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Steel Products for Energy Industries[†]

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Abstract:

Improvements of infrastructure for energy industry, including development, production, transportation and utilization, are promoted in order to tackle the increase of energy demands in the world. Use of steel products with high quality and reliability are critical to improve the energy efficiency and assure the safety of equipment and facilities in energy industry. In this paper, steel products used in energy industry and required properties are described. Finally, the activities of JFE Steel in this business area are introduced.

1. Introduction

Energy consumption, which supports economic activity and individual life, is increasing dramatically due to global population growth and the economic development of the more advanced developing nations, represented by the BRICs.

The infrastructure for the development, transportation, and use of energy is also dynamically constracted to meet this increasing energy demand.

Steel products are widely used in plants for production and use of energy resources, represented by petroleum and natural gas. Steel materials are used in various forms and must provide high levels of performance and quality. In the field of steel products for energy industries, JFE Steel is actively engaged in research and development of materials to meet customer requirements utilizing state-of-the-art material technologies and production equipment.

This paper clarifies the roles of steel products and introduces the efforts of JFE Steel in energy industries.

2. Trends in Energy Demand

As shown in **Table 1**, energy is classified into primary energy, which is distributed in nature, and secondary energy, which is obtained by converting primary energy into more easy-to-use forms. Primary energy is further classified into fossil fuels, renewable energy, and nuclear energy. Fossil energy is represented by petroleum, natural gas, and coal. Renewable energy are hydro power, wind power, and geothermal energy. Secondary energy means electric power and fuels such as gasoline, kerosene, etc., all of which are obtained by conversion of primary energy.

Table 1 Type of energy

Primary energy	Fossil energy	Petroleum Natural gas Coal
	Renewable energy	Hydro power Wind power Geothermal Biomass
	Nuclear power	
Secondary energy	Electricity	
	Fuel	Gasoline Kerosene, etc.

"Annual Energy Outlook 2011" by the United States Energy Information Administration (EIA), announced that energy demand is expected to increase by 53% between 2008 and 2035, as shown in **Fig. 1**[1)].

Consumption of petroleum will increase by 30% (annual rate: 1.0%), natural gas will increase by 53% (annual rate: 1.6%), and coal will increase by 47% (annual rate: 1.4%).

Renewable energy is forecast to grow at an annual rate of 2.8% over the same period and its share will increase to 15%. Thus, use of renewable energy will increase greatly and its share of total energy consumption will also increase. Nevertheless, fossil fuels will account for 80% of total energy consumption even in 2035. Although the share of petroleum will decrease to

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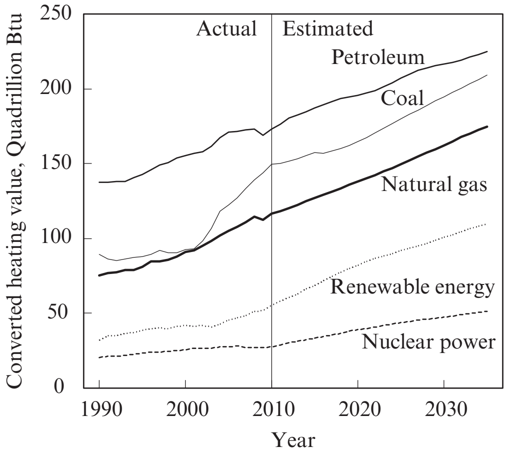


Fig. 1 Consumption of energy

29% in 2035, petroleum will still be the most important fuel in terms of consumption.

3. Energy Supply and Steel Products

3.1 Petroleum and Natural Gas Production, Transportation, and Use Processes

In order to use energy, resources which exist in the natural world are extracted and transported from the producing region to consuming regions and converted into secondary energy by electric power facilities or oil refining equipment.

The steel products apply to energy production, transportation and facilities for energy comsumption[2)] will be explained in this section, focusing on the examples of subsea oil and gas fields. An outline of the processes and examples of the steel products used are shown in **Table 2**.

(1) Development

Drilling rigs used in the development of offshore oil and natural gas can be generally clasified into the fixed type and the floating type. The jack-up rig and submersible rig are types of fixed rigs. These fixed drilling rigs are used in shallow water. Semi-submersible rigs and drill ships are examples of the floating type. Drilling can be performed to a maximum depth of approximately 3 500 m.

Figure 2 shows a schematic drawing of the structure of a jack-up rig as an example of the fixed type. The steel products used in this type of rig include drill pipe, casing, riser pipe, and others. Drill pipe is used to drill wells to extract oil/natural gas from the sea bottom. Casing prevents the drilled well from collapsing. Riser pipe for circulating the fluid used in drilling wells. High strength steel plates are also used in the body of the rig.

(2) Extraction and Production

Offshore production systems for oil and natural gas are also classified into the fixed type and the floating type. Fixed type production systems include the jacket type, gravity based structures (GBS), compliant towers, and so on. These types are used in comparatively shallow water. Floating production systems comprise semi-submergible production systems (floating product system: FPS), floating production storage and offloading units (FPSO), floating storage

Table 2 Application of steel products for development and production system of sub sea wells for oil and gas

Process	Equipment/Plant	Steel products used
Devel-opment	Drilling rig	Drill pipe Casing, Riser pipe High tensile strength steel plates (Marine structures)
Extraction/ Production	Platform	Tubing Casing Linepipe (Flow lines, Gathering lines)
		High tensile strength steel plates (Marine structures)
Trans-portation	Marine transportation Oil tanker Liquefied natural gas (LNG) carrier	Steel products for shipbuilding, Corrosion resistant materials for shipbuilding
	Pipeline	Linepipe Plates for linepipe
Storage	Oil tank Gas holder	High tensile strength steel plates
Refining plant	Plant piping Heating furnace piping	Special tubes (Cr-Mo Steel)
	Pressure vessel	High tensile strength steel plates Clad steel plates
Power generation	Superheater Piping	Special tubes (Cr-Mo Steel)

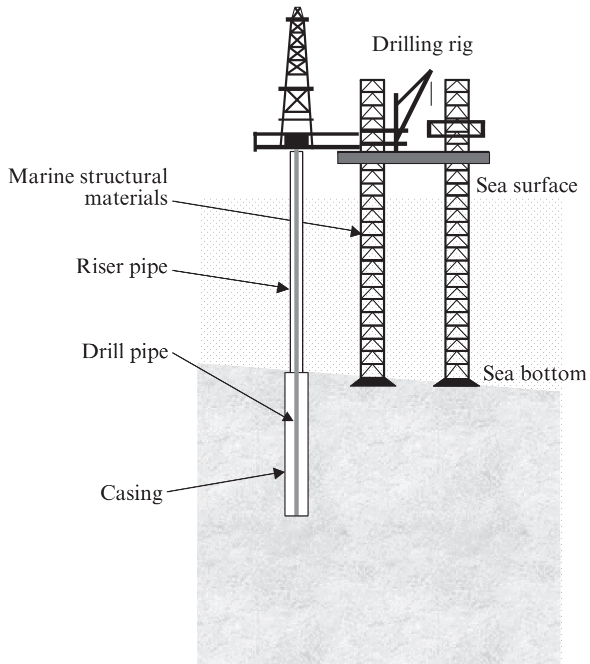


Fig. 2 Schematic drawing of jack up rig and steel products

and offloading systems (FSO), tension leg platform (TLP), and SPAR. These are used in deep water with a depth of 600 m or more. In recent years, the number of underwater production systems which do not use a marine structure has also increased.

In these production systems, for the tubing and casing which make up the production well, linepipe for transporting the produced oil or natural gas, high strength steel materials are used. When used in the North Sea and other cold regions, strict low temperature toughness properties are required for the platform body.

Oil sand and shale gas are classified as unconventional oil and natural gas resources. Steel products also play an important role in recovering these resources. With oil sand, steel tubes for steam injection to increase the fluidity of the heavy oil underground and steel tubes for crude oil extraction are used. In shale gas extraction, tubing and casing are used in the same manner as in extraction of conventional natural gas resources.

(3) Transportation

In many cases, long distance transportation of oil and gas are necessary, as the consuming region is far from place of production.

The means of transportation are marine transportation using oil tankers and LNG carriers (LNG: liquefied natural gas) and pipelines joining the producing and consuming regions.

High quality is required in the materials used in oil tankers and LNG ships to ensure safety. In particular, the reliability of welds is important. In oil tankers, high corrosion resistance is required in crude oil tanks and piping to prevent corrosion by impurities such as H_2S contained in crude oil.

Pipelines are used to transport oil and natural gas from producing regions to consuming regions. As the name indicates, steel pipes are used.

(4) Refining Plants and Electric Power Facilities

In thermal power plants, high Cr alloy steel tubes and plates with improved high temperature strength and oxidation resistance properties are used to increase power generating efficiency.

Large quantities of steel pipes and tubes are used in various piping applications. In ducts, chimneys, and flues, in addition to high Cr alloy steel plates, sulfuric acid corrosion resistant steel plates, stainless clad steel plates, and stainless steel plates and pipes are used.

Titanium alloy and titanium clad steel plates are also used in condensers. As other products, large quantities of heavy section plates are used in various types of tanks which are installed as auxiliary facilities.

In the hydro power fields, high strength heavy section plates are used in penstocks and in casings and rim plates, etc. around generators. Stainless steel plates and clad steel plates are used in water intake and outlet gates.

In the nuclear power fields, heavy section plates are used in the reactor containment vessel and reactor pressure vessel. Pipes and tubes, made by stainless steels and carbon steels, are used in piping in the containment vessel and around the turbine. Titanium alloy and titanium clad steel plates are used in condensers, and stainless clad plates are used in stacks. In general purpose applications, large amounts of carbon steel pipes and tubes (including low alloy steels) are used in low temperature steam piping and general piping.

Steel products are also used in geothermal power generation, which has attracted attention as a form of clean energy; in this field, casing and piping are used to extract steam and geothermal hot water from the ground.

3.2 Properties Required in Steel Products for Energy Industries

As described in the previous section, steel materials play an essential role in plant equipment for energy development, production, and use. This section will introduce the properties required in steel products for energy industries (**Table 3**).

One of the requirement for these plants is economic efficiency, namely, reduction of construction and operating costs. A possible avenue for reducing costs is use of high strength materials. Adoption of high strength materials enables construction of large-scale equipment and use of high pressure, high temperature operating conditions. At the same time, it is also possible to reduce the amount of materials used, resulting reduction of equipment weight and installation work are also possible.

On the other hand, in order to handle oil and natural gas with high energy densities, a high order of safety and reliability is required in materials. This means that it is necessary not only to secure adequate safety with respect to the design conditions, but also against external factors such as natural disasters, corrosion, etc.

Table 3 Requirement for Steel products in energy industory

Economy	Construction cost
	Operating cost
Reliability/Safety	Corrosion
	Natural disaster
	Accident

(1) Oil and Natural Gas Production Wells

In production of oil and gas, steel pipes and tubes are used in large quantities in casings, which provide support to prevent destruction of the oil well, tubing to carry the oil or gas to the ground surface, linepipe for transportation from the well to the oil refinery, and other applications (**Fig. 3**).

In oil and natural gas development, a high performance is required in oil well tubulars, accompanying the increase in deep wells (high temperature/high pressure) and wells containing corrosive gases and progress in drilling technology, such as horizontal drilling and the like. The main property requirements are the following 3 points.

(a) High strength
(b) High corrosion resistance
(c) Threaded joint performance

As the depth of oil wells has increased, high strength materials have also become necessary in order to support the dead weight of the tubing and casing.

Harsh corrosive wells which contain large amounts of CO_2 and/or H_2S gas are characterized by high temperature and high pressure conditions, called deep sour oil/gas wells. Because carbon and alloy steels are often subject to carbon dioxide corrosion and sulfide stress corrosion cracking, corrosion resistant materials are used. The environmental factors affecting corrosion of metal materials in oil/gas wells are shown in **Table 4**. The corrosiveness of wells is determined by the amount of H_2S, CO_2, chlorides, and others contained as impurities in the oil or gas. Gas wells are generally more corrosive than oil wells, as the oil film adheres to the surface of the steel and protects from corrosion. Since corrosion occurs only when water is present, gas wells with water are prone to corrosion.

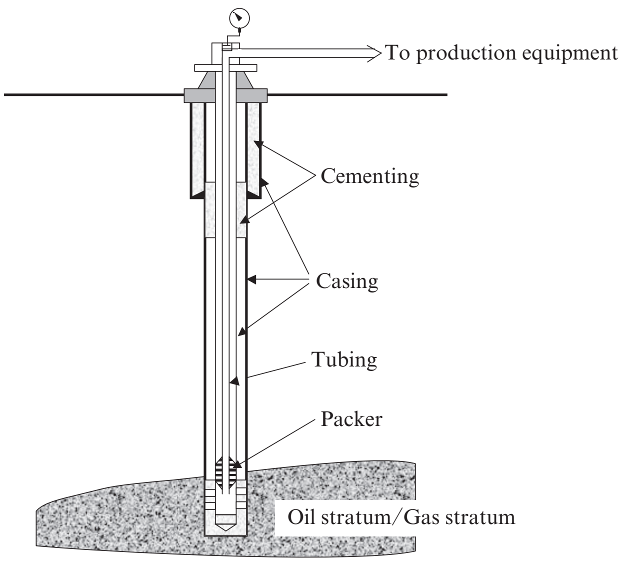


Fig. 3 Schematic drawing of oil and gas well

Table 4 Factor affecting corrosion in oil and gas wells

Composition of production fluid	Oil/Gas moisture content
Concentration of corrosive substances	H_2S, CO_2, Chloride concentration, pH, etc.
Production rate	Flow velocity
Depth of well	Temperature, Pressure

Table 5 Corrosion found in oil and gas environments

General corrosion and pitting corrosion	Most general mode of carbon dioxide corrosion. Strongly affected by temperature, flow velocity, etc.
Sulfide stress corrosion cracking (SSCC)	Cracking occurs in high strength steels when H_2S coexists.
Chloride stress corrosion cracking (SCC)	Cracking occurs in stainless steels when H_2S exists with chlorides.

Carbon dioxide gets thinner pipe wall, and presence of H_2S and chlorides causes stress corrosion cracking. Corrosion is generally more severe under high temperature conditions (**Table 5**).

Oil and natural gas wells are classified as follows from the viewpoint of corrosiveness.

(a) Wells containing mainly CO_2 with temperatures of more than 60°C
(b) Wells in which H_2S and CO_2 coexist with temperatures of more than 60°C
(c) Wells containing mainly H_2S with temperatures of 100°C or less

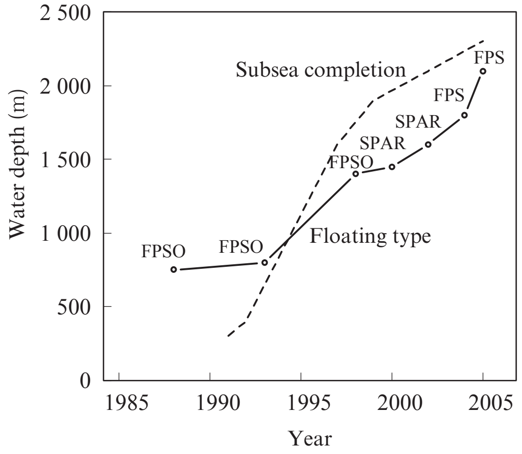
Severe corrosion occurs in carbon steel when the well environment contains CO_2. Inhibitors or corrosion resistant materials such as stainless steel and high Ni alloys are used to prevent this problem.

In environments where H_2S exists, corrosion may enhance hydrogen permeation into the steel and it causes cracking when high strength oil country tubular goods (OCTG) are used. This phenomenon is called sulfide stress corrosion cracking (SSCC). Alloy steels containing Cr and Mo are used to prevent SSCC.

In environments where both of H_2S and CO_2 exist, stainless steel and corrosion resistant alloys are used to prevent carbon dioxide corrosion and SSCC.

(2) Marine Structures

The offshore platforms are exposed to various external forces, such as forces due to wave, ocean currents, and tidal currents, wind, seismic loading, etc. In floating platforms, it is also necessary to consider loaded due to vibration. Since the 1990s, deep water development has been promoted, and floating type production systems have reached water depths of 2 100 m and subsea completion to 2 200 m. Because the effects of wind force, wave force are large in the



FPSO: Floating production, storage, and offloading system
SPAR: Cylindrical type floating oil production equipment
FPS: Semi-submersible type production system

Fig. 4 Change in water depth of sub sea wells for oil and gas

deep water development, excellent properties and quality are required in the materials used. **Figure 4** shows the change in the water depth of subsea oil and gas wells.

The main properties required in materials for marine structures are strength, weldability, and low temperature toughness. Since the effect of external forces increases as structures are up-scaled, high strength materials are required. At present, high strength materials with tensile strength of 780 MN/mm^2 are used.

Steel may lose toughness in extremely low temperature environments. This phenomenon is termed brittle fracture. Impact tests such as the Charpy test and drop weight tear test (DWTT) are required in order to evaluate brittle fracture. The ductile-brittle transition temperature and the ductile fracture ratio, absorbed energy, etc. under the assumed service conditions are used to evaluate toughness. In some cases, fracture mechanics assessments such as crack tip opening displacement (CTOD) are used.

Under harsh weather conditions of arctic seas, the temperature may reach −60°C. Since the ocean surface freezes under these conditions, the mobile arctic caisson rig (MACR), caisson type artificial island rig called CIDS (concrete island drilling system), single steel drilling caisson, and floating type conical drilling unit are used in these areas. Plates with ship class specifications are used in MACR and CIDS, and low temperature toughness at −60°C is required. Excellent weldability is also demanded, as high efficiency large heat input welding is used in welding, and the same low temperature toughness as in the base material is also required in welds.

(3) Pipelines

In pipelines for transportation of natural gas, high operating pressures and use of large diameter pipes is being promoted to reduce pipeline construction and operating costs. Requirements for high strength of linepipe have increased with high operating pressures, reducing the weight of the materials, and field welding costs. For example, application of high strength linepipe of X80 grade have increased in recent years. High strength linepipes of X90, X100, and X120 grades have been standardized in ISO 3183 and API 5L (API: American Petroleum Institute). The history of high strength materials provided under API standards is shown in **Fig. 5**.

A high order of safety is also required in pipelines, because these lines transport flammable substances such as natural gas and oil. **Figure 6** shows the causes of damage in 769 examples (2002–2011) of gas transportation pipelines in the United States reported to the U. S. Department of Transportation (DOT).

Damage due to material-related causes was small, accounting for only 6% of the total, and all of these accidents involved pipelines constructed before the

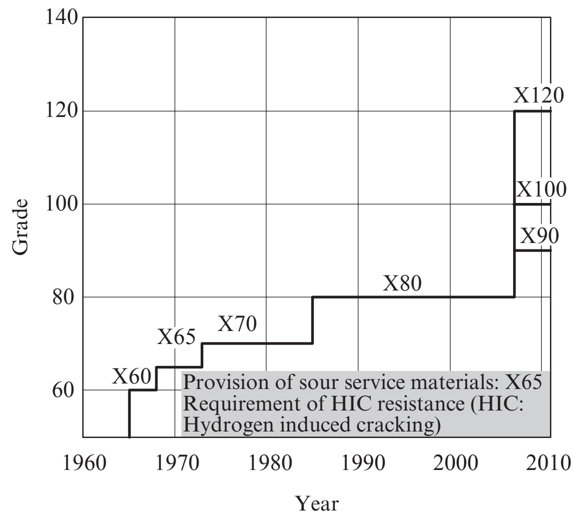


Fig. 5 Development of high strength line pipe in API spec. 5L (API: The American Petroleum Institute)

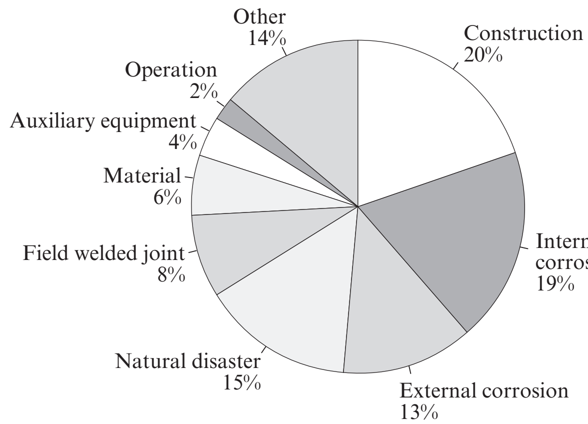


Fig. 6 Causes of gas pipeline damage in U. S. (Based on DOT data)

1970s.

The most common cause of damage was associated with construction, and next is internal and external corrosion. One noteworthy point is 15% of these accidents were caused by natural disasters. Thus, when considering the safety of pipelines, only controlling the materials, construction, and equipment is insufficient by itself; it is also necessary to consider damage accompanying other construction and the effects of natural disasters.

Table 6 shows relationship between the failure modes of pipelines and the material properties. Various properties are required in pipelines in order to improve pipeline safety. The same is also true of oil well tubulars, marine structures, electric power facilities, etc.

The basic principle of pipeline design is to prevent ductile fracture. Combination of material strength, yield stress, elongation, other basic material properties and operating conditions determine the occurrences of ductile fracture.

As with drilling rigs and platforms, pipelines are also laid in cold regions. Under these conditions, the critical property is low temperature toughness. In particular, the ductile-brittle transition temperature is important.

Table 6 Relationship of failure mode of pipelines and material properties

<table>
<tr><td colspan="2">Failure mode</td><td>Material properties affecting failure</td></tr>
<tr><td colspan="2">Ductile fracture</td><td>Yield stress, Tensile strength, Uniform elongation
Strength matching with welding consumable</td></tr>
<tr><td colspan="2">Fatigue fracture</td><td>Fatigue life (SN, da/dN)</td></tr>
<tr><td colspan="2">Brittle fracture</td><td>Ductile-brittle transition temperature
Absorbed energy
Crack tip opening displacement (CTOD; K_c, δ_c, J_c)</td></tr>
<tr><td colspan="2">Propagating shear fracture (Burst)</td><td>Absorbed energy (Charpy/ Drop weight tear test (DWTT))</td></tr>
<tr><td rowspan="5">Buckling</td><td>Elastic buckling</td><td rowspan="5">Roundness, Uniformity of wall thickness
Straightness
Uniform elongation, Work hardening property</td></tr>
<tr><td>Compression</td></tr>
<tr><td>Bending</td></tr>
<tr><td>Compressive bending</td></tr>
<tr><td>Tensile bending</td></tr>
<tr><td colspan="2">Collapsing</td><td>Yield stress (YS), Roundness, Uniformity of wall thickness</td></tr>
<tr><td rowspan="3">Corrosion</td><td>Sulfide stress corrosion cracking (SSCC)</td><td>Material strength/Hardness</td></tr>
<tr><td>Hydrogen induced cracking (HIC)</td><td>Hardness/Inclusions</td></tr>
<tr><td>Internal corrosion</td><td>Alloy composition</td></tr>
</table>

Fatigue fracture is a type of fracture which occurs under cyclical loading and is avoided by evaluating fatigue life.

Resistance to propagating shear fracture property is necessary to prevent damage from developing into a large-scale accident caused by external forces. Larger absorbed energy values in impact tests such as the Charpy test and DWTT give improved resistance to this type crack propagation.

Deformation characteristics are important to prevent pipe buckling, resulting in a gas leak or other accident, due to the movement of the ground caused by earthquakes, flooding, etc. Basically, countermeasures are taken in the pipeline design. However, it is known that material properties also have a large influence on pipeline buckling performance[3)]. Collapse becomes a problem in cases where a pipeline is subjected to large external pressure in sea bottom.

Pipelines are also exposed to corrosion environments as well as tubular goods. Prevention of CO_2 corrosion has become a serious issue in flow and gathering lines, which are used to transport the production fluid before corrosive components and water are removed. In many cases, the production fluid contains H_2S, and it is known that various types of cracks in steel materials are a potential danger in environments where H_2S and water coexist. The types are cracks are classified as follows, depending on whether stress is a factor or not.

(a) Hydrogen induced cracking (HIC)

HIC occurs in environments where H_2S and water coexist without external stress. Cracking occurs parallel to the material surface, originating from a nonmetallic inclusion, etc. extending in the steel. The crack may grow in either a linear shape or in step form.

(b) Blistering

This is one type of HIC; in particular, cracks which occur directly below the surface are called blister.

(c) Sulfide stress corrosion cracking (SSCC)

Sulfide stress corrosion cracking occurs when stress exists under an environment where H_2S and water coexist. In many cases, SSCC originates from a stress concentration such as a surface or internal defect. The crack grows at right angles to the axis of stress. Sulfide stress corrosion cracking is thought to occur easily in areas of high hardness, such as welds, etc.

(4) Refineries and electric power plants

Boilers and heat exchangers play essential roles in various types of plants such as power plants, chemical industry plants, etc. With the trend toward large

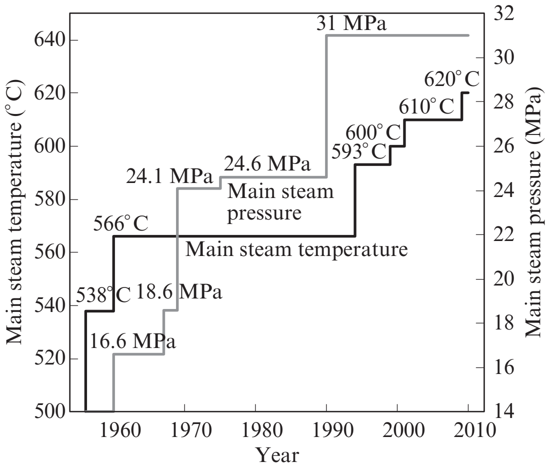


Fig. 7 Change in steam temperature and pressure in coal fire generation system in Japan

scale and high temperature/high pressure operation, higher functions and quality are required in the steel pipes and tubes.

In thermal power plants, high temperature/high pressure steam conditions have been promoted with the aim of improving generating efficiency. New boiler tube materials have been developed corresponding to service conditions. **Figure 7** shows the change in the steam temperature and pressure in coal-fired thermal power plants in Japan.

High strength, especially creep properties, and corrosion resistance against high temperature corrosion are required. Cr-Mo steel, Cr steel, stainless steel, and other materials are selected appropriately depending on the service temperature and environment.

4. JFE Steel Products for Energy Industries

4.1 Steel Pipes and Tubes

4.1.1 OCTG

JFE Steel manufactures and sells products with distinctive features for applications in which corrosion resistance is required (**Table 7**). One group of products is high strength, high corrosion resistance oil well tubulars for use in CO_2-containing environments. The other, materials for use in H_2S-containing environments in oil and gas production. JFE also sells premium joints which are suitable for high strength OCTG. In addition to the grades provided under API standards, JFE Steel manufactures high collapse oil well tubulars, which are capable of resisting collapse, and low temperature oil well tubulars for use in low temperature environments as high functionality OCTG for tubing and casing use.

(1) High Strength, High Corrosion Resistance OCTG[4,5)]

One distinctive feature of the OCTG manufactured by JFE Steel is a series of high strength, high corrosion resistance products which take advantage of the properties of martensitic stainless steel. In addition to conventional 13% Cr steel, JFE Steel offers a diverse product line to meet the requirements of various service environments, such as JFE-HP1-13CR and JFE-HP2-13CR with enhanced strength and corrosion resistance, JFE-UHP™-15CR, which can be used in environments where duplex stainless steel had conventionally been used, and others. Details of these products can be found in individual articles in this special issue of JFE Technical Report.

Table 7 Corrosion resistance and sour grade tubing and casing of JFE Steel

Property	Product name
High corrosion resistance OCTG	JFE-13Cr-80, JFE-13Cr-85 JFE-13Cr-95 JFE-HP1-13CR-95 JFE-HP1-13CR-110 JFE-HP2-13CR-95 JFE-HP2-13CR-110 JFE-UHP®-15CR-125
OCTG for sour service SS: Critical stress for cracking ≧ 80% SMYS (SMYS: Specified minimum yield strength)	JFE-80S JFE-85S JFE-90S JFE-95S JFE-110S JFE-85SS JFE-90SS JFE-95SS JFE-110SS

Table 8 Premium joint of JFE Steel

Joint	Features
FOX™	Uses metal seal; provides higher sealability and anti-galling characteristics than joints provided in API standards (API: The American Petroleum Institute).
JFEBEAR™	Has higher sealability than FOX™, which can be used deep gas production.

(2) Premium Joints

High joint strength and excellent sealability are required in threaded joints used in deep oil and natural gas wells. As original products, JFE Steel supplies two types of products, FOX™ and JFEBEAR™.[6)] The respective features of these joints are shown in **Table 8**. The joint lubrication system "CLEAR RUN™" is applied to reduce the possibility of spills of environmental load substances contained in lubricants into the environment when performing joint makeup work at the site[6)].

4.1.2 Linepipe

JFE Steel has pipemaking processes for seamless pipe, UOE pipe[7)], and electric resistance welding (ERW) pipe[8,9)] and is a total steel pipe maker with a system capable of supplying the most appropriate material corresponding to the application and size range.

JFE Steel's linepipe products with distinctive features includes high strength linepipe for use in long and large pipelines, a high deformability pipe HIPER™ which can be used under seismic and permafrost regions, Mighty Seam™ ERW pipe[10] with high reliability in comparison with conventional ERW pipes, martensitic stainless steel linepipe[11] for use in corrosion environments, and others.

(1) High Deformability Pipe HIPER™ (UOE)

With pipeline construction expanding into regions with severe environments, adequate deformability to prevent local buckling and failure from girth welds is required against pipe deformation due to ground movement, particularly in linepipes laid in seismic regions, discontinuous permafrost zones, etc.[12,13].

(2) High Strength Linepipe

Accompanying high pressure transportation in pipelines and use of large diameter steel pipes, adoption of heavy wall products is increasing, even in high strength linepipe, represented by X80.

To meet requirements for higher strength in linepipe, JFE Steel began commercial production of high strength linepipe of CSA grade 690 (CSA: Canadian Standards Association; corresponds to API X100) for the first time in the world in 2002. In 2004, wintertime pipe-laying was carried out in an extremely cold part of northern Canada. High weldability and base material/weld performance were demonstrated.

Application of X100 linepipe is still limited. Active development of pipeline design technology and use/evaluation technologies is underway, and expanded application is expected in the future[14].

(3) Linepipe Material for Sour Environments

With linepipes, as same as well environments, hydrogen induced cracking is a possibility when H_2S is present. Linepipe material for sour environments is used to prevent this problem. In this material, the amount and form of impurities, and particularly sulfur, are controlled. Strength up to X65 is currently possible, and development of materials with higher strength, such as X70, etc., is progressing.

(4) Mighty Seam™ ERW Pipe

The environments in which oil and natural gas are produced and transported are becoming increasingly severe. JFE Steel has put great effort into the development of production technologies for the materials used in ERW pipes for linepipe and nondestructive inspection techniques for weld seams. A new ERW pipe called Mighty Seam™ which dramatically improves the reliability is developed. This technology makes it possible to design linepipes taking advantage of the high dimensional accuracy, high toughness, etc. which are distinctive features of ERW pipes[10].

(5) Martensitic Stainless Steel for Linepipe (SML)

Until now, duplex stainless steels, etc. had been used as corrosion resistance materials for linepipe. Although duplex stainless steels possess excellent corrosion resistance, various problems have been pointed out, such as the extremely high cost of the material, the difficulty of controlling welding heat input and easy cracking in materials with excessive corrosion resistance.

Martensitic stainless steels[13,15] show an excellent CO_2 corrosion resistance and are economical in comparison with duplex stainless steels.

Based on this background, JFE Steel developed martensitic stainless steel ERW pipe for linepipe use with excellent weldability and corrosion resistance. Weldability was improved by reducing C and N utilizing JFE Steel's outstanding steelmaking technology, and adjusting added components.

4.1.3 Steel tubes for boiler and heat exchanger use

JFE Steel has developed and manufactures ferritic alloy steel tubes with excellent high temperature strength, oxidation resistance, and weldability[11].

The following introduces representative products.

(1) Improved Type 9%Cr-1%Mo Steel Pipe (T91/P91 Steel Pipe)

JFE Steel uses the Mannesmann rolling process to produce improved 9%Cr-1%Mo steel pipe (T91/P91 steel pipe) as provided under ASME SA213 and SA335 (ASME: The American Society of Mechanical Engineers). Features of these products include the following:

(a) Super Hot Steel Pipe with high outside diameter and wall thickness dimensional accuracy
(b) Ultra-long tubes with length of approximately 22 m for use in waste heat recovery boilers
(c) Ultra-heavy wall thickness, medium diameter steel pipes with wall thickness of 50 mm, which can be used in main steam pipes and header pipes

(2) W-Added 2.25% Cr Steel Pipe (T23/P23 Steel Tubes)

The standard for this material was registered as T23 in ASME SA213 in 2004. This is a 2.25%Cr-Nb-V steel with heavy addition of W and has excellent high temperature tensile strength and creep strength. JFE Steel developed a low C-low Al-low N composition steel material with excellent high temperature strength, satisfactory welding, and high heat affected zone (HAZ) cracking resistance, which is used in superheaters and reheaters of waste heat recovery boilers.

(3) W-Added 9% Cr Steel Tubes and Pipes (T92/P92 Steel Tubes)

As a material with higher high temperature strength and creep strength than T91/P91 tubes, T92/P92 tubes and pipes were registered in the ASME standards of 2004. This material is a 9%Cr-Nb-V steel with heavy addition of W and is used in main steam pipes, superheaters, and reheaters.

4.2 Steel Plates

4.2.1 High strength steel plates

Although high strength steel plates are used in buildings, bridges, industrial machinery, and similar applications, these materials are also used in energy-related equipment[16]. High strength steel plates produced by JFE Steel are shown in **Table 9**. High strength steel plates can be used appropriately depending on the property requirements for strength level and application, weldability, low temperature toughness, etc. JFE Steel also developed EWEL™ as a technology for improving weld toughness[17].

4.2.2 Low temperature steel plates

Strict low temperature toughness requirements are applied to drilling rigs and platforms used in extra-cold climates in order to keep the safety. Plates with strict low temperature toughness requirements are applied (**Table 10**).

High yield strength steels such as DH36, EH36, FH36, etc., which are based on ship classification society standards, are widely used in drilling rigs. Among these, high strength steels are used in legs and surrounding parts of jack-up rigs. In particular, the extra-heavy steel plate HT80 is used in racks. Because jack-up rigs also navigate and drill in extra-cold climates, strict low temperature toughness of −60°C is required in some cases. JFE Steel developed JFE-HITEN780ML for use in racks and chords in cold regions.

High tensile strength steels by thermo-mechanical control process (TMCP), represented by API 2W 50 (yield strength 355 N/mm^2 or higher) and 60 (410 N/mm^2 or higher), are used in production platforms, such as jackets, in tension leg platform (TLP) for the top side and piles, and in SPAR for the top side. The CTOD value, which is one strict fracture mechanics approach, is required at the use environment temperature in welded joints of these steels.

The JFE-HITEN 'L' Series, low temperature steel plates, is used in spherical tank and bullet tanks. The JFE Steel product line also includes 2.5% Ni, 3.5% Ni, and 9% Ni steel plates which can be used at lower temperatures.

Table 9 High strength steel plate of JFE Steel

Strength level	Standard name	Features and main applications
590 N/mm^2	JFE-HITEN590 JFE-HITEN610 JFE-HITEN570U2 JFE-HITEN590U2 JFE-HITEN610U2 JFE-HITEN570E JFE-HITEN590E JFE-HITEN610E JFE-HITEN590S JFE-HITEN590SL	High tensile strength steel plates for bridges, penstocks, tanks, marine structures, etc. U2: High weldability high tensile strength steel plate with excellent weld cold cracking resistance E: High tensile strength steel plate with excellent weld cold cracking resistance, suitable for high heat input welding S: Non-heat treated high tensile strength steel plate for construction machinery and industrial machinery SL: Non-heat treated high tensile strength steel plate for same applications as above, with excellent low temperature toughness (−40°C)
690 N/mm^2	JFE-HITEN690 JFE-HITEN710	Ni-Free high tensile strength steel plates for tanks, marine structures, etc.
	JFE-HITEN690M JFE-HITEN710M	Ni-Added high tensile strength steel plates with low carbon equivalent for bridges, penstocks, tanks, etc.
	JFE-HITEN690S	Non-heat treated high tensile strength steel plate with reduced added elements, with priority on strength, for construction machinery
780 N/mm^2	JFE-HITEN780M	Ni-Added high tensile strength steel plates for bridges, penstocks, tanks, etc.
	JFE-HITEN780EX	High performance and high tensile strength steel plate with relaxed preheating for bridges
	JFE-HITEN780S	High tensile strength steel plate with reduced added elements, with priority on strength, for construction machinery
	JFE-HITEN780LE	High tensile strength steel plate with excellent weldability and low temperature toughness (−40°C) for construction machinery and industrial machinery
980 N/mm^2	JFE-HITEN980	High tensile strength steel plate with excellent strength, weldability, and toughness for penstocks
	JFE-HITEN980S	High tensile strength steel plate for construction machinery and industrial machinery

4.2.3 Steel plates with HIC resistance

JFE Steel is actively engaged in research on the problem of SSCC of high tensile strength steel plates used in spherical tanks and the problem of HIC in transportation pipes for natural gas containing H_2S, and supplies materials with HIC resistance (JFE-AH1 and JFE-AH2) that are suitable for use in environments where

Table 10 Steel plate for low temperature application of JFE Steel

JFE Steel standard	Features
JFE-LT 1.5Ni-TM	Aluminum-killed steel for low temperature service is widely used mainly in liquefied petroleum gas (LPG)-related equipment. As material for liquefied gas tanks, priority is given to crack arrest characteristics for brittle cracks. High strength and toughness are realized by application of advanced thermo-mechanical control process (TMCP) technology. Application of JFE Steel's high heat input welding countermeasure technology EWEL™ is also possible.
JFE-LT415TM	Suitable for large-scale low temperature tanks and marine structures for use in icy seas, with which yield point 325 N/mm^2 and 355 N/mm^2 class steel materials had conventionally been used. By applying TMCP, high strength and high toughness are achieved, and material displays excellent welding performance. Application of high heat input welding technology EWEL™ is also possible.
JFE-HITEN590L JFE-HITEN610L	Representative high tensile strength steel plates used in spherical tanks for LPG and ethylene, jack-up rigs, etc. Excellent low temperature toughness.
JFE-HITEN590U2L JFE-HITEN610U2L	Applied to spherical tanks for LPG and ethylene, jack-up rigs, etc. operated in cold regions. Excellent toughness, and preheating for welding can be greatly reduced.
JFE-HITEN690L JFE-HITEN710L JFE-HITEN780L	690 N/mm^2 and 780 N/mm^2 class high tensile strength steels for low temperature service considering weldability, featuring reduced use of expensive alloying elements. In addition to pressurized tanks and bullet tanks, also suitable for jack-up rigs, etc. operated in cold regions.
JFE-HITEN780FL	Ni-Free 780 N/mm^2 class high tensile strength steel for tanks, considering stress corrosion cracking. Used in pressurized tanks, etc. which are exposed to low temperatures. Also suitable for jack-up rigs, etc. operated in cold regions.
JFE-HITEN780ML	780 N/mm^2 Class steel plate for low temperature service, developed for use in jack-up rig legs and chord materials, mainly considering operation in icy seas. Excellent strength and low temperature toughness with plate thicknesses up to 200 mm, while also considering weldability.

H_2S is a factor.

4.2.4 Stainless steel clad steel plates

Clad steel plates are hybrid of steel plates (basemetal) and stainless steel plate (cladding metal). Clad steel plates possess the strength necessary in structural materials (base metal part), and simultaneously, also have functions such as heat resistance, corrosion resistance, etc. (cladding metal). Another important feature is low cost in comparison with products by the cladding metal entirely.

Therefore, clad steel plates are used in various industrial fields, such as pressure vessels, shipbuilding, seawater desalination plants, etc.

Although various methods of producing clad plates exist, JFE Steel manufactures clad steel plates by the rolling method. JFE Steel's products are used in a wide range of fields, as they offer the following features.

(1) Excellent bonding property
(2) Stable performance
(3) Possibility of manufacturing wide and long plates
(4) Excellent dimensional accuracy
(5) Quick and sure response to delivery requirements

Stainless steel and clad steel are also used in dam outlet pipes, etc., and clad steel plates with excellent corrosion resistance are widely used in oil refinery processes.

4.2.5 Steel products for shipbuilding

JFE Steel is constantly challenging the diverse problems of ships such as tankers, container ships, bulk carriers, etc., such as ship weight reduction and high speed, improved construction efficiency, and long life.

The history of steel plates for shipbuilding is the history of high tensile strength steel with improved weldability by TMCP. As a pioneer in TMCP technology, JFE Steel developed and commercialized a 2nd generation TMCP technology, the *Super*-OLAC™. This technology is applied to virtually all high tensile strength steel plates used in shipbuilding.

Fully refrigerated LPG carriers are used at low temperatures of −45°C to −50°C; in addition, high efficiency welding is applied, as the weld lines are long. Excellent toughness is required in steel plates, including the HAZ. To meet this need, JFE Steel developed the EWEL™ welding technology, which secures excellent HAZ toughness and has been used in many LPG carriers.

In crude oil tankers, severe pitting corrosion of crude oil tank bottom plates is sometimes a problem. JFE Steel developed a corrosion resistant steel for crude oil tanks, "JFE-SIP-OT," in order to prevent this type of corrosion[18].

4.2.6 Steel products for reactor containment vessels

In the field of nuclear power, SGV480 steel or high tensile strength steel SPV490 is used in steel containment vessels, and extra heavy section, large unit weight SQV2 is used in pressure vessels. JFE Steel also has an extensive production record in this field, based on strict quality control.

5. Conclusion

Steel products play an essential role in various types of facilities and plants for energy use. In particular, steel products manufactured by JFE Steel, which possess advanced properties and high reliability, have earned the strong confidence of customers at all stages in the development, production, transportation, and use of oil and natural gas.

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