EDITOR'S NOTE

The German submarine U-505—recently moved from the south courtyard of the East Pavilion of Chicago’s Museum of Science and Industry to a new underground structure designed and constructed specifically to house and preserve it—represents not just a type of vessel that threatened Allied forces in World War II. The only German submarine of its class to be captured by the U.S. Navy during the war, U-505 represents a point in American history when a critical battle had just begun—the battle for the Atlantic. Without winning that struggle, the Allies could not have delivered men and matériel to the shores of Europe, could not have defeated Hitler and the Germans, could not have won the war.

The projects undertaken over the course of the past several years to construct a new climate-controlled exhibit hall in which to house this priceless relic and then to carefully lift it and convey it to its new home are representative as well. They represent the care that civil engineers take in executing their duties, the profound understanding they possess of the importance of their work, and the degree to which they embrace collaboration in the genuine spirit of teamwork. The meticulous research and careful planning that went into the design of the exhibit hall—conducted by Chicago-based Halvorson and Partners—and the exacting peer review undertaken by the Chicago office of Thornton Tomasetti of the lifting and moving scheme developed by engineers from NorSat LLC, of Everett, Washington, demonstrate unequivocally the seriousness with which civil engineers approach their work, not just when that work is intended to preserve lives—as is the case with the design of a building or a bridge—but also when the objective is to preserve history.

A description of the significance of U-505 on a Web site hosted by the National Park Service says that the U-boat was selected by the U.S. Navy to serve as a tribute to the heroism of the thousands of Americans who fought the battle of the Atlantic and as a war memorial to those who died doing so. Admiral Daniel Gallery, who persuaded the undersecretary of the navy to donate the submarine to the museum, is reported to have said, “This captured submarine is a monument of national interest, commemorating the thousands of our lads whose national cemetery is the ocean.”

Thanks to the engineers, architects, and contractors involved in this project (see “A Good Move,” page 36), the submarine can continue to fulfill that role for decades to come.

Anne Elizabeth Powell
Editor in Chief

Prior to its move to a specially designed underground exhibit space at Chicago’s Museum of Science and Industry, U-505 occupied the south courtyard of the museum’s East Pavilion. The U-boat has been one of the museum’s most popular exhibits for more than 50 years.
A Good Move

An underground exhibit space constructed at Chicago’s Museum of Science and Industry now serves as the home of the German submarine *U-505*—the only vessel of its class captured by the United States during World War II. The careful lifting and moving of the vessel required precise coordination and meticulous reviews.

On June 4, 1944, the German submarine *U-505* was captured off the west coast of Africa by a U.S. Navy task force. The first and only submarine of the IX-C class captured by the United States during the war, the U-boat was towed to Bermuda, where it was studied for the remainder of the war, revealing German intelligence and military secrets. After the war, the navy had plans to use the vessel for target practice, but Admiral Daniel Gallery, then retired—a Chicago native and the commander of the task force that recovered the vessel—persuaded the undersecretary of the navy to donate the submarine to Chicago’s Museum of Science and Industry. In June 1954, 10 years after its capture, the U-boat arrived in Chicago. That fall it was transported from the shores of Lake Michigan to the south courtyard of the museum’s East Pavilion. For the next 50 years, the submarine proved to be one of the museum’s most popular exhibits.

Over the years, Chicago’s weather and pollution exacted a toll on the U-boat, and in 1991 the museum decided that an indoor facility would be required to protect the submarine from erosion. Various schemes to simply enclose the U-boat with a light roof structure at its existing location were abandoned because such a structure would, it was thought, have detracted from the museum’s classical revival architecture, which dates from its construction in 1893 for the world’s fair in Chicago. Working closely with the Chicago-based architecture firm Goettsch Partners, on June 4, 1944, a U.S. Navy task force seized the German submarine *U-505*, the only vessel of its class to be captured by the United States during World War II, opposite. Germany conducted U-boat campaigns during both world wars, but the campaign was especially effective during World War II. Germany boasted the largest submarine fleet in the world and used the fleet to much avail to stymie merchant convoys transporting supplies from Canada and the United States to Europe. The capture of codebooks aboard the *U-505* enabled Allied convoy commanders to route shipping away from known U-boat locations, substantially inhibiting the effectiveness of German submarine patrols. In 1954 the *U-505* was put on display in Chicago outside the Museum of Science and Industry, and over the years the environment exacted a toll. The plans to carefully move the vessel, above, from its previous display area to a new underground exhibit hall were subjected to an exhaustive review that included analyses of the lateral loads, ground preparations, stability-monitoring instrumentation, and emergency procedures in the event of equipment failure.
Halvorson and Partners—an engineering firm also based in Chicago—designed a structure to serve as the new home for the vessel, and the museum decided to very carefully lift and move the vessel into this belowground space.

The U-boat's new home consists of an indoor, climate-controlled space located 40 ft (12 m) below grade. It is connected to the museum by a new, two-story underground link that measures 100 ft (30.5 m) long by 55 ft (16.7 m) wide. The new exhibit space is essentially an elaborate underground concrete bunker 300 ft (91.4 m) long by 90 ft (27.4 m) wide by 38 ft (11.5 m) tall. Steel box girders and purlins frame its roof. The linking structure consists of steel framing with composite metal deck floors and is also located 40 ft (12 m) below grade. Conceptually, the design of the exhibit hall appears straightforward; however, the limitations imposed by the physical characteristics of the site,
The primary structural system for the new exhibit hall consists of sloping reinforced-concrete walls that taper in thickness from the floor to the roof. The walls are stiffened by tapered concrete buttresses that also serve as support for the roof girders. Those girders are arched steel beams that taper in depth. The walls and buttresses were designed to cantilever vertically so they could withstand the loads generated by the vessel and the equipment as the boat was lowered into the exhibit space.

oughfare located just 350 ft (106.6 m) east of the underground garage—was to be undertaken concurrently with the submarine enclosure project, and a new grading plan for the Lake Shore Drive pedestrian underpass limited the height of the below-grade structure. The link to the museum’s East Pavilion on the south required underpinning of that pavilion while excavating 33 ft (10 m) beneath the foundations and 30 ft (9 m) beneath the water table. In addition to the physical limitations imposed by the site, the design of the structure had to accommodate the process of moving the 700-ton (635 metric ton) submarine from the south side of the East Pavilion to the new exhibit space to the north and then lowering it into its new home.

Since the proposed site was located just 150 ft (45.7 m) from Lake Michigan, the water table was relatively high—only 7 ft (2 m) beneath existing grade. In order to excavate the 42 ft (12.8 m) beneath grade to the bottom of the new foundations, a water cutoff was required. By coordinating their work with the Chicago Department of Transportation—which was realigning Lake Shore Drive and constructing the pedestrian underpass 25 ft (7.6 m) beneath the water table—the engineers devised a solution that consisted of placing sheetpiling around a 7 acre (2.8 ha) area that would include both the new underground structure and the new pedestrian underpass.

At the west end of the submarine site, the sheetpiling tied into a slurry wall that had been constructed for an existing underground garage; a column of jet grouting was used for the tie. During the excavation of the exhibit hall, the trapped water within the 7 acre (2.8 ha) site was pumped out. The link structure also required a water cutoff, which was provided by steel sheetpiling between the exhibit hall sheetpiling and the existing East Pavilion. Since the excavation extended below the foundations of the East Pavilion, a ring of jet-grouted columns was provided around this excavation, with more than half of the columns installed from inside the museum by Schnabel Foundation, of Sterling, Virginia.

The primary structural system for the new exhibit hall consists of sloping reinforced-concrete walls that taper in thickness from 2 ft 3 in. (0.7 m) at the base to 1 ft 3 in. (0.4 m) at the top. The sloping walls are stiffened by tapered concrete buttresses that are 3 ft (0.9 m) thick and spaced at alternating 15 ft (4.5 m) and 30 ft (9 m) intervals. The buttresses also serve as support for the roof girders. The sloping
walls reduce the magnitude of the lateral soil pressure on the wall and help to satisfy the architect’s desire to provide a sense of openness to the underground space. The walls and buttresses were designed both for the permanent condition, when the roof girders would brace the top of the wall, and for the temporary condition, when the walls would act as 42 ft (12.8 m) tall cantilevers supporting the relocation movements of the U-boat.

The roof girders consist of arched steel box girders that taper in depth along their length and span roughly 90 ft (27.4 m) between the buttresses. The girders have a constant width of 2 ft (0.6 m) and a depth of 4 ft 6 in. (1.4 m) at the ends, where they connect to the buttresses, and 2 ft 6 in. (0.8 m) at the center. The lesser depth at the midsection is made possible by the full moment connection of the steel girder to the concrete buttress. The remaining roof structure consists of wide-flange steel purlins spaced roughly 6 ft 6 in. (2 m) apart and a 6 in. (152 mm) lightweight concrete composite metal deck roof. The taper and arching of the girders allowed a maximum roof height at the center of the enclosure while minimizing the roof at the north end to allow for the placement of the Lake Shore Drive pedestrian underpass. The alignment of the roof girders with the buttresses inside the exhibit hall suggests the interior hull structure of a submarine. Ultimately, the roof was covered with a waterproofing membrane and soil so that a lawn could be planted over it. The roof structure was designed to support an average of 18 in. (457 mm) of soil, plus a live load of 150 psf (7,182 Pa). In places where more than 18 in. (457 mm) of material would be required, geofoam fill
Once the U-boat was lowered and rotated into its final position it was held on its temporary shorings, its keel suspended approximately 1 in. (25 mm) above three new foundations.

Construction of the new facility began in March 2003. The Chicago Department of Transportation installed the sheetpiling for the 7 acre (2.8 ha) water cutoff. Dewatering of the site and excavation for the main exhibit hall followed, along with the construction of the concrete walls and buttresses of the exhibit space. The roof over the exhibit hall could not be constructed until the U-boat reached its new home. Construction of the link and the underpinning of the East Pavilion proceeded as preparations were being made to move the submarine.

Late in the summer of 2001, John J. McMullen Associates (JJMA)—an architecture and engineering firm based in Alexandria, Virginia, that has since been acquired by Alion Science and Technology, of McLean, Virginia—conducted a structural analysis of the submarine’s primary hull structure to determine the capability of the structure to sustain the stresses associated with relocation loadings. That analysis revealed that, owing to corrosion of the original steel components, certain hull elements would require reinforcement. The analysis was updated in February 2004 by Arthur H. Symmes, P.E., M.ASCE, who at the time was with JJMA and is now a senior structural engineer working in Green Bank, West Virginia, for the National Radio Astronomy Observatory. Symmes took into consideration the proposed relocation handling and the loadings that would be imposed during the move, which was to be conducted by NorSar LLC, an engineering and construction firm based in Everett, Washington, that specializes in lifting and transporting heavy naval vessels. The updated analysis concluded that the proposed NorSar lifting and moving configuration—which would utilize six areas of cradle support positioned on the keel—would provide a minimum factor of safety of 1.33 over the established structural steel design limiting stress of 25 ksi (179 MPa). It conservatively assumed that the U-boat weighed 850 tons (770 metric tons).

The move itself was designed and engineered by Ralph DiCaprio and Gregory E. Nordholm, P.S., of NorSar. In January 2004 the Chicago office of Thornton Tomasetti was engaged by the museum’s representative—Chicago-based Jones Lang LaSalle, a real estate services and money management firm—to peer-review the planned move. The review included poring over numerous drawings, diagrams, computer models, and calculations provided by NorSar, and it resulted in the creation of a spreadsheet listing various issues and ways of resolving them. The issues ranged from relatively minor

Museum Site
nonstructural ones—such as confirming that all hydraulic oil used on-site was biodegradable and confirming that all tree branches were trimmed and all overhead wires were cleared from the submarine’s path—to more important structural ones, including the incorporation of lateral notional loads that might be generated by seismic events or the inertia from the skidding operation, proper ground preparation and clearing for the move, instrumentation for monitoring the stability of the submarine during the move, and the development of emergency procedures in the event of equipment failure. The initial spreadsheet was issued on January 30, 2004.

On April 15 the Chicago office of Thornton Tomasetti was retained to perform a site examination of a set of shoring towers that had been erected within the new exhibit space. This visual review revealed that the tower assemblies were in general conformity with the documents created by NorSar but that one of the issues raised previously, namely, bracing of the built-up girders for the sliding operation, had not been addressed. The Thornton Tomasetti engineers worked out a bracing scheme with NorSar to prevent lateral torsional buckling of the built-up girders, which at the time of examination had no tie-downs or lateral bracing on the side of the span with ground support and had only clamps at the bottom flanges of the girders on the side with shoring towers. The bracing was installed and a final site examination was conducted late in the afternoon of April 21.

Moving the submarine from its location on the south side of the museum to its final home took five days and began on April 18, 2004. Coordinating its efforts with NorSar, Halvorson and Partners determined that during the move the U-boat could be driven to within 10 ft (3 m) of the cantilevered walls of the exhibit hall without the risk of overstressing or permanently deforming the walls. The temporary loads from the U-boat resting at the top of the wall were the maximum design loads the walls would ever resist.

The U-boat was lowered onto four built-up steel girders and slid sideways roughly 40 ft (12 m) to the north from its resting point on the ground to the shoring towers in the new exhibit space. The slide continued until the submarine was positioned at the center of the eight shoring towers. From its position at the top of the shoring towers, the vessel was lowered in 4 in. (102 mm) increments by jacking and removing pieces of wood cribbing until it reached its final resting position on the new exhibit hall floor. The cribbing was made of eki, a tropical African hardwood.

Once the U-boat was lowered and rotated into its final position it was held on its temporary shorings, its keel suspended approximately 1 in. (25 mm) above three new foundations. The gap was filled with a quick-setting epoxy-based material called Checkfast (produced by TRW Philadelphia Resins, of Montgomeryville, Pennsylvania). These three foundations supported all the gravity loads of the U-boat; there was no positive connection between the keel and the foundations, but 12 steel pipe struts—6 on each side of the submarine—were provided for lateral stability. The struts were located at the original cradle locations.

Crews with W.E. O’Neil wrapped the U-boat in a protective covering and built a temporary roof and working platform to shelter the vessel from the permanent roof construction that was about to begin. With the scaffolding and roof guarding the submarine, the steel roof framing was erected. The girders were shipped to the site and erected in one piece. Since the girders were arched, their gravity loads caused a thrust on the buttresses. To resist that thrust, the girders were designed to fit between and bear directly against the buttresses. Because of this geometry, erection of the girders would have been impossible if the buttresses on each side had been cast with all of their moment-connecting anchor bolts installed. So the placing of the final few feet of concrete for the buttresses on the north side was delayed until the (continued on page 80)
(continued from page 43) girder was fully connected to the south buttress and set on a temporary girder support on the north side. The anchor bolts for the north connection were then fit through the reinforcement cage and into the girder end plate so that the final concrete for the top of the buttress could be placed.

With the girder connection complete, the temporary support was removed. Steel purlins, the metal roof deck, and the concrete slab were then installed to complete the roof structure.

As previously mentioned, the new exhibit hall and link were later covered with a waterproofing membrane, geofoam fill, and soil and grass, returning the museum's front lawn to its original preconstruction condition.

Careful collaboration on the part of the architects, the owner, the engineering firms, the general contractor, the submarine movers, and the underpinning and earth retention contractors produced a structural solution that satisfied the architectural design, fit within the site dimensions, and brought the U-boat to its new home. The exhibit opened on June 5, 2005, ensuring that the history of the U-505 will be preserved for years to come.

Gregory J. Lakota, P.E., S.E., M.ASCE, is a partner of Halvorson and Partners, Chicago, and Andrew Esary is a staff engineer with the firm. William D. Bazz, P.E., S.E., M.ASCE, is a principal of Thornton Tomasetti in Chicago. Ralph DiCaprio is the vice president of operations of NorSat LLC in Everett, Washington. Arthur H. Symmes, P.E., M.ASCE, is a senior structural engineer working in Green Bank, West Virginia, with the National Radio Astronomy Observatory. Edward T. McDonald is the director of exhibits projects for Chicago's Museum of Science and Industry.

PROJECT CREDITS
Owner: Museum of Science and Industry
Architect: Goettsch Partners, Chicago
Structural engineer: Halvorson and Partners, Chicago
General contractor: W.E. O'Neil Construction, Chicago
Submarine transport: NorSat, Inc, Everett, Washington
Structural engineer peer review of submarine transport: Thornton Tomasetti, Chicago
Structural engineer for submarine analysis: John M. McMullen Associates, Alexandria, Virginia (now part of Alion Science and Technology, McLean, Virginia)
Geotechnical engineer: Ground Engineering Consultants, Northbrook, Illinois
Mechanical engineer: Primera, Chicago
Underpinning contractors: Schnabel Foundation, Sterling, Virginia, and sts Consultants, Chicago

(continued from page 71) that result “environment” here refers both to the natural world and to the community; they are themselves logical outgrowths of sprawl. Ingersoll thus uses the metaphor of the weather—in particular, how people simply learn to cope with weather, no it good or bad—to suggest that, like a violent thundershower or several days of drifting snow, sprawl is something that must be dealt with.

Other essays examine somewhat more esoteric topics that may at first seem jarring, but Ingersoll succeeds in tying them back to his theme. These include the ideas that tourism and terrorism have a certain symmetry; that the “scattered” and “awkward” nature of many modern urban forms makes sense when viewed in the context of cinema; and that beauty manifests itself in unexpected places in the modern world. The final essay is “an invitation to consider that the environmental apocalypse . . . has already occurred.” Ingersoll suggests here that we “assume the attitude of cancer patients seeking a way for prolonging life in an agreeable form.” Whether that strikes you as careless or liberating is up to you.

Ingersoll’s message, in the end, is one that he views as hopeful. He perhaps sums it up best as follows: “I am no longer sufficiently idealistic to believe that one can stop the advance of sprawl, but neither am I so cynical as to think that it is too late to revise certain practices. In the end, sprawl is already a mature form of urbanism, one that by now is in desperate need of restoration.”