THE MACKINAC BRIDGE — CONQUERING THE IMPOSSIBLE

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"HELP ME, LORD, TO BUILD MY SPAN"

Anchored firm in solid rock,
On Thy foundation let me build—
Strong to bear each strain and shock,
An arch of dreams and faith fulfilled.

Help me, Lord, to build my span
Across the chasm of the years;
Firm in purpose, true in plan,
Above the drag of doubt and fears.

Help me to build on Thy high road
A bridge to serve the common good;
To smooth the way and lift the load,
A link of human brotherhood.

Introduction

The thought of connecting two sections of the State of Michigan by a physical link across the Straits of Mackinac has challenged the imagination of engineers and the public for the past three-quarters of a century. The difficulties, both physical and financial, appeared insurmountable. Various plans and designs were proposed from time to time during the past forty years. Some of the schemes would have been impossibly fantastic in cost, but the promoters did not know it. One official design for the proposed bridge would have collapsed before completion, but the officials did not know it.

People (who were not engineers) said that the project was impossible; that the cost would be prohibitive; that it could not be financed; that the bridge could not be built; that the foundation prob-

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lems could not be solved; that the wide glacial gorge under deep water in the middle of the Strait could not be spanned; that the bridge, if built, would not stand up; that it would be destroyed by the elements; that no foundation piers could withstand the pressure of ice from the Great Lakes in winter; that no span could withstand the storms and wind forces at the site.

Despite all obstacles and difficulties, both natural and man-made, the project has now been successfully financed; all of the engineering problems have been successfully, economically and safely solved; the difficult foundations have been successfully conquered; and the construction of the bridge, commenced in July 1954, is well under way to meet the scheduled completion date of November 1957.

The Mackinac Bridge is five miles long. In the middle of the five miles, in the deepest water, to span the wide, submerged glacial canyon, a record-breaking suspension bridge is being built; the length, 8614 feet from anchorage to anchorage, makes it the longest suspension bridge in the world. The central span of this suspension bridge,

PERSPECTIVE DRAWING OF MACKINAC BRIDGE.

from tower to tower, is 3,800 feet; this is 300 feet longer than the span of the George Washington Bridge, and is exceeded only by the 4200-foot span of the Golden Gate Bridge. The difficult foundations under the two main towers of the suspension bridge, one at each rim of the submerged gorge, were carried down to rock, reaching the remarkable foundation depths of 205 feet and 210 feet, respectively, below the water surface. The suspension bridge cables are carried on artistic steel towers 550 feet high, each containing 6250 tons of structural steel; and the suspended trusses, carrying the roadway, have a normal clear height of 155 feet above the water.

The total cost of the bridge, including the bond-interest during construction, is $99,800,000; this is the amount of the bond issue. The cost figure establishes a new record for the magnitude and difficulty of a bridge project, and will certainly be a long-time record for a bridge carrying only four lanes of highway traffic and no railway loading.

Without careful economic design, the cost would have been many millions of dollars greater and the financial feasibility of the project would have been defeated. Scientific design made the bridge possible, while at the same time assuring a high margin of strength and safety in generous measure.

By spending a few million dollars more, the span could easily have been made the longest in the world. (In fact, the foundation problems would have been easier.) But the writer feels strongly that an engineer is violating his obligation if he seeks personal glory at the expense of his clients, in this case the traveling public.

The Need for the Bridge

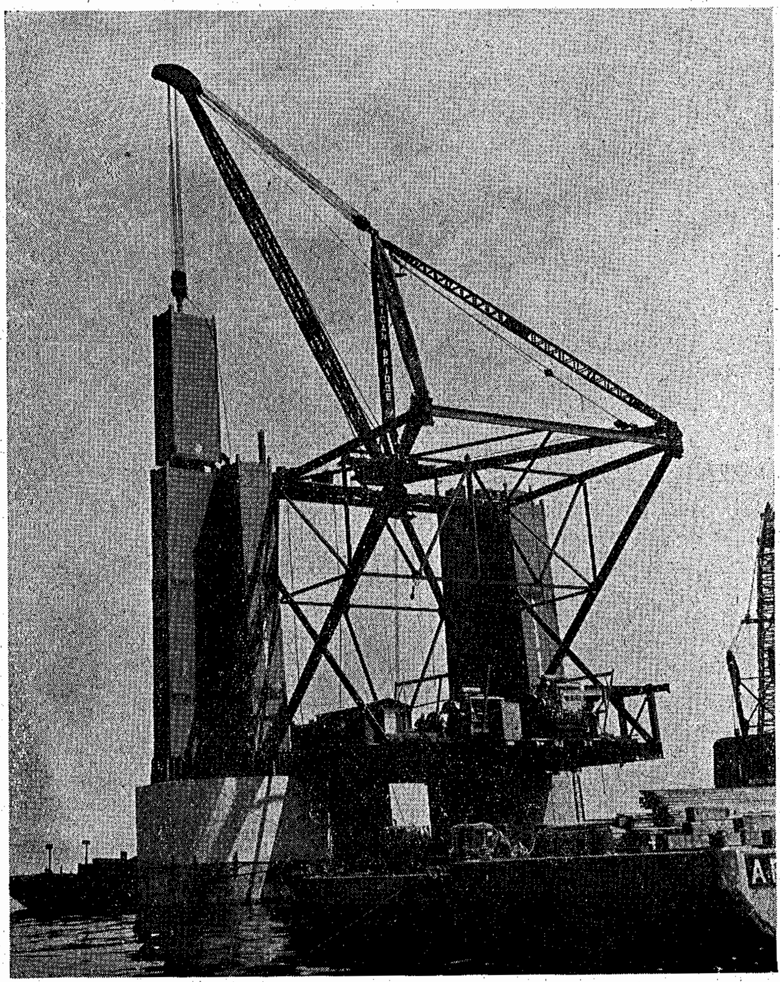
The Strait of Mackinac (pronounced "Mackinaw"), four miles wide, joins Lake Michigan and Lake Huron. These waters divide the State of Michigan into the 41,700 square mile Lower Peninsula and the 16,500 square mile Upper Peninsula.

The far greater part of the population is concentrated in the highly industrialized Lower Peninsula and its large cities such as Detroit; but the Upper Peninsula is possessed of immense natural resources which, when further developed, will attract additional population and industrial activity.

The Upper Peninsula is 400 miles long and is nearly equal to the combined area of four New England states. The principal industries at present are forestry, mining, agriculture, and recreation. Part of this area is world-famous as "The Copper Country." The area is also known as a "Vacation Paradise," drawing tourists and sportsmen from many states for hunting, fishing, camping, sailing, and winter sports.

The Mackinac Bridge will replace the existing State-operated highway ferry system in order to provide an all-year, all-weather, direct, time-saving connection between these two great Peninsulas of Michigan.

It is recognized that the project which will contribute most to the further development of the Upper Peninsula is the Mackinac Bridge. But in a larger measure, it will contribute to the advantages of Michigan as a whole and of the entire Great Lakes area as well as of the Province of Ontario in Canada. In the words of Governor



ERECTION OF BASE OF MAIN TOWER.

G. Mennen Williams, the builders of the Mackinac Bridge "are participating in Empire-building."

People doubted the possibility of financing the Mackinac Bridge because it does not directly connect two large cities or population centers. But modern highway uses have enlarged our vision and our perspective. Within a radius of 500 miles from the Straits of Mackinac there resides a population of 30,000,000 people in the United States and Canada who will benefit from the construction of the Mackinac Bridge and who, in turn, insure the economic practicability of the project.

The major highways of Michigan converge at Mackinaw City on the south and St. Ignace on the north of the Straits of Mackinac. Thus the Mackinac Bridge will funnel traffic from the Lower Peninsula into the Upper Peninsula and then into Canada by way of Sault Ste. Marie, 50 miles north of Mackinac Straits. Furthermore, the Mackinac crossing will provide a shorter east-west route for bonded traffic between the western provinces of Canada and populous southeastern Ontario. At this key location, the Mackinac Bridge will be an essential connecting link in the national and international highway system, and of high strategic importance in our Continent's defense program.

Truck traffic on the Mackinac Straits ferries has been increasing rapidly, and already amounts to 12 per cent of the total vehicular traffic.

The Mackinac ferry rates were increased 45 per cent in 1953 and, in spite of this increase in rates, traffic for the ensuing months increased 12 per cent above the same period of 1952.

The five-mile ferry crossing takes over one hour; the bridge will reduce the crossing time to ten minutes. But, more important, the bridge will save the time now lost in waiting in line for the ferries. During the summer months, this waiting-in-line time amounts to 3 to 4½ hours; and on holidays and during the deer-hunting season, cars have had to wait in line as long as 14 to 17 hours. The lines of waiting cars have extended along the highway as far back as 20 miles from the ferry. Parking fields are provided for the waiting cars, and the occupants find overnight accommodations to resume their place in line in the morning.

Photographs, stereo-views, and movies of these traffic conditions at the Mackinac ferries were used to convince bankers and investors before the bridge bonds were sold.

The proposed toll rates on the bridge will average 10 per cent higher than the present rates on the ferries; the time-saving will be the governing advantage to the motorists. At an average toll rate of $3.08 per vehicle ($2.10 for a passenger auto, more for trucks), the estimated traffic of 2,000,000 cars and trucks in 1958 will yield a revenue of over $6,000,000 in the first year of operation, with progressive increase thereafter. According to the traffic experts, the bridge will pay for itself in 18 years (retiring all bonds), and can then be made toll-free.

From Dream to Reality

In 1920, the Michigan highway commissioner suggested a submerged floating tunnel for the Mackinac Straits crossing.

In 1928, the State highway department recommended a bridge, but the subsequent depression put a stop to the project.

In 1934, a Bridge Authority was created by the State Legislature. The Authority retained three successive consultants, who presented respective diverse plans in 1934, 1935, and 1940. World War II stopped all planning.

In 1950 the present Mackinac Bridge Authority was created by the Michigan State Legislature. The Authority promptly appointed a Board of Consulting Engineers: O. H. Ammann, G. B. Woodruff, and the writer. In 1951 the three-man Board of Consultants reported that construction of the bridge was feasible. The traffic-engineering firm of Coverdale and Colpitts was retained to make the survey of traffic and prospective revenue.

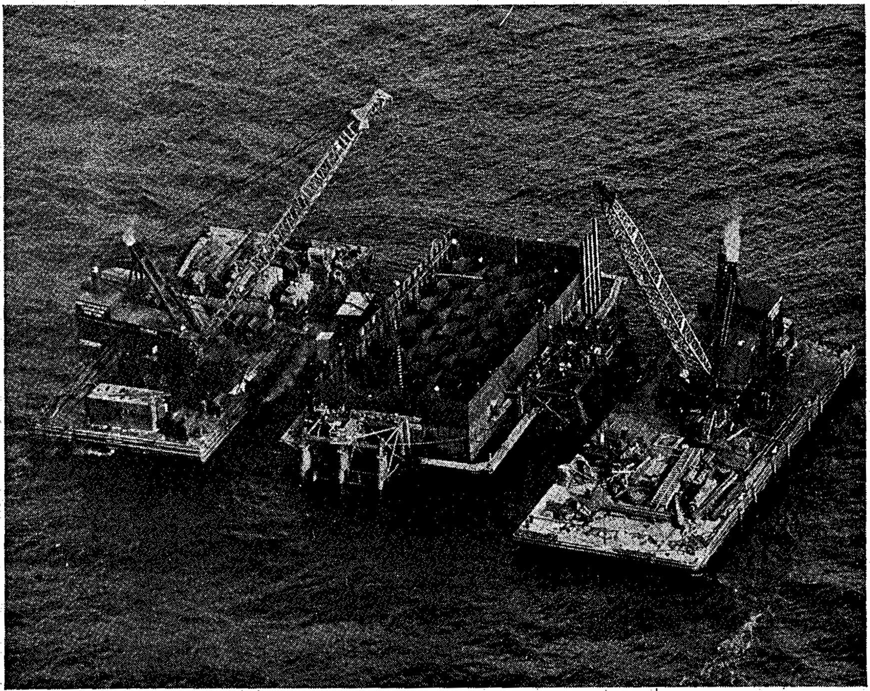
In January 1953, the Authority selected the writer to design and supervise the construction of the bridge, and the writer engaged Glenn B. Woodruff as his Associate Consultant. Within two months, in March 1953, preliminary contract plans and estimates of quantities were ready and the substructure and superstructure contracts were negotiated and awarded for prompt commencement of construction as soon as the bonds could be sold. All plans were rushed to get construction started in the spring of 1953.

Two attempts to sell the bonds were made in April and June, 1953, but the bond market was unfavorable. A new syndicate of investment bankers was formed and, in December 1953, this group of bankers purchased the $99.8 million of bonds to finance the project, at interest rates of 4 per cent for $79.8 million of first-lien bonds and 5¼ per cent for $20 million of second-lien bonds.

On January 18, 1954, the $79.8 million of first-lien bonds were offered by the banking syndicate and sold to the bond houses and investing public in one day. The second-lien bonds were offered to the public but were held by the underwriters for their own accounts.

Through the spring of 1954 the contractors proceeded to order materials and to mobilize equipment. During the next few months, $5 million of floating construction equipment was assembled and in place along the line of the bridge for the substructure contract, said to be the largest and finest floating equipment ever assembled for a construction contract.

On July 10, actual excavation was commenced for the subaqueous foundations. Over 750 men were engaged on the work at the site, working 20 to 24 hours a day. It was a race against time and a battle



SOUTH CABLE BENT PIER—CONSTRUCTED IN RECTANGULAR STEEL CAISSON WITH 21 CIRCULAR DREDGING WELLS.

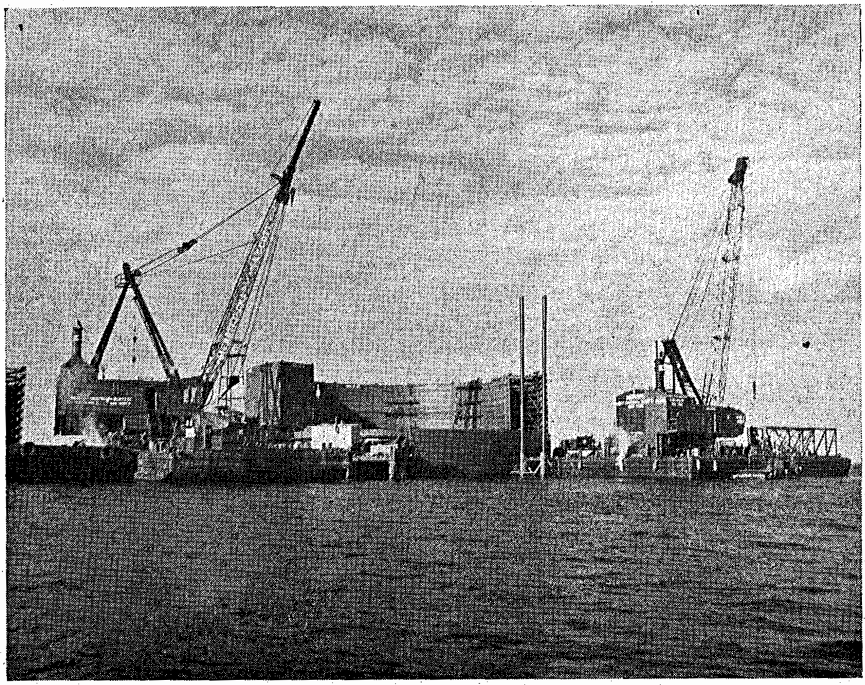
against the elements. The winter ice conditions at the Straits limit the normal working season to eight months. Word went down the line, from the president of the Merritt-Chapman & Scott Corporation to every man in the organization to spare no effort or expense to meet the engineer's schedule and to get all the suspension bridge piers and anchorages down to rock before the freezing of the Straits. To make up for time lost by impossible weather conditions, the men continued working in the rough water of the Straits through the winter cold, snow, and storms until freezing of the Straits finally forced the work to stop on January 14, 1955; but the two main-span piers were safely down into bed rock under the Straits, and the side-span piers and anchorages were already completed as scheduled.

An Ultra-Safe Bridge

Because of the unusual brecciated formation, people said that the rock underlying the Straits could not support the weight of the bridge. To resolve any doubts, outstanding geologists and soil-mechanics authorities were retained. Exhaustive geological studies, laboratory compression tests, and "in-place" load tests on the rock under water at the site established, without a doubt, that the rock under the Straits can safely support more than 60 tons per square foot. This is four or more times as great as the greatest possible load that will be imposed on the rock by the structure, including the combination of dead load, live load, wind load and ice pressure. The foundations were proportioned to keep the maximum possible resultant pressure below 15 tons per square foot on the underlying rock.

Because the public had been alarmed by unscientific claims that no structure could withstand the ice pressure at the Straits, we added a further generous margin of ultra-safety. According to the most recent engineering literature on the subject, the maximum ice pressure ever obtained in the field is 21,000 pounds per lineal foot of pier width, and the greatest ice pressure producible in the laboratory under controlled conditions for theoretically maximum pressure is 23,000 pounds per lineal foot. We multiplied this higher figure by five, and we designed the piers to be safe for a hypothetical, impossible ice pressure of 115,000 pounds per lineal foot, in addition to all of the usual, conventional factors of safety followed in the best engineering practice.

With the maximum possible ice pressure multiplied by five, and the safe foundation pressure divided by four as a basis for design, the combined factor of safety is twenty for the design of the piers against any possible ice pressure. For still further safety against any possibility of ice damage, the concrete of the piers is protected by steel sheet piling, steel caissons, and armor plate.



ERECTING RING 5 ON CAISSON OF SOUTH MAIN TOWER PIER.

The massiveness of the foundations and the resulting stability against the most severe wind reactions, ice pressure, or any other conceivable loads or forces, are represented by figures like the following:

In each of the main piers, which are 116 feet in diameter, the concrete alone weighs 145,000 tons, and this weight is augmented by 30,000 tons by the reaction of the steel tower superimposed upon the pier, making a total of 175,000 tons.

The total pull of the two cables upon each anchorage is approximately 30,000 tons. To resist this pull, the weight of concrete alone, in each anchorage, is approximately 5½ times as much, or 170,000 tons. This resisting weight is further augmented by the reactions from the adjacent truss spans.

Similarly, because the public had been told that no structure could resist the force of storms at the Straits, the design was made ultra-safe against wind pressure. The greatest wind velocity ever recorded in the vicinity is 78 miles per hour; this represents a wind force of 20 pounds per square foot. We multiplied this force by 2½ and designed the bridge to be ultra-safe against a hypothetical, improbable wind pressure of 50 pounds per square foot, in addition to providing all of the usual, conventional factors of safety established in the best engineering design practice.

The Most Stable Suspension Bridge

The main span at Mackinac is a suspension bridge, which is inherently the safest possible type of bridge. The stiffening trusses are 38 feet deep, or 1/100th of the span length. This is the same ratio adopted (after years of exhaustive aerodynamic tests) for the proposed Severn River Bridge in England, and 68 per cent greater than the ratio of the Golden Gate Bridge.

Even without this generously high depth-ratio, the Mackinac suspension span would have more than ample aerodynamic stability. In fact, by scientific design, utilizing all of the new knowledge of suspension bridge aerodynamics, including the writer's discoveries, analysis, and design principles, the Mackinac Bridge has been made the most stable suspension bridge, aerodynamically, that has ever been designed.

This result has been achieved, not by spending millions of dollars to build up the structure (in weight and stiffness) to resist the effects, but by scientific design of the cross-section to eliminate the cause of aerodynamic instability. The vertical and torsional aerodynamic forces tending to produce oscillations are eliminated.

An important feature contributing this high degree of aerodynamic stability is the provision of wide open spaces between the stiffening trusses and the outer edges of the roadway. The trusses are spaced 68 feet apart and the roadway is only 48 feet wide, leaving open spaces 10 feet wide on each side, for the full length of the suspension bridge. The effectiveness of this feature was demonstrated to the profession by the writer in 1940, and this feature has since been used in the construction or reconstruction of all large suspension bridges.

For further perfection of the aerodynamic stability, the equivalent of a wide longitudinal opening is provided in the middle of the roadway. The two outer lanes, each 12 feet wide, are made solid, and the two inner lanes and the center mall (24 feet of width) are made of open-grid construction (of the safest, most improved type). Wind-tunnel tests have confirmed the high aerodynamic stability of this design of cross-section, combining the two outer openings with an opening in the middle of the roadway.

In addition to the foregoing design features yielding assured aerodynamic stability, maximum torsional stability has been secured by providing two systems of lateral bracing, in the planes of the top and bottom chords, respectively. (This feature has recently been added to the Golden Gate Bridge at a cost of $3,500,000.)

The Mackinac Bridge represents a triumph of the new science of suspension bridge aerodynamics. The design was predetermined scientifically in final form, without spending years in groping, cut-and-try experimentation. Now, two years after determination of the design and award of construction contracts, extensive wind-tunnel tests have finally been completed on a large-scale dynamic model of the bridge. No modification of the design has been found necessary or desirable. The wind-tunnel tests show conclusively, as predicted by the writer, that the Mackinac Bridge, as designed, has:

1. Complete and absolute aerodynamic stability against vertical oscillations at all wind velocities and all angles of attack.

2. Complete and absolute aerodynamic stability against torsional oscillations at all wind velocities and all angles of attack.

3. Complete and absolute aerodynamic stability against coupled oscillations (combining vertical and torsional) at all wind velocities and at all angles of attack.

Professor F. B. Farquharson states in his report that: "Tests at angles of attack up to 20 degrees and over the full range of velocities available (191 miles per hour) have failed to develop any indication of instability."

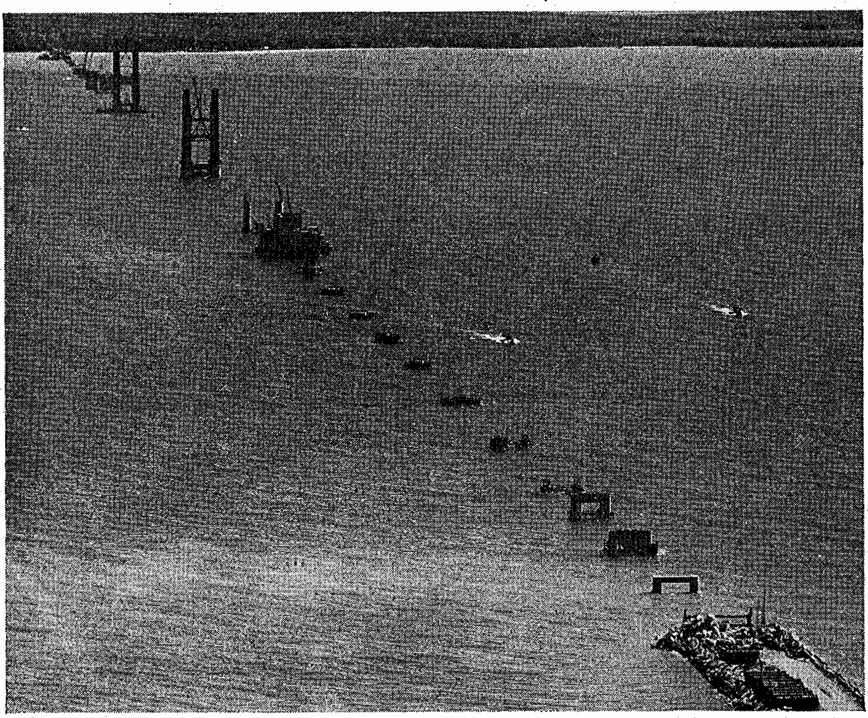
What Makes It Big

The total length of the bridge (including the approaches) is 26,444 feet (5 miles and 44 feet).

The total concrete in the substructure (anchorages, piers, and foundations) is 440,000 cubic yards. Of this amount 350,000 cubic yards are placed under water.

The total weight of the steel superstructure (cables, structural steel, and roadway) is 66,500 tons.

The 33 spans are carried on 34 piers. The two main piers are carried down to depths exceeding 200 feet. (Pier 19 through 140 feet of water and 70 feet of overburden, and Pier 20 through 100 feet of water and 105 feet of overburden.)



AERIAL VIEW OF CONSTRUCTION—MACKINAC BRIDGE.

The substructure contract (lump sum) is $25,735,600, awarded to the Merritt-Chapman & Scott Corporation.

The superstructure contract (structural steel and cables) is $44,-532,900. This is the largest single contract the United States Steel Corporation has ever received; in fact it is the largest single contract in the history of bridge engineering.

Although the suspension bridge appears to dwarf the other spans, continuous-truss spans of notable length are used over a secondary gorge in the crossing. Twenty spans over the deep portions of the waterway range in length from 560 to 330 feet. These span lengths were economically determined by the deep and massive piers required to withstand the ice pressure (with the large factor of safety adopted.)

The use of the Prepakt method for placing concrete in the foundations for the Mackinac Bridge has enabled a new world's record to be established for underwater concrete placement from a single floating plant: 6,250 cubic yards in a 24-hour day.

The wonderful progress that has been recorded on the work despite all difficulties has been made possible by the cooperative teamwork of officials, engineers, and contractors. On this project we have been fortunate in working with the Mackinac Bridge Authority, under the chairmanship of Prentiss M. Brown and under the leadership of Governor G. Mennen Williams. This Bridge Authority has been outstanding for caliber, for competence, for judgment, for integrity, and for ability to put a project through despite all obstacles. Under this inspiring leadership, no effort is being spared to produce the finest, safest and most beautiful bridge that money, skill and brains can build.

THE CHALLENGE

Nature said: "You cannot."
  Man replied: "I can."
From shore to shore, above the tides,
  He built a gleaming span.

Nature said: "You dare not."
  Man replied: "I dare."
He launched his winged ship aloft
  And boldly sailed the air.

Nature said: "You shall not."
  Man replied: "I will."
He caged the thunderbolts of Jove
  And made them serve his skill.

Nature said: "You must not."
  Man replied: "I must."
He split the atom. Now he holds
  A godlike power in trust.