Test Results of the World's First 1,600°C J-series Gas Turbine

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Gas-turbine combined-cycle (GTCC) power generation is expected to be a market success because it is the cleanest and the most efficient thermal power generating system that complements renewable energy sources. Mitsubishi Heavy Industries, Ltd. (MHI) has developed the world's first 1,600°C J-series gas turbine by utilizing components and technology from the national project aimed at developing 1,700°C -class gas turbine. Long-term reliability testing of the M501J gas turbine continues, following testing at the demonstration combined-cycle power plant (T-point) at our Takasago Machinery Works from February to June 2011. The commercial version of the M501J gas turbine has already been shipped to Kansai Electric Power Company's Himeji No. 2 power station and will enter operational use in October 2013. This report describes the features of the M501J gas turbine and the test results of M501J gas turbine at T-point.

1. Introduction

Gas-turbine combined-cycle (GTCC) power generation is the cleanest and most efficient power generating system of all the fossil-fuel-burning approaches. It has the following social and economic impacts: (1) The long-term world market for GTCC power generation is expected to grow. (2) A great demand exists for GTCC power generation in developing countries because GTCC systems can be constructed quickly and provide a stable source of electricity. (3) The need exists in developed countries for highly efficient power generation for further enhancement of economic efficiency and environmental adaptability. (4) The superior load-absorbing capability of GTCC power generation is in increasing demand because of the growth of renewable energy sources.

Mitsubishi Heavy Industries, Ltd. (MHI) developed the M701D 1,150°C-class large-capacity gas turbine in the 1980s and demonstrated high plant thermal efficiency and reliability with a liquid-natural-gas-burning combined-cycle generation plant at Tohoku Electric Power Company's East Niigata Thermal Power Station 3. This led to the development of the M501F gas turbine with a turbine inlet temperature of 1,350°C in 1989 and the M501G gas turbine with a turbine inlet temperature of 1,500°C and steam-cooled combustor in 1997, each with improved efficiency and reliability. Starting in 2004, MHI participated in the national 1,700°C -class gas turbine component technology development project, concentrating on developing new technologies required for higher turbine inlet temperatures and efficiency. We have developed the M501J gas turbine, the first turbine in the world with a turbine inlet temperature of 1,600°C capable of a combined-cycle power-generating gross thermal efficiency of 61.5% under ISO normal low heat value (LHV) conditions (**Figure 1**). We are also developing the M701J for 50 Hz.

This report describes the features of the M501J gas turbine and the results of its first verification test conducted at the T-point facility in our Takasago Machinery Works starting in February 2011.

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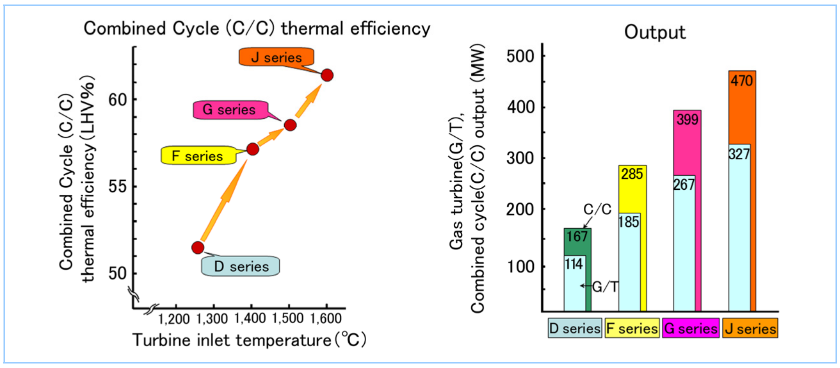

Figure 1 MHI gas turbine (60-Hz machine) efficiency and output

2. M501J gas turbine features

The M501J gas turbine was designed with a turbine inlet temperature of 1,600°C by integrating the proven component technologies used in the 1,400°C F-series and the 1,500°C G- and H-series turbines. The M501J also benefited from the development of key technologies for the national 1,700°C -class gas turbine project (**Figure 2**). Adoption of the higher inlet temperature and latest component technology means that the combined-cycle gross thermal efficiency, which is significantly better than that of conventional machines, will be 61.5% on a LHV basis (**Figure3**, **Table 1**). Therefore, a power plant with a natural-gas-burning J-series combined-cycle plant can reduce carbon dioxide emissions by approximately 60% compared to a conventional coal-burning thermal power plant.

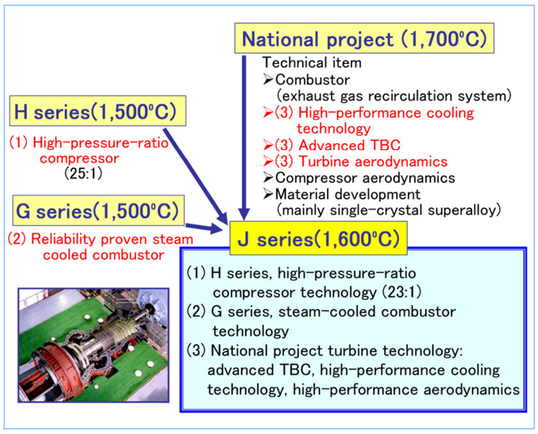

Figure 2 M501J gas turbine concept

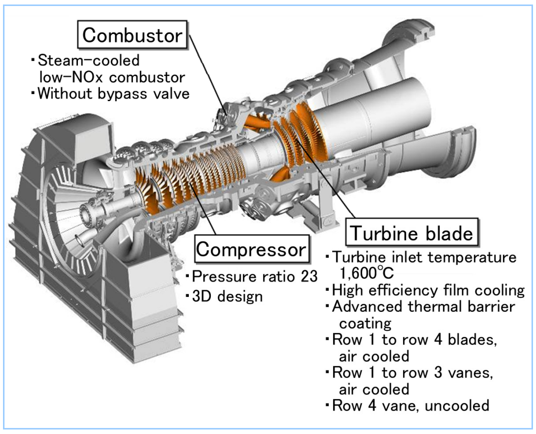

Figure 3 M501J gas turbine features

Table 1 J-series gas turbine performance

Series	M501G	M501J
Turbine inlet temperature	1,500 °C	1,600 °C
Rotating speed	3,600 rpm	3,600 rpm
Gas turbine output (gross)	267 MW	327 MW
Combined-cycle output (gross)	399 MW	470 MW
Combined-cycle efficiency (gross, LHV, ISO base)	58% or higher	61.5% or higher
Compressor/pressure ratio	17 stages/20	15 stages/23
Combustor	16 cans	16 cans
Turbine	Row 1 to row 3 vanes and blades, air cooling; Row 4 vane and blade, uncooled	Row 1 to row 4 blades, air cooled; Row 1 to row 3 vanes, air cooled; Row 4 vane, uncooled

2.1 Overall design

The design of the M501J gas turbine is based on these proven F- and G-series features:

- The compressor shaft end drive connected to the generator reduces the thermal expansion and eliminates the need for a flexible coupling.
- The rotor has a two-bearing structure to support the compressor and turbine ends.
- An axial flow exhaust structure is used to optimize the combined-cycle plant layout.
- The rotor structure has bolt-connected disks with the torque pin in the compressor rotor and a disc with curvic coupling in the turbine rotor to ensure reliable torque transmission.

2.2 Compressor

The M501J compressor was designed as an axial flow type with a pressure ratio of 23; it was based on the technology used in the H-series compressor, which had a pressure ratio of 25. Three-dimensional (3D) advanced design techniques were used to improve the performance and reduce the shockwave loss in the initial stages and frictional loss in the intermediate and final stages. This concept was evaluated by 3D computational fluid dynamics (CFD) software and verified using the full-scale high-speed research compressor (**Figure 4**). **Figure 5** shows an example of 3D CFD analysis results. In addition, bleeding was used in the low-, middle-, and high-pressure stages during compressor start-up. Rotating stall on start-up was suppressed, and the partial-load performance of the combined cycle was improved, by controlling the inlet guide vane (IGV) and three-stage variable stator vanes.

2.3 Combustor

The M501J combustor was based on the proven steam cooling system used in G-series gas turbines. Although the turbine inlet temperature was increased by 100°C from 1,500°C in the G-series to 1,600°C, the emission density of nitrogen oxide (NOx) was suppressed to the same level as that of the G-series through the use of low-NOx technologies, such as reducing the local flame temperature in the combustion area by improving the combustion nozzle (**Figure 6**) for more homogeneous mixing of fuel and air. Air flow tests, atmospheric-pressure combustion tests, and high-pressure combustion tests were conducted to verify the performance and reliability, and the results were applied to the detailed design of the combustor.

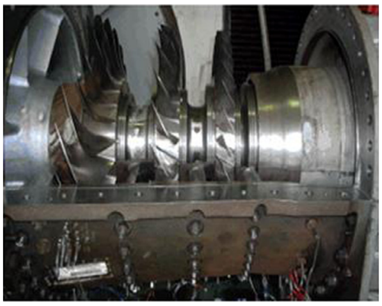

Figure 4 High-speed research compressor

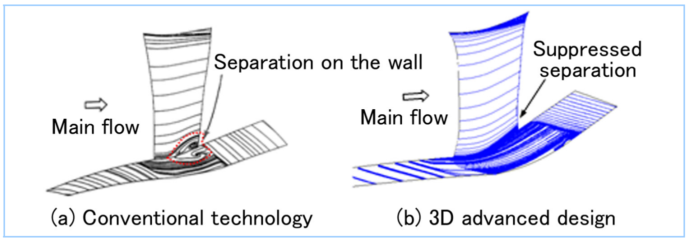

Figure 5 Air flow near the compressor endwall (advanced 3D design result)

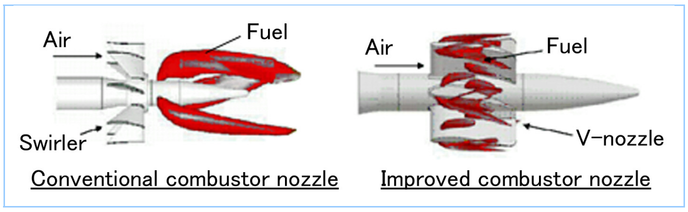

Figure 6 Improved combustion nozzle region

2.4 Turbine

The M501J turbine is an axial-flow, four-stage, high-load, high-performance turbine. To improve its performance, a 3D endwall contouring was used to control the secondary flow generated at the endwall, the design of which considered the flow field interference and horseshoe vortex from the blade leading edge. This was in addition to the complete 3D design used in the G-series turbine. The metal temperature was maintained at the level of a conventional machine using the technology developed in the national 1,700°C -class gas turbine project. The 100°C temperature increase was half offset by high-performance cooling technology and half by an advanced thermal barrier coating (TBC, **Figure 7**).

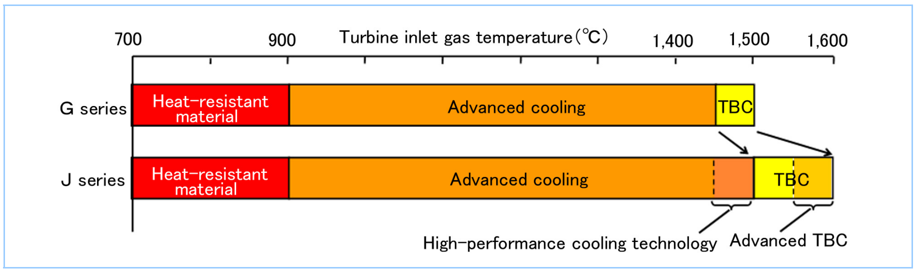

Figure 7 Component technologies for a turbine inlet temperature of 1,600°C

Row 1 to row 4 rotating blades and row 1 to row 3 stationary vanes are air-cooled. The row 4 blades in the G-series turbine were not cooled, but those in the J-series turbine were cooled to cope with the higher inlet temperature. MGA1400 (Mitsubishi Gas Turbine Alloy) used for the rotating blades, while the vanes were made of MGA2400. The row 1 to 3 blades were made of DS (directional solidified) superalloy. MGA1400 and MGA2400 were also used in the F-series and G-series gas turbines.

The cooling structure was improved for the F-series and again for the G-series turbine, and the J-series uses high-performance film cooling and advanced TBC developed in the national project, as shown in **Figure 8**. The film cooling effectiveness of high-performance film cooling was tested after selecting the optimum film shape in a flat plate component test, in a large-scale low-speed rotational test, and in a medium-pressure cascade test (**Figure 9** and **10**). High-performance film cooling and advanced TBC were applied to the M501G turbine blades at T-point, its effectiveness was tested by a special measurement, and then long-term testing of the actual machine took place. The design of the J-series turbine blade was based on these test results, and the final verification was done using the first M501J gas turbine after conducting the high-pressure high-temperature cascade test.

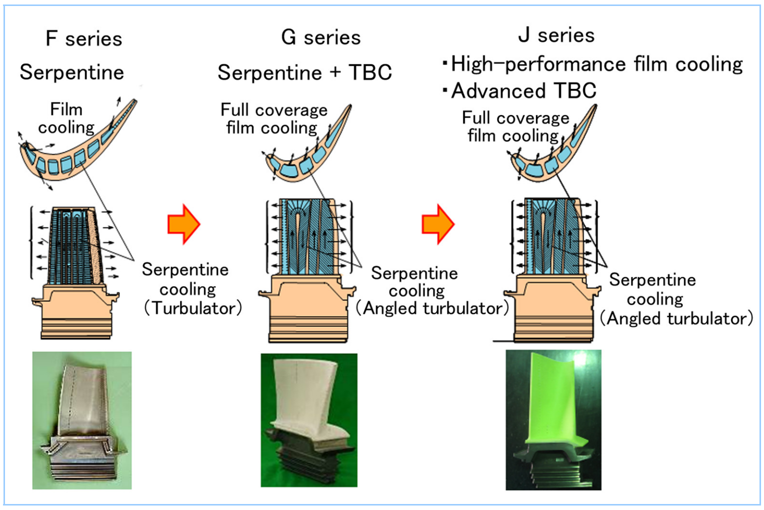

Figure 8 Turbine cooling structure improvement

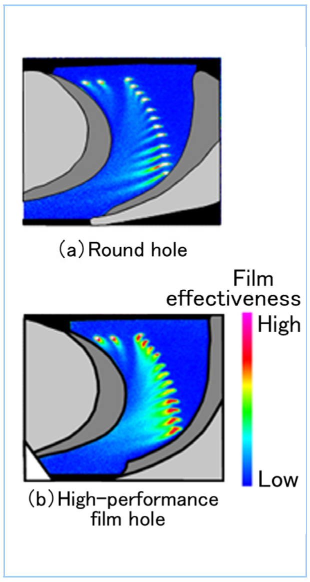

Figure 10 Result of film efficiency measurements with low speed rotating test facility

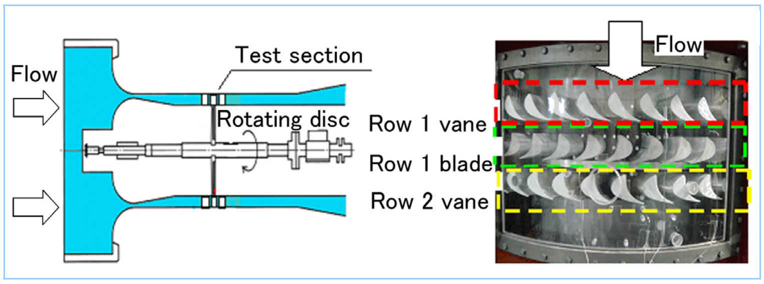

Figure 9 Low speed Rotating test facility overview

3. Verification test results at the T-point demonstration power plant

In developing the M501J turbine, each component was tested in the basic design stage, and the results were reflected in the detailed design. Commercial models were produced only after the entire turbine had been tested in T-point.

Figure 11 shows a photograph of the T-point at the MHI Takasago Machinery Works. T-point was equipped with a M501G gas turbine, a steam turbine, and a heat recovery steam generator boiler. T-point plant has logged more than 2,300 start and stop cycles and 39,253 total operating hours and made a huge contribution to improving the performance and reliability of the M501G gas turbine.

Work to convert the M501G turbine to M501J started in October 2010, and operating tests of the first M501J gas turbine started in February 2011. The tests proceeded as scheduled with the first spin-up on February 2nd and the first ignition on February 7th; the inlet temperature reached 1,600°C on the seventh start-up. Various tests were then conducted until the end of April when the turbine was disassembled and each part inspected. Long-term reliability operational testing started in July 2011, resulting in 58 start-up tests and 3,540 hours of operation by the end of December 2011 (**Figure 12**). The special measurement and the test results of each component are described in the sections that follow.

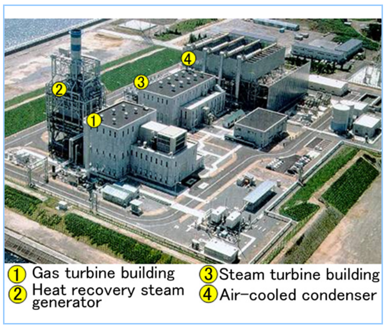

Figure 11 MHI Takasago Machinery Works T-Point demonstration combined-cycle power-plant

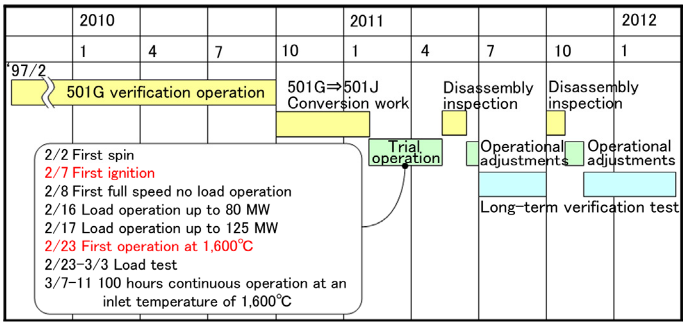

Figure 12 M501J test operational record at T-point

3.1 Special measurement outline

The M501J turbine at T-point was equipped with at least 2,300 special measuring sensors, including approximately 100 rotating parts monitors in addition to the more usual monitoring devices.

3.2 Compressor

The natural frequency, vibration stress of blades and vanes, and pressure fluctuation were measured to determine the starting characteristics and the blade/vane reliability in the compressor. Desirable characteristics, such as the extinction of rotating stall at approximately 60% of the rotating speed, were confirmed (**Figure 13**). Compressor efficiency and inlet air flow were measured at each IGV angle to show that the design performance was achievable.

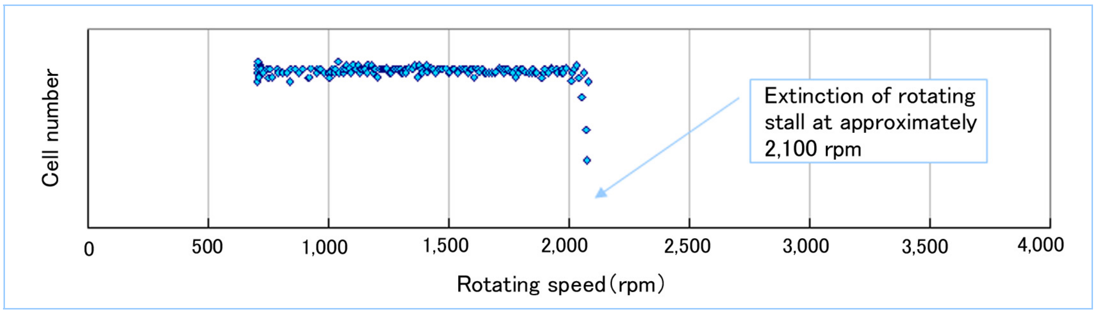

Figure 13 Compressor starting characteristics

3.3 Combustor

The metal temperature, vibration stress, and stress fluctuation were measured in the combustor. During operation with a turbine inlet temperature of 1,600°C, the metal temperature of the combustion liner was less than the maximum allowable temperature (**Figure 14**). The combustion pressure fluctuation and vibration stress were confirmed to be within the allowable range.

3.4 Turbine

The metal temperature was measured by installing thermocouples on turbine blades and vanes. The metal temperature of rotating blades was measured using a telemetry system. The temperature was verified to be lower than the allowable metal temperature at the 1,600°C inlet temperature. **Figure 15** shows the distribution of the metal temperature on the turbine row 1 vane. The temperature distributions of the row 1 blade surface and platform were measured with a pyrometer. **Figure 16** shows a typical temperature measurement of the moving blade platform.

Detuning to the natural frequency was verified across the operational range, and the vibration stress was verified to be lower than the maximum allowable stress.

3.5 Disassembly inspection result

The gas turbine was disassembled in June 2011, and the soundness of each part was confirmed as shown in **figure 17**. Long-term operational reliability testing then began, and the turbine and combustor were inspected in October 2011.

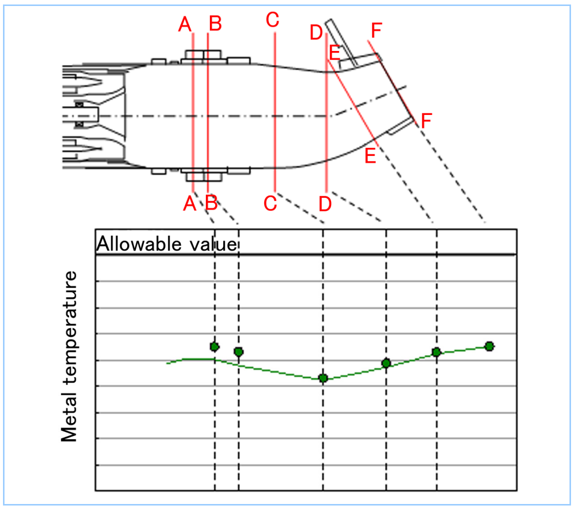

Figure 14 Metal temperature of combustion liner at a turbine inlet temperature of 1,600 °C

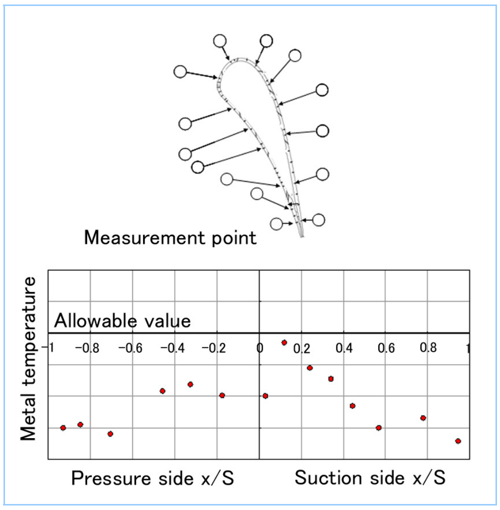

Figure 15 Metal temperature measurement of the row 1 vane

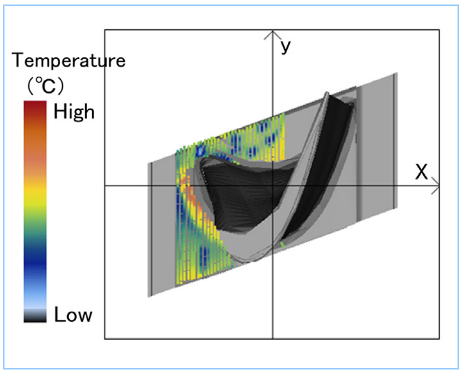

Figure 16 Temperature distribution on platform in the turbine row 1 blade obtained using a pyrometer

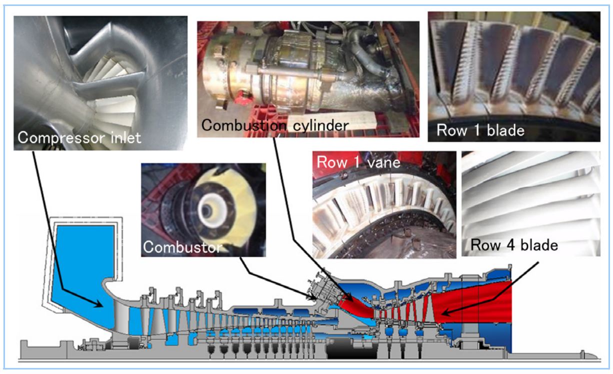

Figure 17 Disassembly inspection result

4. Conclusion

GTCC power generation is the cleanest and most efficient approach to power generation using combustion of fossil fuels and has many favorable social and economic aspects. MHI has developed the world's first 1,600 °C J-series gas turbine using technologies developed during the Japanese national 1,700 °C -class Ultra-high Temperature Component Technology Development project. The first M501J gas turbine has now completed the trial operation. MHI will contribute to the reduction of carbon dioxide emissions and help stabilize electric power generation with the J-series GTCC power generation system, which has a gross thermal efficiency of 61.5% (LHV basis).

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