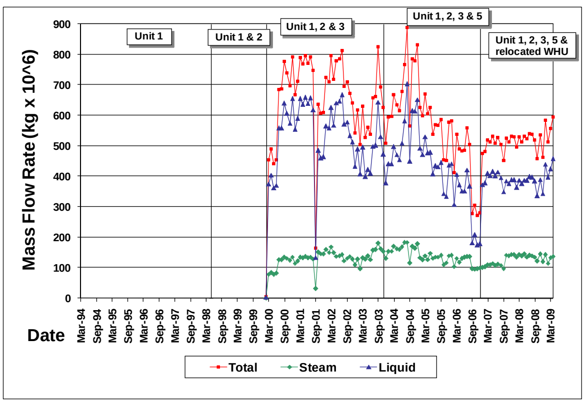

Figure 3: Monthly mass flows in Satellite 7.

Some of the technical specifications and performance measures for Unit 3 can be observed in Table 2; Table 3 gives the current (2009) operating conditions.

Table 2: Technical specifications and performance.

Plant	
Start-up year	2000
Type	Single-flash, condensing
Rating, MW	29
Net power, MW	27.5
Resource temperature, °C	240
Turbine	
No. cylinders	1
No. flows	1
No. stages	5
Inlet pressure, kPa	560
Inlet temperature, °C	156.8 (sat)
Exhaust pressure, kPa	9.0
Steam mass flow, kg/s	57.7
Last-stage blade ht., mm	635
Speed, rpm	3600
Condenser	
Type	Direct-contact, side-by-side
CW flow rate, kg/s	2143
CW temperatures, °C:	
Inlet	27.4
Outlet	40.8
Wet bulb	21.7
NCG removal system	
Steam jet ejector	
No. stages	2
Steam flow rate, kg/s	1.517
Vacuum pump	
Power consumption, kW	460
Plant performance	
Specific geofluid consumption, (kg/s)/MW	14.5
Specific steam consumption, (kg/s)/MW	2.10
Utilization efficiency [(1)], %	29.7, gross; 28.1, net

[(1)] Dead-state temperature = 21.7°C.

3. THERMODYNAMIC ANALYSIS AND TECHNICAL PERFORMANCE

Unit 3 is a single-flash condensing power plant of the modular type. Typical for such plants, the condenser is situated on the same level as the turbine, eliminating the need for deep excavation compared to a low-level condenser. This reduced plant capital cost and led to a short construction and installation period of only 13 months. As a result, the unit came on-line in March 2000, ahead of the expected date of May 2000. The total plant cost, including all wells and the gathering system, was $80,000,000, or $2,909/kW.

A simplified schematic flow diagram for the power plant and the geofluid gathering and reinjection systems is shown in Figure 4. The thermodynamic process diagram in temperature-entropy coordinates for a typical single-flash unit is depicted in Figure 5. The thermodynamic state-point properties for Unit 3 are shown in Table 4. These data correspond to typical operating conditions observed from 2006 to 2008. With the exception of the noncondensable gases which increased from 1.2 to 1.5%, the conditions have remained essentially steady over these two years. The turbine isentropic efficiency is 84.9% based on a gross power output of 29.6 MW and a net plant output of 26.9 MW.

Table 3: Unit 3 current operating conditions.

Steam System	
Vapor pressure (Collector), bar,g	4.6
Steam flow rate, kg/s	60.0
Temperature, °C	157
Turbine	
Serial No.	N-1391
Nominal output, MW	29.45
Nominal speed, rpm	3600
Steam inlet pressure, bar,a	5.7
Steam inlet temperature, °C	156.5
Outlet pressure, bar,a	0.1
Generator	
Voltage, V	13800
Current, A	1374
Power factor	0.9
Frequency, Hz	60
Speed, rpm	3600
No phases	3
Water Circulation System	
Condenser water level, m	1.41
Condenser pressure, mm Hg	75
Condenser temperature, °C	40
Cooling tower water level, m	1.50
Water flow rate, m^3	8200

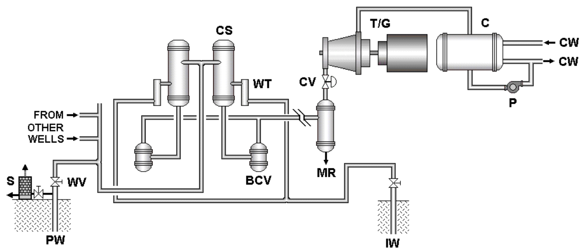

Figure 4: Plant flow diagram.

Based on a dead-state temperature of 21.7°C, and the typical operating conditions from Table 6, Unit 3 has a Second Law utilization efficiency of 37.8% (gross) and 34.5% (net). Both of these are higher than the nominal values expected from the design specifications given in Table 2.

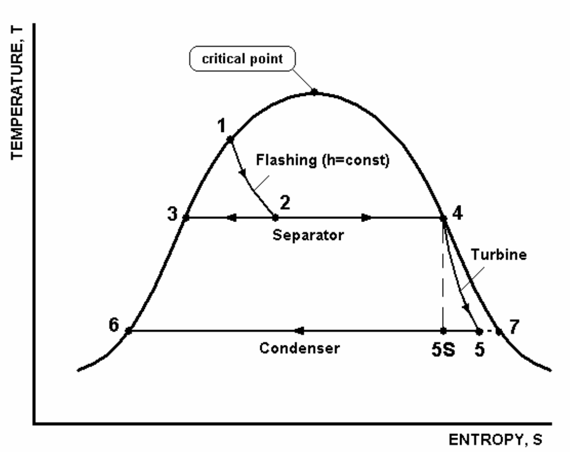

Figure 5: Temperature-entropy diagram.

Table 4: Thermodynamic state properties: Typical values for 2006-2008.

State	Press. bar,a	Temp. °C	Entropy kJ/kg K	Enthalpy kJ/kg	Mass flow kg/s
1	33.47	240	2.7020	1037.6	320.6
2	5.61	156.2	2.7863	1037.6	320.6
3	5.61	156.2	1.9047	659.09	264.2
4	5.61	156.2	6.7819	2753.2	56.424
5	0.09	43.76	7.0766	2228.7	56.424
6	0.09	43.76	0.6223	183.25	56.424
7	0.09	43.76	8.1858	2580.2	---

The average monthly specific steam consumption (SSC) for the first eight years and four months of operation is shown plotted in Figure 6. The data are somewhat erratic and have been smoothed by the elimination of six points that had SSC values greater than 2.5 or less than 2.0 (kg/s)/MW. The average is 2.22 (kg/s)/MW.

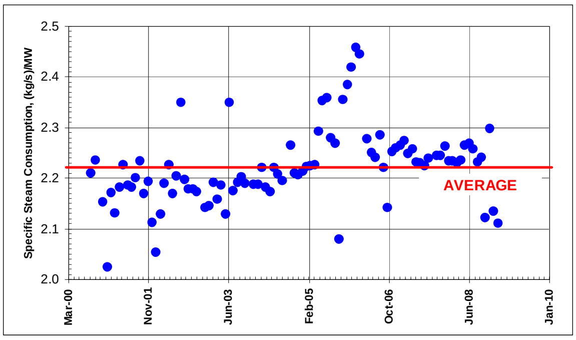

Figure 6: Specific steam consumption from September 2000 through December 2008.

From Table 5 it can be seen that the total parasitic power requirements are about 9.2% of the gross turbine power.

Table 5: Annual generation of Miravalles Unit 3.

Year	Peak power MW	Avg. power MW	Gross Generation kWh	Net Generation kWh
2000	26.983	26.390	196,493,704	179,436,932
2001	26.769	25.776	246,233,651	223,983,500
2002	26.353	25.998	247,914,556	225,063,634
2003	28.970	25.842	247,826,651	223,732,447
2004	26.015	25.545	240,454,146	219,768,595
2005	25.873	24.948	239,856,150	217,067,625
2006	25.826	24.480	233,478,800	211,633,938
2007	25.675	25.161	241,789,810	219,371,072
2008	26.595	25.115	241,543,236	219,294,060

Table 6 gives the load, capacity and utilization factors for each year of operation. These average 96.0%, 92.6% and 96.6%, respectively.

Table 6: Annual performance of Miravalles Unit 3.

Year	Load factor %	Capacity factor, %	Utilization factor, %
2000	97.8	96.0	98.1
2001	96.3	93.7	97.3
2002	98.7	94.5	95.8
2003	89.2	94.0	105.3
2004	98.2	92.9	94.6
2005	96.4	90.7	94.1
2006	94.8	89.0	93.9
2007	98.0	91.5	93.4
2008	94.4	91.3	96.7

4. UNIT 3 ENVIRONMENTAL ASPECTS

On March 19th, 2002, ICE approves its environmental policies, which is based in the principle of sustainable development. At the Miravalles geothermal field, there is an Environmental Management Program to guarantee that all the activities carried out in the field follow the sustainable development principle, which at the same time is based on the standard ISO 14001. This standard is being implemented through the Environmental Management System (EMS) which includes: disposal management, field environmental management, environmental education, water quality in superficial aquifers, evolution of the rain pH and air quality.

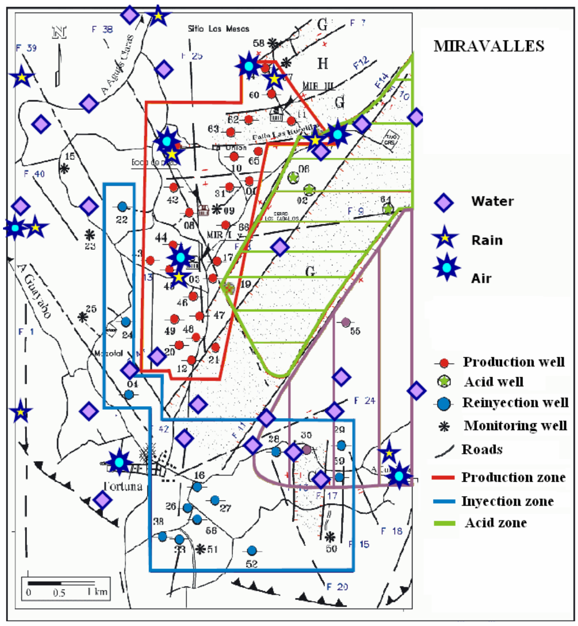

Figure 7: Environmental stations at Miravalles.

A report on the environmental aspects is prepared annually e.g., Guido (2008). This report indicates that given the recent results (up to December 2008) on the different control parameters, there are no significant environmental impacts due to the commercial exploitation of the Miravalles geothermal field. Several stations for the different control parameters are located inside and outside the production zone. Figure 7 shows the location of these stations.

As it can be seen in Figure 7, there are 23 stations for water quality control, 7 stations for the air quality control and 8 stations for the evolution of the rain pH control.

The closest stations for water quality control, air quality control and the evolution of the rain pH control are shown in Figures 8, 9 and 10, respectively. Figure 8 shows that the pH, the Cl and the conductivities have been stable since 1990 (almost three and a half years prior the commissioning of the first unit).

It can be seen in Figure 9 that the amounts of H_2S and CO_2 emissions have been very low since year 2000. These emissions have remained the same even though the generation has varied between 976 and 1,214 GWh.

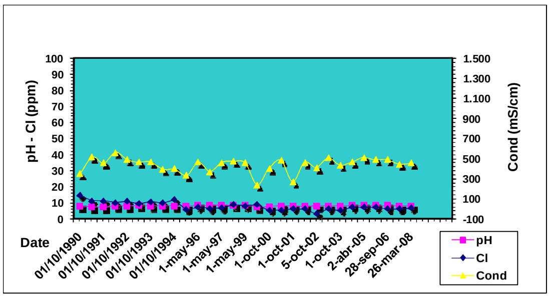

Figure 8: Quebrada Hornillas - Water quality control station at the Miravalles geothermal field.

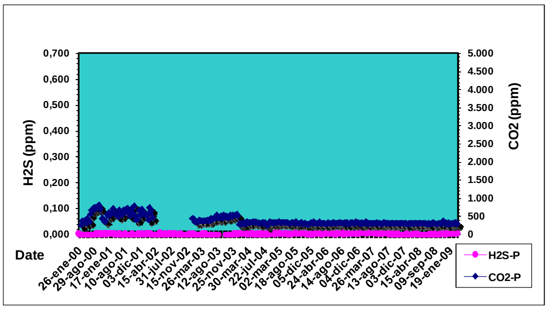

Figure 9: PGM-14 - Air quality control station at the Miravalles geothermal field.

The behavior of the pH in the rain can be observed in Figure 10. The pH has mainly ranged between 4 and 7 since June 1987 to date. This indicates that the generation at the Miravalles geothermal field has not modified the value of the pH values. The same variation of the pH values in the rain took place before the first unit was commissioned in 1994.

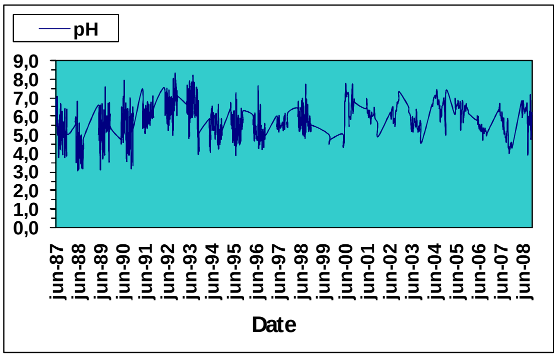

Figure 10: La Unión - Evolution of the rain pH control station at the Miravalles geothermal field.

As it was mentioned before, besides these three stations, there are more environmental control stations around the Miravalles geothermal field. Basically all of them show the same behavior, that is, there is no alteration of the pattern before and after generation started at the Miravalles geothermal field.

5. CONCLUSIONS AND DISCUSSION

ICE developed the Miravalles Geothermal field in just one decade (1994-2004). The initial installed capacity was 55 MW and 10 years later the capacity was already 163 MW. The generation associated with this installed capacity represents around 15% of the total energy generation in the country.

Despite the conclusion of the feasibility study (i.e., it is impossible to determine the feasibility of adding further units in this zone), ICE decided to build Unit 3 and wait longer for the construction of Unit 4 which has not been built so far.

The earlier generation units at the Miravalles field (Unit 1, WHU-1 and Unit 2) were all financed by the Interamerican Development Bank (IDB), but for Unit 3, it was decided that the finance scheme would be a BOT (Build-Operate-Transfer) power purchase agreement (PPA). The 15-year PPA began in March, 2000 and it will last five more years (until 2015).

Unit 3 has averaged 96.0% load factor, 92.6% capacity factor and 96.6%, utilization factor over its 9-year life. The geothermal load factors are the highest ones of all types of energy plants in the country. Over the last two years, with the exception of the noncondensable gas content in the steam which increased from 1.2 to 1.5%, the plant operating conditions have remained essentially steady.

Production wells that could feed Unit 3 are: PGM-02, PGM-06, PGM-07, PGM-11, PGM-14, PGM-60 and PGM-62. These wells, when connected to the gathering system, supply their two-phase flow to Separation Station No.7 (also called Satellite 7). Even though PGM-06 and PGM-62 are connected to Satellite 7, they are not currently used because of their high noncondensable gas content (around 4 and 2.5%, respectively).

Basically all the environmental stations show the same behavior, that is, there is no alteration of the pattern before and after generation started at the Miravalles geothermal field.

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