MOLYREVIEW

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INTERNATIONAL MOLYBDENUM ASSOCIATION

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Moly beats in the heart of ships

The quantity of raw materials, fuels, foodstuffs and finished goods that are moved around the globe every day is enormous. The only way to do that economically is by sea transport. Since the cost of transport is a significant issue, ships are becoming ever larger in size and more efficient in fuel consumption. In the beating heart of a ship, the marine diesel engine, molybdenum is an important alloying element providing superior performance and longevity.

Large container ships and bulk carriers are the backbone of our worldwide transportation system. Minerals, oil, grain, industrial and consumer goods are just some examples of daily consignments that are shipped around the world. These products often have destinations far away from the production site. Iron ore, for instance, is transported to its destination by bulk carriers capable of moving several hundred thousand tons at a time. In many cases such bulk carriers are sailing on fixed routes back and forth since the size of the vessel requires special adaptations of the harbor environment. Many types of goods are shipped by large container vessels to turnover hubs from where complex onward routings take them to their final destinations. From the first generation of container ships in the late 1960's to the current seventh generation, boat length and width have nearly doubled. To maintain a cruise speed of at least 25 knots, necessary to allow fast delivery schedules for goods, very powerful marine engines are needed.

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Living above it all: The world's tallest residences

The lucky few who can afford it have two spectacular new options for living well above the crowds: Burj Khalifa in Dubai and The Trump International Hotel and Tower in Chicago are now the tallest residential buildings in the world. The elegant Type 316 stainless steel and glass exteriors of these curved multi-tiered towers stand out not only because of their impressive height but also because they capture light like glimmering jewels on the skyline.

Stainless steel has been the preeminent material for elegant, progressive, modern building exteriors since the completion of the Chrysler Building in 1930. It is not only beautiful but also very practical. When properly specified, uncoated stainless steel can provide hundreds of years of service without replacement. Relative to other long-lasting materials, it is less expensive and can be indefinitely recycled into the same high-quality material. This makes stainless steel a cost-effective and environmentally friendly choice for any long-term, potentially iconic design.

Burj Khalifa and Trump Tower were both designed by the Chicago office of Skidmore Owings & Merrill (SOM), which has created very tall, high-profile stainless steel buildings for over 50 years. Type 316 stainless steel was selected for the elegant exteriors of both towers for its beauty and corrosion resistance. The molybdenum addition makes Type 316 more resistant to the coastal and deicing salts found in these two very different, corrosive locations.

Conditions in Chicago

Chicago's use of deicing salt to combat snow and ice in winter makes the environment here as corrosive as in many coastal locations. Salt has ➔

The Type 316 and glass clad Trump Tower as viewed from the Chicago River. Photo: Catherine Houska/TMR.

Content

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been found as high as the 50th floor of the city's tall buildings and causes damage to susceptible materials. Although occasional cleaning of the surfaces to remove the salt may be necessary, Type 316's proven corrosion performance in Chicago makes it a natural choice for buildings that will be admired for decades or even centuries.

Trump Tower

Completed in 2009, Trump Tower Chicago is a glimmering 96-story (423 m) skyscraper condo-hotel. Its sparkling stainless steel and glass exterior and prominent location make it the most visible building on the city skyline. The building is strategically positioned along the north bank of a bend in the prestigious Chicago River so that residents and hotel guests have unique, unobstructed full height views of Chicago and the Lake Michigan lakefront. The lower floors are elevated and recessed along the popular River Walk to create an expansive landscaped promenade lined with retail stores and public gathering spaces. The beautifully detailed entrances, column covers, storefronts and riverside walkway canopies are stainless steel and glass. Many of the interior lobby details are also stainless steel.

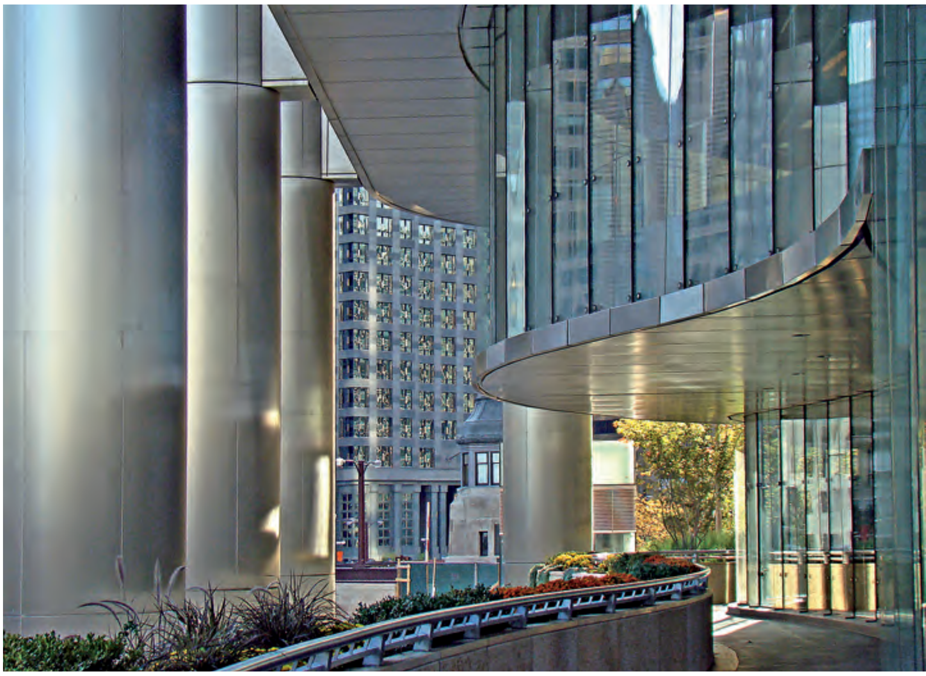
The remainder of the tower is clad in about 7,000 m^2 of Type 316 curtain wall with a very fine No. 4 finish and about 42 km of mirror polished exterior fins on its vertical window mullions. This glistening finish combination highlights the building's elegant lines and ensures visual domination of the skyline. It is the second tallest building in the United States after Chicago's Willis (formerly Sears) Tower but stands out much more than that dark-toned building. Since the completion of Burj Khalifa in early 2010, Trump Tower is the world's eighth tallest building and second tallest residence.

Conditions in the Middle East

Some coastal locations in the Middle East are among the most corrosive places in the world: Those areas have low rainfall, high temperatures, high humidity and high levels of salt accumulation from the sea. Stainless steel selection in such areas can be challenging and requires careful evaluation of the site. Type 316 with a very smooth finish can be selected if the surface is regularly cleaned to remove salt and other deposits and if the location is not too close to the coast. Otherwise, a more corrosion resistant stainless steel with higher molybdenum content should be used.

Burj Khalifa

At 828 m, the widely publicized Burj Khalifa is both the world's tallest building and structure. It houses residences, offices, a hotel, mosque and observation area. Most of the exterior is Type 316 stainless steel and glass. A linen pattern applied over a smooth bright annealed finish was selected for the curtain wall and a brushed No. 4 finish was used for the tubular elements. The result is a shimmering silver tower gently reflecting the desert sun.



Chicago River Walk curves along the base of Trump Tower. Photo: Catherine Houska/TMR.

Two buildings wrapped in stainless

Both buildings ultimately provide residents and hotel guests on opposite sides of the world with two of the world's most prestigious addresses. Both incorporate many sustainable features such as roof gardens, high-performance glass and high-solar reflectance stainless steel panels that reduce heat gain. These magnificent iconic buildings have reshaped skylines and made it possible to live above the clouds. (ch)

The Burj Khalifa, a shimmering silver tower gently reflecting the desert sun. Photo: Emaar.

Molybdenum – a real superhero in medicine

Everyday, molybdenum takes on the role of superhero in the world of medicine. The radioisotope Mo-99 and its derivative Tc-99m are the mainstays of nuclear medical diagnostics. They are used many times each day saving countless lives and improving the quality of life for many others.

Popular entertainment is full of superheroes. Superman has x-ray vision. While enjoyable, the battles fought in the pages of comic books and on movie screens by costumed crusaders can never match the drama of reality – in real life, villains and monsters are often unseen. And yet, the courageous battle against them happens on a daily basis – actually about 70,000 times each day. That is the number of nuclear medical procedures conducted every day by doctors and health care professionals across the globe. Borrowing from Superman and his x-ray vision, health care professionals can not only see you, they can see inside you to root out and conquer sickness and disease.

What makes this seemingly fictional ability real? The dynamic pair of molybdenum-99 (Mo-99), an isotope of molybdenum, and its direct by-product technetium-99m (99mTc) – the most extensively used radioisotope in health care for internal diagnostics. Yes, the heroic (even super heroic) is possible.

While there are a variety of isotopes used in nuclear medicine, the Mo-99/99mTc pair contains distinctive attributes that make them indispensable. Mo-99 is the “parent” of 99mTc. With a half-life of 2.7476 days, Mo-99 progressively decays directly into 99mTc; moreover, Mo-99’s half-life is long enough for it to travel for reasonably long distances and is readily distributed to health care facilities around the world.

Nuclear medical diagnostic scan of the human brain. Photos: iStockphoto.com/Banksphotos (left), iStockphoto.com/Brad Wieland (right).

Technetium-99m is ideal for three reasons. Its half-life is a short six hours. This is long enough for diagnostic purposes, yet short enough to not require extended hospitalization. Often, a patient can be examined and go home in the same day. Combined with 99mTc’s short half-life, are the low energy gamma rays that it produces. The type of radiation that it releases is readily detected by medical equipment and at the same time easily escapes the human body, which results in minimal radiation exposure to the patient. Finally, the make-up of 99mTc is so adaptable that it can easily be combined with a variety of pharmaceuticals that carry the radioisotope to the exact location in the body that needs to be examined.

The number of hospitals and health care institutions that rely upon Mo-99 and 99mTc attest to its significance in modern health care. Eighty-five percent of all nuclear medical diagnostic procedures – evaluating major organs, circulatory conditions, bone health, and brain functioning – depend on these two radioisotopes. And while alternatives exist, they are often more costly and present considerably more risk to patients.

The diagnosis of heart disease is one example of how vital 99mTc has become to healthcare. Technetium-99m provides a non-invasive, non-surgical way for doctors to determine the condition of a patient’s heart. Moreover, the diagnosis can be done almost immediately, allowing doctor and patient to act with the appropriate sense of urgency. Without this diagnostic technique, many would undergo unnecessary surgery (such as angioplasty); or worse, those who really needed surgery would not undergo the procedure.

Management and treatment of cancer has also been profoundly affected by 99mTc. With breast, skin, and similar types of cancer, 99mTc is targeted to infected lymph nodes, which allows doctors to determine the extent of the cancer without surgery. The radioisotope allows such precise targeting that what used to require major surgery and an extended hospital stay has been replaced by a minimally invasive procedure. “A targeted incision lead by 99mTc leads to better sampling, a small incision, less pain, and a quicker recovery,” said Dr. Kenneth Gow, pediatric surgeon at Seattle Children’s Hospital in Seattle, Washington. While an alternative technique of injecting a colored dye around the tumor area exists, “it lacks the precision,” explains Dr. Gow.

The Mo-99/99mTc pair was unintentionally “discovered” in 1958 by scientists at the U.S. Department of Energy’s Brookhaven National Laboratory while working with other radioisotopes. It was first used medically to measure blood flow in patients and has since become the most widely used radiopharmaceutical in modern medicine.

Every day, patients old and young receive life saving treatment that would not have been possible 40 years ago. Each year, scientists discover new uses and new possibilities for the Mo-99/99mTc pair. No comic books, no movie sequels, just another service provided by your friendly neighborhood radioisotope with the assistance of molybdenum. (as)

Molybdenum in its most beautiful form

Those of us who work with molybdenum will be pleased to know that molybdenum can take on a beautiful form as it occurs in nature. The form taken is that of a rarely found mineral known as Powellite. It qualifies as a gemstone not only because of its gorgeous yellow-gold glow, but also through qualities of rarity and durability. The story of its discovery and namesake is exciting.

Powellite is made of the elements calcium (Ca), molybdenum (Mo) and oxygen (O) combined as $CaMoO_4$. The oxygen atoms are arranged in a so-called "tetragonal" geometric crystal structure. This structure produces natural crystals that look like elongated squares with pyramids at the bottom and top. The oxygen, calcium and molybdenum atoms take on and give electrons respectively to become ions. The chemical bonds between positive cation atoms (Ca and Mo) and the negative anion oxygen atoms are very strong. This produces the hard durable structure that is required for a gemstone. The crystal has a yellow-gold glow but would be colorless if it did not contain some impurities that act electronically to produce color. These impurities are likely iron or nickel.

Common properties used to describe gemstones are chemistry, refractive index, hardness and crystal structure. Powellite has a high refractive index, similar to diamond. A high index indicates that the crystal has high brilliance and luster, making it beautiful. It does not have nearly the high hardness of diamond. These properties are very different from the properties of its better-known cousin "Molybdenite", the mineral from which we obtain molybdenum metal. Molybdenite is black, opaque and soft (not durable), and relatively abundant.

Story of adventure and discovery

The story of Powellite begins with a mission of discovery that took place in the southwest United States. In early 1869 Major John Wesley Powell, a civil war hero, undertook a government assignment to explore the Colorado River. In May of that year his group embarked onto the Green River in Wyoming. Three long and harrowing months later they emerged from the Colorado accomplishing what no other men had done before; they navigated the wild Colorado and in the process discovered the Grand Canyon, now considered one of the Seven Wonders of the Natural World. Throughout the trip Powell made careful records that stimulated further exploration. His continuing interest in geology was eventually rewarded when he was named Director of the U.S. Geological Survey in 1881. (More information about Powell and early photographs of the Grand Canyon can be found at www.powellmuseum.org.)

In the later half of the 18th century considerable interest developed in the mineral deposits of the American West partly due to the efforts of Major Powell. Prospectors searched for mineral treasure beneath the desserts, sandstone uprisings, and peaks of the Rocky Mountains. In 1891 a man named R.L. Packard, searching at the mouth of the abandoned Peacock Mine in the Seven Devils area of western Utah, found an interesting mineral. He forwarded a sample to Dr. W.H. Melville at the U.S. Geological Survey.

Doubly terminated powellite crystal, 6 cm in length, with scolecite; from Nashik, Maharashtra, India. Credit: Carnegie Museum of Natural History specimen CM28419. Photo courtesy of Wright's Rock Shop, Hot Springs, Arkansas.

Documentation and naming

Dr. Melville examined the specimens provided by Packard. In the records Melville described two other associated common mineral species and then came a statement: "the strong reactions for molybdenum suggest a new species". He went on to carefully document the appearance, chemistry and crystal structure of the new species. He provided "Type Material" to the National Museum of Natural History, Washington, D.C., (Type: T: 080674). He also took great pleasure in naming this new mineral in honor of Major J. W. Powell, Director of the U. S. Geological Survey. The fascinating account of Professor Melville's examination is published in the American Journal of Science, (1891) ser. 3, 41,138.

Today, Powellite is well known to mineralogists and gemologists around the world. It has been found in at least seven countries with some of the best specimens coming from Chile and India. Collectors search out Powellite for its rarity and beauty. Powellite indeed displays outward beauty and provides a source of inner pleasure to collectors and museum visitors. (ck)

Continued from page 1

Moly beats in the heart of ships

Ship propulsion – engines as large as a house
Propulsion of commercial ships is mainly achieved by two different technologies. Medium speed diesel engines are used to drive a generator producing electricity. The generated electricity is used to drive the propeller via an electric motor. This technology mainly applies to smaller ships and cruise liners. Huge container ships and bulk freighters, however, are typically powered by low-speed diesel engines. The propeller in this case is directly connected to the engine via a drive shaft without clutch and transmission. With a build size of up to 15 m height and 28 m length (about the size of a house), and a weight of over 2,000 tons (about 1,000 cars), the largest two-stroke diesel engines' power output reaches more than 100,000 hp. These engines operate in the range from 60 to 200 revolutions per minute, so they are known as low-speed engines. Companies like MAN B&W Diesel and Wärtsilä are the market leaders in design and manufacturing of large low-speed Diesel engines. Since the marine engine accounts for nearly 10 percent of the total ship construction cost, ship operators prefer container ships to be equipped with only one engine and a single propeller to keep investment costs reasonable.

Ship diesel engines are as large as a house and weigh over 2,000 tons. Photo Wärtsilä

Such large engines power huge container vessels, for example the 350-meter long "COSCO Guangzhou". This 12-cylinder engine was designed in Europe, yet, it is built under license in South Korea, China and Japan, close to the world's major shipyards. The engine is indeed too big to be transported and therefore has to be assembled right in the ship during construction. Another container giant with the incredible length of 397 meters is the "Emma Maersk". The ship was taken into service in September 2006 as the world's largest container vessel at the time and has now been joined by seven identical sister ships. Here, the power plant is a 14-cylinder engine. The two extra cylinders make sure that these very large container carriers can maintain a cruise speed of 26 knots. The engine displacement of this giant corresponds to that of 14,000 mid-size car engines.

Low vessel operating costs are the key for economically competitive transport of goods. Large two-stroke diesel engines typically run on cheap low-grade heavy fuel, also known as "Bunker C" fuel. This lowest fraction of all crude oil distillates has a viscosity resembling that of asphalt. Using it in a fuel circuit at ambient temperature would be like sucking chewing gum through a straw. Therefore the fuel has to be heated to a temperature of about 150°C to reduce its viscosity before injecting it through fuel pipes into the engine's cylinders. This is usually achieved by re-using the heat of the exhaust gases. In fact, two-stroke diesel engines are the most economical of all combustion engines reaching efficiencies of well above 50 percent. In comparison, modern car engines achieve only 30 to 40 percent efficiency.

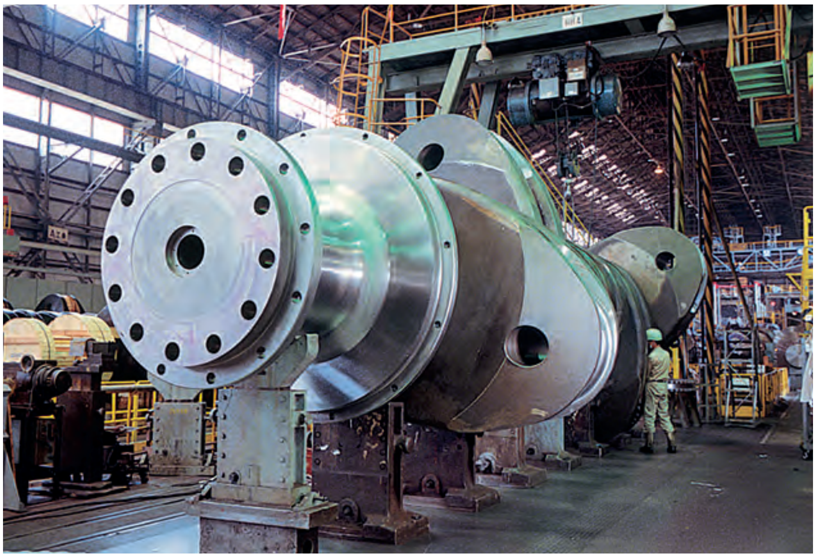
To operate at competitive costs, ships have to be in use as much as possible over the year. Time is money in the shipping world. This means dock times for maintenance have to be minimized. The reliability of large engine components is especially crucial in this respect. These components cannot be replaced due to their size once the engine is assembled in the ship and repair work is complicated as well as time-consuming. With a yearly ship operating time in the order of 8,000 hours (there are 8760 hours in a year) and a projected lifetime of 30–40 years the challenge in terms of reliability is extremely tough. Accordingly, the demands on the performance of iron and steel alloys used in marine engines are high. Only a few highly-specialized forges and foundries in the world are capable of fulfilling these performance demands.

Marine crankshafts turn around with moly
Much like a bicycle wheel rotates by pedaling, a crankshaft's basic role is to convert linear piston movement, delivered by the explosive power of combusted fuel in the cylinder, into rotation. While small and medium size crankshafts are manufactured in a single unit, large crankshafts are built up from several components. All parts are manufactured separately before the final steps of assembly and processing. A crankshaft may appear to be just an ordinary machinery component at first glance, but it isn't easy to actually produce one. Many hurdles must be overcome to produce high-quality crankshafts. The biggest crankshafts currently produced are as long as 27 meters and weigh as much →

as 400 tons. Running a ship at cruise speed, these huge pieces of steel rotate with over 100 revolutions per minute driving a propeller that has a diameter of up to 9 meters weighing more than 130 tons. This means crankshafts must be processed to a high degree of accuracy and must be exceptionally strong. Before a crankshaft ever rotates in the belly of a ship it will do so on an ultra-large sized lathe to be precisely machined into its final shape. From casting the alloy to the final machining takes as much as 6 months. Not only the size, but also the price of a large marine crankshaft is comparable to that of a comfortable family house.

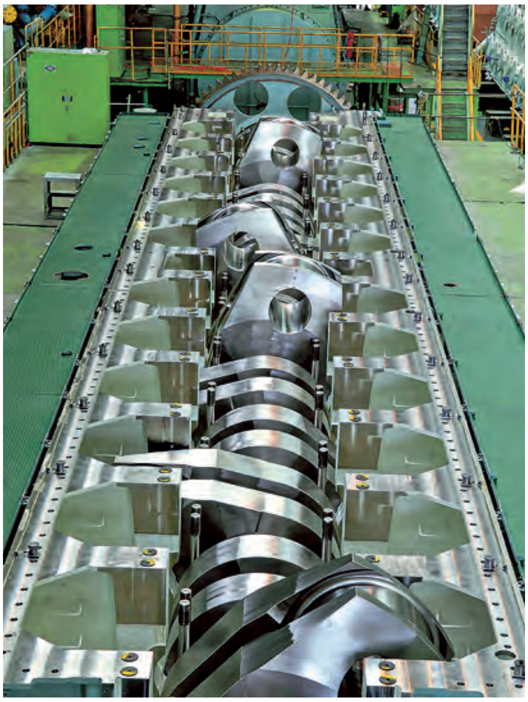
The strength of crankshaft components is determined by the alloy composition, by the manufacturing processes such as forging and casting as well as by subsequent heat treatments. Molybdenum is always present in such alloys as a key element that provides high strength and good toughness at the same time. It does this by controlling the hardenability and the microstructure of the alloy in a favorable way. Compared to other alloying elements such as nickel, chrome and manganese, molybdenum is very effective in relatively small amounts (Table 1).

Solid type crankshafts used for smaller marine engines are produced in one piece. An ingot is forged to a long round bar, which is then step machined on a turning lathe. Now it looks like a stack of thick and thin barrels. In a second forging process, the step-machined bar is partially heated and the three parts that will become crankpin and throws are formed sequentially in specific molds. It takes only about two minutes for one throw to be forged.



A large crankshaft being inspected after final assembly and machining. Photo: Kobe Steel

Larger crankshafts are assembled from individually manufactured throw, journal and crankpin components by shrink fitting. Cast steel throws can be produced faster than forged steel throws. This is an important consideration for the small handful of suppliers which struggle to meet the high demand for ship engines. However, cast throws of grade 3 and 4 (Table 2) have not been used in some types of engines, due to inadequate mechanical properties. The higher "grade 5" alloy developed in Japan has overcome these limitations, as its strength is significantly higher than that of forged steel throws, thanks to the increased molybdenum content. With typical alloy compositions, the largest marine crankshafts contain around one metric ton of molybdenum. (hm)



A crankshaft resting in the crankcase of a large diesel engine being assembled within a new ship. Photo: MAN Diesel & Turbo

Table 1: Typical alloy compositions (weight %) of steels for forged crankshaft components

	C	Si	Mn	Ni	Cr	Mo
34CrNiMo6	0.34	0.25	0.65	1.50	1.50	0.25
40CrMo8	0.40	0.25	1.00	–	2.00	0.25

Table 2: Typical alloy compositions (weight %) of throw casting grades

	C	Si	Mn	Ni	Cr	Others
Grade 3,4	0.24	0.07	1.05	0.40	0.35	Mo, V
Grade 5	0.18	0.10	1.00	1.65	0.35	Mo, V

Duplex 2205: The new choice for nuclear power piping

Nuclear power is experiencing a revival. Worldwide there are 64 new plants at various stages of startup, construction or planning. One of the reasons for this renaissance is their low carbon footprint. This trend could provide a new market opportunity for 2205 duplex stainless steel piping: Service water systems, which are an essential component of nuclear power plants.

A key factor in the safe operation of every nuclear power plant is the service water piping system. This complex system can consist of thousands of feet of pipe ranging from large to small diameter. Its function is to provide a dependable water supply for cooling plant equipment. Usually there is a non-safety-related operating part and a safety-related emergency part. The non-safety-related piping system must provide adequate cooling water for the normal heat removal of plant equipment. The safety-related system must, in the event of an emergency, supply sufficient water to bring the reactor under control and to shut it down safely. The piping material used in all of these systems has to resist corrosion by the cooling water over the lifetime of the plant.

Depending on the plant location, the cooling water can range from relatively clean fresh water to polluted seawater. Therefore, the amount of corrosion in piping material can vary widely. Experience has shown that, as systems age, a variety of corrosion-related problems can arise and, if not addressed, could jeopardize a system's integrity, inhibiting its ability to supply the required cooling water. The long-term performance of service water piping systems has ranged from "very good" to cases where entire systems have had to be replaced.

System materials and problems

When problems occur they typically relate to the specific piping material and its interaction with the cooling water at a given site. System fouling (blockage) and corrosion-associated leakage have been the most common problems. One or more of the following conditions usually causes fouling: sediment deposition, buildup of marine growth (bio fouling), buildup of corrosion products, and blockage by foreign objects. The leakage problems are often due to microbiologically influenced corrosion (MIC). MIC is a very aggressive form of corrosion caused by certain kinds of microbes in the water. This form of corrosion often attacks carbon steels and low-alloyed stainless steels. →

Inside diameter of carbon steel piping showing the fouling/bio-fouling typical of the problems encountered in service water piping.

Large diameter 2205 piping installed at the Catawba Nuclear Station.

Most plants operating in North America today were built with carbon steel piping, sometimes coated or lined with either cement or rubber. Reliability issues have necessitated constant surveillance and produced high maintenance costs. As a result, many plants have replaced, and continue with programs to replace, at least part of their carbon steel piping with more corrosion resistant materials. Improved materials are also now being considered to meet the 60-year or longer design life recommended for new nuclear plants.

Stainless steels have long been recognized as a viable option for building new service water piping systems and for the repair or replacement of existing carbon steel systems. Until recently, virtually all upgrades in stainless steel have used either Type 304L (UNS S30403), Type 316L (UNS S31603) or 6% Mo stainless steel (UNS N08367). Unfortunately, there is a large gap in performance and price between Type 316L and the 6% Mo grades. With aggressive untreated waters where MIC is a concern Types 304L and 316L are not viable options. Therefore, plants have had to either upgrade to a 6% Mo stainless steel or accept the high maintenance costs of a carbon steel system. In many cases utilities have chosen to stay with lined carbon steel piping due to the lower initial cost.

Field trials with 2205 duplex stainless

Duke Power Company's Catawba Nuclear Station in South Carolina, USA, is the first nuclear plant to specify and gain experience with 2205 (UNS S32205) duplex stainless steel in their system. This grade contains approximately 3.2% molybdenum for improved corrosion resistance and is much more resistant to MIC than 304L and 316L stainless steels. In a plant trial, the 2205 grade was used to replace the above ground portion of the piping that supplies the makeup water to the main condenser cooling towers. The original system had been made of lined carbon steel pipe.

The 2205 replacement pipe was installed in 2002. The project utilized 60 m of 76.2 and 91.4 cm diameter piping in a standard wall thickness of 0.375 inch (0.95 cm). The system was constructed in accordance with Code Case 153 for ASME B31.1, the Power Piping Code. This Code is part of the specifications governing the safe use of piping in power plants in the United States and it is widely used in other parts of the world.

Duplex stainless steel proves to be an excellent choice

A thorough inspection of the system took place after 500 days of service. The performance of the 2205 was very good, the inspection revealed no fouling or evidence of corrosion. The 2205 piping has continued to perform very well over the eight years since installation. As a result of this experience the Duke Power Company now has plans to use 2205 piping in other sections of their system.

With 2205 duplex stainless steel, designers of nuclear service water systems now have an additional option when choosing a corrosion resistant piping material for aggressive cooling waters. Success with this material will reduce maintenance costs, shutdown times and assure plant safety. (jf)

Inside diameter of the 2205 piping after 500 day service. Removal of surface stains revealed no corrosive attack at weld.

ASTM A 240 compositional ranges* (weight %) for stainless steels commonly used in service water piping systems

Name	UNS Number	C	N	Cr	Ni	Mo	Cu
304L	S30403	0.030	–	18.0–20.0	8.0–12.0	–	–
316L	S31603	0.030	–	16.0–18.0	10.0–14.0	2.0–3.0	–
6% Mo	N08367	0.030	0.18–0.25	20.0–22.0	23.5–25.5	6.0–7.0	0.75
2205	S32205	0.030	0.14–0.20	22.0–23.0	4.5–6.5	3.0–3.5	–

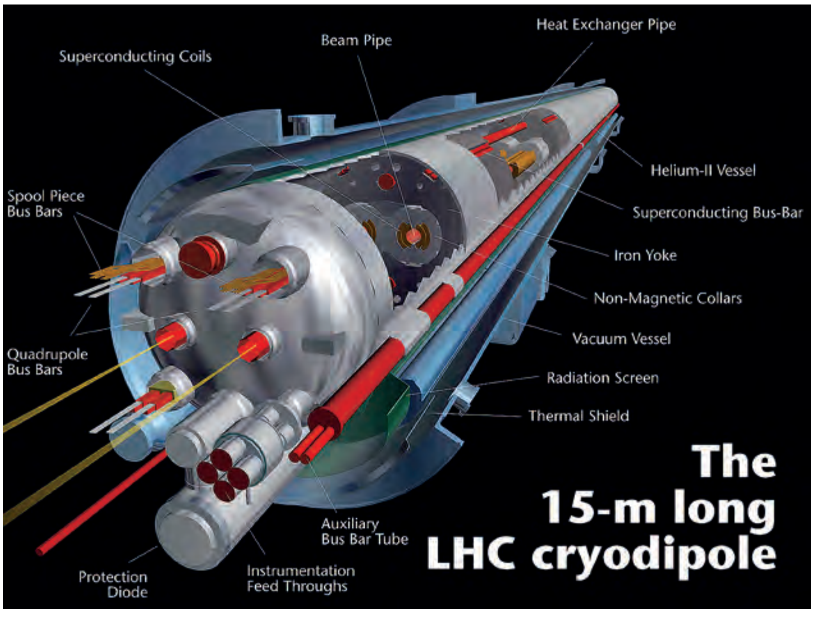
* maximum, unless range is indicated

Particles on collision course

Scientists are continually searching for new knowledge and an understanding of our Universe, and high-energy particle physicists are no exception. Their latest tool is the Large Hadron Collider located in Geneva, Switzerland. This machine uses two 27.4 km long Type 316LN stainless steel pipes to carry high-energy particles. This moly grade austenitic stainless steel was selected because it is non magnetic and it has excellent mechanical properties. After years of planning and construction the collider is now operating and scientists are evaluating initial results with high anticipation.

The science of high-energy particle physics has as its goal the discovery of the ultimate constituents of matter, and the understanding of their properties and the forces that hold them together. In other words, trying to find out what everything is made of and why. Over the last 100 years or so, beginning with the discovery of the electron in 1897, physicists have made great strides in fulfilling these goals. We now know that all matter is composed of atoms, made up of a very dense nucleus, containing protons and neutrons, surrounded by a cloud of fast-moving electrons. By using particle accelerators with ever-increasing energies, particle physicists have delved deeper and deeper into the structure of the protons and neutrons, as well as discovering a whole host of new, heavier sub-atomic particles. Over the last 30 years, a consistent model of all of the known particles has been constructed. This model says that all particles are either fundamental, such as the electron, or are composed of combinations of more basic constituents, called quarks. This so-called Standard Model of particle physics has been tremendously successful in explaining all the known particles and their properties. However, physicists are not sure that quarks are the ultimate constituents, and do not understand why there are six quarks, for example, and why these quarks have the properties that they do.

Schematic showing the parts of an LHC superconducting magnet and pipe assembly. Photo: LHC



Planning for a high-particle energy machine
There is clearly some underlying deep principle that is producing this pattern, but we don't know what this principle is. We do know that our present Standard Model is incomplete and actually breaks down at high energies. Many theories over the last 20 years have been proposed to expand the Standard Model and explain the patterns that we see. Almost all of these theories predict the existence of much heavier, so far undiscovered, particles. So the goal of experimental particle physicists is to build a particle accelerator with energy high enough to possibly produce these new particles and thus better understand the patterns that we see.

The basic unit of energy for accelerators is called the electron-volt. This is the energy an electron or proton would gain by being accelerated through an electric potential of 1 volt. Early accelerators, such as the cyclotron, could accelerate protons up to a few million electron-volts (MeV). By the 1960's, so-called synchrotron accelerators were able to reach 30 billion electron-volts (GeV), and 400 GeV by the 1970's. All of these machines accelerated protons to their highest possible energy and then extracted them from the accelerator, where the protons then hit a target, about which the experimental apparatus was built. However, starting in the 1970's a new type of accelerator began to become the norm – a colliding-beam machine. In these accelerators, counter-rotating beams of particles would stay in the accelerator and continuously collide head on with each other, with the experiments built around these collision points. This made for a much more violent and higher-energy collision. The current highest-energy colliding beam accelerator is the Tevatron at Fermilab outside Chicago, which has a center-of-mass energy of 2 trillion electron-volts (TeV). While many discoveries have been made with the Tevatron, no deviation from the Standard Model has been found. Most theories predict that the new, as-yet undiscovered particles, will have masses too large for the Tevatron to produce. So for the last 20 years or so, plans have been made to build an even higher-energy accelerator.

The completed machine
These plans have finally reached fruition with the completion of the Large Hadron Collider (LHC) at the European accelerator center CERN, located just outside Geneva, Switzerland. The LHC is a 14 TeV proton-proton colliding-beam accelerator, seven times higher in energy than the Fermilab machine. →

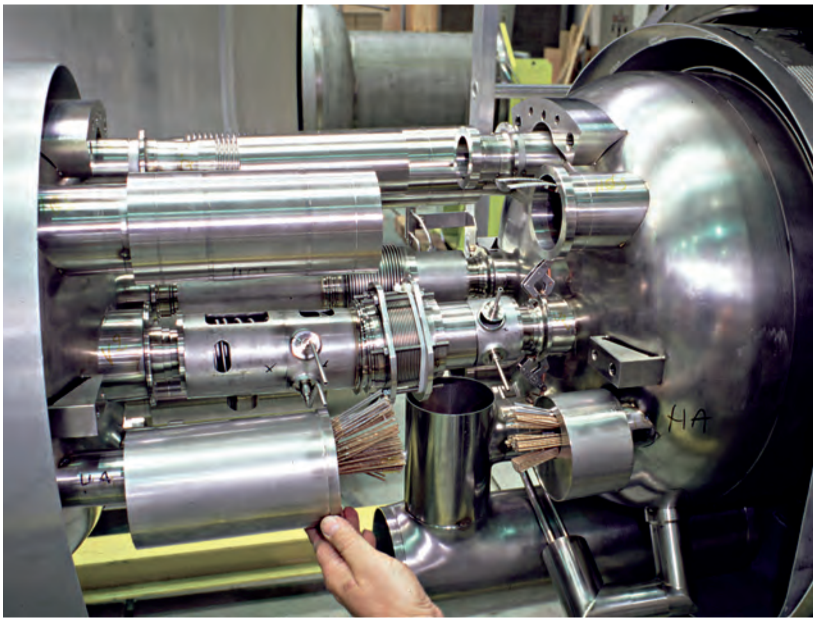
The LHC tunnel showing the line of blue superconducting magnets which are the major components of the LHC. The curve of the tunnel can be seen in the distance. Photo: LHC

The LHC is housed in a 3.7 m diameter circular tunnel, 27.4 km in circumference and 91 m underground. Inside the tunnel, the accelerator is composed of 1232 superconducting dipole magnets that bend the counter-rotating beams of protons around in a circular path. The magnets are each 14.7 m long and are cooled to 1.9 K using liquid helium to make the niobium-titanium wire in them superconducting. A current of 12,000 amps is then put through the wires, producing a very large magnetic field of 8.33 tesla. This cooling required the construction of the largest liquid helium cryogenic system in the world. The two beams of protons travel in opposite directions through the magnets in separate vacuum pipes and collide at four points around the ring where the experiments are located.

The LHC vacuum pipes are made by welding together 15.6 m lengths of seamless Type 316LN stainless steel tubing. The tubes are 53 mm in diameter, with a wall thickness of 1.5 mm. The pressure in the pipes must be reduced to an ultra-high-vacuum value similar to that in the near-vacuum atmosphere 1,000 km above the Earth, so that the beams of protons rarely scatter off any remaining air molecules in the pipes and get ejected from the accelerator. The vacuum pipes are surrounded by the liquid helium used to cool the magnets and thus are also at 1.9° K in temperature.

Why use Type 316LN?

The Type 316LN is an austenitic, chromium-nickel stainless steel, containing 2–3% of molybdenum. The “L” stands for low carbon (less than 0.03%), and the “N” means the steel is strengthened by nitrogen addition (0.13%). This type of stainless steel is corrosion resistant, with excellent welding characteristics, good properties at cryogenic temperatures, and a high tensile strength. Crucial to its use in the LHC is the fact that this type of stainless steel also has a very low magnetic permeability (is non-magnetic), even after welding. If this weren’t true, the pipe would feel large magnetic forces from the magnets, and induced magnetism in the pipe material could also ruin the uniformity of the magnetic field, with dire consequences for the operation of the accelerator. In other words, no other construction material has the unique set of properties needed for this demanding application at a reasonable cost.



Joint between two LHC superconducting magnets showing the stainless steel pipe connections and other components. Photo: LHC

First experience and results

The final LHC magnet was installed in the tunnel in April 2007, and the entire accelerator was cooled to liquid-helium temperatures by June 2008. The first tests with beam started in September 2008 and initial progress was very good. However, on September 19, 2008 when testing the magnets at 8,000 amps, a short circuit developed in one of the interconnections between magnets, which caused an electrical arc that blew a hole in the liquid helium line. The rapid expansion of gas destroyed several magnets. It took over a year to understand the accident, repair the damage and install improved protection. In November 2009, the accelerator started operation again and this time was successful in colliding beams at a total energy of 2.36 TeV, the highest energy ever reached. In March of this year, the accelerator’s energy was raised to 7 TeV, a factor of 3½ higher than the Tevatron, and the four experiments began a two-year program to record data at this energy.

With the LHC beginning to run smoothly, thanks in part to the excellent properties of the molybdenum-bearing stainless steel beam pipes, there is much excitement and hope in the particle physics community that we will soon have a better understanding of the most fundamental particles in nature. (tf)

Seminar on Mo in steels held in Beijing

The "International Seminar on Applications of Mo in Steels" was held in Beijing at the end of June 2010. Leading researchers from Chinese steel companies, universities and research laboratories attended. This important event was co-sponsored by IMOA and hosted by the Central Iron and Steel Research Institute (CISRI), a number of highly respected experts delivered papers on performance and significant advantages of using Mo in steels.

Professor Han Dong, Vice-President of the Central Iron and Steel Research Institute, told delegates: "Continuous large production of steels has burdened our society by causing resource shortages, energy consumption and environmental pollution. To solve the problems, high performance steels are increasingly demanded since the life span of steel components can be extended, and steel consumption can be reduced, if higher performance steels are used instead." He added that a key element in improving the performance of steel under high stress, high or low temperatures and severe corrosion risk was to alloy it with molybdenum, which played a "multi-functional role."

Professor Zhiyong Yang, Deputy Director of the Institute for Structural Materials at CISRI, told delegates that molybdenum improved corrosion resistance in austenitic and ferritic stainless steels, an effect that became more evident with a higher Mo content. In high strength stainless steels, molybdenum plays a more important role in improving strength than it does in corrosion resistance.

Prof. Dong Han of CISRI welcomed the more than 150 participants.

Molybdenum is typically alloyed to high strength low alloy (HSLA) steels when mechanical properties of the highest level are demanded. For instance in the oil and gas, automotive and construction industry as more performance with less steel is the goal.

Professor Dr Hardy Mohrbacher told delegates: "Increasing attention is being paid to the economic advantages that high-strength low alloy steels have to offer. These advantages include lower cost structural components, increased resistance to brittle failure, economies during construction and transportation as a result of lower cost in handling lighter sections, fewer man-hours of welding and lower electrode consumption as a result of lighter sections."

Dr George Krauss, Emeritus Professor at the Colorado School of Mines in the USA, said that molybdenum was an extremely important alloying element in low-alloy steels that were heat treated to excellent combinations of high strength, fatigue resistance, fracture resistance and wear resistance. He said: "Applications of Mo-containing bar and forging steels include parts such as gears, bearings, shafts, oil country tubulars, fasteners, aircraft landing gear and tools. The Mo combines with steel carbon content and other alloying elements to enhance hardenability and properties of microstructures produced by quenching and tempering heat treatments."

The seminar was held at the Beijing Friendship Hotel on 27 & 28 June and was sponsored by: IMOA; Beijing Antaike; Jinduicheng Molybdenum Co Ltd; China Molybdenum Co Ltd; Jinzhou New China Dragon Molybdenum Co Ltd and CoMoTech, Chile.

The proceedings of the seminar and all papers are available to download, free of charge, in English and Chinese at www.imoa.info and www.nercast.com (website of the National Engineering Research Center of Advanced Steel Technology in China).

IMOA rated highly effective by members

External consultants recently conducted a membership survey, consisting of a number of in-depth telephone interviews and a membership-wide web-based questionnaire, on behalf of IMOA. The survey revealed that, in the opinion of members, IMOA is regarded as a highly effective and credible trade association. Eighty-three percent rated us as good or above at providing an effective voice with regard to future regulatory legislation, 90% at promoting the use of molybdenum and 91% at raising the profile of molybdenum and its applications. The survey also provided invaluable feedback for the future direction and activities of the Association. We would like to thank all those members who participated.