Reliability Technology for Submarine Repeaters

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Fujitsu's submarine repeaters have been installed on the seabed worldwide. In 1969 Fujitsu delivered its first submarine coaxial cable system laid along the Uchiura Bay route off Hokkaido, and now deploys the most advanced optical-amplifying repeaters. Fujitsu has thus far delivered a total of about 2400 submarine coaxial and optical repeaters in its latest cable systems. Fujitsu repeaters are widely acknowledged as being the most reliable products in the submarine cable industry and have never required ship-based repair during commercial use since the inception of this industry. These highly reliable submarine repeaters have been achieved thanks to a consistent concept of developing components, design, development, manufacturing, and inspection. Fujitsu has also built a mechanism for promoting close communication among all personnel and organizations concerned to sustain and improve reliability skills. This paper describes the various activities undertaken by Fujitsu with regard to its highly reliable submarine repeaters.

1. Introduction

Fujitsu has delivered a number of submarine cable systems for use not only in the seas near Japan, but also throughout the world. Since the submarine cable system business began with the coaxial transmission system in 1969, until the delivery of the latest optical transmission systems, Fujitsu submarine cable systems have been highly praised by customers. **Figure 1** shows the routes of WDM submarine optical cable systems supplied by Fujitsu to date.

As a leading system supplier, Fujitsu has provided highly reliable submarine cable systems by dedicating the full use of total engineering. This begins with project planning and a cable route engineering survey. Then it proceeds to the system design, development, design, and manufacturing of submersible equipment (such as submarine repeaters and branching units) and submarine line terminal equipment, construction work involving cableships, and maintenance following system installation and operation (**Figure 2**).

A submarine cable system consists of a submersible plant and a submarine line terminal plant. The submersible plant includes submarine repeaters, branching units, and submarine cables. The submarine line terminal plant includes submarine line terminal equipment, power feeding equipment, and equipment installed at the landing station. Should failure occur in any unit of the submersible plant, the submarine cables and repeaters must be recovered from the seabed, repaired, and re-laid, which entails considerable time and high cost. Moreover, a main artery of international communications will be interrupted, imposing a huge impact on society. Accordingly, highly reliable submarine repeaters represent a mandatory requirement for submarine cable systems.

Fujitsu has deployed brand-new technologies to provide submarine cable systems through

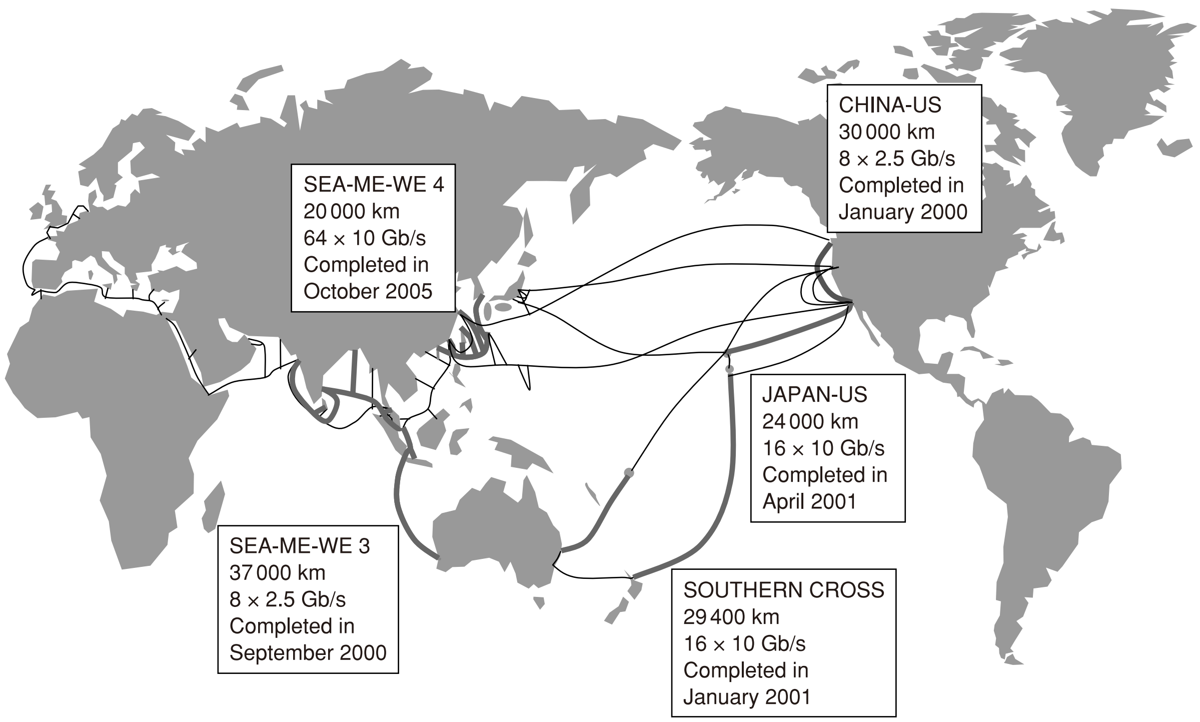

Figure 1
Fujitsu WDM submarine cable systems deployed in Asia-Pacific region.

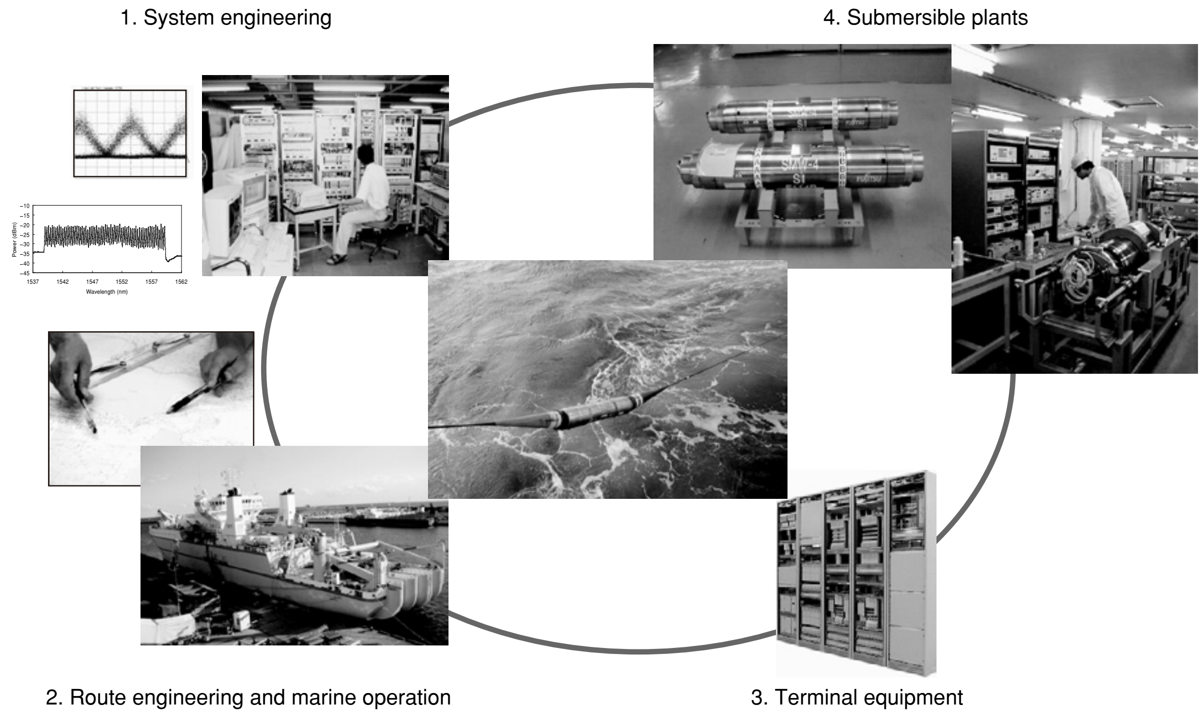

Figure 2
Fujitsu total submarine cable network system.

evolving generations, and the submarine repeaters delivered by Fujitsu have yet to experience failure.

This paper describes the reliability technology developed by Fujitsu to achieve highly reliable submarine repeaters ever since its first submarine transmission system was delivered.

2. Reliability of submarine repeaters

2.1 Specification requirements

Submarine repeaters to be laid 8000 meters below the sea surface must be sufficiently resistant to corrosion from seawater under high-hydraulic pressure. Also, given the prohibitively high cost of salvaging and repair work, the internal circuitry of submarine repeaters also requires both high quality and high reliability.

2.1.1 Main features of submarine transmission system

The following gives an example of the latest submarine optical transmission system.

- Transmission bit rate: 10.709 Gb/s (transmission capacity of 9.95328 Gb/s STM-64: S64.2 ITU-T G.691)
- Configuration: Optical-amplifying repeater
- Power feeding current: 1.0 A
- System voltage: ±12 kV or less
- Maximum water depth: 8000 m
- Operating temperature: 0 to 35°C
- Supervisory system: C-OTDR, repeater monitor system (input monitor, output monitor, laser diode [LD] current monitor)

2.1.2 Required reliability

The reliability required depends somewhat on the total system length and location where the system is installed. The specification requirements of a typical long-distance system are as follows:

- System lifetime: 25 years
- Average repair count (number of ship-based repairs)[note 1]: 3 or less (in 25 years)
- Number of fits[note 2] per repeater (for 4 systems): 22 fits or less @ 5°C CL 95%

The lifetime required for a submarine transmission system is typically 25 years due to its very high initial investment cost. A system such as the Trans-Pacific Cable requires about 200 repeaters. When 22-fit repeaters are used, the repair count in 25 years is estimated to be 1 or less.

2.1.3 Environmental conditions[1),2)]

Maintaining stable system operation for 25 years on the seabed at a depth down to 8000 meters requires the environmental resistance characteristics described below. Current submarine optical repeaters adopt the technologies used to achieve environmental resistance, as well as new technologies specific to submarine coaxial repeaters.

1) Anti-corrosion and anti-hydraulic pressure

The housing of repeaters is made of a beryllium copper alloy that offers excellent anti-corrosion resistance and mechanical strength in seawater.

2) Airtight structure

The repeaters feature an airtight structure to resist a hydraulic pressure of 800 kgf/cm^2 (78.5 MPa) and prevent humidity from rising above 20%RH inside the housing for 25 years. This degree of airtightness has been made possible through the following:

- Sealed circumferential welding at both ends of the cylindrical pressure-tight housing.
- Collective insertion of optical fibers and power feed cable into the pressure-resistant cabinet while maintaining airtightness. The optical fiber cable features a structure sealed by metal with solder; the power feed

note 1) (Total fit rate of submersible plant) × 24 (H) × 365 (D) × 25 (Y) × 10^{-9}.

note 2) Abbreviation for “failure unit”, a unit of failure rate. 1 fit = 10^{-9} count/hour. For example, 22 fits indicates a Mean Time Between Failures [MTBF] of 5188 years.

cable has a structure sealed by polyethylene molding and a metal cone.

- Air tightness tests for all submarine repeaters using a pressure equal to the operating hydraulic pressure to check airtightness at the final stage of manufacturing.

3) Dielectric strength

A polyethylene cylinder is placed between the internal unit and external housing to achieve a dielectric strength structure of ±15 kV or more.

4) Evaluation of surge resistance

The submarine repeater is protected against power surges that may result from a sudden interruption of the high voltage supplied on the cable. The submarine repeater surge protection circuit consists of a gas tube arrester, coils, and high-power Zener diodes and resistors. These circuit components are used in evaluating electric current and transient properties at a simulated surge, and enable surge resistance to be evaluated using a surge test generator under the following conditions:

- ±15 kV
- ±200 A

5) Vibration and impact resistance

A vibration and impact test is conducted to check whether the system can withstand vibration and impact during transport and installation.

6) Evaluation of individual parts

Individual parts are checked to see if they can withstand the environmental conditions when they are integrated into the internal circuit, during manufacturing, and after installation.

The evaluation items include resistance to radiation, drying, magnetism, hydrogen gas, barometric pressure, fiber strength, and internally generated corrosive gas.

7) Temperature-humidity test

A temperature cycle test is conducted along with a high/low temperature shelf test.

2.2 Submarine repeater configuration and measures to ensure high reliability

To maintain the reliability of submarine repeaters, traditional and proven techniques should be employed in the design as much as possible. New parts and techniques must be evaluated over a long period to improve reliability. The test process requires a system for detecting failures in parts or at the earliest possible stage of manufacturing.

2.2.1 Redundant configuration

The submarine optical repeater has achieved a system of high reliability. For instance, the pump laser diodes and control circuit of the optical amplifier have redundant configurations to improve reliability. Since a system consists of four pump laser diodes, any failure that may occur in three of the four pump laser diodes has no impact on the system performance.

2.2.2 Design reliability

The resistors and Zener diodes are rated, respectively, at 4 and 10 times their maximum operating powers.

2.2.3 Manufacturing test methods

1) Automatic tests

To conduct different tests in a short time, all process tests are conducted automatically. In the adjustment test, adequate adjustment resistance values are automatically calculated based on characteristics obtained by simulating the application of electric current from outside instead of based on variable resistance.

2) Building a database

Everything from the test data on repeater optical electric parts, data acquired during the manufacture of repeaters, to the final test results is stored in a database. Parts are automatically combined for each system unit to obtain uniform characteristics based on the database. The assembly and manufacturing processes directly affect these combined parts.

3) Test specifications

Any failure in parts or manufacturing defects can be detected early by comparing the test results obtained in each process with the estimated values calculated from the parts data. Test specifications are defined to satisfy the system specification requirements. Likewise, more rigorous test specifications should be set based on accumulated test result data of previously manufactured repeaters. In this way, any unchecked parts that have deviated from data distribution can be prevented from being sent to the next process.

4) Statistical processing

Statistical processing is performed for parts data and test results stored in the database. Statistical processing helps us to detect parts that have deviated from distribution at an early stage and analyze the causes.

3. Reliability of components

Ensuring the reliability of components of submarine repeaters that need a service life of 25 years or longer is a very important factor. This section describes the techniques employed by Fujitsu to ensure the reliability of various components of its submarine repeaters.[3),4)]

1) Failure mode analysis and high-reliability design

Based on existing field data and a prototype evaluation, we analyzed the factors of degradation for the characteristics of each component element, degradation caused by variations in joint areas, and damage to structural elements. To confirm failure modes and eliminate various disadvantages, we made such design improvements as reviewing and selecting proper materials, and changing element structures.

2) Screening test

Before evaluating reliability, we established a high-reliability screening method for removing components subject to initial failure factors and aging in order to stabilize characteristics.

As an example of the screening test, we performed electric power aging in a temperature cycle from −60 to +150°C for several 10s of cycles, and at Ta = 150°C for 500 hours. We employed a technique that certainly satisfied the test standards before and after the screening test.

3) Lifetime test

We conducted a variety of tests on components that passed the screening test, such as a continuous operation test, high-temperature/high-humidity shelf test, temperature cycle test, and accelerated test. Then we estimated the lifetimes and acceleration rates of individual components, and confirmed that the components satisfied the targeted reliability.

4) Manufacturing process management

To stably manufacture the components needed to achieve high-reliability design, we established various work methods, developed facilities and jigs, and thoroughly conducted production control and in-process inspection. Accordingly, we designed a manufacturing process that eliminates any factors that might adversely affect reliability.

5) Lot assurance test

We further sampled components manufactured in the established process for each manufacturing lot and conducted a lot assurance test to prevent the inclusion of any defective lots.

4. Reliability management in manufacturing of submarine repeaters

Highly reliable submarine repeaters are achieved by establishing manufacturing and quality control systems throughout the manufacturing process, as well as various designs focusing on the development and reliability of high-reliability components. This section describes the reliability technology utilized in manufacturing and producing our submarine repeaters.[5)]

4.1 Building reliability management systems

1) Execution system and organization

A brand-new organization and management system have been adopted for manufacturing submarine repeaters, so that the departments concerned can work closely together to achieve the reliability targeted at the design stage. These departments include the design department responsible for the development and design of components and equipment, the factory department responsible for manufacturing, inspection, manufacturing technology, production management, and quality control, and the purchase department. As an example of cooperative activities, "liaison meetings between the design and factory departments" are periodically held with a high level of communications. The meetings are intended to develop schemes of basic policies, solve problems and issues, and review manufacturing progress.

2) Data processing and traceability management

A new management system has also been adopted for the assembly process. This system allows us to record data for all work conditions, management items, and test results from the reception of parts materials to the final completion of repeaters. This data is finally processed on the computer. A traceability management system has also been established to search for causes of failure retroactive to part materials for any failure detected in postprocessing or after product shipment.

3) Corrective actions

A corrective action procedure has been established for any failure that may be detected in manufacturing or inspection to prevent the recurrence of similar failure.

4.2 Selecting and qualifying workers, and building education and training system

1) Selecting workers and offering general education

To stably, efficiently, and continuously manufacture highly reliable submarine repeaters, workers are carefully selected by assessing their suitability, including their physical and mental conditions, experience, and skills.

The workers selected are then trained to acquire the following relevant knowledge necessary to provide highly reliable submarine repeaters:

- A general knowledge about the circuit configuration, structure, performance, and roles of submarine repeaters
- A general knowledge about reliability and quality assurance
- The proper mental attitude as workers engaged in manufacturing submarine repeaters

2) Qualifying specialists and offering education

Specialized work including the splicing of optical fiber, soldering, polyethylene molding, sealing cabinets by welding, and X-ray inspection requires advanced techniques. Workers engaged in this specialized work or a particular work such as conducting an air tightness test using high-pressure gas are trained and given aptitude tests. These activities include:

- Education and training for improving practical skills, knowledge, and reliability for each specialized work according to the instructor's programs
- Creating education and training records, and maintaining and improving worker skills
- At the end of the education and training program, undergoing practical and academic examinations, with certification granted to workers who pass the examinations

4.3 Specifying and automating assembly work

Based on the structural design specifications and manufacturing conditions established in the preliminary prototype evaluation, various work specifications and manufacturing method standards have been developed and established. The work specifications define the assembly methods and conditions in each process, work control items, jigs and tools, manufacturing plants, and environmental conditions. Control items are checked and recorded in each process, and product quality is evaluated and checked according to these specification documents. In this way, we have achieved highly reliable repeaters.

Typical processes in assembling submarine repeaters include polyethylene molding and sealing the repeater housing by welding. Polyethylene molding assures insulation essential to long-term reliability and repeater housings sealed by welding require a pressure tightness and airtightness lasting at least 25 years at a depth of 8000 meters below the sea surface. For these processes, techniques for automating work, facilitating product homogenization, and recording the work status in each process have been established to improve reliability.

4.4 Establishing inspection and test process

Highly reliable submarine repeaters require assured quality through conclusive inspections and tests, as well as carefully managed assembly work as mentioned above. The inspection and test process has been established for all operations from the assembly of circuit units to the final completion and shipment of repeaters. The test specifications that define test items, test facility specifications, test methods and procedures, and test standards have been established for the tests and inspections in each process.

5. Delivery results and reliability

To date, Fujitsu has delivered a total of about 2400 submarine repeaters since its first delivery in 1969.

The cumulative operating time of all the submarine repeaters we have delivered is at least about 0.3 billion hours. During this time, no Fujitsu submarine repeaters have experienced failure. The number of fits per repeater as calculated from the cumulative time above is 3.3 or less.

Given these results, Fujitsu submarine repeaters are widely acknowledged as being the most reliable in the world.

6. Conclusion

Highly reliable submarine repeaters can be achieved thanks to the reliability technology established based on a consistent concept of developing components, design, manufacturing, and other numerous factors.

Fujitsu submarine repeaters have been operating on international lines of communication on the seabeds of oceans, seas, and bays around the world. From the first delivery of Fujitsu submarine coaxial repeaters in 1969 to the latest submarine optical-amplifying repeaters, our repeaters have never experienced ship-based repair over several generations.

Fujitsu is now promoting the adoption of reliability technology developed for submarine repeaters, as well as the development of next-generation technologies. In a growing global submarine market, Fujitsu will proactively continue to offer its highly reliable devices and systems.

References

1) M. Motegi et al.: Optical Submarine Transmission Systems. (in Japanese), *FUJITSU*, **37**, 6, p.465-472 (1986).
2) K. Shimoyamada et al.: Optical Submarine Repeaters and Branching Units. (in Japanese), *FUJITSU*, **40**, 4, p.188-196 (1989).
3) H. Karibe et al.: Integrated Circuits for Submarine Optical Repeaters. (in Japanese), *FUJITSU*, **40**, 4, p.213-220 (1989).
4) K. Yakuwa: CS-36 MD-System High-Reliability Parts. (in Japanese), *FUJITSU*, **26**, 2, p.193-207 (1975).
5) T. Ikeda et al.: Reliability Technology for Submarine Repeaters. (in Japanese), *FUJITSU*, **29**, 6, p.919-931 (1978).

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