Development of Emergency Gas Turbine Generator Unit with High Earthquake Resistance for Nuclear Power Plants

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The new nuclear regulations established after the nuclear accidents caused by the Great East Japan Earthquake required that additional power sources featuring diversity and independency (locational separation) be installed with the existing emergency power sources for nuclear power plants. To meet this requirement, Mitsubishi Heavy Industries Ltd. (MHI) started the development of the world's first gas turbine generator unit with high earthquake resistance for nuclear power plants, the MEG-6000, which is an emergency generator unit with principle and cooling means that differ from those of existing emergency power sources. We conducted verification and demonstration of the basic specifications, earthquake resistance, reliability, etc., of this unit and completed it, which is the system designed so that the main equipment is contained in the package, as an emergency generator unit. The unit was approved by the Nuclear Regulation Authority and the site installation work and test operation were both accomplished. We plan to install about 20 gas turbine generator units, almost all of which have already been manufactured. The MEG-6000 unit has been steadily establishing a track record as an emergency gas turbine generator unit with high earthquake resistance for nuclear power plants.

1. Introduction

After the nuclear accidents caused by the Great East Japan Earthquake, the new nuclear regulations were enacted to secure the world's highest level of safety (July 2013). These new regulations required the additional installation of various backup power sources featuring diversity and independency (locational separation) with the existing emergency power sources for nuclear power plants and we needed to develop a new power source that satisfied the requirement. MHI worked toward the development of a gas turbine generator unit (hereinafter referred to as a GTG unit) featuring earthquake resistance and reliability as a new backup power source. This report describes the background of the introduction of the GTG unit, the basic specifications of the GTG unit, the technical studies about earthquake resistance, reliability etc., as well as the actual status of nuclear permit/approval acquisition and the actual deliveries.

2. Background of introduction of GTG unit

2.1 States of emergency power sources when the Great East Japan Earthquake occurred

One of the major factors of the the Fukushima Daiichi Accident caused by the Great East Japan Earthquake was that due to the tsunami associated with the earthquake, the functionality of the emergency power sources (water-cooled diesel generator units) for supplying power to the safety equipment, which should have brought the accidents under stable control, was lost. Based on this experience, the new nuclear regulations were established and power sources are required to feature diversity (prevention of failures due to common factors) and independency (locational

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separation), in addition to redundancy for a further increase in robustness against earthquakes and tsunamis. Therefore, we needed to develop a new emergency generator unit that meets the regulatory requirements.

2.2 Configuration of emergency power source under new nuclear regulations

The configuration of emergency power sources for nuclear power plants under the new nuclear regulations is shown in **Figure 1**. Conventionally, as emergency AC power source units, two diesel generator units (water-cooled) were installed. The new regulations were enforced and the additional installation of backup power sources in case of a severe accident(Note 1) and specialized severe accident(Note 2) is now required. These additional power sources must also feature diversity and independency from existing emergency power sources.

To contribute to the increased safety of nuclear power plants, MHI started the development of a new emergency power source that meets the requirements of the new nuclear regulations. We selected a gas turbine engine that utilizes a principle (thermal cycle) different from that of the diesel engines used in existing emergency generator units and that is an air-cooled engine, which does not require water.

Note 1: Severe accidents at nuclear power plants that are beyond a credible design basis accident and cause significant damage to core, etc.

Note 2: Severe accidents that cause significant damage to core, etc., due to intentional large aircraft crashes or other terrorism

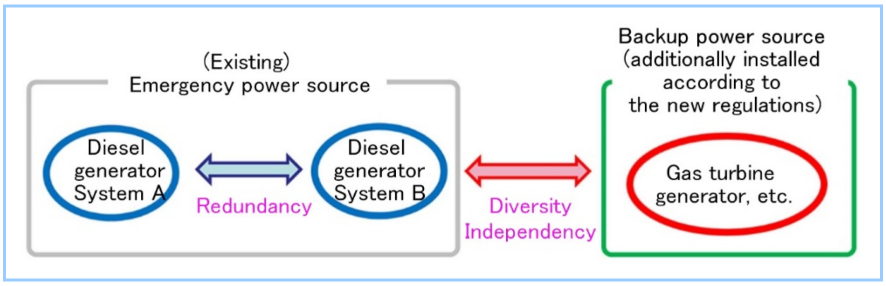

Figure 1 Configuration of emergency power sources for nuclear power plants under new nuclear regulations

3. System configuration and basic specifications of gas turbine generator unit

A system configuration example of MHI's GTG unit is shown in **Figure 2**. Main equipment such as a gas turbine engine, a generator, a reduction gear and other auxiliary facilities are installed and packaged in an enclosure (a housing for storing the components of the unit) (**Figure 3**). The gas turbine produces high-temperature and high-pressure combustion gas by taking in combustion air at the compressor and combusting the fuel oil supplied from the fuel storage tank at the combustor. The combustion gas converts thermal energy into rotational energy at the turbine, which generates power and is then discharged outside as exhaust gas. The ventilation system in the enclosure is simply configured so that it can provide not only ventilation of the exhaust heat coming from the gas turbine engine, the generator and other components, but also cooling air required for heat exchange of the oil cooler.

The basic specifications of the gas turbine package are shown in **Table 1**. As an emergency power source to be used in the event of a severe accident or specialized severe accident at a nuclear power plant, its output was set at 6000 kVA. In addition, to immediately supply power to the safety equipment in an emergency, the GTG unit can start up quickly within 60 seconds.

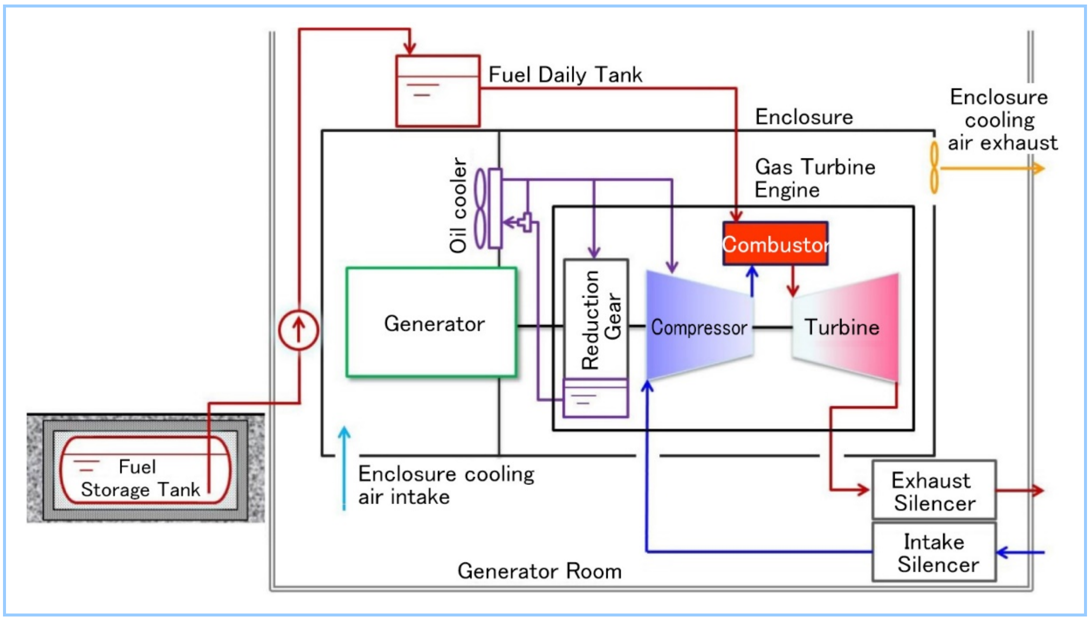

Figure 2 System configuration example of gas turbine generator unit

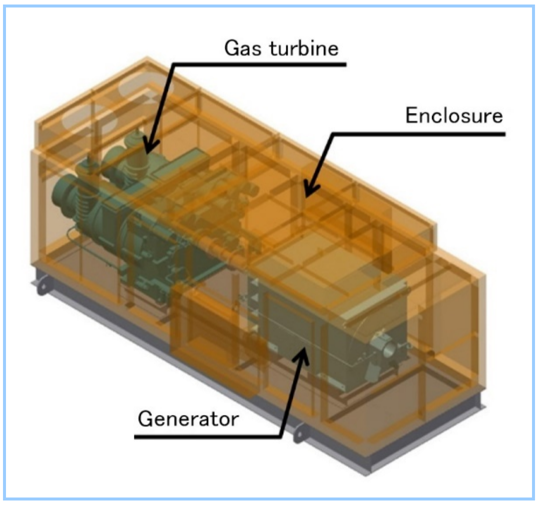

Figure 3 Appearance of gas turbine package

Table 1 Basic specifications of the gas turbine package

Item	Specification
Model	MEG-6000
Rated output	6000kVA/6900V (4800kW)
Frequency	50/60Hz
Startup time	Within 60 sec.
Type of fuel used	Diesel oil
Dimensions	3.2m x 8.3m x 3.7m (height)
Weight	About 53 tons

4. Studies for adoption of GTG for nuclear power plants

Before the enforcement of the new nuclear regulations, MHI had not delivered GTG units with high earthquake resistance for nuclear power plants in Japan. We newly designed and verified a GTG unit that conforms to the new nuclear regulations and the various conventional regulations. Hereinafter, the technical features of MHI's GTG unit and the studies for adoption at nuclear power plants are described.

4.1 Securement of diversity and independency

Existing emergency power sources for nuclear power plants use diesel engines. MHI adopted a gas turbine engine which provides diversity in terms of thermal cycle and cooling system.

A comparison of the combustion process of each thermal cycle between a gas turbine engine and a diesel engine is shown in **Figure 4**. Although both engines are internal-combustion engines, a diesel engine converts thermal energy into reciprocating motion and then into rotational motion to generate power, while a gas turbine engine converts thermal energy directly into rotational motion to produce power. This difference in the process allows the requirement for diversity of emergency power sources in the new nuclear regulations to be satisfied. In addition, a diesel engine installed in nuclear power plants has an indirect water-cooling system that uses seawater, while a gas turbine engine has an air cooling system that does not use seawater. In this respect, the adoption of a gas turbine engine also satisfies the requirement for diversity. Furthermore, a gas turbine engine does not need to be installed near seawater supply equipment and can be installed on high ground that is not vulnerable to tsunamis. From the perspective of locational separation, a gas turbine engine also provides a high degree of flexibility by an air cooling system that does not use seawater.

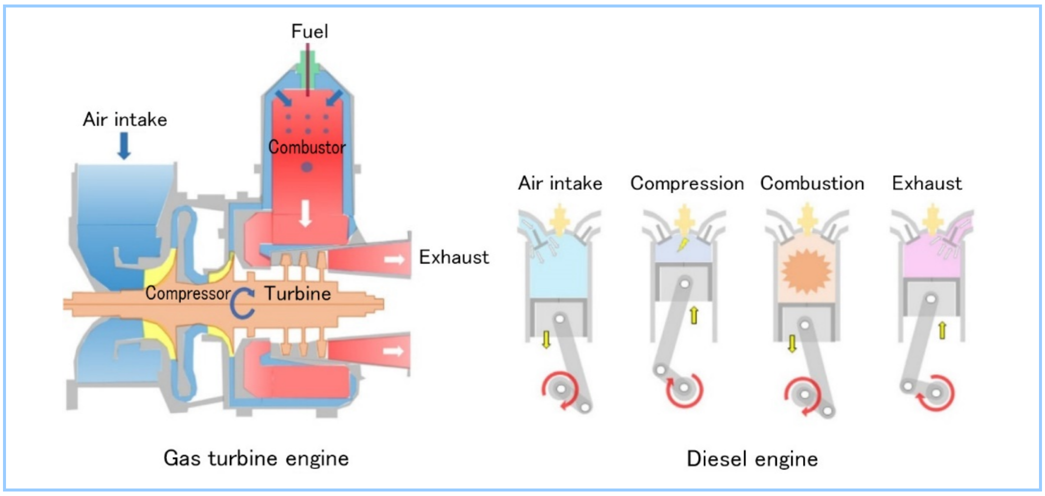

Figure 4 Comparison of combustion process between gas turbine engine and diesel engine

4.2 Verification of earthquake resistance of gas turbine engine to satisfy nuclear requirements

(1) Verification of earthquake resistance of gas turbine engine

To supply electricity to the safety equipment for a nuclear power plant in the event of an earthquake, a GTG unit must withstand the maximum earthquake motion assumed in design (basic earthquake ground motion). To this end, we designed and verified the earthquake resistance of the gas turbine engine by analysis and evaluation.

There is no description about the confirmed acceleration for function maintenance (acceleration with which the earthquake resistance was confirmed with vibration tests) of a gas turbine engine in JEAG4601. Therefore, referring to previous knowledge and past examination results, we established the methods for confirming the behaviors in the event of an earthquake and evaluating the earthquake resistance using FEM analysis (the numerical analysis using the finite element method), etc., and confirmed that the functionality of the gas turbine engine could be maintained when an earthquake occurred.

Through the vibration test for the actual gas turbine engine scale, we also confirmed that the gas turbine engine had earthquake resistance to horizontal acceleration of about 2.2G and vertical acceleration of about 3.1G[1]. (**Figure 5**.)

Figure 5 Vibration test for gas turbine engine

(2) Verification of earthquake resistance of auxiliary facilities

For auxiliary facilities (enclosure, pumps/tanks/ducts/pipes, etc.) other than the gas turbine engine, we verified the earthquake resistance based on the conventional evaluation method of JEAG4601. Among the auxiliary facilities, the equipment in the exhaust system, in which high-temperature exhaust gas (about 600°C) flows, require both earthquake resistance (high rigidity) and heat resistance (absorption of thermal expansion) which are conflicting characteristics. But it is difficult to satisfy the requirement with an exhaust gas silencer being placed at the gas turbine exhaust outlet with high heat load. We comprehensively designed to integrate the seismic evaluation methods for nuclear power plants and the design method using heat transfer analysis for high-temperature devices and achieved to acquire a structure with different functions and characteristics. In this structure, as shown in **Figure 6**, highly-rigid frames are set outside the relatively-low-temperature equipment to secure the earthquake resistance, while the inside silencing section that is exposed to high-temperature gas has a structure with panels that does not restrain thermal expansion. The panels are placed on the support plates and supported in the plane direction with the holding plates and can absorb thermal expansion by sliding in the in-plane direction. Even if adjacent panels contact each other, they do not restrain each other, resulting in the suppression of thermal stress generation. The adoption of the double structure that separates the functions inside and outside the equipment achieved to acquire both earthquake resistance and reliability. (Japanese Patent No. 6649119)

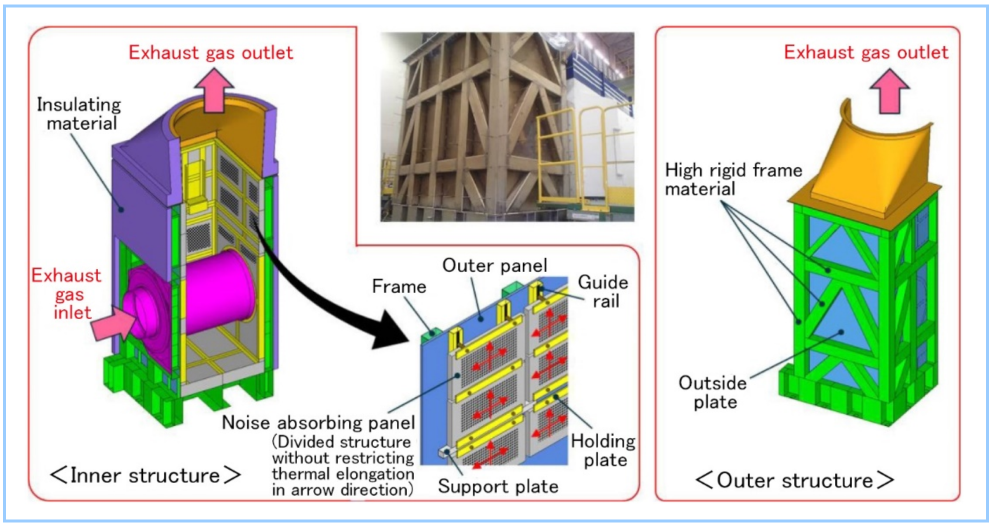

Figure 6 Overall view of sliding panels at silencer

4.3 Verification of reliability of gas turbine generator as emergency power source

GTG units are required to have the same high level of reliability as existing emergency generator units. We conducted verification of the actual equipment for reliability in accordance with the reliability verification tests (Initial Type Tests) specified in the IEEE Std 387 U.S. standard for existing emergency diesel generator units.

The reliability verification tests consist of three test items shown in **Table 2** and we conducted the tests at the facilities of MHI's Kobe Shipyard & Machinery Works during the period from January to February 2014.

Table 2 Content of reliability tests for gas turbines

Reliability verification test	Content
Load capability test	To check the integrity of the gas turbine performance by continuous operation at rated load for the specified period of time and load rejection operation.
Start and load acceptance test	To check the integrity of the gas turbine operation by startup within the period of time necessary to satisfy the actual equipment requirement and input of load.
Margin test	To check the integrity of the gas turbine control over voltage and frequency fluctuations at an instantaneous input/rejection of load exceeding 10% of the required output of the actual equipment.

(1) Load capability test

In the load capability test, we mainly conducted a 100% rated load continuous operation for a period if 24-hours and confirmed the integrity and stability of the engine performance characteristics such as fuel consumption and exhaust gas temperature. The verification results of the fuel consumption showed that the GTG unit has a high level of design accuracy to the fuel storage amount and we confirmed that concerning the requirement of "the power shall be supplied for seven days after the external power supply is lost" in the event of a specialized severe accident, etc., in the new nuclear regulations, the reliability of the fuel consumption is secured.

(2) Start and load acceptance tests

In the start and load acceptance tests, we conducted 100 consecutive start and stop operations and confirmed the engine integrity of response to operation commands. This is a severe test specifically designed for emergency generator units in which quick startup within 60 seconds and stop operations are repeated by 100 time in the state of the engine being not fully cooled (hot condition). The GTG unit passed this test without any trouble and it was verified that the GTG unit is highly reliable as an emergency power source.

(3) Margin tests

A margin tests is conducted to check the integrity of the stabilizing control of voltage and frequency fluctuations after an instantaneous input and rejection to a load 10% larger than the maximum output, which is required in the actual equipment operation. In this test, we conducted input and rejection with 100% rated load, which is even broader in scope than the standard requirement and confirmed the integrity. Through this test, we also confirmed that the GTG unit has a high level of stability toward the load fluctuation caused by the high-speed and large rotational inertia force of the gas turbine engine and its high reliability as well as control integrity was verified.

As described above, the GTG unit (MEG-6000) successfully passed the reliability verification tests in accordance with IEEE for the first time as a GTG unit for nuclear power plants in Japan and its high reliability has been verified.

Figure 7 Group photo of the individuals involved in the GTG unit reliability tests

5. Permits and approvals obtained/construction work results

For installation of a GTG unit at a nuclear power plant, an application for an installation permit must be filed and the Nuclear Regulation Authority's approval for the construction plan is required based on the Nuclear Reactor Regulation Law. MHI's GTG unit passed the examination based on the new nuclear regulations, which are regarded as the strictest in the world, and obtained approval for installation. (As of October 2020, approval has been obtained for 9 nuclear plants: Sendai Nos. 1 and 2, Takahama Nos. 3 and 4, Takahama Nos. 1 and 2, Ikata No. 3 and Genkai Nos. 3 and 4.) We delivered MHI's first GTG unit in March 2018 and as of October 2020, the site installation and test operation for 7 units have been completed. We plan to install more than 20 GTG units, some of which have already been installed at the aforementioned plants. MHI's GTG unit has been steadily establishing a track record as Japan's first emergency GTG unit with high earthquake resistance for nuclear power plants.

6. Conclusion

MHI newly developed a gas turbine generator unit that satisfies the world's strictest requirements under the new nuclear regulations, featuring diversity, earthquake resistance and reliability. We are now striving to conduct construction work for delivery to domestic nuclear power plants. From the lessons of the nuclear accidents caused by the Great East Japan Earthquake, we realized again that in bringing a nuclear power plant safely under stable control in the event of an emergency, power supply plays an important role in ensuring the safety of nuclear power plants. We will make efforts to increase the reliability of emergency power sources through the manufacture and delivery of highly reliable gas turbine generator units and conduct system designs not only for gas turbine generator units, but also for various emergency power sources. These emergency power sources include emergency diesel generator units and power source vehicles, and system design will be carried out properly according to plant specifications, thereby increasing the reliability of all emergency power sources. In turn, these efforts will contribute to improving the safety of nuclear power plants.

References

(1) Yoshiki Ogata, et al., Initial Type Test Result of Class 1E Gas Turbine Generator System, (2013), https://www.nrc.gov/docs/ML1400/ML14002A353.html〕