ENGINEERING and CONSTRUCTION CONSIDERATIONS
for the
MACKINAC PIPELINE COMPANY'S CROSSING
of the
STRAITS of MACKINAC

The Mackinac Pipeline Company and its Consulting Engineers have placed the greatest importance on the safety factors affecting their pipeline crossing of the Straits of Mackinac.

Early in the planning stages, it was realized that every possible precaution should be taken to insure continuous and uninterrupted service of the pipeline, as a permanent installation for supplying crude oil to the refineries at Sarnia, Ontario. Not only would the construction of such a line be a very costly venture, which would have to be completed during the relatively brief period during late spring and summer when the Straits were not frozen over, but the loss in revenue which would result from any possible break in the line and shutdown in the flow of oil, would be of the most serious importance.

Any precautions which might be taken to prevent this would be fully justified. The seriousness of possible contamination of the Lake waters was considered and every effort has been made to insure that this could not happen.

With this importance associated with the design of the crossing, thorough investigations were made of every conceivable factor affecting the safety of the pipeline. A route was chosen across the narrowest part of the Straits, from Point La Barbe on the St. Ignace side to McGulpin Point just west of Mackinaw City.

For purposes of extra flexibility, extra strength and a greater factor of safety against possible damage, two smaller size lines of extra heavy wall pipe were chosen, operating in parallel and approximately 1300 feet apart.

These two 20" lines will parallel the submarine cable of the Michigan Bell Telephone Company. One will be located approximately 800 feet to the west of the cable and the other approximately 500 feet to the east.

In selecting the exact location for each line, full advantage was taken of the hydrographic survey and test boring information available from the report for the proposed bridge across the Straits. Mr. Glenn Woodruff, who was a consultant on that investigation, was called in, in a consulting capacity to assist in preparing a recommendation for the construction of this crossing.

Echo soundings of the entire Straits' bottom were furnished by the U. S. Lake Survey, Corps of Engineers and U. S. Army.

This method provides a continuous sounding, correct to approximately a half foot, for all of the possible routes. After intensive study of the bottom profiles, plotted from these soundings, the two best routes were chosen for the lines, based on the most even profile, eliminating as many changes of grade or curvature of pipe as possible, in turn, eliminating causes of pipe stress. Sharp "dips" and "humps" were avoided wherever possible, and the relatively few places where these conditions occur, it will be possible to excavate or fill the area

to provide an even bed, within allowable limits of curvature, on which the pipe will rest. Side slopes were avoided, as far as possible, where the pipe might have a tendency to roll. This condition was thoroughly investigated and it was found that a 4 degree or smaller slope would offer no problem, even if the pipe did not sink into the soft bottom material. From discussions with Professors Baier and Landes of the University of Michigan, Departments of Engineering and Geology respectively, it seems quite certain that the material in the deep area is a fairly soft clay material which would permit the pipe to settle into position and probably bury itself, eliminating any possibility of movement.

Extensive investigations were made of ships' anchoring practices in the Straits and it was determined that rarely, if ever, do ships anchor in the Narrows, in the vicinity of the telephone cable and the area where the pipeline will be constructed. In case of a storm or heavy fog, the safer place to anchor would be in one of the sheltered bays or protected areas rather than in the actual Narrows. The telephone cable has never been damaged by ships' anchors, according to our discussion with their engineers, even though it lays unburied and unprotected on the floor of the Straits. As protection against ice packs or other possible damage in the shallow area, it has been decided to bury the lines to a safe depth, from shore out to a point where the water is 40 to 50 feet deep. From that point on, the amount of cover will "taper off" and the lines will lie on the bottom with no cover, in the deeper area.

The pipe itself has been specified to meet certain critical requirements as to a high degree of ductility, extra heavy wall thickness, low carbon content, and very rigid inspection during its manufacture. The pipe will meet the requirements of API Specifications 5L for Grade A Seamless Steel pipe, with the added provisions that the maximum carbon content is to be held to .22 to .24%, the minimum yield strength is to be 30,000 psi and the maximum yield strength is to be 44,000 psi with the pipe having a yield of 30,000 to 34,000 psi selected for installation in the deep unburied portion of the line, because of its higher degree of ductility. The pipe will be 20" O.D. with a wall thickness of .812" and will weigh 166.40 lb. per foot with a weight tolerance of -1.75% per carload lot. It will be given a hydrostatic shop test of 1700 psi. This specification provides the best chemical and physical characteristics for pipe to fit the critical conditions which have been considered in this crossing.

The pipe will be preheated, electric shield-arc welded, X-rayed, and multiple joints welded together on shore will be tested to 1500 psi. After coating with asphalt primer, fiberglass inner wrap and an asbestos felt outer wrap, and after attaching 1" X 4" wood slats to the full circumference of the pipe, it will be lowered into a previously prepared "bed" on the floor of the Straits. It will be protected from excessive curvatures in bending during the laying operation, and will be placed on a bed which will insure spans no greater than those allowable for this particular pipe, and vertical curves within the allowable bending limits. After the lines are completed, they will be given a 1200 psi hydrostatic test, in place.

To take care of the "one chance in a million" that the line may be broken by a sinking ship or some similar accident, automatic shut-off valves have been specified for installation in the upstream piping manifold. These valves will automatically close upon a pressure drop in the line. On the downstream side of the line, check valves will be installed in the manifold preventing back-flow in the line in the event of any possible break.

An extensive study of the structural behavior of the pipe has been made. A copy of the calculations is attached to this report. The study comprises all possible load conditions and every geometric configuration the pipe may take when laid according to the specifications. In each of these conditions, conservative assumptions have been made so that in their overall combination a substantial additional safety factor has been introduced.

The following stresses have been investigated:

1. Hoop stresses or those which tend to burst the pipe.
2. Longitudinal tension or compression stresses.
3. Bending stresses in a horizontal and/or vertical plane.
4. Shear stresses.
5. Torsion stresses.
6. Combination of any or all of the above stresses which produce the maximum critical stresses.

Methods of analysis based upon accepted engineering practice and accepted formulas of the theory of elasticity have been used to determine these stresses.

The stresses mentioned above have been determined for the following loading conditions:

1. Weight of the pipe empty or filled with water or oil taking into account the uplift of the submerged pipe.
2. Outside pressure due to water currents.
3. Interior pressures for operating as well as testing conditions.
4. Bending of the pipe due to the conformation of the line to the bottom of the Straits or trench.
5. Stresses due to oil temperature changes and due to the temperature differential between the oil in the pipe and the water outside.
6. Hydrostatic pressure exerted on the outside of the pipe in case the pipe is empty.

As we follow the calculations attached to this report, we find that first, the lateral pressure of the current on the pipe and the weight of the pipe were determined, computing the resulting bending stresses, under the assumption that certain portions the pipe may span, unsupported over a valley. A table was developed showing the stresses for different span lengths. Then the stresses due to internal pressure, under operating and test conditions, were calculated and added to the stresses due to current and weight. A second table shows these combined stresses. It served to determine the maximum allowable unsupported span over a valley, once the maximum allowable stress had been established. For this condition, the conservative assumption of a beam on simple supports was used, ignoring the favorable influence of span continuity.

The next step was to determine the maximum curvature which the pipe would be permitted to assume in its final position on the bottom. By conforming to the bottom of the Straits or trench, stresses are introduced in the pipe which are similar to those due to bending. This means that the same loading conditions govern the specification of the maximum curvature as were used to determine the maximum unsupported span.

The calculations described in the preceding paragraphs were found sufficient to specify the profile to which the pipe should conform in its final position at the bottom of the Straits. Another series of computations was made to make sure that the pipe would suffer dangerous additional stresses and that it would stay in the position specified. A description of these additional computations and an evaluation of their influence upon the pipe is given in the following paragraphs:

The maximum shear stress was determined for the most unfavorable combination of loading conditions and it was found that these stresses are within the allowable limit specified for the pipe material.

Longitudinal temperature stresses were determined using an assumed temperature differential of 40 degrees F., plus or minus.

An investigation of the lateral displacement of the pipe in any straight run on the bottom, due to thermal buckling, indicates that the induced longitudinal stresses will be relieved due to such lateral displacement.

The ring thermal stresses due to a temperature differential of 30 degrees F between the interior and exterior of the pipe was investigated under the assumption of a thick pipe. These stresses are mainly hoopstresses and have been added to the hoopstresses due to internal pressure. Since the hoopstresses are not governing for the specifications of the profile, these are not affected.

The rolling and sliding effect on the pipe due to sloped banks and the action of the current was considered. The friction was found to be great enough to prevent sliding. The torsional shear and moment values were found to be far short of critical, and effectively prevent the pipe from rolling.

The sliding or lateral movement of a straight run of the pipe on the bottom was investigated for the two conditions of a full pipe and of an empty pipe, due to current. In these calculations no allowance has been made for the favorable fact that the pipe will settle into the top layer of the bottom. Taking this into account, the pipe will not be displaced by the water currents in the Straits.

Another consideration was the possibility of the pipe resting on a sharp edge. The stresses due to this condition are not great and are very localized, hence they do not constitute any hazard for the pipe.

An investigation of the catenary action on a free span was made. This occurs only if the ends of the pipe are prevented from moving towards each other. A reduction of approximately 20% in displacement was derived, which relieves the bending stresses.

The possible vibration induced by pumps or steady current flow were considered and found to be of little consequence.

The factors discussed in this report are believed to be those of the greatest concern in the development of a safe and efficient design. All forseeable conditions, as described, have been carefully investigated, and have been found to satisfy the design criteria and conditions established.

Any possible contamination of the waters, caused by oil spillage from the pipeline crossing is considered remote in comparison to the amount and possibility of spillage from oil tankers.

Letters are attached from Mr. Glenn B. Woodruff, Consulting Engineer, Mr. H. H. Hall, Consulting Engineer (previously, Chief Engineer, Standard Oil Company of California) and Mr. J. M. Evans, Chief Engineer, Standard Oil Company of California, Prof. L. A. Baier, Department of Architecture and Marine Engineering, University of Michigan, and from Prof. M. Salvadori, Professor of Civil Engineering, Columbia University. These men have been consulted on various phases of the investigation and design of the crossing, and have indicated their complete confidence in the safety and soundness of this engineering and construction venture.

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REPORT ON THE STRUCTURAL ANALYSIS OF THE SUBAQUEOUS CROSSING OF THE MACKINAC STRAITS.

The 20-inch pipe of thickness 13/16 inch was investigated on the basis of the best available engineering knowledge for a variety of loading and support conditions in order to determine the most unfavorable state of stress during operation and testing.

The maximum stresses thus determined are well within safe limits and the pipe built according to the limitations listed therein is sound.

The following conditions have been considered in detail in order to specify the limitations recommended at the end of this report and to set up specifications for the materials and the construction of the pipe.

1. Forces due to the Current

   Under the action of a recorded current of 1.96 knots, the pipe bends laterally. It is assumed that the pipe will rest on the bottom of the river on two points and will span a valley. The pipe span is assumed simply supported to magnify the existing stresses. The maximum permissible span due to current stresses is thus determined.

2. Stresses due to Vertical Loads

   Under the action of its own weight (negative buoyancy) the pipe will bend in the vertical direction when spanning a valley. The pipe is considered full of water or empty and the corresponding maximum valley span is determined under the assumption of simple supports. The favorable influence of continuity of spans is ignored.

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3. Combination of Horizontal and Vertical Forces

The stresses due to the current and to the vertical loads are combined to obtain the maximum safe span under both forces, both when the pipe is empty and when it is full.

4. Stresses due to Pressure

The stresses (hoop and longitudinal) due to internal operating and testing pressure were investigated, assuming the pipe to be a thin cylinder and a thick cylinder. The longitudinal stresses were obtained under the assumption of a pipe closed at both ends.

5. Combination of Bending Stresses and Pressure Stresses

The stresses under (3) and (4) were combined in such a way as to obtain the worst possible condition of stress in both tension and compression. The maximum shear stress due to these principal stresses was also determined.

6. Longitudinal Temperature Stresses

A maximum temperature differential of 40° F. was assumed as the basis for the determination of longitudinal stresses due to the prevented expansion of the pipe. This type of stresses is relieved by extension of the pipe due to bending.

7. Critical Length for Thermal Buckling

A temperature increase of 30° F. was assumed to determine the buckling length of pipe under fixed ends and simply supported ends conditions. These spans are longer than the minimum recommended spans.

8. Friction Required to keep Pipe in place during Thermal Expansion

The available friction on the bottom of the river is not capable of preventing the lateral displacement of the pipe due to thermal buckling. Hence the pipe will be displaced laterally and thermal longitudinal stresses will be relieved.

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9. Ring Thermal Stresses

The stresses due to a temperature differential at 30° F. between the oil and the water were investigated under the assumption of a thick pipe. The pipe being thin, these stresses will not be reached.

10. Temperature Increase in Curvature

The increase in curvature due to temperature differentials of the order considered were found negligible. Thus, the corresponding bending stresses may be neglected.

11. Limitations on Curvature

In order to limit the bending stresses in the pipe due to the curvature of the bottom of the river, the minimum allowable curvature is determined and recommended.

12. Collapse of Empty Pipe

Under the assumption of an abnormal condition (due to imbsion) which will suddenly empty the pipe, the external pressure is found not to be capable of buckling the pipe. The pipe, hence, will not collapse, due to external pressure, even if empty.

13. Local Buckling Stress

The maximum longitudinal compressive stress is much smaller than the buckling compressive stress for the pipe. Hence, no danger of local buckling is present.

14. Torsional Stresses Due to Slanted Approaches

The pipe does not follow the line of maximum slope on the banks of the river. This condition produces torsional moments and torsional shear stresses. The determination of these stresses under wide conditions proves that they are far from dangerous.

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15. Rolling Tendency

The pipe has a tendency to roll under the action of the current pressure and of the lateral component of its weight on the slanted banks of the river. The available friction is proved to be sufficient to prevent such motion.

16. Lateral Motion of Pipe

Available friction on the full pipe is proved sufficient to prevent the lateral motion of the pipe under the pressure of the current at the bottom of the river. The friction available on the empty pipe may possibly not be sufficient to prevent its lateral motion and a minimum additional negative buoyancy is recommended for the pipe.

17. Knife Edge Cradle Stresses

The possibility of the pipe resting on a sharp edge is considered and the stresses due to this condition, assimilated to a line pressure all around the perimeter of the pipe, are determined. The angle subtended by the knife edge support is varied between 30° and 180°.

18. Catenary Action

The reduction of lateral displacement due to catenary action, under the assumption that the ends of a pipe span be prevented to move one towards the other by friction or other obstacles, is found to be of the order of 20%.

19. Miscellaneous Stresses

Other conditions of load and support have been considered and found to be unimportant. For example, the possibility of a concentrated load acting on the pipe is excluded due to the slats and wrapping.

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20. Twin Pipes

The possibility of two pipes located a few feet apart and connected laterally was briefly considered. It is not felt that the twin pipes would be in a worse state of stress than the single pipe. On the contrary, twin pipes could present a better solution (from a purely structural view point) under various loads and support conditions.

Conclusions

The main recommendations arrived at on the basis of the evaluations outlined above are as follows:

a. The pipe must not be allowed to span a valley of more than 140 feet.

b. The pipe should under no circumstances be bent to a radius of less than 1,750 feet.

c. The pipe, if laid empty, should be weighted down with 20# per linear foot (20# of negative buoyancy) to prevent sliding due to the current. This figure may vary somewhat depending upon local conditions at the bottom of the river.

Calculations

The numerical evidence for the results given above is contained in the report entitled "Calculations for the Subaqeuous Crossings of Mackinac Straits, Saginaw River and St. Clair River", January 10, 1953, which was written under my personal supervision.

Statement

It is my opinion that the pipeline built according to the specification based upon this report and the report referred to under "Calculations" is structurally sound according to the best available engineering knowledge.

M. G. Salvadori

Mario G. Salvadori

New York, January 19, 1953