World Cultural Heritage—Solving 10 Mysteries of Nirayama Reverberatory Furnace

T. Kanno
Kimura Chuzosho Co., Ltd., 1157 Shimizu-cho, Shizuoka Prefecture, Japan

Key-Words: Nirayama reverberatory furnace, World Heritage, Cannon, Cast iron, Pig iron, Melting temperature, Bellows, Fuel, Firebrick

1. Introduction

Nirayama reverberatory furnace is located in Izunokuni city, the Izu Peninsula, Shizuoka Prefecture. As shown in Fig. 1, they are composed of four furnaces in total: two pairs of twin towers, 15.6 m in height.[1)] Though the existing reverberatory furnace is also in Yamaguchi Prefecture, Nirayama's is the only existing one which was actually used to melt cast iron in the world. Being one of the constituent properties of "Sites of Japan's Meiji Industrial Revolution: Kyushu-Yamaguchi and related Areas," it was decided to be the government's recommendee for the World Heritage registration in 2015, on September 17th, 2013. Every year one site is selected in the aim of promoting domestic cultural properties for inclusion on the World Heritage List.

This application aims to register as one of the group of "Heritages of Industrial Modernization in Kyushu area and Yamaguchi," not Nirayama's individually. The group is composed of 8 areas, 11 sites, and 23 properties, including the castle town in Hagi city, Shuseikan in Kagoshima city, Nirayama reverberatory furnace in Izunokuni city, Hashino blast furnace in Kamaishi city, Mie Tsu Naval Training Center in Saga city, Hashima Coal Mine and Glover House in Nagasaki city, Miike Coal Mine in Arao city and Omuta city and Yahata Steel Works in Kitakyushu city. Some people judge the value of a reverberatory furnace by its capability to melt cast iron, but we think otherwise. The purpose of the application is to hand down to posterity one of the important assets in human history which contributed to "spread of industrial modernization throughout Asia." ICOMOS, an advisory body of UNESCO, advised them to inscribe these sites on the World Heritage List on May 4th, 2015. On July 5, 2015, World Heritage list registration of "Sites of Japan's Meiji Industrial Revolution" including Nirayama reverberatory furnace was decided.

What is important for the registration is local residents' cooperation in its preservation and enhanced interest in it. Under these circumstances, we had activities to raise public interest. We produced miniature cannons by a cupola furnace and hosted a workshop for kids to make accessories by casting on February 24th, 2013, when Symposium for Registration of Nirayama reverberatory furnace was held. As shown in Fig. 2, thanks to the cooperation of Mr. Murata, the president of Naniwa Roki, we could show cupola-style casting in the open. Since then about 40 children have participated in the workshop every year.

Fig. 1 Nirayama reverberatory furnace and 24 pounder

Fig. 2 Cupola (*1) and casting workshop

*1 Cupola: a furnace to obtain molten cast iron that does not get chilled, using combustion heat of coke. Nagasaki Ironworks' is the first cupola built in Japan. The principle in melting is the same as that of a blast furnace. Japanese original furnace *koshiki* is also the same in principle but the only difference is its fuel--coal and charcoal instead of coke. The furnace is named after an earthen vessel, *koshiki*, used to be a tool to steam rice, whose shape resembles to that of the furnace. Although *koshiki* tends to be confused with *tatara*, they are not the same and have different shape. *Tatara* is a furnace to make *tamahagane*, special steel to process into Japanese swords.

It was 20 years ago, around July in 1997, when I first got involved with the reverberatory furnace. There was a concern that it was inappropriate for Nirayama to exhibit a cement cannon, from Prof. Madono, an authority in casting, and Prof. Nakae, my former teacher of Waseda University. In March the next year, we Kimura Chuzosho Co., Ltd cast a 24 pounder and donated it to Izunokuni city. It was around 2004 when I began in earnest to investigate the furnace with all my family. Of my children, so young 13 years ago, my eldest son and daughter have become members of society while my second son and second daughter have grown up to go to university (Fig. 3). Prof. Nakae, who afforded me the opportunity to produce the cannon, currently serves as the chief investigation committee member of National Museum of Nature and Science. With Firearms Historical Academy of Japan, he is making a detailed survey of cast cannons from the closing days of Tokugawa regime to Meiji era, based on a perspective of casting engineering.

Here I unravel mysteries of producing cannons with Nirayama reverberatory furnace beyond time, weaving into this article the studies by Prof. Nakae, an adviser of Kimura Chuzosho Co., Ltd at present, and ours on the furnace.

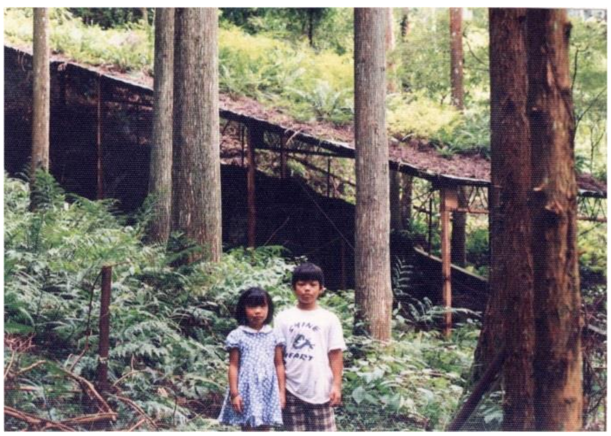


Fig. 3 My children and climbing kiln (*2)

*2 Climbing kiln: the characteristic is that it consists of several chambers built stepwise on a sloping land. It is structured to send heat, smoke, and ash from the bottom, where firewood is burned, through chambers into the kiln top. In Japan, it started from Edo period (1610), famous for early Imari ware. Even today, it is burned at about 1200-1250°C. This temperature is 50-100°C higher than the melting temperature 1153°C of the high-carbon cast iron. Around the climbing kiln at Nashimoto, much alumina white clay is seen, and it is conceivable that people burned firebricks made with the clay.

2. What Is a Reverberatory Furnace?

2.1 History of Metal and Casting

Human beings have first encountered metals in 5000-6000 B.C. when people were processing natural gold/silver/copper by hand beating.[2] It is thought that people's first encounter with iron was realized by meteorite. In Egypt, an iron necklace made from meteorite around 3000 B.C. was found. Thus, the first processing method of metals was forging. Beating, that is, forging gradually pushes out dust and impurities included in metal. Carbon also get eliminated into outside. Human beings have eliminated impurities from metal with hammering, controlled carbon contents, and made tools and weapons for a long time. Come to think of it, Japanese sword is the most advanced forging product in the world.

The casting technology by pouring molten metal into a mold and solidifying started in 3600 B.C. at Mesopotamia. It was approximately 5600 years ago. Pouring molten bronze into a mold is considered as the beginning.[3] It is the beginning of Bronze civilization, that is, the beginning of casting. This means casting has 5600 years history.

The situation that people cast a door while sending wind with stepping *bellows* (*3)was described in an Egyptian papyrus of about 1500 B.C. in Fig. 4.[4] Humans could get higher temperature by the invention of *bellows*, and the Bronze Age reached the golden age. By the way, the melting point of bronze is approximately 800°C with Cu-25%Sn. Considering pouring, it has a possibility that the melting temperature had exceeded 900-1000°C.

*3 Bellows: A manual or treadle blower which is simply structured. Bellows were used for furnaces small in size to send air to the fuel.

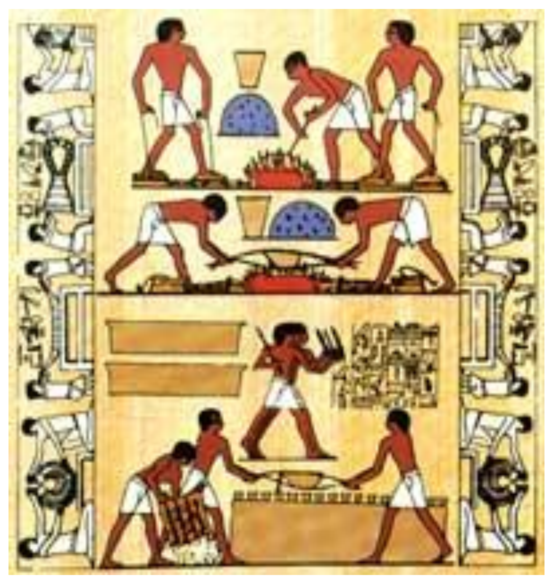


Fig. 4 Casting bronze doors (around 1500 B.C. in Egypt)

Since iron is oxidized on earth, it cannot be used as iron if not be deoxidized. It has been believed that in 1700 B.C., the Hittite empire first obtained much iron by deoxidizing iron ore. People used a batch-type furnace which deoxidized iron sand by charcoal, and took out spongiform pure iron which gathered at the bottom of the furnace. They obtained ironware by heating and forging that iron. It was written in an epic poem of Homer in the eighth century B.C. that iron was highly expensive. Probably, the price of iron was 5-10 times as high as that of gold. Iron has a defect that it is easy to rust unlike gold and bronze. Therefore, only few historical relics of iron are left because they have rusted and returned to soil. The technology of producing iron has spread throughout Europe because Hittite empire lost at Trojan War, famous for the Trojan horse and Achilles, in about 1200 B.C.

Strangely, the iron production by forging has continued until the fourteenth century, but casting, a method in which molten metal is poured into a mold, has not been started until after the fourteenth century. Also, it is thought that saber became a European weapon, considering the difference in history of how to produce iron.

The casting technology of pouring molten iron instead of bronze into a mold, was developed in China in the early seventh century B.C.[5] China is thought to have had a technology to generate considerably high temperature with *bellows* in bronze production. Apparently this technology allowed them to make various tools by melting the iron which had high carbon composition (generally, it is called cast iron when its carbon content is more than 2.1%). While the melting temperature of low-carbon iron composition is 1536℃ and high, that of high-carbon cast iron is 1153°C and low. This low-carbon iron enabled iron casting for its excellent flowability. The composition of the casting iron of around fourth century B.C was C2.5-4.3%, Si0.1-0.2%, Mn0.01-0.2%, P0.1-0.5%, S0.01-0.1%.[3] The Si content was higher than Japanese cast iron (less than 0.1%), so it is possible to assume that they have gotten high temperature. However Si even in the composition of this cast iron was also low. It became a hard and brittle material that is called chill (*4) and didn't have graphite.

This chilled cast iron is hard and brittle, so it has the biggest disadvantage that it cannot be machined. It is difficult to machine the chilled cast iron even with present machines. The microstructure of the hard and brittle chilled cast iron is shown in Fig. 5. As there is little graphite in this chill casting, it makes good sound like a wind-bell. On the other hand, in the modern cast iron which can be machined shown in Fig. 6, some flake graphite comes out, and its ability to absorb sound vibration is high. If a wind bell is made with current machinable cast iron, the sound would hardly come out. The modern cast iron is used for base materials of machining tool or industrial equipment, with taking advantage of vibration absorbing quality.

In China, they produced whiteheart malleable cast iron (shown in Fig. 7) in about 470 B.C. by heating this cast iron (shown in Fig. 5) in about 900-1000°C oxidized iron for three days[6]. The celebrated swords which belonged to Cao Cao and Zhuge Liang in the era of *the Three Kingdoms* are assumed to be made by heat treatment(*5)and forging this malleable cast iron to adjust the amount of carbon. According to a book on industrial technology published in 1637, *Heavenly Creations*, wrought iron was created already during Han dynasty around the second to the third century B.C. as shown in Fig. 8. Their wrought iron is the same as that later made through puddling process using a reverberatory furnace which Henry Cort invented in 1784.[7] In China, from this drawing, using *bellows* and a blast furnace like *koshiki* enabled to obtain molten iron of a considerably high temperature. Historically, the whiteheart malleable cast iron (iron close to modern steel which has no graphite in Fig. 7) was invented by Réaumur in France in 1772. Also, blackheart malleable cast iron (shown in Fig. 9) was produced by Boyden in America in 1826.[8] Even today, malleable cast iron is infrequently used, but the amount of production has decreased, because spheroidal graphite cast iron (shown in Fig. 10) was invented by Morrogh in 1948. By the way, some of the parts requiring excellent elongation of Brunat's engine used in Tomioka Silk Mill, designated a World Heritage in 2014, are turned out to be malleable cast iron from my investigation.

The Chinese iron history changed from bronze to chill casting, to malleable cast iron made by heat treatment, and then to wrought iron.

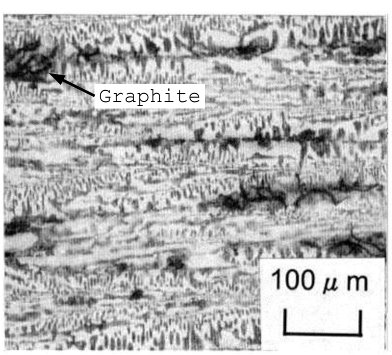


Fig. 5 Microstructure of old chill casting which is hard and brittle (*4)

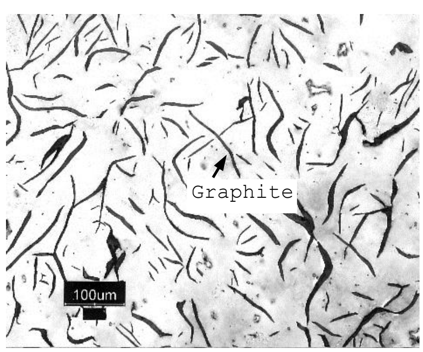


Fig. 6 Microstructure of modern machinable cast iron

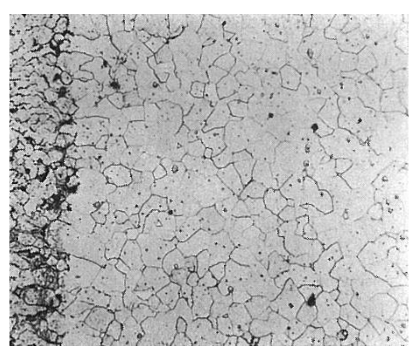


Fig. 7 Microstructure of white heart malleable cast iron same as that of steel which made from chill casting.[7]

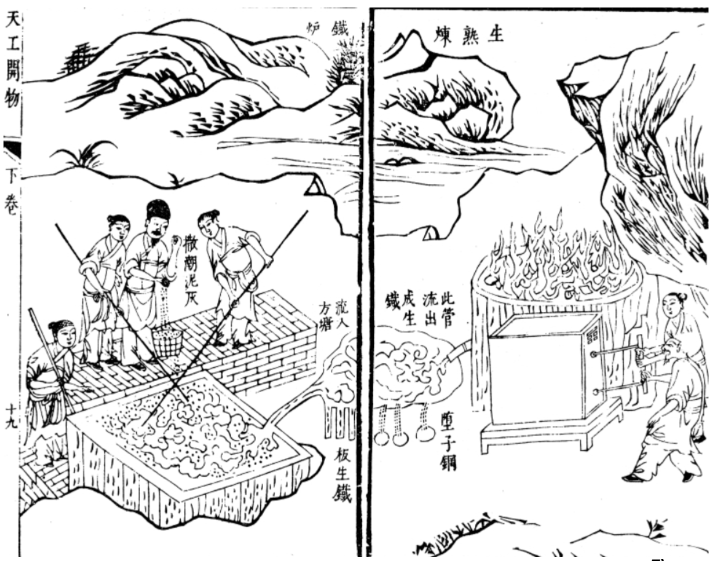


Fig. 8 Refining furnace of cast iron and wrought iron[7]

*4 Chill casting: Originally, chill has the meaning of cooling or cooling down. In a casting process, the speed for molten metal to cool down is controlled by putting pieces of metal called chillers outside of a mold, and if the speed is too high, it would be a chill casting with no graphite, and be a defective. From this experience, as the parts which were put chillers to often formed chill, so those parts became called chill. Anyhow, unless casting includes some Si or high carbon, it would become easily chilled cast iron. Chill casting is too hard to machine.

*5 Heat treatment: A process to achieve a desired property by heating and cooling iron, steel, and non-ferrous metals at below the melting point.[23] For example, as mentioned above, Réaumur developed a method to turn chill casting into steel-like iron by heat treatment.

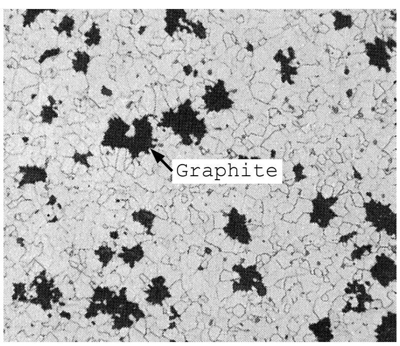


Fig. 9 Microstructure of blackheart malleable cast iron made of heat-treated chill casting.[9]

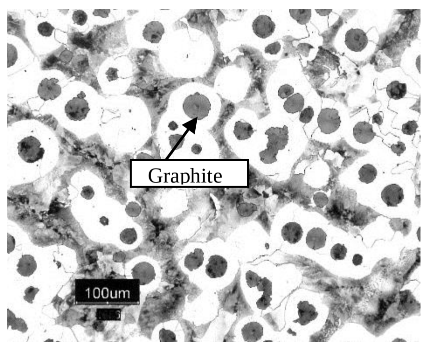


Fig. 10 Modern spheroidal graphite cast iron

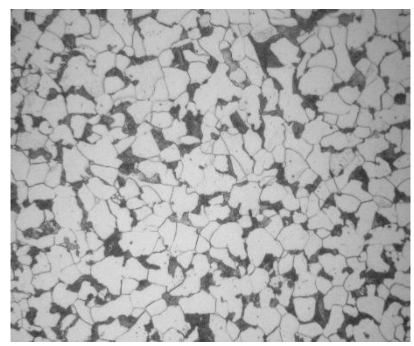


Fig. 11 Microstructure of steel (S25C)

This brittle characteristic of chilled cast iron seems to be a cause that iron casting technology had not been introduced to Europe until the fourteenth century. Therefore, from the seventh century B.C. to the eighteenth century of the Industrial Revolution in Europe, cast iron was hard and brittle. Also, in Japan, chilled cast iron was used mainly until the end of the Edo period before blast furnaces were introduced. No wonder for forged iron made by hammering was valued in Europe and Japan, as it has a good viscosity, gets hardened by quenching, and is made by hammering. Meanwhile in China, people produced malleable cast iron by heat treatment to chilled cast iron, and they had gotten materials like steel (shown in Fig. 11). From *Heavenly Creations*, they seem to have made wrought iron using sort of blast furnaces with *bellows*.

Increasing silicon (Si) content changed cast iron's property largely. Iron Bridge was built in England in 1779, when high silicon and non-chilled cast iron was developed (Fig. 12). In England, Darby the second achieved producing cast iron with a blast furnace, and high silicon cast iron began to be produced. Because non-chilled cast iron appeared, cast iron became machinable for the first time. It enabled to produce steam engines, and led to the Industrial Revolution. In such meaning, cast iron was the mother of the Industrial Revolution, and is an important material to support industry nowadays.

Fig. 12 The Iron Bridge made from non-chilled flake graphite cast iron, in 1799 (World's Cultural Heritage in Coalbrookdale, UK)

In summary, there were four types of cast iron: (1) iron to forge, (2) hard and brittle chill casting, (3) the hard and brittle chill casting softened by heat treatment, and (4) a kind of iron called wrought iron which requires high temperature to create as China succeeded using *bellows*.

When seeing metal history in terms of reduction of oxide, you may find some interesting things. Fig. 13 shows the graph of the relationship of stability and temperature of oxides.

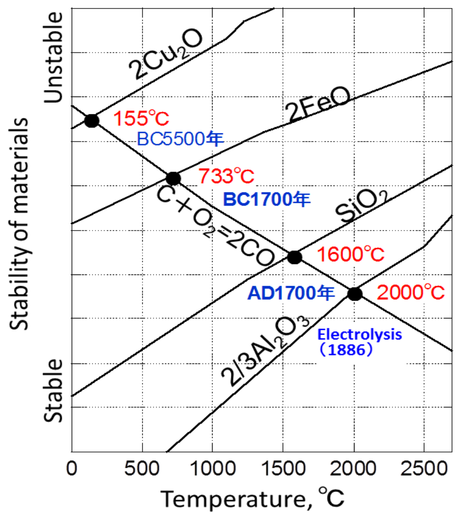


Fig. 13 Relationship of temperature and stability of oxides

Seeing the Fig. 13, all materials become unstable with increasing temperature, because the atom vibration becomes large. It is the same as changing from ice to water and to steam with increasing temperature. However, only carbon monoxide (CO gas) becomes stable with temperature rise apart from this law of the universe. It is the special material which becomes more stable if the temperature gets higher. Thanks to existence of carbon monoxide, human civilization was born and built up by reducing oxidized metal. Let's take copper as an example, in Fig. 13. Copper oxide is reduced to copper when it is put among charcoal (carbon) whose temperature is kept over 155°C, about as hot as a bonfire. We could know from Fig. 13 that the lower the reducing temperature is, the older history metal has. I described previously that production of non-chilled casting needs silicon, that Si became possible to get from silica stone (including much SiO_2). It was after A.D. 1700, when the furnace capable to reach higher than 1600°C was developed. Thinking this way, we can say that human civilization has fought against temperature.

2.2 Historical Position of a Reverberatory Furnace

As mentioned above, it was in 1735 when Darby second enabled to make machinable high-silicon cast iron using a blast furnace in Britain. His machinable cast iron became the most significant material for a steam engine. The engine worked as a device to blow strong wind into a blast furnace, generating high temperature inside. The point of his invention is that it enabled to produce machinable castings without chill, while malleable cast iron was not fit for large and thick castings. The best days of casting are from the invention of a blast furnace till that of a converter. A reverberatory furnace was invented by Thomas and George Cranage in 1766, behind success of a blast furnace. It is a technology to re-melt pig iron (*6), which was made with a blast furnace in advance, by burning coal in a reverberatory furnace. This invention made it possible to get large amount of molten cast iron independently of a blast furnace. Note that it is not in 1766 when a reverberatory furnace itself was invented, but it was already in use to melt copper and lead in low temperature. After that, in 1772, Réaumur invented whiteheart malleable cast iron (modern iron similar to steel), which is made by heat-treating chill casting. In 1784, Henry Cort developed a method to reduce amount of carbon to produce steel (wrought iron) by puddling molten metal in a reverberatory furnace (puddling process). The wrought iron is a kind of steel which contains 0-0.25% of carbon. The process is as follows: first put iron oxide into a reverberatory furnace and reduce amount of carbon through reaction between the molten pig iron and iron oxide ($FeO + C \rightarrow Fe + CO\uparrow$). Then puddle the iron with rods to make a steel ball, which is later forged into steel. Therefore reverberatory-furnace wrought iron had a fault that 10-20% inclusion remains inside due to the slags(*7). Through this process, about 200 kg of steel (wrought iron) is created at a time. The Eiffel Tower, built in 1889 for Universal Exposition, was made of this wrought iron. Its iron frames weigh 7000 t, which gives us the impression of a big project. By the way, the Tokyo Tower weighs 4000 t, and the Skytree 36,000 t only above the ground part. In China, as mentioned above, wrought iron was made during Han Dynasty, from the third century to the second century B.C., through puddling process. In the literature it is often described simply as iron was produced with a reverberatory furnace through puddling process. I need to emphasize the meaningful change as follows: the furnace was used (a) to melt copper or lead which has low melting temperature in the early period, (b) to re-melt pig iron which was made by a blast furnace in the middle period, and (c) to produce wrought iron with puddling process. Puddling process was a way to produce another kind, wrought iron (Table 1).

Table 1 Historical Position of Reverberatory Furnace

<table>
<tr><th colspan="2"></th><th>Year</th><th>Furnace and material</th><th>Inventor</th><th>Contents and historical importance</th></tr>
<tr><td rowspan="3">Cast iron age (for about 50 years)</td><td></td><td>1735</td><td>Blast furnace and cast iron</td><td>Darby the second</td><td>Enabled producing machinable high-silicon cast iron.</td></tr>
<tr><td rowspan="3">Reverberatory-furnace age (for about 90 years)</td><td>1766</td><td>Reverberatory furnace and cast iron</td><td>Thomas and George Cranage</td><td>Enabled to get large amount of molten cast iron independently of a blast furnace, by re-melting pig iron (*4) made with a blast furnace.</td></tr>
<tr><td>1772</td><td>Whiteheart malleable cast iron</td><td>Réaumur</td><td>Turned iron similar to steel by heat-treating the unmachinable chill casting.</td></tr>
<tr><td>Wrought iron age (for about 70 years) (for age (for about 70 years)</td><td>1784</td><td>Reverberatory furnace with puddling process and wrought iron</td><td>Henry Cort</td><td>Made wrought iron by puddling molten iron in a reverberatory furnace and reducing amount of carbon (puddling process): the Eiffel Tower, built for Universal Exposition in 1889, is made of wrought iron</td></tr>
<tr><td colspan="2">Steel age</td><td>1856</td><td>Bessemer's converter and steel</td><td>Bessemer</td><td>Enabled to make steel whose carbon content is under 2.1% directly from molten iron, while that had needed forging before.</td></tr>
</table>

*6 Pig iron: It is a general term for iron materials processed into steel or cast iron. In old times they were called *zuku*. Created by reducing iron ore (iron oxide) with high-carbon cokes or charcoal, pig iron includes much carbon and impurities.

*7 Slag: Unwanted substances produced in melting process due to reactions among metal oxides, solvents and lining materials.[23)] It is required to prevent slags from entering into space of molds because they can cause defects. In operations at Nirayama, it is considered that they took slags out through the slag hole first, and then poured metal through the tap hole.

As explained in the history of casting, it was since Bessemer's invention of a converter in 1856, when it became possible to get steel, not the forged type but one with carbon content under 2.1% directly from molten metal. By the way, some of the parts requiring excellent elongation of Brunat's engine used in Tomioka Silk Mill, designated a World Heritage in 2014, are turned out to be malleable cast iron from my investigation.

In response to the changes of the times from Darby the second's cast-iron manufacture by a blast furnace to steel manufacture by a converter, reverberatory furnaces during the Industrial Revolution in Britain, gradually shifted its shape: to those to melt cast iron independently of blast furnaces, and then to those to make steel called wrought iron. By the way, malleable cast iron cannot be obtained by heat-treating non-chilled cast iron. The main reason why reverberatory furnaces were used to produce cannons in Europe is as follows: first, they could obtain from blast furnaces non-chilled pig iron with high silicon content. Secondly, they were the most appropriate to get large amount of molten metal, and in the third place, reverberatory furnaces made it possible to reduce carbon content from 4.3% to 3.2% to produce castings with high strength. It is a kind of refining to reduce carbon in a reverberatory furnace, but not such refining as to remove impurities in a converter.

3. Could They Cast Iron Cannons with Nirayama Reverberatory Furnace?

3.1. Consideration from the Structure of Nirayama Reverberatory Furnace

Fig. 14 shows the structure of Nirayama reverberatory furnace. It is constituted of four furnaces and a pouring platform, 2.7 m deep. Each chimney is 15.6 m high, 5.0 m wide, and 6.0 m long. Fuel such as charcoal, coal or coke was burned on its fire grate. Then metal materials were put through a hole into the hearth and were melted with heat of the furnace. With *koshiki*, the iron material was made in advance as the following size: 10 cm wide, 10 cm long, and 100 cm high. Molten metal and slags go down the slope to the tap, where they gather. Stirring the liquid with rods through *hoko*, a square hole, evens out its temperature and accelerates the separation of metal and slags. As following describes, the South furnace, which was built earlier, has a structure to focus radiant heat around the materials, while that of the North one, built later, focuses it on molten iron. The chimneys are narrowed with a dent at the bottom. Such structure, called *misaki*, prevents heat from getting out and at the same time draws a more draft due to Venturi effect which is caused by change in pressure in the chimneys.

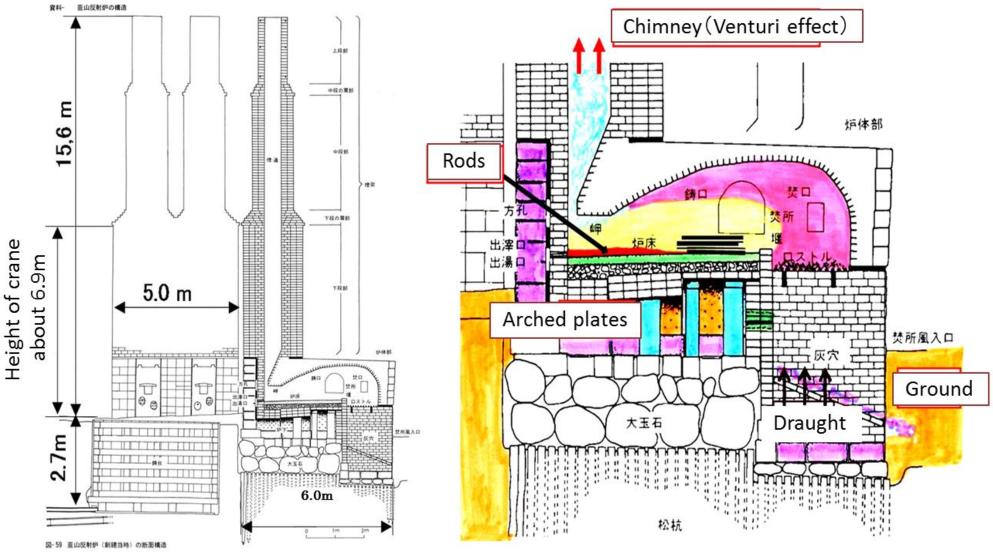


Fig. 14 Structure of Nirayama reverberatory furnace[1)]

Table 2 Unsolved mysteries of Nirayama reverberatory furnace and general opinions

	Unsolved Mysteries of Nirayama reverberatory furnace	General opinions
How to melt	1. Was cast iron melted with Nirayama reverberatory furnace?	Because the iron starts to melt at 1600°C, the temperature in the furnace did not go up high enough to melt iron.
	2. How high was the melting temperature?	
	3. How long did it take to melt materials?	It took long because they used charcoal as fuel.
	4. Was metal poured directly into a mold, or into a ladle (*8) before pouring?	They used a ladle because the furnace has a facility to install a crane to lift it.
	5. Were *bellows* used?	They did not use *bellows* as Venturi effect allowed the firebox to draw a draft.
	6. What was the fuel? Was coke used?	They did not use coke.
	7. What kind of material were used, iron sand from Iwami, gantetsu (iron ore) from Iwate, imported pig iron (Namban iron) (*9), or ballast?	While Saga domain (*10) used ballast, gravel placed at the bottom of a ship, Nirayama did not.
Bricks	8. Where were the bricks forming the furnace fired?	Nashimoto in Kawazu-cho and the hill behind Nirayama reverberatory furnace
Others	9. How many cannons were produced, and finished at Nirayama?	Two iron cannons and 128 cannons including bronze ones.
	10. Defects caused by compositions of cast iron cannons	It included many impurities such as titanium and sulfur. In addition, molten metal’s temperature was not high.

Table 2 summarizes the unsolved mysteries of Nirayama reverberatory furnace. As to general opinions seen in the literature, authors avoid clear expressions, ending up in ambiguous answers. I am going to examine the mysteries by comparing the literature with my own experiments.

Visitors would doubt that iron was actually melted with such a small, simple furnace. Due to this impression many people deduce that it was impossible. First, it is necessary to emphasize that the material was not pure iron whose melting point is 1536°C, but cast iron, with a carbon content of over 4.3%, melting point 1153°C. If the cast iron is composed to solidify at 1153°C, the sufficient temperature to melt it (the melting temperature) is about 1250°C, which is 100°C higher. It is slightly higher than that of the kiln used to fire bricks because the temperature in it was between 1200°C and 1250°C.

Fig. 15 is the reverberatory furnace depicted in *the Casting Method at the Royal Liege Foundry for Iron Cannons* written by U. Huguenin. It has a hearth sloping at a greater angle and no cavity under the ground. Except those differences, it is highly congruent with Nirayama's in terms of the *misaki* and the shape of the furnace.

Takisho hunyuko is an entrance of air into the firebox (Fig. 16). By Venturi effect of the chimney, a large quantity of air is drawn through it. There are firebricks marked with a circle in many parts of this hole or the furnace. They were burned in Nashimoto, Shimoda, where they were used to construct a local reverberatory furnace, and then later they were brought to Nirayama. From the bend of the cast-iron bar of a fire grate at *takisho hunyuko*, you could see how high the temperature went up there.

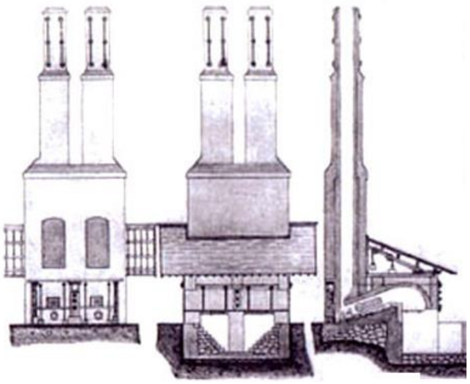
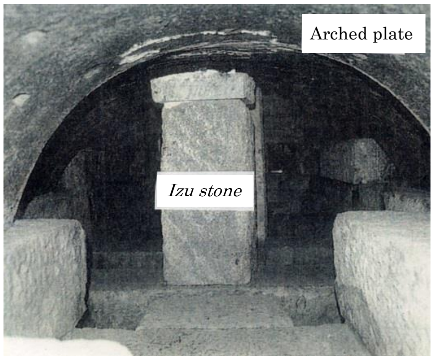


Fig. 15 Reverberatory furnace drawn in the Casting Method at the Royal Liege Foundry for Iron Cannons owned by the National Diet Library

Fig. 16 Entrance of air into firebox



Compositions of cast-iron materials made at reverberatory furnace, %

Iron	C	Si	Mn	P	S	Cu	Ti
Arched panel	3.5	0.016	-	-	0.026	-	0.003
Lintel	4.2	0.02	-	0.14	0.014	-	0.008

Fig. 17 Arched plates and Izu stones[1)]

*8 Ladle: A heat-resistant vessel to transport molten metal from the tap hole to molds. Depending on the size of castings, the shape varies from a large spoon with a long handle to a large pot carried with a car or an overhead crane. Compared to the method to pour metal directly from the tap hole into a mold, the poured melt's temperature decreases by around 100°C when the metal is collected in a ladle before transportation.

*9 Namban iron: Iron produced in India. During the Age of Civil Wars (around 16th century), Japan imported Namban iron through intermediatry trade with Portugal to deal with a shortage of iron for swords and guns. The iron was preferred material as well as ballast. However, a survey revealed that Namban iron was chill casting unmachinable for its low Si content.

*10 Saga domain: A domain located in the northwest Kyushu. The feudal lord at the time, Naomasa Nabeshima, was enthusiastic about introducing Western techniques, encouraging medical science and military theory in his domain. After translating Huguenin's book by his command, they built a reverberatory furnace and cast an iron cannon for the first time in Japan. Their cannons were trusted so high that the Tokugawa shogunate made a large order. Due to their outstanding ability, Saga domain had a significant influence on Japan's coastal defenses.

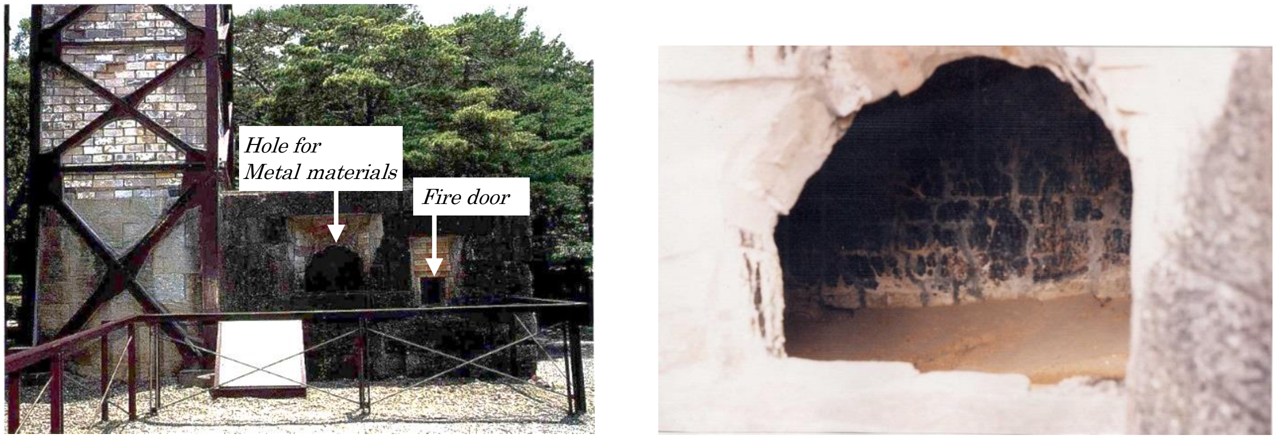


Fig. 18 Holes to put metal materials onto fire grate and to put fuel into firebox

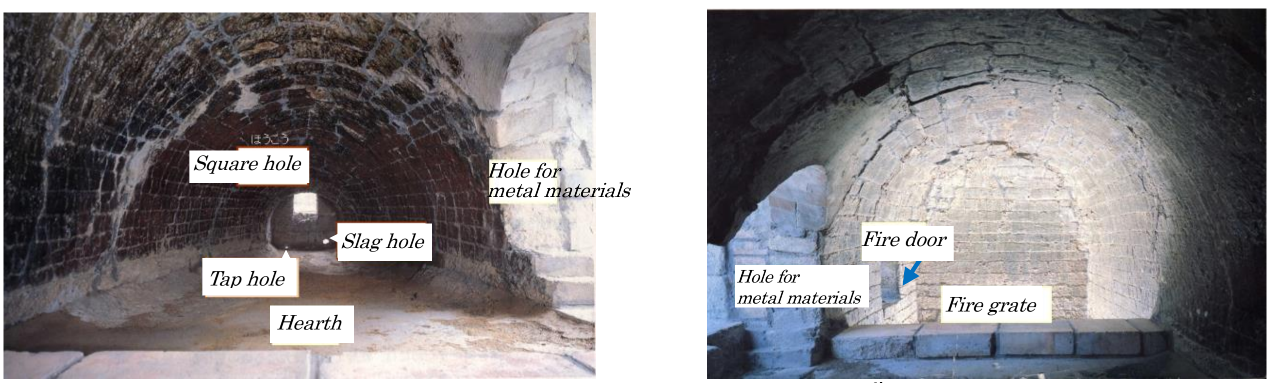


Fig. 19 Inside of reverberatory furnace[1)]

Fig. 20 Tap holes and slag holes

ceiling, which is made of metal plates bent semi-circle and the plates are supported by Izu stones (Fig. 17). The ceiling has square holes so that water from the hearth drops through them without mixing with molten iron. The idea seems to belong exclusively to Nirayama as Huguenin's book does not mention such a structure.

A hole to put through cast iron made by *koshiki*, is unusually big meanwhile *takiguchi*, a hole to put fuel through, is not so (Fig. 18). It is said that all materials were more, refining is all the more unnecessary. The reason will be explained later.

largeness is nevertheless incomprehensible.

Like a climbing kiln, inside of the furnace is coated with glass apparently for the purpose of reflecting radiant heat (Fig. 19). The slag hole is a hole to discharge slags, and the tap hole is a hole to tap molten iron. *Hoko*, a square hole, is made to get rods through and stir slags and the metal. Though some insist that iron was refined by puddling process, I regard such refining as removing impurities was not done. As for cast iron with carbon content of 4.3% and

From outside of the reverberatory furnace, *hoko*, the slag hole, and the tap hole can be seen (Fig. 20). Just in front of the tap hole, there is a pouring platform to set a mold on.

Because it is built so close to the tap hole, molten metal is considered to have been poured directly through it. As for the mystery of the platform, I will mention it later.

3.2 Consideration from the Operation Record of Nirayama Reverberatory Furnace

Table 3 shows the excerpts from the operation record of Nirayama reverberatory furnace (hereinafter referred to as the reverberatory furnace diary).[1] According to the reverberatory furnace diary, they produced at least three 18 pounders from cast iron. Also orders were placed for 60 t of coal, 10,000 bales of Amagi charcoal (also used for baking bricks), and lime and oyster shells as flux to soften slags. As metal materials, they ordered 43 t of pig iron and 13.7 t of iron (equivalent to 12 pieces of 18 pound cannons), 2700 kg of copper, 270 kg of tin (this copper-tin ratio is exactly equivalent to bronze which contains 10% tin). Considering that the majority of the total orders is associated with iron, I have no doubt Nirayama reverberatory furnace was built for the purpose of melting cast iron. Also you can see from the diary that they conducted a firing test on at least one cast-iron cannon, though the pig iron had some problems.

The diary shows that crews of Perry's black ships broke into the construction site of Shimoda's reverberatory furnace, which caused transferring the site to Nirayama. Also until Sugitani from Saga domain arrived, they were making metal flasks for cannon production with the South furnace. For flasks, chill casting was enough. With the cooperation of Saga, on September 9th, they cast an 18 pounder for the first time with the South furnace. The help of engineers from Saga domain was indispensable. They started to drill the barrel of the first 18 pounder on December 4th. Though it is recorded that machining continued until February 17th, no information about the cannon after that appears in the diary. Probably it had some problems to be used in actual combat. The South furnace which was used to produce the first cannon had a structure to concentrate heat not on molten metal but on metal materials, which is revealed by the study of Nirayama high school students as following describes.

Table.3 Excerpt from the operation record of Nirayama reverberatory furnace[1]

Year	Date	Event
1853	December	**[Shimoda, Izu]** Prepared for the construction at Takoma, Shimoda.
	January	Mined white clay at Nashimoto.
	February 1	Leveled the ground for the construction of the reverberatory furnace.
	February 17	Started to produce firebricks.
	March 4	**Perry's black ships entered the port of Shimoda.**
	March 8	Gave notice of sending Edo pig iron.
	March 16	The ridgepole-raising ceremony of the house for boring machines took place.
	March 18	Pig iron arrived from Osaka.
	March 27	**Foreigners broke into the construction site.**
	April	Purchased 60 t of Chikugo coal 10,000 bales of Amagi charcoal.
	April 6	Ordered to transfer the construction site.
	April 9	Joban coal 6 t
	April 17	Shipped foundation stones. All directors departed.
	May 29	**[Nirayama, Nakamura]** Off-loaded building materials at Numazu.
	June 4	Sorted firebricks to send on.
	July 25	Ordered two bales of lime and four bales of oyster shells.
	July 18	Started to lay firebricks.
	July 22	Cast iron slabs.
	August 8	Cast front slabs for an 18 pounder.
	August 14	Cast iron slabs for an 18 pounder.
	September 17	Started to plaster walls.
	November 4	The major earthquake of Ansei (Nothing wrong with the reverberatory furnace)

1855	January 16	**Zaemon Taro Egawa died.**
	February 21	Cast with one of the first furnace pair. At 1:00 cast 2 t of pig iron as the first operation of the furnace. At 11:00 cast a metal flask for an 18 pounder. At 13:00 operation ended.
	April 23	A foundry expert, Kuno, arrived at Nirayama for consulting about a metal flask for a 36 pounder.
	August	**Requested Saga domain to help Nirayama.**
	December	Saga domain accepted the request.
1856	April 11	**Finished construction of the tar factory.** Cast four times in this month.
1857	February 5	Sugitani arrived from Saga. (The first furnace of the South furnace pair was almost finished.)
	July 1	Test operation with the South furnace
	September	Test operation with one of the East furnace pair Test operation with metal flasks
	September 9	**Poured into an 18 pounder mold.** Started at 1:00 and finished pouring at 12:00.
	November 7	Operation started with the second North furnace. [Pig iron 2270 kg]
	November 19	Operated with the second South furnace. [Pig iron 2660 kg]
	December 4	Started to machine the 18 pounder. Started at 4:30 and ended at 2:16.
	December 6	**The second furnace (the North furnace)** [Pig iron 4500 kg] (Used two furnaces) (Probably the second 18 pounder)
1858	January 8	**Machined the first 18 pounder. (Continued until February 17th.)**
	February 22	**Cast the third 18 pounder. [4870 kg]**
	February the last day	Cut off the riser. The cannon had no shrinkage cavity.
	March	Finished building one of the triple boring machines. **Using pig iron made with Nagasaki's blast furnace, it is possible to produce cannons same as those Western-style.** However, the usual pig iron would be used for cannons for urgent orders, because the result of tests showed that the cannons made with the usual pig iron had a good endurance.
	March 13	**Firing test on the third 18 pounder**
	March 22	All dispatched members from Saga domain departed.
	October	Answered on casting bronze cannons to the government. A reverberatory furnace for bronze castings has no chimney, which reduces the internal temperature down to one-seventh. Being poured into a sand mold in a wooden flask, a cannon became poor in quality. A metal flask was better.
1859	January 25	Four bronze 80 pounders and a 24 pounder
	August 21	Ordered to produce a bronze 80 pounder and a 24 pounder.
	October 28	Repaired the reverberatory furnace.
1860	January 5	Repaired the chimney of the first furnace which had been badly damaged.
From July 1863 to February 1864		Cast a cannon with the trainees dispatched from the *kobusho* military academy and persons concerned with the Egawas. The product was mostly defective.
1864	November	**A suggestion was made that Nirayama reverberatory furnace should be discontinued.**

*11 *Kikko* pattern: A pattern formed over the surface of molten cast iron. Oxide film is generated over the surface of molten metal. Torn and drifting, this film forms various types of patterns. The patterns have been an indicator of the quality of molten metal throughout the ages because they are affected by temperature, chemical composition, and oxidation level. Our experiment shows that the requirement for formation of the patterns are the following four points: S content of over 0.02% and Si content of over 0.5%, generation of SiO_2 film, and appropriate content of C. Bamboo leaves, pine needles, and hexagons are the typical patterns. Of these patterns, the hexagonal pattern is called *kikko* (turtle shell) pattern, as hexagons arranged side by side look like the pattern of a turtle shell.

For the third 18 pounder which was cast with the North furnace on February 22th, 1858, 1125 kg of *kikko* pig iron (*12) was used (Fig. 21). *Kikko* (*11), a turtle shell, is the same name as the hexagonal type of patterns formed on molten metal's surface, which is described later. As the total amount of the melted material is 4870 kg, the pig iron accounts for 23% of it. On the other hand, no mention is made about *kikko* pig iron in the item of November 7th, maybe because the melting process was not for cannon production. Our research on surface patterns on molten iron revealed that it requires 0.5% silicon or more for the hexagonal pattern to appear.[10] Also even hyper-eutectic cast iron with a high carbon content does not form the hexagonal pattern, when the amount of silicon in the iron is lower than 0.5%. Therefore, it is quite likely that silicon was contained in *kikko* pig iron. It cannot be a coincidence that the name *kikko* stands for both the pattern on molten cast iron of high quality (Fig. 22) and the kind of pig iron in the Casting Diary owned by the Egawa family. The description of the firing test on the third 18 pounder, cast on February 22nd using pig iron, means at least one cast-iron cannon was finished in Nirayama. However, quantity of the gunpowder used here was probably about half the usual quantity, as it was only a test. To summarize, a firing test was run on at least one cannon. According to the Casting Diary, the riser (*13) was cut off on the last day (30th) of February and a firing test was run on March 13th. The record means it took less than 15 days to machine the third 18 pounder. On the other hand, for the first 18 pounder, machining continued for 73 days, starting on December 4th and ending on February 17th. Probably the casting partly got chilled because it was made without *kikko* pig iron, of which following describes.

Saga domain is believed to have succeeded in producing cannons by using ballast (*14) of the Denryumaru they bought from the Netherlands. Ballast is the cast-iron (pig-iron) pieces used to weight down sailing ships with tall masts and keep their balance. In leaving Europe they were placed at the bottom of a ship, and in leaving Japan cargos were loaded instead of them.

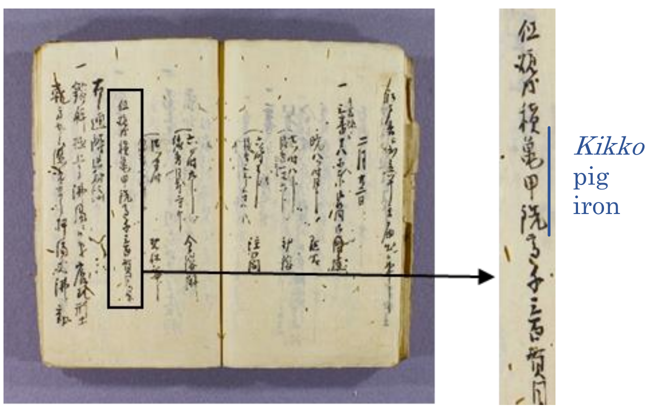


Fig. 21 Casting Diary of November 7th, 1875 (owned by the Egawa family)
Kikko pig iron was described to be used.

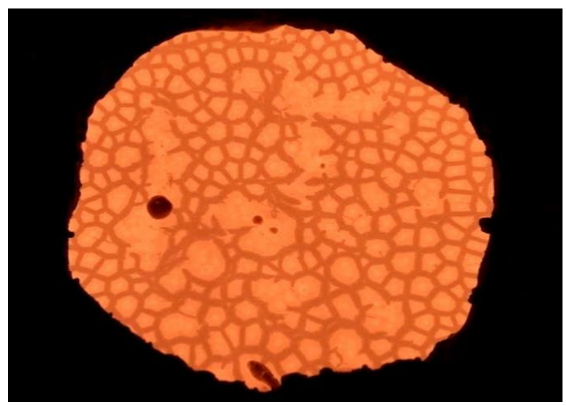
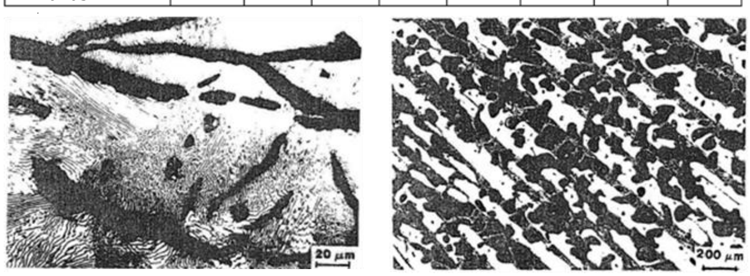


Fig. 22 Kikko pattern seen on surface of molten cast iron of high quality
(One kind of Marangoni convection which occurs due to differences in surface tension)

	C	Si	Mn	S	P	Ti	Cu	V
Canno	3.0	0.5	1.1	0.03	0.6	0-0.4		
Ballas	3.01	0.01	0.25	0.03	1.17	0.05	0.02	0.007



(a) Microstructure of (b) Microstructure of ballast

Fig. 23 Compositions of cannon and ballast (*14) loaded on ship wrecked near coast of Australia in 1770[11]

*12 *Kikko* pig iron: Material recorded in Casting Diary owned by the Egawa family. As the name agrees with that of *kikko* pattern mentioned above, it is thought to be pig iron which forms *kikko*, that is, hexagonal surface pattern (which looks like the pattern of a turtle shell), when melted. The third 18 pounder made of this pig iron was machined and endured a firing test.

*13 Riser: If molten metal is poured in the same volume as a product, cavities form on the surface or inside of the casting, because molten metal shrinks largely as it solidifies. To prevent this, molten metal needs to be kept in a pool (riser) built above and linked to the part which potentially cavitates. As solidification proceeds, the product part shrinks and runs short of molten metal, which a riser is designed to supply to. In cannon casting at Nirayama, a riser was used.

*14 Ballast: as ships in those days were basically sailing ships, iron pieces were loaded at the bottom of them. Some insist Saga domain cast cannons from the ballast which had been loaded on the Denryumaru, the ship they purchased from the Netherlands. However, it seems unusual to use pig iron with high silicon (Si) content for ballast, as you can see from the origin of the word *ballast*, deprived from “bare,” implicating its ”worthlessness.” In addition, the small amount of the Denryumaru’s ballast contradicts the large number of the cannons they produced.

According to the overseas literature on this ballast in 1980, as shown in Fig. 23, the silicon content of the cannon loaded on the ship, (also known as the famous Captain Cook’s[11]), is 0.5% and is flake graphite cast iron. The silicon content of the ballast of this ship is small as 0.01%, and the ballast’s microstructure is chill[12]. There is a pronounced difference between the iron material for cannon casting and that for ballast.

As for Namban iron, which is thought to have been used as often as ballast, it is analyzed by Kenji Sato in the Tokyo Metropolitan Industrial Technology Research Institute[13]. Table 4 shows the result, each type of Namban iron has low silicon levels.

Many point out that the view of Saga domain’s using ballast contradicts the fact that they produced a large number of cast-iron cannons.[14] Few of these cannons remain today, in addition, which could entail their use of hyper-eutectic cast iron, as following describes. Therefore, it can be said that hyper-eutectic cast iron is a leading theory.

Table 4 Chemical Composition of Namban iron, %[13]

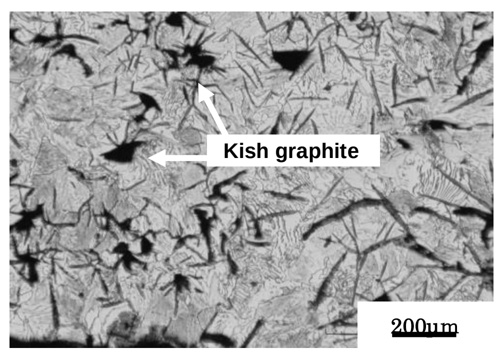
	C	Si	Mn	P	S
Oval	1.60	0.080	0.009	0.076	0.003
Thin bar a	1.58	0.016	0.017	0.011	trace
Surface of thin bar b	0.49	0.038	trace	0.037	0.002
Left side of thick bar	0.06	0.070	trace	0.101	trace

Considering from the facts, Saga domain had to use pig iron from a blast furnace in order to obtain high silicon pig iron. Huguenin’s book on cannon casting clearly describes that pig iron from a blast furnace should be melted in a reverberatory furnace. Apparently people in those days were well aware of the necessity of blast-furnace pig iron. In the reverberatory furnace diary “the same cannon as the Western one can be made with the pig iron of the Nagasaki’s pig iron. However…” Such description shows that they knew it very well. If that is the case, it is the greatest mystery what kind of metal *kikko* pig iron was.

Since 1859, bronze became main material for cannons. One of the reasons of this trend was because the cannons with a rifled barrel which used streamlined rocket-type bullets replaced the old cannons which used spherical bullets, as time passes.

3.3 Yasujiro Masuda’s Method to Create Non-chilled Cast Iron without Silicon

There is evidence that a technology existed in Edo era to create machinable cannons without generating chill even if silicon content was insufficient. The cannon Anori shrine exhibits is said to have been made in the closing days of the Tokugawa regime by a founder, Yasujiro Masuda. Fig. 24 is the pictures of its figure and microstructure. This cast iron contains a high amount of carbon, which makes its composition *hyper-eutectic*. Increasing the carbon content up to 4.5% enables to create non-chilled casting. Founders in those days knew that, though most of present-day casting engineers do not. In the microstructure, you can see rough and large graphite, kish, which directly crystallizes from the molten metal.



C4.48%-Si0.13%-Mn<0.001%-P0.117%-S0.034%- Ti0.005% (made by Yasujiro Masuda)

Fig. 24 Cast-iron cannon of Anori shrine and its microstructure (offered by Prof. Nakae)

Fig. 25 shows the result of our experiment. We examined the temperatures at which they finish solidification. Black dots stand for modern machinable cast iron with a high silicon content. White dots stand for chilled cast iron made by adding the element of tellurium (Te) into the former molten cast iron. We compared how the temperature (of finishing solidification) changes depending on the amount of carbon contained in each metal. With carbon content of more than 4.3%, cast iron does not generate chill and turns to machinable cast iron like that of present day.[15)]

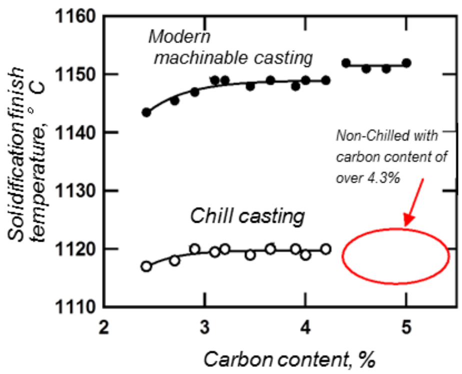


Fig. 25 Carbon content and chill casting[15)]

In molten metal whose composition is hyper-eutectic (*15), graphite crystallizes out first as its temperature decreases. These graphite particles become nucleuses for flake graphite to grow from, which prevents the cast iron from getting chilled. On the other hand, the molten metal with less than 4.3% carbon turns into chill casting because iron itself crystallizes out first as the molten metal solidifies (the crystal is called primary austenite in technical terms). Table 5 shows the compositions of cast-iron castings made between 1590 and 1840 in Japan. Foreign-made castings in the table are made from non-chilled cast iron, which have a higher silicon content than those made in Japan. As for Japanese cast iron, their compositions are mostly near hyper-eutectic containing much carbon, whereas silicon content is less than 0.1%. Of such castings, those with over 4.3% carbon are machinable, because rough and large flake graphite (kish in Fig. 24) crystallizes in such hyper-eutectic compositions. Examining the compositions of these Japanese old products reveals it was common knowledge that cast iron needed to be hyper-eutectic to prevent it from getting chilled.

According to Ohashi, Yasujiro Masuda, who had made the cannon of Anori shrine, became a millionaire, by producing 213 cannons and 41,323 cannonballs.[16)] He is also known to have been highly trusted by Shuhan Takashima. It is highly possible that his method of hyper-eutectic cast iron was adopted to produce cannons at Saga domain and Nirayama. Fig. 26 shows the temperatures at which iron containing carbon starts to solidify. The temperature decreases as the molten metal has a higher carbon level. When carbon content is 4.3%, the solidification start temperature goes down to 1153°C. From the fact that the compositions of Japanese castings from the seventeenth to eighteenth century were nearly eutectic, we can infer that they knew the metal melts at low temperature when its composition is hyper-eutectic. Also the existence of non-chilled castings with carbon of over 4.3% may have been recognized. Mixing with tin lowers the solidification point of molten copper, which results in decreasing the melting temperature. By maintaining the temperature of iron after melting at 1250°C, about 100°C higher than 1153°C, and adding carbon to cover the surface of the molten iron, the carbon content spontaneously increases up to 4.5%, according to the solubility of graphite. In the circumstances difficult to acquire silicon, this was the only way to make machinable cast iron.

Table 5 Compositions of cast-iron

No.	Casting item	Year of manufacture	Area of manufacture	Chemical compositions, %					Kind of cast iron	Furnace
				C	Si	Mn	P	S		
1	Garden lantern with bamboos and tiger pattern	1591	Kyoto	4.35 ~ 4.47	0.05 ~ 0.06	-	0.23 ~ 0.24	0.020	Rough and large graphite cast iron of hyper-eutectic composition (*6)	Koshiki
2	Tea kettle	1600s	Kyoto	4.30	0.03	0.002	0.204	0.027	Chill casting	Koshiki
3	Tea kettle	1700s	Kyoto	4.17	0.07	0.014	0.191	0.019	Chill casting	Koshiki
4	Tea kettle	1800s	Kyoto	4.30	0.04	0.025	0.279	0.020	Chill casting	Koshiki
5	*Torii* gateway	1839	Nara	4.57	0.05	0.006	0.240	0.025	Rough and large graphite cast iron of hyper-eutectic composition	Koshiki
Reference	IRON BRIDGE	1779	UK	3.25	1.48	1.05	0.54	0.037	Machinable cast iron	Cupola
	Cannon (Tokyo)	About 1820	America	3.22	0.69	0.27	0.275	0.132	Machinable cast iron	Cupola?

*15 Hyper-eutectic cast iron is cast iron whose carbon content is over 4.3%. Such iron does not get chilled because carbon works as the seeds which graphite grows from. On the other hand, cast iron with carbon content of less than 4.3% is called hypo-eutectic cast iron. Without silicon, hypo-eutectic cast iron gets chilled. When cast iron contains carbon of 4.3%, it is called eutectic cast iron.

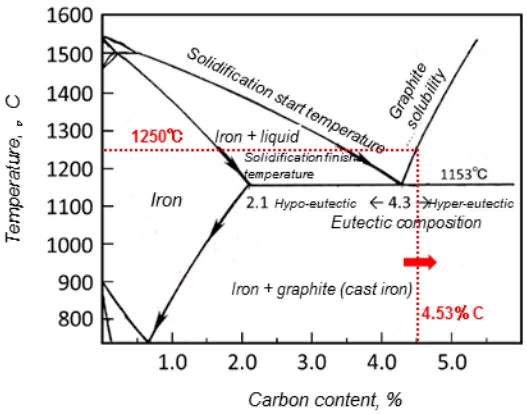


Fig. 26 Carbon amount and solidification temperature

(a) C4.31% (b) C4.53%

Fig. 27 **Microstructures of cast iron**

Fig. 27 is the microstructures of two kinds of cast iron prepared in different ways: (a) the molten metal of the first one was prepared in ordinary way (C 4.31%) while (b) the surface of the molten metal of another was covered with graphite at a temperature of 1250°C and kept as it was (C4.53%). There is an outstanding difference between the two microstructures. However, the tensile strength of this hyper-eutectic cast iron is only 100MPa, which leaves a question if a cannon made from it is actually usable. By the way thin castings made from cast iron with carbon content of less than 4.5% tend to get chilled, whereas cast iron with carbon content of more than 4.5% shows rapid decrease in strength. To acquire balance of the two characteristics, 4.5% is the best composition. This carbon content magically corresponds with that of Masujiro Yasuda. As for the 24 pounder of Saga domain, it contains only 3.2% carbon, which can be a good reason for being an imported one. Actually Ohashi writes in his paper that the cast-iron 24 pounder of Saga domain was made in America.[14)]

By the way, the strength of cast iron with carbon content of 3.2% is 250MPa. Cast-iron cannons produced with Japanese reverberatory furnaces do not remain today, because they were made of hyper-eutectic cast iron which had low strength and low impact value. Cannons of such compositions quite possibly exploded in actual combat even if they endured machining and firing tests. In Prof. Nakae's investigation either, the existence of a cannon surely made in Japan was not identified. This would support the view that these cannons with low strength did not endure combat.

Compared to the old cast iron (with 0.05% silicon) shown in Table 5, silicon content in the composition of Masuda's cannon is a little higher, 0.13%. As for Nirayama reverberatory furnace, as mentioned above, 23% of the materials for the third 18 pounder is *kikko* pig iron. Regarding the silicon content of *kikko* pig iron as 0.5% which is the sufficient amount to form *kikko* pattern, the silicon content of the 18 pounder is calculated as follows: (0.5% x 0.23) + (0.05% x 0.77) = 0.15%. The silicon content of the 18 pounder comes to 0.15%. This value almost coincides with that of Masuda's cannon. It is highly possible that he knew the existence of *kikko* pig iron and adopted it in his works.

Fig. 28 is the microstructure of the hyper-eutectic cast iron made in our laboratory. Its structure resembles that of Anori shrine's cannon. In the structure, you can see flake carbide similar to Widmannstatten pattern, often found in meteorites.

C 4.53%-Si <0.01%-Mn 0.070% -P 0.158%-S 0.040%

Fig. 28 Microstructure of the hyper-eutectic cast iron made in our laboratory

3.4 Melting Time of Reverberatory Furnace

I examined the melting time of the reverberatory furnace from the operation record of Saga domain and Nirayama. In Edo period, they used the temporal hour system. Daytime, from sunrise to sunset, and nighttime, from sunset to sunrise, are divided each into six equal parts. One of the daytime parts means two hours and 38 minutes on the summer solstice, whereas it means an hour and 50 minutes on the winter solstice. The time from the start of melting to tapping (when the molten metal is tapped out) is expressed with 16.7 cm incense sticks in the reverberatory furnace diary of Nirayama. It comes to seven sticks (about four or five hours). The melting time was the same as the furnace of Saga domain. Saga domain wrote the details such as the time from lighting, and referring to it, the average of melting time is as shown in Fig. 29.

Probably, it took three hours to heat whole reverberatory furnace, and cast iron started melting in two hours after materials were thrown in the furnace. They collected the molten metal for two hours from the start of melting to the start of tapping, after that, they poured it into the mold. As the combustion temperature of fuel such as charcoal is low, it is inferred that it was used to preheat the furnace which required heat quantity most.

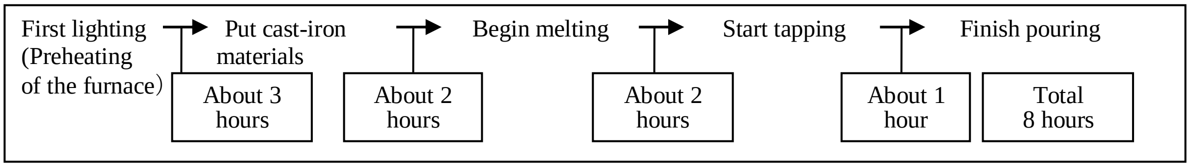


Fig. 29 Melting time of reverberatory furnace （Example of Saga domain）[17)]

Since it took about an hour from the start of tapping (getting out molten metal) to finish pouring, molten metal could be considered to come out consecutively like in cupolas. From the common sense in casting, the defect such as cold shut (*16) occurs unless sufficient molten metal is collected and is poured in a short time. The structure of reverberatory furnace is suitable for storing molten metal, so certain quantity of molten metal was collected and was poured in a short time. When receiving molten metal with a ladle, the temperature of molten metal decreases by about 100ºC, so it is difficult to pour with a ladle. We can think that they poured directly into the molds of cannons. Nevertheless, the height from the pouring platform to the tapping hole is only 3 m, and an 18 pounder is 3.5 m long, so a discrepancy remains. Also, the platform was just a place for molding, so the question or inference occurs that the surrounding area of the platform might have been about 4.5 m deep, longer than the cannon. In the investigation of the pouring platform in 1988, they did not excavate around the tapping hole of the reverberatory furnace[1)]. It is indispensable to excavate around the tapping hole in order to make clear whether they poured molten metal directly from the hole.

*16 Cold shut: If poured melt's temperature is too low, the boundary occurs at meeting place of molten metal inside of mold. This phenomenon is called cold shut.

3.5 Consideration from Melting Test of Nirayama Reverberatory Furnace

In order to infer the maximum temperature in the furnace, heat analysis including radiation heat has to be conducted. We have not conducted the heat analysis yet. In here, based on the composition of Saga domain's 24 pounder (some people say it was made in America), whose cast iron contains 0.69% silicon, and half-moon plate, whose cast iron contains 0.05% silicon, we investigated the difference of molten metal's qualities owing to Si existence and the melting temperature for casting cannons. The compositions of molten metal are shown in Table 6.

Osaka pig iron that was recognized as poor quality and used in Nirayama reverberatory furnace is thought to be made from pig iron of Sanin Iwami. Edo pig iron (also called soft iron) that was evaluated as a little better quality is thought to be made from rock iron of Kamaishi (Magnetite which is a kind of relatively high purity iron ore). I conducted a test with a focus on the amount of silicon. We did melting aiming the target composition of Saga domain cannon shown in Table 6, and investigated the following relationship: melting temperatures, changes of molten metal surface pattern, existence of sparks, and degree of adhesion of molten metal to the graphite crucible(*17).

Table 7 shows the change of the molten metal surface pattern and the degree of adhesion of the molten metal to the graphite crucible at 1290ºC. The surface pattern can be seen on the molten metal with high silicon, but it cannot be seen on molten metal with low silicon. Moreover, in the molten metal with low silicon, sparks generate rapidly at high temperature range. At the same time, molten metal swells and is likely to spout out. This phenomenon was written in the operation record of Saga domain, and there is a description of "sparks and smoke rose much"[17)] in it. The hexagonal surface pattern can be seen on molten metal with 0.7% silicon. However, it cannot be seen on molten metal with 0.05% silicon, and sparks generate.

The molten metal of the Saga domain's cast iron, which has 3.2% carbon and 0.7% silicon, comes to adhere to the mixing stick and the graphite crucible at 1290ºC, so about 1350ºC even at low temperature is needed to melt. Solidification start temperature that is obtained from the composition of Saga domain's cast iron is 1248ºC, so at 1280ºC molten metal was thought to start adhering to the mixing stick. Generally, pouring temperature for large castings is 100ºC higher than solidification start temperature, so we can consider that 1350ºC is the proper melting temperature for the composition of Saga domain's cast iron. However, Okumura and Ohashi dispute made obvious that Saga domain's cannon was made in America, so the prospect temperature 1350 ºC itself has no meaning.

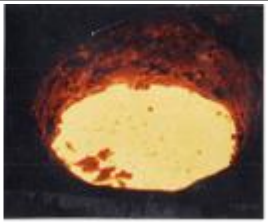
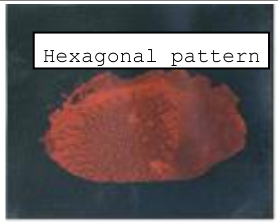
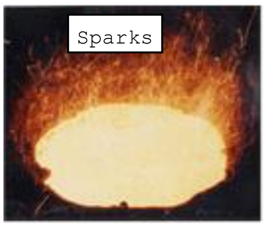
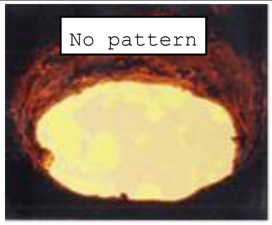
In contrast to this, if carbon of Saga domain's and Nirayama reverberatory furnace's cast iron were eutectic composition (4.3% carbon), then the solidification start temperature would be 1153ºC, so the pouring temperature would be enough at 1250ºC.

Table 6 Molten metal composition used in test[17)]

	C	Si	Mn	P	S	Ti	Cu
Saga domain's 24 pounder	3.22	0.69	0.27	0.27	0.13	0.01	<0.01
A little silicon	3.20	0.05	0.30	0.27	0.13	0.01	<0.01

*17 Graphite crucible: A fire-resistant container made of graphite. It is used to melt cast iron, light alloy, and copper alloy.

Table 7 Difference of molten metal surface pattern (*18) depending on silicon content

Silicon 0.69%				
	The film forms completely at 1290ºC.	The hexagonal molten metal surface pattern is seen at 1290-1340ºC.	The color of molten metal turns orange at 1400ºC.	The adhesion of molten metal to the graphite crucible is seen under 1290ºC.
Silicon 0.05%				
	At 1290ºC, sparks' rapid generations are seen.	In 1290-1320ºC, some surface pattern is generated, but it is not clear.	The color of molten metal turns white at 1400ºC.	If molten metal is stirred, then cast iron adheres to the mixing stick at 1280ºC.

*18 Surface pattern: On molten cast iron, which has over 0.5% silicon and over 0.02% sulfur, made in a cupola or an electric furnace, surface patterns such as bamboo-leaf type, pine needle type and hexagonal type appear. The people of the past judged molten metal with hexagonal type to be good and that with bamboo-leaf type to be bad. I do not think that it is a coincidence that there is a similarity between the name "hexagonal pig iron" in the Casting Diary with the hexagonal pattern type on molten cast iron. This pattern forms are caused by Marangoni convection owing to the difference of surface tension.

From the above, the melting temperature of cast iron in Nirayama reverberatory furnace is thought to be 1350ºC with composition of cannon made with Saga domain's furnace, and as for high carbon cast iron (more than 4.3% carbon), which was mainstream at that time, the melting temperature is thought to be 1250ºC. The solidification start temperature of bronze chips (Cu90%-Sn9%) excavated at Nirayama reverberatory furnace, which I will mention later, was 1028ºC, so the required melting temperature is more than 1120ºC.

3.6 Heat Distribution of Nirayama Reverberatory Furnace

Fig. 30 shows the thermal energy intensity ratios between the South furnace, whose first operation was held in July, 1857 and the North furnace in November, 1857. It was investigated by Nirayama high school students[18, 19]. The South furnace was built completely before Saga domain came to help. The North furnace was built with cooperation of Saga Domain. While the south furnace's structure allows heat to concentrate on melted materials, the North furnace's structure allows heat to concentrate on molten metal. Judging from the original meaning of a reverberatory furnace, the heat distribution of the North furnace built later is ideal.

In addition, the students conducted an experiment controlling the flame by bellows, and they have advocated a theory that the bellows were used in Nirayama reverberatroy furnace.[18, 19] We cannot deny the theory easily because it became clear that a ventilation hole from the outside was installed toward the chimney.[20]

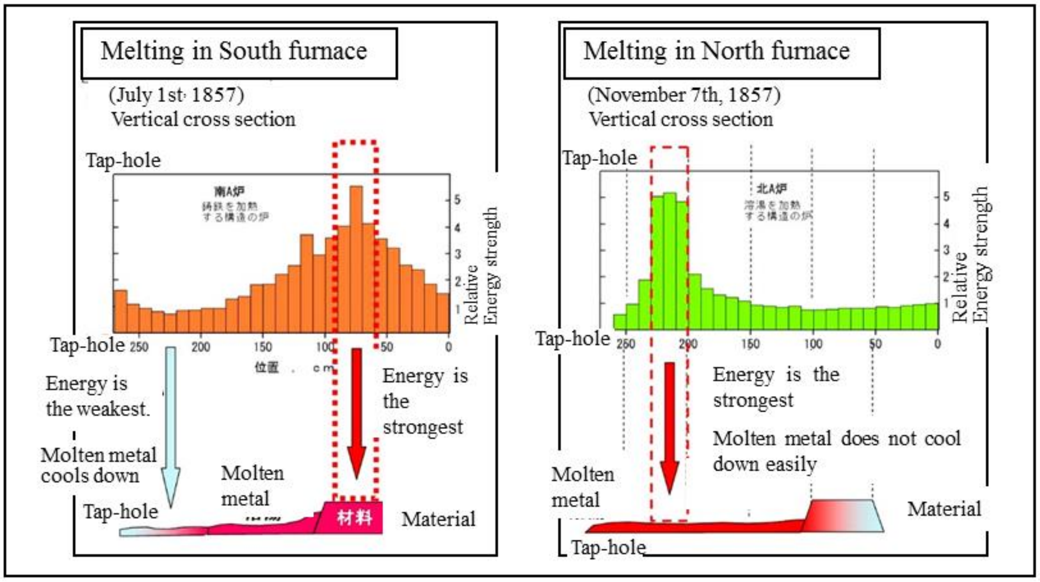


Fig. 30 Comparison of thermal energy intensity ratios between South furnace and North furnace[18, 19]

3.7 Whole Aspect of Nirayama Reverberatroy Furnace

In Fig. 31, the whole aspect of Nirayama reverberatroy furnace was drawn in old picture map. You can see that reverberatory furnace itself was a group of munitions factories. From the existence of a drying barn, they appear to have used a type of molds made by baking green sand molds, whose material is sand mixed with clay and a small amount of water. Also, *koshiki* furnace was there, so it is assumed that materials for construction of reverberatory furnace and melted materials were produced with *koshiki* furnace in advance. Depending on the literature, it is described as a *koshiki* or *tatara* furnace. Because *tatara* furnace is for production of *tamahagane* (steel), it is not suitable to make cast iron. *Koshiki* furnace can produce high carbon cast iron, so we have to recognize that people melted materials not with *tatara* furnace but with *koshiki* furnace.

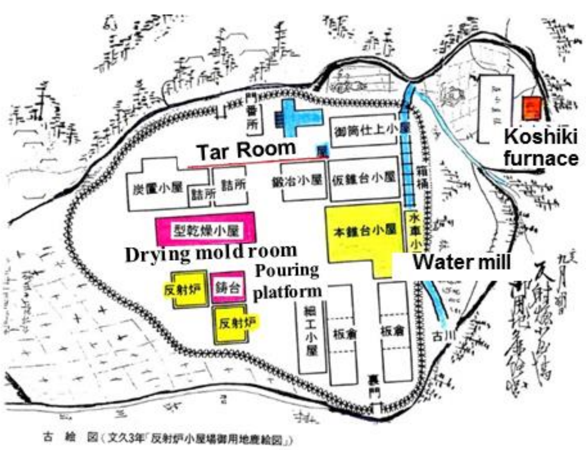


Fig. 31 Site of reverberatroy furnace in old drawing[1]

There was a barn to produce tar, so there is no doubt that people had produced coke from coal. There are arguments regarding use of coke, but the evidences to deny it do not exist anywhere in the drawing. Fig. 32 is a picture of the reverberatory furnace that seems to have been taken around the time when the furnace was handed over to the ministry of military affair in 1872. We can see piping in front of the furnace. The piping match the drawing of the piping to produce tar from coke left in the collection of the Egawa family (Fig. 33). From this picture and the drawing from the Egawas' collection, we could consider that a tar room was made in the aim of producing coke from coal, and tar was made as by-product of coke production. This tar was used for Western-style sailing ship, the Toda, which was built firstly in Japan in 1855. Therefore, a probability that coke was used as fuel of the reverberatory furnace is high during the period, since it needs much heat, when cast-iron materials started to be melted until pouring was finished.

Because *shachidai* (stilted building) can be seen in front of the furnace in the drawing (Fig. 32), some insist that molten metal was poured into a mold with a ladle lifted by a crane. It is considered that they turned the water wheel by using water of a river called Furukawa, and made a hole inside the cannon. As mentioned above, the period it took to machine the third 18 pounder is thought to have been less than 15 days.

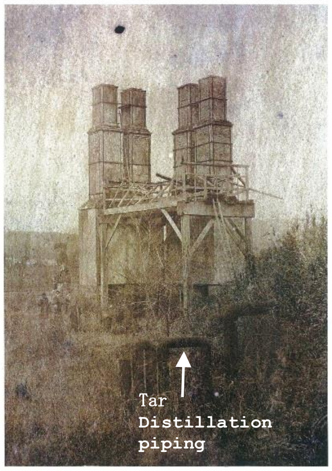


Fig. 32 Nirayama reverberatroy furnace in about 1872 (Meiji era) (owned by the Egawa family)

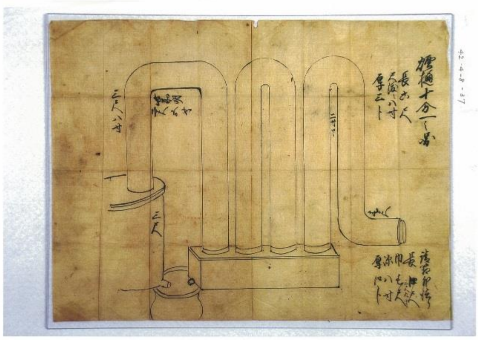
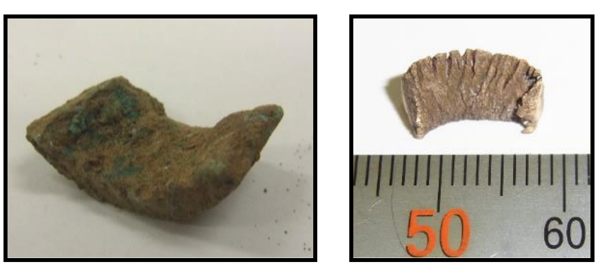


Fig. 33 Tar distillation piping to produce coke from coal (owned by the Egawa family)

Bronze chips were found at the excavation in 2013, and the result was shown in Fig. 34. This chip is made from only copper and tin, and lead was not included. The ratio of tin is about 10%, and it matches the description in the reverberatory furnace diary of Nirayama that they bought copper 2700 kg and tin 270 kg. From this chip, we can predict that cannon had been cast with bronze whose solidification start temperature is approximately 1020ºC, and been machined as described in the reverberatory furnace diary. The total bronze cannons produced at Nirayama is estimated to be four 80 pounders and one 24 pounder from the diary.



Chip just after excavation Chip after cleaning

Cu：89.7% Sn：9.20% Pb undetected

Fig. 34 Bronze chip found at excavation of Nirayama reverberatroy furnace

3.8 Number of Cannons Cast with Nirayama Reverberatory Furnace

Although there are various theories about the number of cannons cast with Nirayama reverberatory furnace, it is not clear enough. The research result in the literature that has a higher reliability is shown in Table 8. Inferring from this result, it is valid to assume that only three cannons were made from cast iron.

Table 8 Estimated number of cast iron cannons produced at Nirayama reverberatory furnace

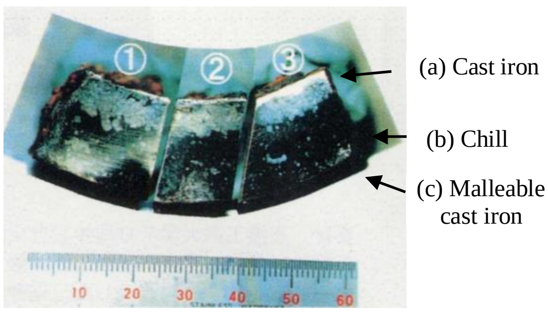
Reference	Contents	Number of cannon
The operation record of Nirayama reverberatory furnace etc.[1, p.23]	18 pounders were produced with cast iron. The first one was machined. The third one was machined, and its firing test was conducted. 4 bronze 80 pounders, a 24 pounder, total 5 cannons.	3 cast-iron 18 pounders were cast. More than 3 bronze cannons, and firing tests were conducted on one cast-iron cannon.
Catalog of the army magistrate in 1866[1, p.23]	Finished cannons: 14 Incompleted: 50 Defective: 36	Materials are unclear. Purchased cannon might be included.
Investigation book on the number of cannons[1, p.20]	Planned to cast, and sent to Odaiba, Shinagawa, 86 cannons from Nirayama, 50 from Saga domain, 175 from Yushima Sakuranobaba cannon factory, and 5 from Osaka.	However, the number is unknown because it was only a plan.
The Shimazu family investigation, *Weapons and reverberatory furnaces of each domain*[1, p.21]	Ten 80 pounders, two 24 pounders, twelve 12 pounders, and 4 long howitzers, total 28 cannons were made at Nirayama reverberatory furnace, were sent to No.1 Odaiba.	28 cannons.
Masao Serizawa: *Yoshiki Seitetsu no Hoga*[21, p.94]	Trial casting 5times, 3 times cast 18 pound in two furnaces combined. From 1863 to 1864, 128 bronze cannons were produced and 100 cannons became defect.	3 cast-iron 18 pounders, 128 bronze cannons (100 of them were defective).
Kurao Kubota; Material Science and Technology[22, p.67]	75 cast iron cannon were produced, and 12 cannons had no defects such as cavity shrinkage.	12 cannons succeeded among 75 cannons.

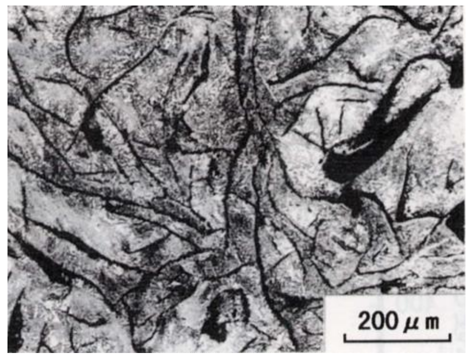
One of the three was cast with high-quality pig iron whose melted surface pattern is hexagonal one and which is called hexagon pig iron (*kikko* pig iron). After machining, it maybe had a firing test.

3.9 Cannonball Used in a Firing Test in Hagi

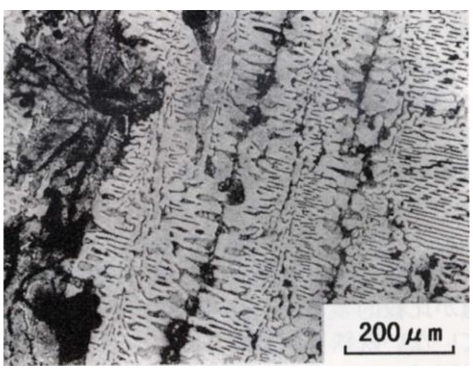
Cannonball used in a firing test in Hagi and its microstructures are shown in Fig. 35. This cannonball was made from a composite material of three kinds of iron. (a) Inside is made of machinable cast iron (flake graphite cast iron), (b) outside is made of chilled cast iron, and (c) the surface is made of whiteheart malleable cast iron (steel) that is made by heat-treated chilled cast iron. Also, flake graphite parts had silicon as high as 0.17%, and carbon was 4.32% that is hypereutectic composition. Interfaces of gray cast iron and chilled cast iron were rough, and then it is assumed that the balls were made from the composite material made by pouring two kinds of molten metal having different compositions. Cannonballs are hollow inside, so it is an interesting mystery how to prevent separation of those two kinds of components, owing to gravity.

By the way, the maximum flying range of 24 ponder was 2793 m, and that of 18 ponder was 2600 m. The flying distance of the bronze 20 duim mortar, which is located at Nirayama reverberatory furnace, was 1364 m surprisingly, with 469 g of gunpowder.

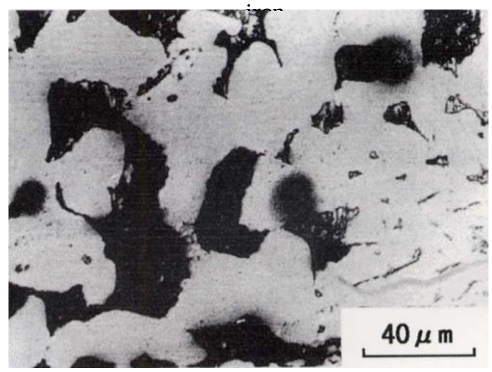




White part on inside (a) of cannonball made of gray cast iron



Chill microstructure on outside (b) of cannonball



Surface (c) of malleable cast iron

	C	Si	Mn	P	S
Composition range of the Hagi cannonball	3.7～4.3	0.0015～0.16	—	0.05～0.16	0.05～0.14
Flake graphite part	4.32	0.17	＜0.005	0.15	0.018

Fig. 35 Microstructure of the cannonball which was shot as a trial at Hagi (Offered by Professor Nakata Takeshi of Shibaura Institute of Technology)

Conclusion

Although I could not explain about all items (mysteries of Nirayama reverberatory furnace) due to limitations of space, Table 9 summarizes the mysteries.

It is difficult to conclude that cast iron had not been melted in Nirayama reverberatory furnace, if we guess from the reverberatory furnace diary. According to the diary, it is appropriate to think that three cannons were produced from cast iron, and one of those cannons had a firing test. In order to make non-chilled cast iron (machinable cast iron), the possible way is as follows: (a) set the quantity of *kikko* pig iron with about 0.5% silicon at 23% of the total materials, which makes the molten iron contain 0.15% silicon. (b) Spread carbon over the molten iron of just its carbon content to 4.5%. This temperature, 1250ºC, is low enough to prepare in Nirayama reverberatory furnace.

Namban iron and ballast of ships are considered as a good melted material, but according to this investigation, they were chilled cast iron. At that time, people bought cast-iron cannons from abroad, so there is a high possibility that existing cannons which contain 3.2% carbon and about 0.5% silicon are imported cannons. It was after blast furnaces' invention that they could get high silicon and could produce cast-iron cannons of low carbon and of high machinability.

I hope that this paper will help in "Sites of Japan's Meiji Industrial Revolution: Kyushu-Yamaguchi and related Areas" including Nirayama reverberatory furnace as World Industrial Heritage Site.Moreover, I would really appreciate it if many people would get interested in foundry engineering.

Table 9 Conclusion of mysteries remained in Nirayama reverberatory furnace

	Remained mystery	Conclusion
How to melt	1. Was cast iron melted with Nirayama reverberatory furnace?	Pouring temperature was about 1250 ºC with about 4.5% carbon content same as that of the cannon of Anori shrine. It was made by Yasujiro Masuda who was a founder in Kawaguchi.
	2. How high was the melting temperature?	
	3. How long did it take to melt materials?	About eight hours from first lighting to completion of pouring. Though casting time was written as an hour, it was conceivable that certain quantity of molten metal was collected and was poured in a short time.
	4. Was metal poured directly into a mold, or into a ladle (*8) before pouring?	The molten metal seems to have been poured directly into the upright cannon mold. Neither a ladle nor a crane was used.
	5. Were *bellows* used?	There is a possibility that they were used to control the flame.
	6. What was the fuel? Was coke used?	Coke was used.
	7. What kind of materials were used, iron sand from Iawami, gantetsu (iron ore) from Iwate, imported pig iron (Namban iron), or ballast?	It is said that Saga domain used ballast and increased content of silicon, but there is a possibility that ballast did not contain silicon. Kikko pig iron (high-quality pig iron) which probably included high silicon (about 0.5%) was used in the third cannon at Nirayama. "Where people could get Kikko pig iron from" becomes a next mystery.
Bricks	8. Where were the bricks forming the furnace fired?	Bricks marked with a circle were made in Kawazu Nashimoto, and those without a circle were made at the back hill of Nirayama. Bricks were fireproof brick made with burned white alumina clay.
Others	9. How many cannons were produced, and finished at Nirayama?	Four iron cannons were cast, and two of them had firing tests. Four 80 pounders and one 24 pounder were made of bronze.
	10. Defects caused by compositions of cast iron cannons	The main reason is that people could not get the melting materials with high silicon contents. Therefore people cast hyper-eutectic molten metal whose carbon contents was more than 4.3% and did not get to chilled same as the cannon of Anori shrine. It was made by Yasujiro Masuda who was a founder in Kawaguchi. If the cannon was hyper-eutectic, the cannon could be machined and had a firing test that needs half of powder. However, those cannons had a high possibility to have exploded in actual combat because of low strength and low impact value. That's the reason why no cannon exist in Saga and Nirayama.

* According to the latest research, it is found that four iron cannons were cast (not three) and had firing tests.

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