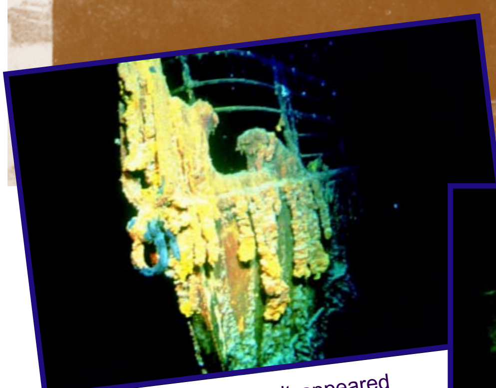
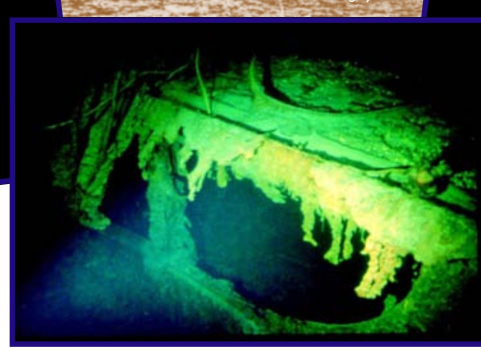
The Royal Mail Ship *Titanic:* Did a Metallurgical Failure Cause a Night to Remember?

Katherine Felkins, H.P. Leighly, Jr., and A. Jankovic

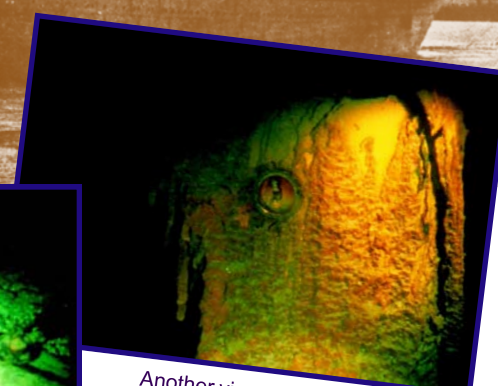
The *Titanic*. (Photo courtesy of the Titanic Historical Society.)



The bow of the ship as it appeared during a 1986 expedition. (Photo courtesy of Woods Hole Oceanographic Institution.)



The ship during a 1986 expedition. (Photo courtesy of Woods Hole Oceanographic Institution.)



Another view of the *Titanic* during a 1986 expedition. (Photo courtesy of Woods Hole Oceanographic Institution.)

A metallurgical analysis of steel taken from the hull of the Titanic's *wreckage reveals that it had a high ductile-brittle transition temperature, making it unsuitable for service at low temperatures; at the time of the collision, the temperature of the sea water was –2°C. The analysis also shows, however, that the steel used was probably the best plain carbon ship plate available at the time of the ship's construction.*

Editor's Note: A hypertext-enhanced version of this article can be found on the TMS web site at http://www.tms.org/pubs/journals/JOM/9801/Felkins-9801.html.

INTRODUCTION

In the early part of this century, the only means of transportation for travelers and mail between Europe and North America was by passenger steamship. By 1907, the Cunard Steamship Company introduced the largest and fastest steamers in the North Atlantic service: the *Lusitania* and the *Mauritania*. Each had a gross tonnage of 31,000 tons and a maximum speed of 26 knots. In that year, Lord William James Pirrie, managing director and controlling chair of the Irish shipbuilding company Harland and Wolff, met with J. Bruce Ismay, managing director of the Oceanic Steam Navigation Company, better known as the White Star Line (a name taken from its pennant). During this meeting, plans were made to construct three enormous new White Star liners to compete with the *Lusitania* and *Mauritania* on the North Atlantic by establishing a three-ship weekly steamship service for passengers and mail between Southampton, England, and New York City. This decision required the construction of a trio of luxurious steamships. The first two built were the RMS *Olympic* and the RMS *Titanic*; a third ship, the RMS *Britannic*, was built later (the fate of the sister ships is described in

Over the last 30 years, there has been a discernible increase in the number of scholars who have focused their research on early industrial organizations, a field of study that has come to be known as **Archaeotechnology**. Archaeologists have conducted fieldwork geared to the study of ancient technologies in a cultural context and have drawn on the laboratory analyses developed by materials scientists as one portion of their interpretive program. Papers for this bimonthly department are solicited and reviewed by **Robert M. Ehrenreich** of the National Materials Advisory Board of the National Research Council.

the sidebar).

The *Titanic* began its maiden voyage to New York just before noon on April 10, 1912, from Southampton, England. Two days later at 11:40 P.M., Greenland time, it struck an iceberg that was three to six times larger than its own mass, damaging the hull so that the six forward compartments were ruptured. The flooding of these compartments was sufficient to cause the ship to sink within two hours and 40 minutes, with a loss of more than 1,500 lives. The scope of the tragedy, coupled with a detailed historical record, have fueled endless fascination with the ship and debate over the reasons as to why it did in fact sink. A frequently cited culprit is the quality of the steel used in the shipÕs construction. A metallurgical analysis of hull steel recovered from the shipÕs wreckage provides a clearer view of the issue.

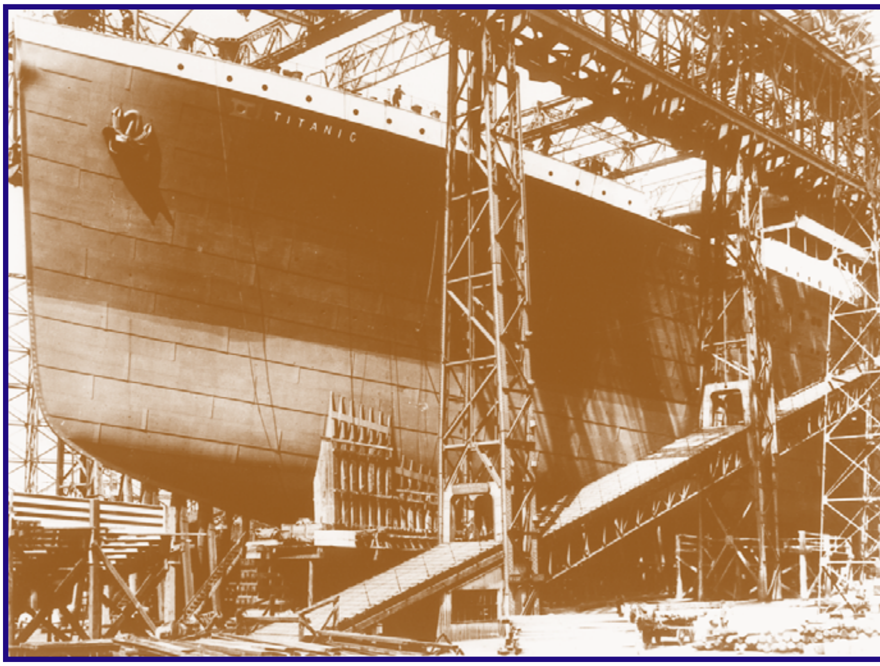


Figure 1. The *Titanic* under construction at the Harland and Wolff shipyard in Ireland. (Photo courtesy of the Titanic Historical Society.)

THE CONSTRUCTION

The three White Star Line steamships were 269.1 meters long, 28.2 meters maximum wide, and 18 meters tall from the water line to the boat deck (or 53 meters from the keel to the top of the funnels), with a gross weight of 46,000 tons. Because of the size of these ships, much of the Harland and Wolff shipyard in Belfast, Ireland, had to be rebuilt before construction could begin; two larger ways were built in the space originally occupied by three smaller ways. A new gantry system with a larger load-carrying capacity was designed and installed to facilitate the construction of the larger ships. The *Titanic* under construction at the shipyard is shown in Figure 1.

The ships were designed to provide accommodations superior to the Cunard ships, but without greater speed. The first onboard swimming pools were installed as was a gymnasium that included an electric horse and an electric camel, a squash court, a number of rowing machines, and stationary bicycles, all supervised by a staff of professional instructors. The public rooms for the first-class passengers were large and elegantly furnished with wood paneling, stained-glass windows, comfortable lounge furniture, and expensive carpets. The decor of the first class cabins, in addition to being luxurious, differed in style from cabin to cabin. As an extra feature on the *Titanic*, the CafŽ Parisienne offered superb cuisine.

The designed speed for these ships was 21–22 knots, in contrast to the faster Cunard ships. To achieve this speed, each ship had three propellers; each outboard propeller was driven by a separate four-cylinder, triple expansion, reciprocating steam engine.[2] The center propeller was driven by a low-pressure steam turbine using the exhaust steam from the two reciprocating engines. The power plant was rated at 51,000 I.H.P. To provide the necessary steam for the power plant, 29 boilers were available, fired by 159 furnaces. In addition to propelling the ship, steam was used to generate electricity for various purposes, distill fresh water, refrigerate the perishable food, cook, and heat the living space. Coal was burned as fuel at a rate of 650 tons per day when the ship was underway. Stokers moved the coal from the bunkers into the furnaces by hand. The bunkers held enough coal for a ten-day voyage.

The remodeled shipyard at Harland and Wolff was large enough for the construction of two large ships simultaneously. The keel of the *Olympic* was laid December 16, 1908, while the *Titanic's* keel followed on March 31, 1909. The *Olympic* was launched on October 20, 1910, and the *Titanic* on May 31, 1911. In the early 20th century, ships were constructed using wrought-iron rivets to attach steel plates to each other or to a steel frame. The frame itself was held together by similar rivets. Holes were punched at appropriate sites in the steel-frame members and plates for the insertion of the rivets. Each rivet was heated well into the austenite temperature region, inserted in the mated holes of the respective plates or frame members, and hydraulically squeezed to fill the holes and form a head. Three million rivets were used in the construction of the ship.

The construction of the *Titanic* was delayed due to an accident involving the *Olympic*. During its fifth voyage,[3] the *Olympic* collided with the British cruiser, HMS *Hawke*, damaging its hull near the bow on the port (left) side. This occurred in the Solent off Southampton on September 20, 1911. The *Olympic* was forced to return to Belfast for repairs. To accomplish the repairs in record time and to return the ship to service promptly, workmen were diverted from the *Titanic* to repair the *Olympic*.

On April 2, 1912, the *Titanic* left Belfast for Southampton and its sea trials in the Irish Sea. After two days at sea, the *Titanic*, with its crew and officers, arrived at Southampton and tied up to Ocean Dock on April 4. During the next several days, the ship was provisioned and prepared for its maiden voyage.

THE LIVES OF THE SISTER SHIPS

The RMS *Olympic* made more than 500 round trips between Southampton and New York before it was retired in 1935 and was finally broken up in 1937. In 1919, it became the first large ship to be converted from coal to oil. On May 15, 1934, as the *Olympic* approached New York, it struck the Nantucket light ship during a heavy fog, cutting it in half. Of the crew, four were drowned, three were fatally injured, and three were rescued.[1]

The third ship of the series, the *Britannic*, had a short life. While it was being constructed, the *Titanic* was sunk. Immediately, the design was changed to provide a double hull and the bulkheads were extended to the upper deck. Before the *Britannic* was completed, World War I broke out, and the vessel was converted into a hospital ship. On November 21, 1916, it was proceeding north through the Aegean Sea east of Greece when it struck a mine. Because the weather had been warm, many of the portholes had been opened, hence rapid flooding of the ship occurred. The ship sank in 50 minutes with a small loss of life; one of the loaded life boats was drawn into a rotating propeller.

Table I. A Summary of Damaged Areas in the Hull by Compartment*[6]

Compartment	Computer Calculations (m^2)
Fore Peak	0.056
Cargo Hold 1	0.139
Cargo Hold 2	0.288
Cargo Hold 3	0.307
Boiler Room 6	0.260
Boiler Room 5	0.121
Total Area	1.171

* The compartments are listed in order from the bow toward the stern.

THE VOYAGE

On the morning of April 10, 1912, the passengers and remaining crew members came to Ocean Dock to board the ship for its maiden voyage. Shortly before noon, the *Titanic* cast off and narrowly avoided colliding with a docked passenger ship, the *New York* (which broke its mooring cables due to the surge of water as the huge ship passed), before proceeding down Southampton Water into the Solent and then into the English Channel. After a stop at Cherbourg, France, on the evening of April 10th and a second stop at Queenstown (now Cobh), Ireland, the next morning to take on more passengers and mail, the *Titanic* headed west on the Great Circle Route toward the Nantucket light ship 68 kilometers south of Nantucket Island off the southeast coast of Massachusetts. The Irish coast was left behind about dusk on April 11.

During the early afternoon of April 12, the French liner, *La Touraine*, sent advice by radio of ice in the steamship lanes, but this was not uncommon during an April crossing. This advice was sent nearly 60 hours before the fatal collision. As the voyage continued, the warnings of ice received by radio from other ships became more frequent. With time, these warnings gave more accurate information on the location of the icefields and it became apparent that a very large icefield lay in the shipÕs course. On the basis of several reports after the accident, it was estimated that the icefield was 120 km long on a northeast-southwest axis and 20 km wide;[4] there is evidence that the *Titanic* was twice diverted to the south in a vain effort to avoid the fields. The ship continued at a speed of about 21.5 knots.

On the moonless night of April 14, the ocean was very calm and still. At 11:40 P.M., Greenland time, the lookouts in the crowÕs nest sighted an iceberg immediately ahead of the ship; the bridge was alerted. The duty officer ordered the ship hard to port and the engines reversed. In about 40 seconds, as the *Titanic* was beginning to respond to the change in course, it collided with an iceberg estimated to have a gross weight of 150,000–300,000 tons. The iceberg struck the *Titanic* near the bow on the starboard (right) side about 4 m above the keel. During the next 10 seconds, the iceberg raked the starboard side of the shipÕs hull for about 100 m, damaging the hull plates and popping rivets, thus opening the first six of the 16 watertight compartments formed by the transverse bulkheads. Inspection shortly after the collision by captain Edward Smith and Thomas Andrews, a managing director and chief designer for Harland and Wolff and chief designer of the *Titanic*, revealed that the ship had been fatally damaged and could not survive long. At 2:20 A.M., April 15, 1912, the *Titanic* sank with the loss of more than 1,500 lives.

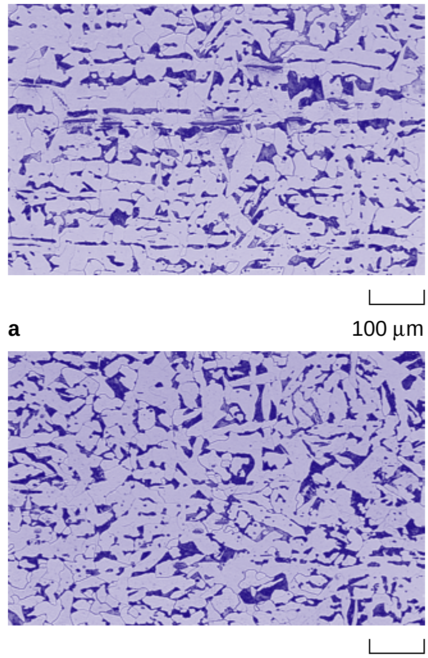


Figure 2. An optical micrograph of steel for the hull of the *Titanic* in (a) longitudinal and (b) transverse directions, showing banding that resulted in elongated pearlite colonies and MnS particles. Etchant is 2% Nital.

THE SINKING

Initial studies of the sinking proposed that a continuous gash in the hull 100 m in length was created by the impact with the iceberg. More recent studies indicate that discontinuous damage occurred along the 100 m length of the hull. After the sinking, Edward Wilding, design engineer for Harland and Wolff, estimated that the collision had created openings in the hull totaling 1.115 m^2, based on the reports of the rate of flooding given by the survivors.[5] This damage to the hull was sufficient to cause the ship to sink. Recent computer calculations by Hackett and Bedford[6] using the same survivorsÕ information, but allocating the damage individually to the first six compartments that were breached is given in Table I. This shows a total damage area of 1.171 m^2, which is a slightly larger area than the estimate by Wilding.

At the time of the accident, there was disagreement among the survivors as to whether the *Titanic* broke into two parts as it sank or whether it sank intact. On September 1, 1985, Robert Ballard[5] found the *Titanic* in 3,700 m of water on the ocean floor. The ship had broken into two major sections, which are about 600 m apart. Between these two sections is a debris field containing broken pieces of steel hull and bulkhead plates, rivets that had been pulled out, dining-room cutlery and chinaware, cabin and deck furniture, and other debris.

The only items to survive at the site are those made of metals or ceramics. All items made from organic materials have long since been consumed by scavengers, except for items made from leather such as shoes, suitcases, and mail sacks; tanning made leather unpalatable for the scavengers. The contents of the leather suitcases and mail sacks, having been protected, have been retrieved and restored. Ethical and legal issues associated with the recovery of such items are described in the sidebar authored by C.R. McGill.

THE STEEL

Composition

During an expedition to the wreckage in the North Atlantic on August 15, 1996, researchers brought back steel from the hull of the ship for metallurgical analysis. After the steel was received at the University of Missouri–Rolla, the first step was to determine its composition. The chemical analysis of the steel from

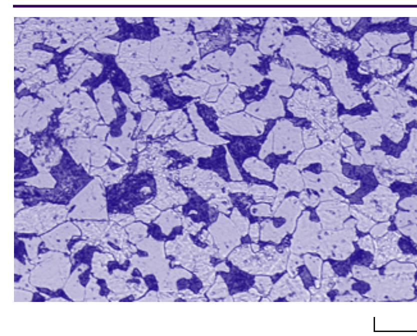


Figure 3. The microstructure of ASTM A36 steel showing ferrite and pearlite. The mean grain diameter is 26.173 µm. Etchant is 2% Nital.

Table II. The Composition of Steels from the *Titanic*, a Lock Gate, and ASTM A36 Steel

	C	Mn	P	S	Si	Cu	O	N	Mn:S Ratio
Titanic Hull Plate	0.21	0.47	0.045	0.069	0.017	0.024	0.013	0.0035	6.8:1
Lock Gate*	0.25	0.52	0.01	0.03	0.02	Ñ	0.018	0.0035	17.3:1
ASTM A36	0.20	0.55	0.012	0.037	0.007	0.01	0.079	0.0032	14.9:1

* Steel from a lock gate at the Chittenden ship lock between Lake Washington and Puget Sound, Seattle, Washington.

the hull is given in Table II. The first item noted is the very low nitrogen content. This indicates that the steel was not made by the Bessemer process; such steel would have a high nitrogen content that would have made it very brittle, particularly at low temperatures. In the early 20th century, the only other method for making structural steel was the open-hearth process. The fairly high oxygen and low silicon content means that the steel has only been partially deoxidized, yielding a semikilled steel. The phosphorus content is slightly higher than normal, while the sulfur content is quite high, accompanied by a low manganese content. This yielded a Mn:S ratio of 6.8:1Ñ a very low ratio by modern standards. The presence of relatively high amounts of phosphorous, oxygen, and sulfur has a tendency to embrittle the steel at low temperatures.

Davies[7] has shown that at the time the *Titanic* was constructed about two-thirds of the open-hearth steel produced in the United Kingdom was done in furnaces having acid linings. There is a high prob-

THE *TITANIC* IN THE ARTS

Since its tragic voyage in 1912, the RMS *Titanic* has captured the attention and the imagination of the world. The shocking, untimely death of more than 1,500 people, the irony of the "unsinkable" ship doing the unthinkable on its maiden voyage, and the first-hand accounts of the approximately 700 survivors have spurred countless debates and discussions on the reasons for the ship's demise. As the debate continues in scientific, historical, and even legal circles, the ship, her crew, and passengers have been memorialized time and again through the arts.

Numerous accounts of the ship and her sisters, the *Olympic* and *Britannic*, have been published during the past 80 years; some have been factual, others fictionalized adaptations. One of the first non-newspaper accounts, and one of the most popular, is the book *A Night to Remember*, written by Walter Lord in 1955. According to Lord, in the four decades following the sinking there was no worldwide general interest in the ship and no historical accounts of the voyage. Based on historical materials and first-hand accounts of survivors and witnesses, *A Night to Remember* is reportedly the first book to give a factual account of the night the ship sank. A nearly countless number of books have followed.

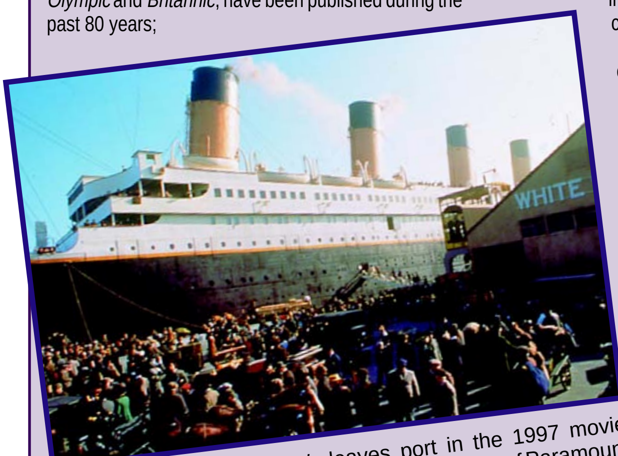


Figure A. The RMS *Titanic* leaves port in the 1997 movie *Titanic*. (Photo by Merie W. Wallace and courtesy of Paramount Pictures and Twentieth Century Fox.)

On film, the *Titanic* has been the subject for a number of docudramas and early disaster films. One of the first was *Titanic*, done in 1926. About 16 years later, Herbert Selpin directed a German film on the subject. Arguably the most well-known film on the *Titanic* is the same-titled film directed by Jean Negulesco in 1953. A fictionalized account of one family on the *Titanic*, the film won two Academy Awards that year for Best Art Direction and Best Original Screenplay. The movie, starring Barbara Stanwyck and Clifton Webb, set the standard for early disaster films in the United States. On the other side of the Atlantic, English filmmakers adapted Lord's *A Night to Remember* into a film of the same name in 1958. Unlike the romanticized U.S. version, producer William MacQuitty and director Eric Ambler created a gritty, realistic docudrama using state-of-the-art special effects. For one of the first times in filmmaking, the actors worked on sets that were tilted by hydraulic jacks, creating loud, grinding noises that imitated the sounds the ship would have made in sinking.

When Robert Ballard and an American-French search team discovered the site of the *Titanic* in 1985, interest in the ship and her history resurged. Images of the ship on the sea floor taken by underwater robots more than 70 years after the disaster brought the *Titanic* and its saga back into international pop culture. Today, there are videos, CD-ROMs, and even computer games available that allow users to become a passenger on the ship. The emergence of the Internet has enabled people from around the world to access a wealth of photographs, animated film clips, sound clips, and historical information on the subject or join groups composed of other *Titanic* enthusiasts.

Plays on the *Titanic* appear everywhere from dinner theaters throughout the United States to the Great White Way—Broadway. In 1997, the Broadway musical *Titanic* won a Tony Award for the Best Musical, released a top-selling cast album, and, on the average, surpassed ticket sales for any show on Broadway.

The most recent addition to the collection is *Titanic*, a 1997 film by Twentieth Century Fox and Paramount Pictures that focuses on the love story of two young passengers. Released on December 19, the film reportedly became the most expensive film ever made ($200 million according to some reports) in its attempt to be as historically accurate as possible. To assist the production crew, a group of historians and experts on the *Titanic* were brought aboard as consultants, including Don Lynch, the historian for the Titanic Historical Society, and Ken Marschall, noted artist of the ship. Shipbuilders Harland and Wolff provided copies of the original blueprints of the *Titantic* and Thomas Andrews' own notebook on the ship's design features to the production crew. In addition, the manufacturer of the original carpeting, which is still in business, had the original patterns on file and reproduced the dyes.

To make the ship as authentic as possible, director James Cameron chartered a Russian scientific vessel and made 12 dives to the actual wreck site to film the interior of the ship. Using an off-the-shelf 35 mm camera modified to fit in custom-made titanium housings, the camera brought back reels of film showing the ship's interior—everything from window frames, light fixtures, a brass door plate, and even a bronze fireplace box. "We were able to come back with this rich harvest of film and video images," Cameron said. 'We sent our remote vehicle inside and explored the interiors. We literally saw things that no one has seen since 1912, since the ship went down. We've integrated these images into the fabric of the film and that reality has a profound impact on the emotional power of the film."

The complete set was built at Fox Baja Studios in Mexico beginning on May 30, 1996; it was completed 100 days later. The set featured a 64.2 million liter exterior seawater tank (the largest shooting tank in the world). Whereas the 1953 movie used a 8.5 m model of the ship, the 1997 movie recreated a nearly full size, 236 m long exterior set of the *Titanic* standing nearly 14 m tall from the water line to the boat deck floor, with its four funnels towering another 16 m.

To recreate the sinking of the ship, several exterior and interior shooting tanks were used. (A still from the movie appears on the cover of this issue.) The first-class dining saloon and three-story grand staircase were constructed on a hydraulic platform at the bottom of the 9 m interior tank designed to be angled and flooded with 19 million liters of filtered seawater drawn from the ocean. Camera cranes and jacks were placed above the ship for the final filming stages, when the ship was separated into two pieces. The front half was sunk in 12 m of water using hydraulics.

Preliminary reviews of the movie at the time this issue goes to press in early December (prior to the movie's release) have been very good, and the movie has already made several top ten lists for 1997, including one by *Rolling Stone* magazine. *The Hollywood Reporter* says, "*Titanic's* visual and special effects transcend state-of-the-art workmanship . . . Pencil [Gloria] Stuart in for a likely best supporting actress nomination this winter. Also on the Oscar front, clear the deck for multiple technical nominations. . . . The iron monster is a heart stopper."

It is doubtful that the *Titanic* will be the last film made about this ill-fated ship. Through the years, the saga of the *Titanic* has taken on a life of its own. As songs, poems, historical accounts, and novels continue to be created, the story has merged into modern urban folklore.

"The tragedy of the *Titanic* has assumed an almost mythic quality in our collective imagination," Cameron said. "*Titanic* is not just a cautionary tale—a myth, a parable, a metaphor for the ills of mankind. It is also a story of faith, courage, sacrifice, and above all else, love."

Tammy M. Beazley
JOM

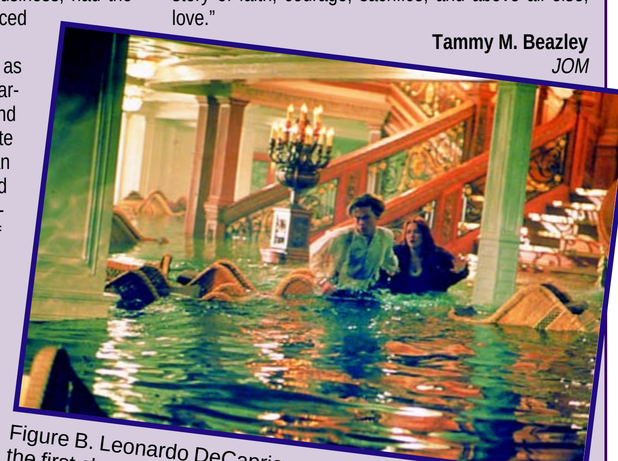
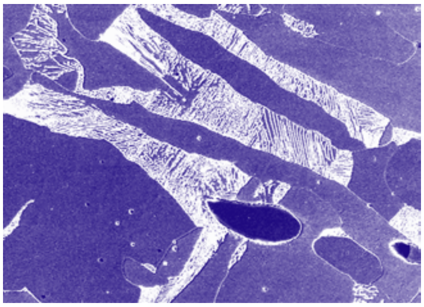


Figure B. Leonardo DeCaprio and Kate Winslet wade through the first class dining saloon in a scene from *Titanic*. (Photo by Merie W. Wallace and courtesy of Paramount Pictures and Twentieth Century Fox.)



10 μm

Figure 4. A scanning electron micrograph of the etched surface of the *Titanic* hull steel showing pearlite colonies, ferrite grains, an elongated MnS particle, and nonmetallic inclusions. Etchant is 2% Nital.

ability that the steel used in the *Titanic* was made in an acid-lined open-hearth furnace, which accounts for the fairly high phosphorus and high sulfur content. The lining of the basic open-hearth furnace will react with phosphorus and sulfur to help remove these two impuri-

Table III. A Comparison of Tensile Testing of *Titanic* Steel and SAE 1020

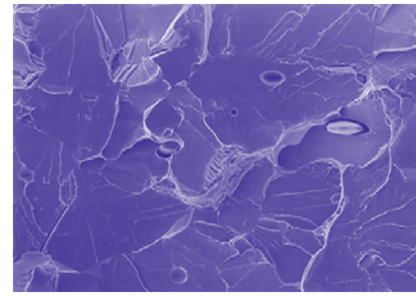
	Titanic	SAE 1020[11]
Yield Strength	193.1 MPa	206.9 MPa
Tensile Strength	417.1 MPa	379.2 MPa
Elongation	29%	26%
Reduction in Area	57.1%	50%

ties from the steel. It is likely that all or most of the steel came from Glasgow, Scotland.

Included in Table II are the compositions of two other steels: steel used to construct lock gates at the Chittenden Ship Lock between Lake Washington and Puget Sound at Seattle, Washington,[8] and the composition of a modern steel, ASTM A36. The ship lock was built around 1912, making the steel about the same age as the steel from the *Titanic.*

Metallography

Standard metallographic techniques were used to prepare specimens taken from the hull plate of the *Titanic* for optical microscopic examination. After



20 μm

Figure 5. A scanning electron micrograph of a Charpy impact fracture surface newly created at 0°C, showing cleavage planes containing ledges and protruding MnS particles.

grinding and polishing, etching was done with 2% Nital. Because earlier work by Brigham and Lafreni•re[9] showed severe banding in a specimen of the steel, specimens were cut from the hull plate in both the transverse and longitudinal directions. Figure 2 shows the microstructure of the steel. In both micrographs, it is

THE ETHICAL AND LEGAL ISSUES IN SALVAGING THE *TITANIC*

Author's Note: The author thanks Michael McCaughan of the Ulster Folk and Transport Museum, Northern Ireland, for his assistance in the preparation of this sidebar.

The *Titanic* has engaged the attention of a rapt world audience for almost a century now. As the most famous and historic of all shipwrecks, it is enshrouded in a cloak of mystery and controversy; the traumatic effect that the loss of the ship had on the public at the time of the disaster has not abated, making the *Titanic* seem almost eternal.

Numerous plans to salvage the ship and its cargo were developed over the 73 years that the *Titanic* lay undiscovered 4 km below the ocean surface. It was not until 1985 that salvage became feasible, when Robert Ballard of the Oceanographic Institute in Woods Hole, Massachusetts, discovered the ship's exact location as part of a joint American-French research team.

Serious issues were immediately raised over the controversial question of salvage rights, the main issue being that the wreck lay in international waters; there is no legal protection in international waters for wrecks of historical or archaeological significance. In such cases, wrecks are subject to salvage law, which stipulates that the first salvor on the site has exclusive rights to the site. Thus, other salvors are prevented from accessing the site as long as expeditions are being planned and conducted to recover artifacts from the wreck.

Robert Ballard could not legally claim salvage rights to the wreck, since he discovered it while working on a government research project. The French Oceanography Institute, which was the French component of the joint American-French research team and had received little acknowledgement for its contribution in the discovery of the wreck, had no such constraints, however. It was soon involved in the formation of the commercial salvage company that was to become RMS Titanic, Inc.

More than 1,500 people—rich and poor, representing more than 20 countries—perished in the disaster. The ship had broken into two separate parts, with the stern section lying about 804.5 m beyond the bow portion. A huge field of debris covers the ocean floor between the two pieces. RMS Titanic, Inc., stated early on that they only intended to record the site; recover, conserve, preserve, and tour just those artifacts recovered from the debris field; and keep the collection together rather than sell it to individual buyers around the world. The culmination of the project would be a Titanic Memorial Museum in which all of the artifacts recovered would be kept. (It should be noted, however, that RMS Titanic, Inc., has recently made available for sale to the general public authenticated coal from the sea bed.)

Reaction was strong and immediate. Individuals and organizations from around the world vehemently opposed the idea of salvage work being done on the *Titanic,* claiming that the wreck was a grave site and should be left undisturbed as a memorial to those who died. Such organizations as the Titanic Historical Society (the largest and most senior of the *Titanic* enthusiast bodies) of the United States and the Ulster Titanic Society of Northern Ireland (where the ship was built) set themselves against the salvage operation. Robert Ballard, who strongly believes in the sanctity of the site, worked to get a U.S. federal law passed making it illegal to buy or sell artifacts from the site in the United States.

Other individuals and institutions allied themselves with the salvage, provided that it was done well and in good taste. They were concerned that artifacts would be sold and dispersed if a company other than RMS Titanic, Inc., were the salvors dealing with the wreck; unscrupulous salvors interested only in pure commercial profit would not employ the same sort of painstaking recording, recovery, and conservation methods that RMS Titanic, Inc., used to retrieve materials recovered during the four research and discovery expeditions conducted between 1987 and 1996. Interestingly, although the Ulster Titanic Society opposes the salvage of the wreck, the society believes that as long as salvage work continues, RMS Titanic, Inc., is the best salvor to do the job.

In the face of serious international and, at times, hostile criticism from the public, maritime archaeologists, and museum professionals, the National Maritime Museum of Greenwich joined RMS Titanic, Inc., in a partnership to present the first exhibition of artifacts recovered from the wreck. In 1994–95, 150 of the several thousand artifacts recovered from the debris field were displayed in an exhibition titled "Wreck of the *Titanic."* The exhibition was billed as the "largest ever public display of *Titanic* artifacts" and was a huge success in terms of audience attendance and media coverage. More than 500,000 visitors saw the show.

The exhibit brought the museum into direct conflict with the International Congress of Maritime Museums (ICMM), however, of which it is a member. The museum and ICMM disagreed on the subject of salvors and salvage law. The ICMM was concerned that the exhibition included artifacts recovered from the site since 1990, and "relics raised illegally or in inappropriate circumstances after . . . 1990 . . . are considered out-of-bounds for ICMM-member museums."[1]

Richard Ormond of the National Maritime Museum claimed that "the objectives of the exhibition were to demonstrate the technical achievement of finding and exploring the site, to show conservation techniques and the extraordinary survival of objects on the sea bed, and to examine the controversy in detail."[2] The museum stressed that none of the artifacts on display came from the hull of the ship, which was the true grave site of the victims. Michael McCaughan, a *Titanic* expert from the Ulster Folk and Transport Museum in Northern Ireland visited the exhibition and felt that the "150 artifacts were displayed sensitively in a variety of contexts . . . Fundamentally this was not an exhibit about the past, but about the present and its appropriation of the past. The exhibit was not a requiem for the dead, nor did it address the metaphorical meaning of *Titanic.* Rather, it was an enshrinement of the triumphs of deep-sea exploration and the reviving wonders of conservation laboratories."[3]

Despite the controversy and arguments over the salvage work conducted by RMS Titanic, Inc., there is no doubt whatsoever that the company's work is legal. RMS Titanic, Inc., was granted salvor-in-possession rights to the wreck by a U.S. federal court in 1994. Despite a challenge, these rights were reconfirmed in 1996, giving the company exclusive rights to own artifacts recovered from the wreck. The 1996 judgment took into consideration the site recordings, artifact conservation, and commitment of RMS Titanic, Inc., to keep the artifact collection together for public display.

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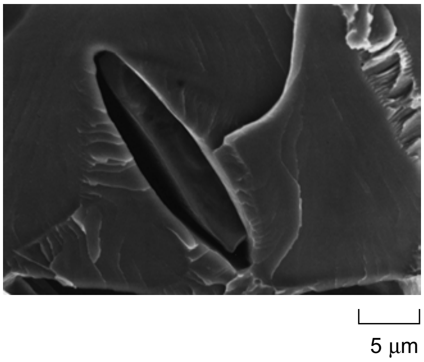

Figure 6. A scanning electron micrograph showing a fractured MnS particle protruding edge-on from the fracture surface.[13]

apparent that the steel is banded, although the banding is more severe in the longitudinal section. In this section, there are large masses of MnS particles elongated in the direction of the banding. The average grain diameter is 60.40 µm for the longitudinal microstructure and 41.92 µm for the microstructure in the transverse direction. In neither micrograph can the pearlite be resolved. For comparison, Figure 3 is a micrograph of ASTM A36 steel, which has a mean grain diameter of 26.173 µm.

Figure 4 is a scanning electron microscopy (SEM) micrograph of the polished and etched surface of steel from the *Titanic.* The pearlite can be resolved in this micrograph. The dark gray areas are ferrite. The very dark elliptically shaped structure is a particle of MnS identified by energy-dispersive x-ray analysis (EDAX). It is elongated in the direction of the banding, suggesting that banding is the result of the hot rolling of the steel. There is some evidence of small nonmetallic inclusions and some of the ferrite grain boundaries are visible.

Tensile Testing

The steel plate from the hull of the *Titanic* was nominally 1.875 cm thick, while the bulkhead plate had a thickness of 1.25 cm. Corrosion in the salt water had reduced the thickness of the hull plate so that it was not possible to machine standard tensile specimens from it. A smaller tensile specimen with a reduced section of 0.625 cm diameter and a 2.5 cm gage length was used.[10]

The tensile-test results are given in Table III. These data are compared with tensile-test data for an SAE 1020 steel, which is similar in composition. The steel from the *Titanic* has the lower yield strength, probably due to a larger grain size. The elongation increases as well, again due to a larger grain size.

Charpy Impact Tests

Charpy impact tests[12] were performed over a range of temperatures from –55°C to 179°C on three series of standard Charpy specimens: a series of specimens machined with the specimen axis parallel to the longitudinal direction in the hull plate from the *Titanic,* a series machined in the transverse direction, and a series made from modern ASTM A36 steel. A Tinius Olsen model 84 universal impact tester was used to determine the impact energy to fracture for several specimens at the selected test temperatures. A chilling bath or a circulating air laboratory oven was used to prepare the specimens for testing at specific temperatures. The specimens were allowed to soak in the appropriate apparatus for at least 20 minutes at the selected temperature. Pairs of specimens were tested at identical test temperatures.

Figure 5 is an SEM micrograph of a freshly fractured surface of a longitudinal Charpy specimen tested at 0°C. The cleavage planes, (100) in ferrite, are quite apparent. There are cleavage plane surfaces at different levels that are defined by straight lines. These straight lines are steps connecting parallel cleavage planes; the edges are parallel to the [010] direction. The crystallographic surfaces of the risers are the (001) plane. In addition, there are curved slip lines on the cleavage planes.

Particles of MnS identified by EDAX can be observed. Some of the MnS particles exist as protrusions from the surface. These protrusions were pulled out of the complimentary fracture surface. In addition, there are the intrusions remaining after the MnS particles have been pulled out of this fracture surface. One of the pearlite colonies lying in the fracture surface is oriented so that the ferrite and cementite plates have been resolved. Figure 6 shows a fractured lenticular MnS particle that protrudes edge-on from the fractured surface.[13] There are slip lines radiating away from the MnS particle.

Figure 7 is a plot of the impact energy versus temperature for the three series of specimens. At higher temperatures, the specimens prepared from the hull plate in the longitudinal direction have substantially better impact properties

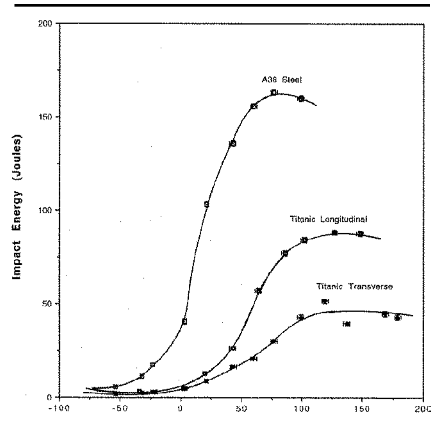

Figure 7. Charpy impact energy versus temperature for longitudinal and transverse *Titanic* specimens and ASTM A36 steel.

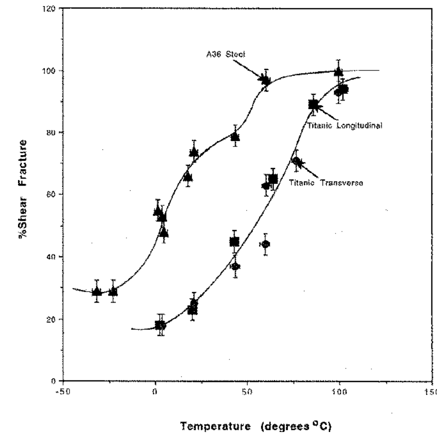

Figure 8. Shear fracture percent from Charpy impact tests versus temperature for longitudinal and transverse *Titanic* specimens and ASTM A36 steel.

than for the transverse specimens. At low temperatures, the impact energy required to fracture the longitudinal and transverse specimens is essentially the same. The severe banding is certainly the cause of the differences in the impact energy to cause fracture at elevated temperatures. The specimens made from ASTM A36 steel have the best impact properties. The ductile-brittle transition temperature determined at an impact energy of 20 joules is –27°C for ASTM A36, 32°C for the longitudinal specimens made from the *Titanic* hull plate, and 56°C for the transverse specimens. It is apparent that the steel used for the hull was not suited for service at low temperatures. The seawater temperature at the time of the collision was –2°C.

Comparing the composition of the *Titanic* steel and ASTM A36 steel shows that the modern steel has a higher manganese content and lower sulfur content, yielding a higher Mn:S ratio that reduced the ductile-brittle transition temperature substantially. In addition, ASTM A36 steel has a substantially lower phosphorus content, which will also lower the ductile-brittle transition temperature. Jankovic[8] found that the ductile-brittle transition temperature for the Chittenden lock gate steel was 33°C. The longitudinal specimens of the *Titanic* hull steel made in the United Kingdom and those specimens from the Chittenden lock steel made in the United States have nearly the same ductile-brittle transition temperature.

Shear Fracture Percent

At low temperatures where the impact energy required for fracture is less, a faceted surface of cleaved planes of ferrite is observed, indicating brittle fracture. At elevated temperatures, where the energy to cause fracture is greater, a ductile fracture with a shear structure is observed. Figure 8 is a plot of the shear fracture percent versus temperature. There is a fairly strong similarity be

NIST Revises Advanced Technology Program

The National Institute of Standards and Technology (NIST) has made several changes to the Advanced Technology Program (ATP) to strengthen the program's emphasis on research ventures and consortia with a broad range of participants and ensure that large companies pay a majority of the costs on their projects. The rules will take effect immediately and will apply to future ATP competitions, but do not apply retroactively to ongoing ATP projects.

Under the new rules, large business will be defined according to total annual corporation revenue for the purpose of ATP competitions. The rule requires the ATP to publish an annual dollar value to be used as the cut-off for determining large businesses during each year's competition.

When large companies apply to the ATP as individual firms outside of a joint venture, they must now provide cost-sharing funds at a minimum of 60 percent of total project costs to encourage large companies to participate in joint ventures. Previously, all companies had been treated alike regardless of size, and companies applying as individual firms were not required to provide any specific amount as their part of the cost share.

Several modifications were made to the ATP's project selection criteria used in the evaluation of candidate projects. The modifications place greater emphasis on joint ventures and consortia with a broad range of participants to encourage the teaming of large companies with smaller companies.

The valuation of goods, such as computer software, and related services provided by one member of an ATP joint venture to another was revised. Companies may count at least a portion of the actual cost of goods and services they provide in support of an ATP project toward their share of a project's costs, but it can be difficult to calculate the cost of certain types of goods, for example, company-developed computer software, where the actual cost of the product is unclear and hard to document. The revisions are intended to provide a consistent method of determining the value of these contributions.

Other revisions were made to ATP administration and clerical procedures. Although the multistep ATP selection process was not changed, it has been more clearly defined.

The changes are a result of a study by the ATP initiated by U.S. Department of Commerce secretary William M. Daley. Conducted by the department's Technology Administration, the study solicited comments from the public and experts on research and technology on strategies to strengthen the program and increase its effectiveness. The report is one of a series of studies commissioned by the ATP as part of the program's evaluation and analysis efforts.

Case Study

One of the first joint research ventures funded by the ATP led to dramatic R&D efficiencies for the participants, accelerated research, and produced significant technological advances for the industry, according to a project case study released by the ATP.

The 1990 project proposal "Printed

(Continued on page 54.)

tween this figure and Figure 7, which should be expected as they represent the different measurements of the same phenomenon. Using 50% shear fracture area as a reference point, this would occur in ASTM A36 at –3°C, while for the *Titanic* steel, this value would occur at 49°C in the longitudinal direction and at 59°C in the transverse direction. At elevated temperatures, the impact-energy values for the longitudinal *Titanic* steel is substantially greater than the transverse specimens, as shown in Figure 7. The difference between the longitudinal and transverse shear fracture percent from the *Titanic* is much smaller. This suggests that the banding is a more important factor in the results for the impact-energy experiment as compared with shear fracture percent.

CONCLUSIONS

The steel used in constructing the RMS *Titanic* was probably the best plain carbon ship plate available in the period of 1909 to 1911, but it would not be acceptable at the present time for any construction purposes and particularly not for ship construction. Whether a ship constructed of modern steel would have suffered as much damage as the *Titanic* in a similar accident seems problematic. Navigational aides exist now that did not exist in 1912; hence, icebergs would be sighted at a much greater distance, allowing more time for evasive action. If the *Titanic* had not collided with the iceberg, it could have had a career of more than 20 years as the *Olympic* had. It was built of similar steel, in the same shipyard, and from the same design. The only difference was a big iceberg.

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