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Geology and Hydrology of the Elk River Minnesota Nuclear-Reactor Site

GEOLOGICAL SURVEY BULLETIN 1133-C

Prepared in cooperation with the U.S. Atomic Energy Commission

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By R. F. NORVITCH, ROBERT SCHNEIDER, *and* R. G. GODFREY

STUDIES OF SITES FOR NUCLEAR-ENERGY FACILITIES

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GEOLOGY AND HYDROLOGY OF THE ELK RIVER, MINNESOTA, NUCLEAR-REACTOR SITE

By R. F. Norvitch, Robert Schneider, and R. G. Godfrey

ABSTRACT

The Elk River, Minn., nuclear-reactor site is on the east bluff of the Mississippi River about 35 miles northwest of Minneapolis and St. Paul.

The area is underlain by about 70 to 180 feet of glacial drift, including at the top as much as 120 feet of outwash deposits (valley train) of the glacial Mississippi River. The underlying Cambrian bedrock consists of marine sedimentary formations including artesian sandstone aquifers.

A hypothetically spilled liquid at the reactor site could follow one or both of two courses, thus: (1) It could flow over the land surface and through an artificial drainage system to the river in a matter of minutes; (2) part or nearly all of it could seep downward to the water table and then move laterally to the river. The time required might range from a few weeks to a year, or perhaps more.

The St. Paul and Minneapolis water-supply intakes, 21 and 25 miles downstream, respectively, are the most critical points to be considered in the event of an accidental spill. Based on streamflow and velocity data for the Mississippi River near Anoka, the time required for the maximum concentration of a contaminant to travel from the reactor site to the St. Paul intake was computed to be about 8 hours, at the median annual maximum daily discharge. For this discharge, the maximum concentration at the intake would be about 0.0026 microcurie per cubic foot for the release of 1 curie of activity into the river near the reactor site.

INTRODUCTION

The objective of this report is to determine the geologic and hydrologic conditions that would affect the movement of a hypothetically spilled liquid at the Elk River, Minn., nuclear-reactor site and to evaluate the possibility of such a spill reaching a major water facility downstream along the Mississippi River.

The report was prepared by the U.S. Geological Survey for the Atomic Energy Commission. The study was under the direct supervision of Robert Schneider, district geologist, Ground Water Branch, St. Paul, Minn. Leon R. Sawyer, district engineer, Surface Water Branch, compiled most of the streamflow data for the Mississippi River.

The study involved collection of well data and a reconnaissance of the geology. Water-level altitudes were determined with an aneroid barometer, and most of the surficial geology was mapped directly from aerial photographs. No topographic quadrangle map of the area is available.

Regional ground-water conditions of the Elk River area have been described by Thiel (1947), and the surficial glacial history was studied by Cooper (1935).

ACKNOWLEDGMENTS

The following well drillers furnished well logs and gave oral information on ground-water conditions in the area: McAlpine Bros., Dayton, Minn.; McAlpine Bros., Rogers, Minn.; and Kate Thomas, Elk River, Minn. Special thanks are due E. J. Nelson, Rural Cooperative Power Association plant superintendent; R. W. Anderson, Platting Engineer of Anoka County; and Richard Halter, Superintendent of Utilities, village of Elk River, for their cooperation.

LOCATION

The area under investigation may be approximately encompassed by a circle of 2-mile radius centering at the Rural Cooperative Power Association steampower plant at Elk River, Minn. (pl. 1), where the nuclear reactor is located. The plant is on the east bluff of the Mississippi River about one-quarter mile southeast of the village of Elk River. The village is about 35 miles northwest of Minneapolis and St. Paul at the confluence of the Elk and Mississippi Rivers in southeastern Sherburne County. The area is traversed by State Highways 101 and 218 and U.S. Highways 169, 52, and 10. The Great Northern and Northern Pacific Railways serve the area and their main tracks are directly east of the plant site.

Additional information was compiled on major water facilities located downstream along the Mississippi River as far south as the Minneapolis municipal water-supply intake at Fridley, Minn. (fig. 1).

GEOLOGY

BEDROCK FORMATIONS

The deepest wells in the Elk River area penetrate sandstone, shale, siltstone, and dolomite of the St. Croixan series. (See table 1.) The formations below the St. Croixan rocks are unknown; but to the south, in the Minneapolis-St. Paul area, the St. Croixan series is underlain by about 1,000 to 2,500 feet of Precambrian sandstone and shale, the sediments for which may have been derived from eroded Precambrian lava flows (Schwartz, 1936, p. 24, 81). The flows are not present at

TABLE 1.—*Principal formations penetrated by wells in the vicinity of Elk River, Minn.*

System	Series	Formation		Approximate thickness (feet)	Physical characteristics	Water-bearing properties
Quaternary	Recent	Alluvium and lake deposits		(?)	Clay, silt, sand, gravel, and marl.	Undetermined.
	Pleistocene	Glacial drift	Till	70–180	Heterogeneous, unsorted deposits containing sand and gravel in lenses and irregularly shaped bodies; material ranges in size from clay to boulders.	Yields small supplies to a few domestic wells.
			Outwash		Poorly to well stratified and sorted deposits ranging in size from clay to gravel.	May yield small to large supplies.
Cambrian	St. Croixan	Undifferentiated		500±	Friable sandstone predominates; some dolomite, shale, and siltstone.	Sandstone beds yield large supplies under high heads. A large number of flowing wells are completed in the sandstones.

the Twin Cities but are exposed in the gorge of the St. Croix River at Taylors Falls, Minn., about 35 miles to the northeast. The oldest rock in the Minneapolis-St. Paul area is Precambrian granite whose upper surface is about 1,350 feet below sea level.

Regionally the bedrock strata are on the northwest rim of a shallow structural basin whose center is near the Mississippi River in Minneapolis (Schwartz, 1936, p. 88). The basin is slightly elongated northeast-southwest and is formed by rocks of Cambrian and Ordovician age, including several important artesian aquifers. Faults have been mapped at Hastings, Minn., about 45 miles southeast of Elk River, and in the St. Croix River valley about 40 miles east of Elk River; the possibility of subsequent earth movements of any great magnitude in this region probably is very remote.

GLACIAL DEPOSITS AND ALLUVIUM

During Pleistocene time, glaciers advanced over the area several times, depositing till (heterogeneous, unsorted material ranging in size from clay particles to boulders) directly from the ice. In addition, stratified sorted outwash was deposited by melt-water streams within and in front of the ice mass.

In the Elk River area, the surficial deposits are largely sand and gravel (valley train). These deposits are found in a broad belt along the present Mississippi River and include the hill of sand and gravel upon which the Rural Cooperative Power Association plant is situated (pl. 1).

The valley-train deposits in this area are bounded by glacial drift (including till and outwash deposits) on the north and south, and by an extensive series of outwash deposits known as the Anoka sand plain (Cooper, 1935, p. 39–65) on the east, several miles beyond the east border of plate 1.

The alluvium consists of deposits of clay, silt, sand, and gravel that were deposited on the river flood plain. It covers at least part of the valley-train deposits, but is not differentiated from them on plate 1 because of the similarity in lithology.

TOPOGRAPHY

The surface of the valley-train deposits is relatively flat, but includes some gently sloping hills and undrained depressions. In contrast, the area of undifferentiated drift north of the valley train is of high relief; it has steeply sloping hills and many undrained depressions.

Altitudes in the area range from about 852 feet above sea level (mean altitude of the Mississippi River) to about 1,100 feet, on a morainic hill about 1 mile north of the north-central part of the map on plate 1. An isolated morainic hill in the NE¼ sec. 2, T. 32 N., R. 26 W., is more than 1,000 feet above sea level.

The Rural Cooperative Power Association plant is on an elongate hill trending about S. 10° E. The main plant structure was built into the west side of the hill; the surface altitude is about 871 feet at the base of the building and about 902 feet in the backyard on top of the hill. The west slope of the hill ranges in altitude from about 902 feet at the plant to about 858 feet at the base of the bluff; the 44-foot drop occurs in a horizontal distance of about 360 feet. The slopes on the west side of the hill immediately north and south of the plant are somewhat steeper. The hill slopes more gently to the northeast, from about 902 feet at the top to an estimated altitude of 875 feet in a creek channel about 1,200 feet from the plant.

HYDROLOGY

SURFACE WATER

The Mississippi River and the tributary Elk River are the major streams in the area. The Elk River is dammed at the village-owned hydroelectric plant, forming Lake Orono in the village of Elk River. The altitude of the flashboards at the dam is 871 feet above mean sea level, or about 19 feet higher than the mean altitude of the Mississippi River (852 ft). The following table summarizes the discharge characteristics of the Mississippi River:

Discharge of Mississippi River

[cfs, cubic feet per second]

	Mississippi River			
	At Elk River (1)		Near Anoka (2)	
	Cfs	Date	Cfs	Date
Maximum	49, 200	4/12/52	75, 900	4/14/52
Average	5, 324		6, 997	
Minimum	278	11/15/33	586	9/13/34

1. Gaged at Elk River; drainage area 14,500 sq mi (approx); period of record 1915–56. Flow slightly regulated, except during extreme floods, by 6 Government reservoirs on headwaters; total usable capacity, 1,640,610 acre-ft; total normal operating capacity, 948,900 acre-ft. Gage height during maximum discharge about 10 ft higher than average.
2. Gaged 6½ miles downstream from Anoka; drainage area 19,100 sq mi (approx); period of record 1931–56. Flow slightly regulated as stated in preceding note. Gage height during maximum discharge about 14 ft higher than average.

The area east of the plant was, under natural conditions, poorly drained. Intermittent creeks apparently flowed eastward to the Rum River, which joins the Mississippi at Anoka. County ditch 10 was dug in a segment of one such creek channel, reversing the flow from eastward to westward in the SW¼ sec. 2 and the NE¼ sec. 11, T. 32 N., R. 26 W. (pl. 1). The upper reach of the creek channel, northeast of the plant, drains into the northern part of county ditch 10; a series of culverts under the railroad tracks and highway lead to the Mississippi River.

The Rural Cooperative Power Association plant area has a well planned system of sewers which will be discussed more fully under the section "Course of Accidentally Spilled Wastes."

The city of Minneapolis uses the Mississippi River for its municipal water supply. The intake is at Fridley, about 25 miles downstream from Elk River. The following information on the Minneapolis supply was obtained from Prior, Schneider, and Durum (1953, p. 40):

Population supplied		about 536,400
Average daily use (1951)	millions of gallons	about 55
Maximum daily use (1950)	do	102. 1
Storage, raw water	do	none
Finished water	do	61

Treatment at the Fridley Plant, Minneapolis, consists of prechlorination, softening with lime and soda ash; coagulation with ferrous sulfate, and with Ferrifloc as required; clarification stabilization with alum, carbon dioxide, or Ferrifloc, or a combination of these as required; rapid sand filtration; postchlorination; and ammoniation.

The principal source of water for the city of St. Paul is the Mississippi River intake at Fridley, about 21 miles downstream from Elk

River. The water is not treated directly, as in Minneapolis, but is pumped into a storage reservoir (Vadnais) made up of a system of lakes. The city also has two artesian-well fields with a total of 34 wells in reserve. The following information on the St. Paul supply was obtained from Prior, Schneider, and Durum (1953, p. 40–42):

Population supplied	about 325,000
average daily use (1951) millions of gallons	about 30
Maximum daily use (1950) do	62
Storage, raw water do	6, 750
Finished water do	70

Treatment at the St. Paul plant consists of aeration, coagulation with alum, softening with lime, recarbonation for pH stabilization, rapid sand filtration, and postchlorination.

The storage of the river water in the impounding lakes has some effect on the quality of the water. The lakes afford opportunity for settling of silt and clay, the death of some forms of bacteria, and some reduction in color. However, there is some increase in low forms of animal and vegetable life. The main value of the lakes is that they tend to equalize the daily fluctuations in the quality of the river water and act as a raw-water storage reservoir to guarantee a constant source of supply.

The Northern States Power Co. has a hydroelectric plant at Coon Rapids, about 18 miles downstream from Elk River. No other large users of surface water are known between Elk River and the St. Paul municipal water-supply intake.

The Mississippi River is used also for fishing, boating, and swimming; however, no public beaches are known.

GROUND WATER

AQUIFERS

The valley-train deposits and river alluvium are considered as a single hydrologic unit in this report. The available well-log data indicate that the unit ranges in thickness from a few feet to 120 feet and is made up of sediments ranging in size from silt to coarse gravel. A sand point can be driven almost anywhere within the limits of the valley-train deposits to obtain an adequate domestic supply of water.

Other sand and gravel bodies occur within the drift beneath the valley-train deposits, and they may constitute important aquifers in some parts of this area.

The depth to the water table in the area ranges from about 5 to 40 feet. The water table is about 5 feet below the land surface near the outer edges of the valley-train deposits where the land surface rises rather abruptly. On the flood plain west of the river the water table is about 10 feet below the land surface, whereas on the elongate hill on which the Rural Cooperative Power Association plant is located, it is about 40 feet below the land surface (pl. 2).

Immediately below the glacial drift are interbedded strata of sandstone, shale, siltstone, and dolomite of the St. Croixan series. Wells in the area penetrate these formations at depths ranging from about 70 to 180 feet. The thickness of the St. Croixan series in this area is about 500 feet. The sandstones contain abundant water under artesian pressure, and a large number of flowing wells are completed in them. Thiel (1947, p. 206) suggested that the high static head is due to the southeastward dip of the beds, and the static level in the sandstones is almost the same as the static level in the drift in the central part of Sherburne County.

NATURAL RECHARGE, DISCHARGE, AND MOVEMENT

The shallow aquifers in the Elk River area are recharged by local precipitation. The bedrock aquifers may be recharged directly by precipitation where they are at or near the land surface, or they may receive recharge from the overlying drift where the static level in the bedrock is lower than the water level in the drift. In the area of this report, however, the head in the artesian aquifers is higher than that in the glacial drift and alluvium. In the winter, when the land surface is frozen, little or no ground-water recharge occurs from precipitation. Generally the largest increments of recharge occur at the time of the spring thaw. The amount of recharge from rains is, in part, dependent upon antecedent soil-moisture conditions; recharge may occur only after soil-moisture and vegetal requirements are satisfied.

Unconfined ground water moves by the most direct route from areas where the water table is high to those where it is low. In general, shallow ground water moves toward streams, discharging as streambed seeps and springs and (or) moving downstream by underflow. Because the shape of the water table is a subdued model of the surface topography, the probable direction of movement of ground water is everywhere toward the nearest body of surface water. Scattered elevations on the water table, mostly north and east of the Mississippi (fig. 1), indicate apparent southward slopes of about 20 feet per mile in the north-central part of the area and about 5 feet per mile in the southeastern part. The apparent westward slope is about 10 feet per mile, but it becomes much steeper adjacent to the river.

Silt and fine sand transmit water rather slowly, perhaps on the order of tens of feet per year. The rate of ground-water movement in coarser materials may be hundreds or even thousands of feet per year, depending upon the permeability and the prevailing hydraulic gradient.

The static levels in the artesian sandstone aquifers are higher than the water table in the glacial drift; consequently, under natural conditions, water from the sandstone tends to move upward into the drift.

ARTIFICIAL DISCHARGE

Between Elk River and Columbia Heights (fig. 1) three municipalities, Elk River, Anoka, and Coon Rapids, obtain water from the bedrock formations. The village of Elk River (population 1,763) has 1 well completed in sandstone at 312 feet, pumping an average of 210,000 gpd (gallons per day) and a maximum of 280,000 gpd. Anoka (population 10,562) has 3 wells in sandstone that range in depth from 430 to 450 feet, pumping an average of 1 mgd (million gallons per day) and a maximum of 3¼ mgd. Coon Rapids (population 14,931) has 1 well which is cased to 217 feet and open in the bedrock to 472 feet. In August 1958 another well was being drilled to an anticipated depth of about 900 feet. No data were available on the pumpage because the water system was new.

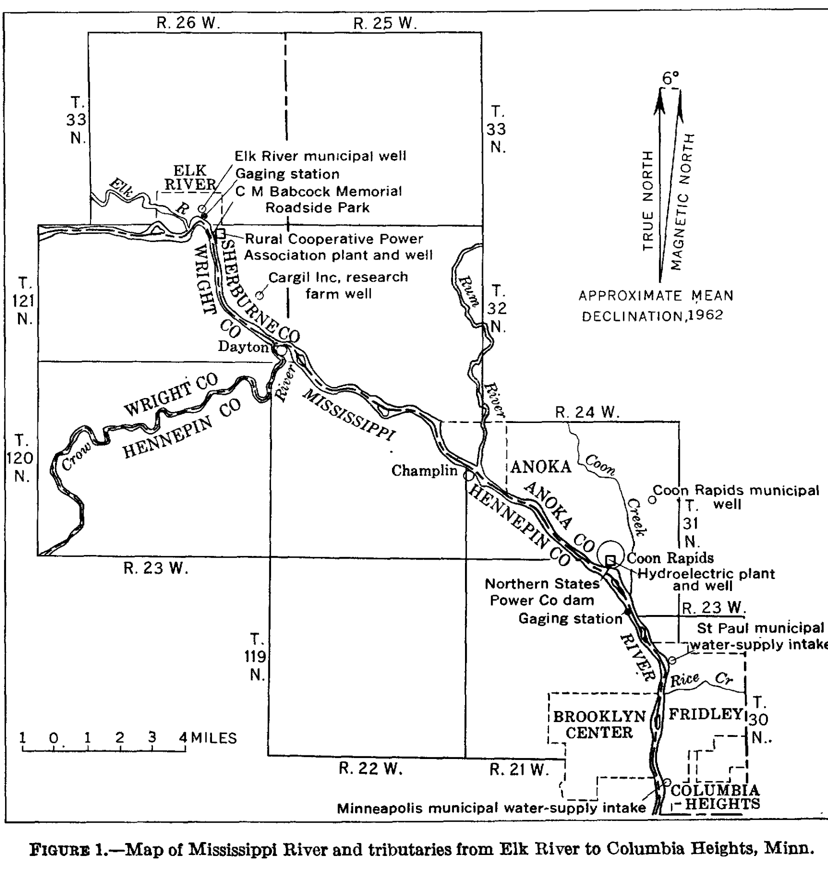

FIGURE 1.—Map of Mississippi River and tributaries from Elk River to Columbia Heights, Minn.

The C. M. Babcock Roadside Memorial Park, on the bank of the Mississippi River, is maintained by the Minnesota Highway Department and is used by a great number of tourists during the summer months. There is only one shallow hand-pumped well for the use of the public, but the park is mentioned here because it is directly across the highway to the west of the Rural Cooperative Power Association plant.

Private water supplies downstream include: (1) the well on the Cargill, Inc., Research Farm, about 2 miles southeast of the reactor site, completed in white sandstone at a depth of 315 feet; there are also 5 sand-point wells scattered throughout the farm area, completed at depths of 25 to 30 feet; (2) the Northern States Power Co. well at the Coon Rapids dam, completed in bedrock at a depth of 397 feet; this well is used for cooling bearings and for the sanitary and domestic needs of the plant and eight dwellings on the company property; (3) an undetermined number of wells used by small commercial establishments including motels and trailer courts; and (4) wells used by housing developments, individual residences, and farms, most of which are on the river terraces; the source for most of the wells is the shallow outwash deposits.

QUALITY OF WATER

The water in the outwash deposits is reported to be generally hard and to contain a moderate quantity of iron. Some well owners report excessive amounts of iron. The temperature of the water is about 49°F. Water in the bedrock aquifers ranges in hardness from about 170 to 260 ppm (parts per million) and contains a rather large amount of iron; as a result, some wells are equipped with iron-removal units. The temperature of the water is about 48° to 49°F. Table 2 contains four chemical analyses of water from wells completed in bedrock; one analysis is included for untreated Mississippi River water collected at the St. Paul municipal water-supply intake at Fridley.

COURSE OF ACCIDENTALLY SPILLED WASTES

A large volume (several thousand gallons) of liquid spilled accidentally on the surface at the reactor site could follow one or both of two courses. It could flow over the surface, through a system of drainage lines and ditches, into the Mississippi River; or it could seep into the ground, percolate downward to the water table, and move laterally to the Mississippi.

SURFACE

Plate 2 is a plan view of the Rural Cooperative Power Association plant showing the approximate location of the existing plant drainage

TABLE 2.—*Chemical analyses of ground water at Elk River and Coon Rapids, Minn., and of Mississippi River water at Fridley, Minn.*

[Analytical results in parts per million except as indicated. All analyses rounded to conform to Geological Survey practice]

Location	Depth of well (feet)	Analyst	Date of collection	Temperature (°F)	Silica (SiO_2)	Total iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Sum	Dissolved solids: Residue	Hardness as $CaCO_3$	Turbidity	Specific conductance (micromhos)	pH	Color	Remarks
Coon Rapids Municipal well, SW¼NW¼ sec. 13, T. 31 N., R. 24 W.	472	Minnesota Dept. of Health.	4/22/58	----	----	0.42	0.28	----	----	----	----	2.0	----	0.1	4.4	----	----	170	----	----	7.6	----	
Northern States Power Co. Hydroelectric Plant well, SE¼NE¼ sec. 27, T. 31 N., R. 24 W.	398	Northern States Power Co.	12/22/53	----	----	(Al+Fe) 0.3	----	55	16	15	262	19	1.8	----	----	236	----	204	----	335	7.5	----	H_2S=0.3
Rural Cooperative Power Association Plant well, SE¼NW¼NE¼ sec. 3, T. 32 N., R. 26 W.	275	H. M. Mueller Co., Minneapolis, Minn.	--------	----	18	1.10	----	140	94	24	----	10	3.0	----	----	256	----	233	----	----	7.4	----	
Elk River Municipal well, NW¼NE¼SW¼ sec. 34, T. 33 N., R. 26 W.	308	Minnesota Dept. of Health.	12/19/57	----	----	.52	<.01	54	----	----	----	----	----	1.6	----	----	----	260	----	----	7.7	----	
Untreated Mississippi River Water (average).	----	City of St. Paul.	1940–49	52	9.0	.30	.10	44	16	(Na and K as Na) 3.0	----	16	3.0	----	.4	----	241	179	9.1	----	8.1	62.5	Dissolved O_2=9.6 Al=0.72.

system and the diameters of the lines. The backyard of the plant, around the reactor containment, is a concrete slab about 5 inches thick. A fluid spilled upon it would probably run into the drain at the southeast corner of the building, flow down a 44-foot embankment directly into the highway ditch in front of the plant, and then flow through a 24-inch culvert under the double-lane highway to the river. This is assuming that little or none of the liquid ran into the artificial drainage system, but flowed off the slab to the west, and that soil conditions were such as to allow little percolation into the ground. If the fluid should flow to the southeast and remain west of the railroad tracks (fig.1), it would probably be impounded in a discontinuous ditch between the tracks and a bituminous-surface road behind the plant. If the ditch could not contain the fluid, it would probably flow into a small depression about one-quarter of a mile from the plant and remain there, or continue southward into county ditch 10, through two 36-inch culverts under the double-lane highway, and into the river. If a spill were to pass over the railroad tracks and into the creek drainage system east of the plant, it would probably flow into one of the sloughs (shallow, closed depression with a swampy bottom) a short distance east of the tracks and might remain there indefinitely. If the spill were of sufficient volume to flow through the sloughs, it would enter county ditch 10 and flow westward into the river. It is conceivable that a mass of liquid could flow to the north along the bituminous-surface road between the railroad tracks and the plant. In this event it might flow either along the road or in a discontinuous shallow ditch between the road and the railroad fill and make its way into the village of Elk River. Along this route a large portion of the spill would probably flow off the road to the west, down the slope to the ditch system on the east side of the double-lane highway at the base of the bluff, and thence into the Mississippi River.

The above-mentioned possibilities of surface drainage are based on the assumption that little or no accidentally spilled liquid would seep into the ground. This condition would prevail if there were an abundance of soil moisture or if soil frost prevented or impeded infiltration. The first condition would exist in the spring of the year, at the time of thaw or immediately after, or during intense rainstorms. The second condition is possible during the winter months (November through March); however, the frost layer may not be continuous throughout the plant area because the system of sewers would tend to keep the ground from freezing completely.

A postulated fluid spill reaching the river by way of the plant drainage system would probably present the greatest hazard so far as contamination of the river is concerned. By this route, several thousand gallons of fluid might reach the river in perhaps 5 to 10 minutes. The greatest hazard involved is possible contamination of the water supplies of St. Paul and Minneapolis, whose intakes are 21 and 25 miles downstream. In assessing this hazard, the time of travel and dilution of the waste must be considered. Figure 2 is a plot of discharge versus average velocity as measured on the Mississippi River at Elk River, and figure 3 is a similar plot for the gaging station near Anoka.

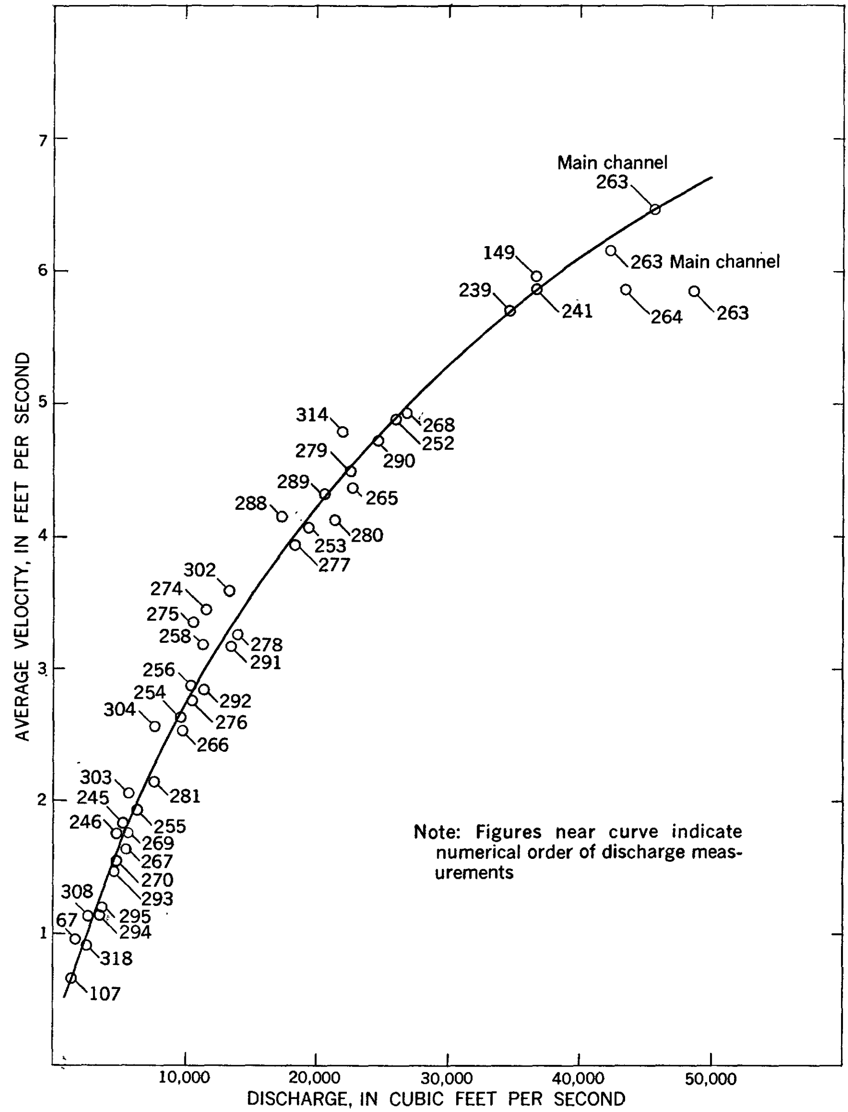

Figure 2.—Graph showing average velocity-discharge relation of Mississippi River at Elk River, Minn.

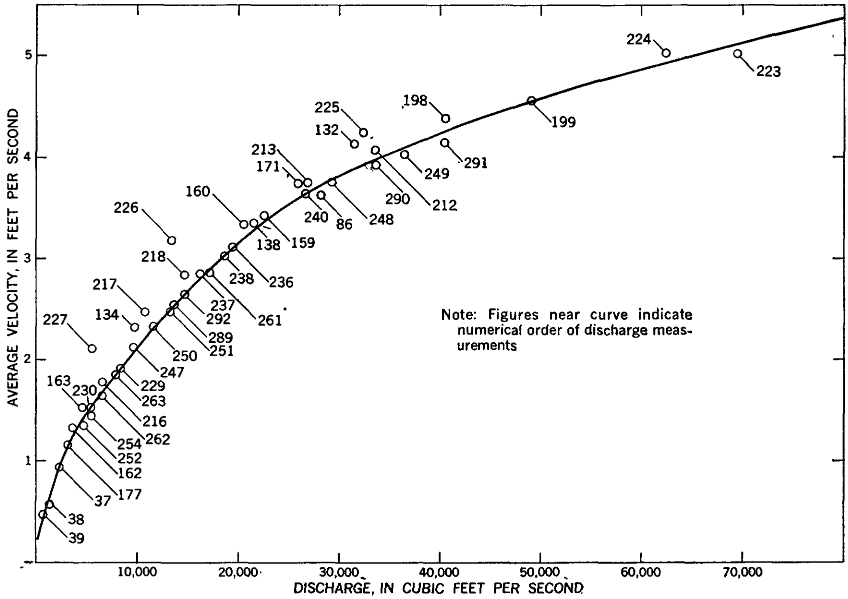

FIGURE 3.—Graph showing average velocity-discharge relation of Mississippi River near Anoka, Minn.

From figure 3 and the discharge records and channel properties at Anoka, the dispersal patterns can be computed for the following flow conditions (assuming the discharge-velocity relation at Anoka is generally representative of the average condition for the river reach from Elk River to Fridley):

1. Median annual maximum daily discharge, about 29,000 cfs
2. Median annual minimum daily discharge, about 2,000 cfs
3. Average discharge, 7,000 cfs.

The discharge measurements at Anoka yield the following information for these selected discharges:

Discharge (cfs)	*Average velocity (fps)*	*Mean depth (ft)*
2,000	0.90	4.5
7,000	1.75	6.7
29,000	3.75	12.4

Three questions regarding any contaminant entering the stream at the reactor site are of interest to Twin City water users:

1. For a given amount of contaminant what concentrations may be expected at the St. Paul water intake at Fridley?
2. What distribution will this contaminant have with respect to time or distance along the reach?
3. How soon after the contaminant enters the Mississippi River at the reactor site will it reach Fridley?

The answers to these questions can be gained by examining the dispersal pattern in the Elk River-Fridley reach of the Mississippi River for three selected discharges. The dispersal pattern in the Elk River-Fridley reach can be computed by means of the following equation given by Taylor (1954, p. 446–468):

$$C=\frac{M}{BD\sqrt{\pi 4Kt}}\,e^{\frac{-(x-\overline{V}t)^2}{4Kt}}$$

where C is the concentration, in millicuries per cubic foot
M is the amount of contaminant introduced, in millicuries
B is the stream width, in feet
D is the mean stream depth, in feet
t is the time, in seconds, after introduction of contaminant
x is the distance, in feet, downstream from the point of introduction of the contaminant
$\overline{V}$ is the average velocity, in feet per second
K is the dispersion coefficient, in square feet per second

If the parameter K can be computed for this reach, then the dispersal pattern can be determined. Previous experimental work indicates that a conservative estimate of the dispersion coefficient as related to the maximum concentration is

$$K=20.2D\,(gDS)^{\frac{1}{2}}$$

where S is the slope of the water surface and g is the acceleration of gravity, in feet per second per second.

The reach between the gaging stations at Elk River and Anoka is 19.8 miles in length, and the difference in water-surface altitude is about 43.5 feet for the range in discharge under consideration; thus, the average water-surface slope is 0.000416.

The dispersion coefficients for the three conditions are tabulated below:

Discharge (cfs)	*Dispersion coefficient (ft² per sec)*
2,000	23
7,000	41
29,000	103

With the basic dispersion equation, the dispersal patterns at Fridley can be computed and are shown in figure 4. The curves indicate the distribution of concentration of a slug of contaminant when its midpoint is at Fridley.

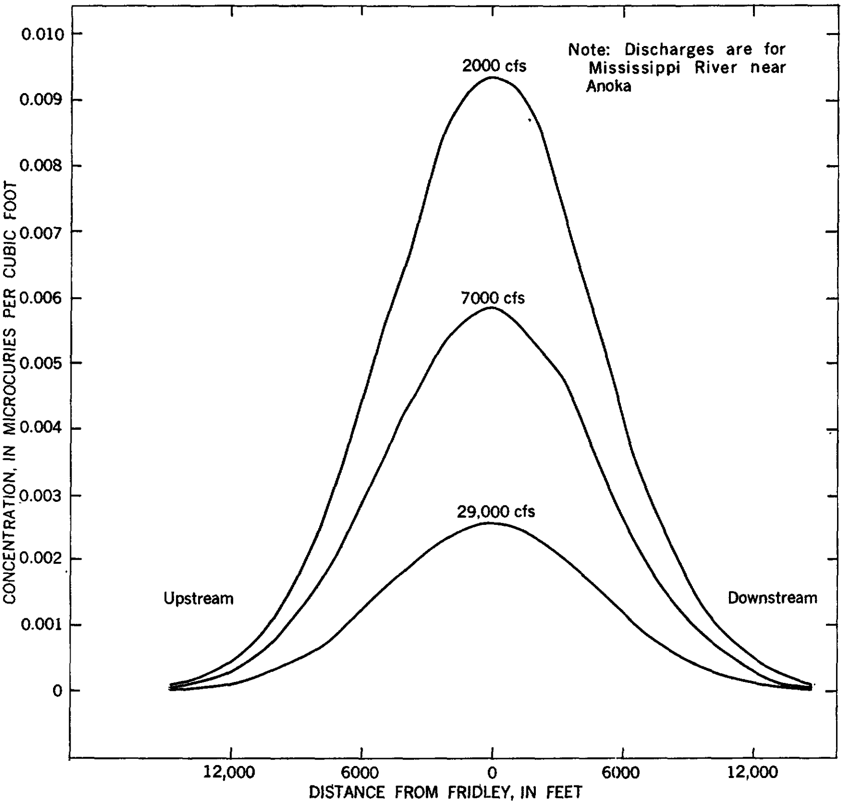

FIGURE 4.—Distribution of concentration of a contaminant at Fridley, Minn., for release of 1 curie of activity into the Mississippi River at the Elk River nuclear-reactor site.

In the computations given below the following assumptions have been made:

1. Cross-sectional properties at Anoka are representative of the entire reach.
2. Uniform flow throughout the reach.
3. Spot injection of a soluble contaminant.
4. No loss of contaminant through uptake by sediment or aquatic life.

It must be pointed out that these assumptions will not be completely satisfied, and that the dispersion will be greater (the concentration peaks lower) than shown herein.

The maximum concentrations shown on figure 4 are tabulated below for a release of 1 curie:

Anoka discharge (*cfs*)	Maximum concentration at Fridley per curie released	
	μc/ft³	*μc/ml* (×10⁻⁷)
2,000	0.0093	3.3
7,000	.0058	2.1
29,000	.0026	.9

It is coincidental that the three curves are spread over the same linear distance. The depth and velocity increase in such a manner as to offset each other.

If amounts of contaminant other than 1 curie were introduced, the resulting concentrations at Fridley would be proportional to the spill.

The time of travel of the center of the slug of contaminant is directly related to the mean velocity. The following times of travel were computed for the indicated discharges:

Anoka discharge (*cfs*)	Mean velocity (*fps*)	Time of travel to Fridley (*hr*)
2,000	0.90	34
7,000	1.75	17
29,000	3.75	8

As shown in figure 4, the initial arrival of the contaminant will precede the center of the slug because the fringe of the dispersed contaminant is more than 12,000 feet from the point of maximum concentration.

SUBSURFACE

Assuming that accidentally spilled liquid does not flow overland but percolates into the ground, it would filter through about 40 feet of dry to partially saturated fine sand to coarse gravel before reaching the water table (pl. 2). About 7 feet below the surface at the reactor site is a carbonate-cemented gravel layer ranging in thickness from ½ to 1½ feet and apparently dipping about 3° to the south. Because this layer is, in places, poorly cemented and permeable, it is conceivable that part of the layer would impede downward percolation of a fluid for sometime, and other parts would facilitate its movement. Drillers report a similar "hardpan" layer a few feet thick, at depths of 16 feet or more in the valley-train deposits south of the plant. They report that water is found immediately under this layer.

At an altitude of about 861 feet, water-table springs issue as seeps along the base of the hill on which the Rural Cooperative Power Association's plant is situated. (See pls. 1 and 2.) It is possible that at least part of a fluid contaminant that might join the water table near the plant would eventually issue from these springs.

Because of the variable permeability of the outwash, it is difficult to estimate the time that it would take for a fluid to percolate through the outwash at the plant site. In all probability, part of the fluid would be held by capillary attraction until subsequent recharge from rainfall either displaced or washed it down. Downward percolation to the water table and lateral movement at or below the water table would be slow. The rate of lateral ground-water movement in outwash deposits of the type found in this area might be on the order of hundreds or perhaps thousands of feet per year. The reactor site is about 750 feet from the river.

CONCLUSIONS

An accidental liquid spill at the reactor site would ultimately reach the Mississippi River. There are essentially two courses for the liquid to take.

1. The liquid may flow directly over the surface or through a system of drainage ditches and sewers into the Mississippi River. The time required to reach the river might vary over extremely wide limits, depending on the route traveled and the amount of liquid spilled. By direct flow overland or in the sewer system, a contaminant might reach the river in a matter of minutes. Through the sloughs and drainage ditches east of the plant, a spill might take a relatively long period of time to reach the river, or it might remain in the sloughs indefinitely.
2. Part of the liquid may percolate into the ground, in which case it must percolate downward through about 40 feet of dry to partially saturated permeable material before reaching the water table; it would then move laterally at or below the water table toward the Mississippi River. The time required for the material to reach the river might range from a few months to a year or perhaps more, depending, in part, on the permeability and the prevailing hydraulic gradient. Another possibility is that part of the underground movement would be toward the springs south of the plant, from which point the liquid would reach the river by way of the highway-drainage system.

Under natural conditions, it is unlikely that shallow ground water would percolate into the bedrock formations, because the static head in the bedrock is higher than the static head in the glacial drift. Also, in most places, there is relatively impervious till, or shale, or both, between the drift aquifers and the bedrock aquifers.

Based on streamflow and velocity data obtained at the Anoka gaging station, the time of travel of the maximum concentration of a contaminant from Elk River, Minn., to the St. Paul water-supply intake (21 miles) was computed to be about 8 hours for the median annual maximum daily discharge (29,000 cfs). For this discharge, the maximum concentration at the intake would be about 0.0026 microcurie per cubic foot (about $1 \times 10^{-7} \mu c$ per ml) for the release of 1 curie of activity at the reactor site. The initial arrival of the contaminant would precede the maximum concentration by about 1 hour.

Further investigative work would be needed to answer the several questions that have been raised. Specifically, field determinations should be made of the permeability of the outwash deposits at the plant, and detailed water-table maps should be constructed to determine the direction of ground-water movement. Consideration should be given also to the experimental determination of the course and time of travel of a spilled liquid containing a suitable tracer. If it is found that ground water from the plant area issues from the springs to the south, they should be monitored and sampled periodically to establish background activity.

WELL LOGS AND SOIL BORINGS

The well logs shown in table 3 were compiled from drillers' records, drillers' logs reported from memory, and from the files of the Minnesota Geological Survey. Because drilling samples were not available for verification of the logs, the logs are presented verbatim as collected. The soil borings shown in table 4 were collected from records of engineering firms and also are presented verbatim. A soil-classification table is included on plate 2 to better interpret the soil-boring logs.

TABLE 3.—*Well logs*

[Source of log: (1) driller's records; (2) driller's logs reported from memory; (3) files of Minnesota Geological Survey]

Material	Thickness (feet)	Depth (feet)
Coon Rapids municipal well, SW¼NW¼ sec. 13, T. 31 N., R. 24 W.[1]		
Sand	45	45
Clay, blue	15	60
Clay, sandy	41	101
Hardpan	23	124
Sand	21	145
Sand and clay	3	148
Sand and gravel	20	168
Hardpan	9	177
Sandstone, soft	30	207
Sandstone and shale	158	365
Clay, red	5	370
Shale and sandstone	26	396
Sandstone with some shale	12	408
Sandstone (417–437 very soft)	36	444
Sandstone and some shale	24	468
Shale	4	472

TABLE 3.—*Well logs*—Continued

[Source of log: (1) driller's records; (2) driller's logs reported from memory; (3) files of Minnesota Geological Survey]

Material	Thickness (feet)	Depth (feet)
NE¼NE¼NE¼ sec. 2, T. 32 N., R. 26 W.[2]		
Sand, reddish	25	25
Hardpan	7	32
Clay	5	37
Sand, "dirty"	5	42
Sand and gravel	18	60
NE¼NE¼NW¼ sec. 2, T. 32 N., R. 26 W.[2]		
Clay	38	38
Sand, fine	7	45
Till	23	68
Sand and gravel	40	108
NE¼SE¼SE¼ sec. 3. T. 32 N., R. 26 W.[2]		
Sand and gravel	65	65
Clay, yellow to blue	35	100
Sand and gravel	65	165
Shale, varied colors	75	240
Sandstone, white	170	410
Rural Cooperative Power Association plant well, SE¼NW¼NE¼ sec. 3, T. 32 N., R. 26 W.[2]		
Pit	14	14
Sand and gravel	16	30
Clay, sandy	10	40
Clay, blue	44	84
Sand, gravel, rocks, and hardpan	52	136
Sandstone	22	158
Shale	47	205
Sandstone, some shale	65	270
Sandstone, soft	20	290
Sandstone, caving	1	291
NW¼NW¼NW¼ sec. 11, T. 32 N., R. 26 W.[2]		
Sand and gravel	40	40
Clay, blue	85	125
Sandstone, soft	70	195
Sandstone, hard	60	255

TABLE 3.—*Well logs*—Continued

[Source of log: (1) driller's records; (2) driller's logs reported from memory; (3) files of Minnesota Geological Survey]

Material	Thickness (feet)	Depth (feet)
SW¼SE¼NE¼ sec. 32, T. 33 N., R. 26 W.[3]		
Sand, gravel, and boulders	20	20
Sand and gravel	15	35
SE¼SE¼NW¼ sec. 32, T. 33 N., R. 26 W.[2]		
Sand	25	25
Clay	45	70
Gravel, coarse, and sand	50	120
Shale	6	126
Sandstone	21	147
SW¼NE¼SW¼ sec. 32, T. 33 N., R. 26 W.[2]		
Sand and gravel	30	30
Sand, gravel, and clay	30	60
Sand and gravel	6	66
NE¼SW¼SW¼ sec. 33, T. 33 N., R. 26 W.[2]		
Sand	25	25
Sand and gravel, "dirty"	25	50
Gumbo, hard, black	50	100
Shale, green	75	175
Sandstone	35	210
Elk River municipal well, NW¼NE¼SW¼ sec. 34, T. 33 N., R. 26 W.[3]		
Sand and gravel	120	120
Sandstone, yellowish, and shale	50	170
Sandstone, white	130	300
Sandstone, dark-red	8	308

TABLE 3.—*Well logs*—Continued

[Source of log: (1) driller's records; (2) driller's logs reported from memory; (3) files of Minnesota Geological Survey]

Material	Thickness (feet)	Depth (feet)
SW¼SW¼NW¼ sec. 35, T. 33 N., R. 26 W.[2]		
Sand	15	15
Clay	25	40
Sand and gravel	10	50
NW¼NW¼SW¼ sec. 35, T. 33 N., R. 26 W.[2]		
Sand	40	40
Clay, gray	20	60
Sand and gravel, reddish to gray	25	85
SE¼SE¼SW¼ sec. 35, T. 33 N., R. 26 W.[2]		
Clay, yellow	30	30
Sand and gravel, "dirty"	50	80
Sand, green	5	85
NW¼NE¼NW¼ sec. 26, T. 121 N., R. 23 W.[2]		
Sand and gravel, fine	40	40
Clay, gray	60	100
Sand and gravel, "dirty"	20	120
Sandstone, soft	55	175
Sandstone, hard	80	255

TABLE 4.—*Logs of soil borings* [1]

Material	Thickness (feet)	Depth (feet)
ACF 1 [2]		
Fine brown sand	2	2
Fine sand	2	4
Medium to coarse sand	1	5
Medium to coarse sand and gravel with veins of fine sand	1	6
Medium to fine sand with small stones 1 in. in diameter	1	7
Fine sand with layers of coarse sand	1	8
Medium to fine sand and gravel	7	15
Fine sand	1	16
Medium to fine sand and gravel	3	19
Medium sand and gravel	1	20
Fine sand	3	23
Medium to fine sand and gravel	4	27
Medium to fine sand with trace of gravel	1	28
Medium to fine sand and gravel	3	31
Fine sand and gravel	3	34
Medium to fine sand and gravel	6	40
ACF 2		
Fine sand with trace of gravel	1	1
Fine brown loamy sand	2	3
Fine sand	1	4
Fine brown loamy sand	2	6
Medium to fine sand	1	7
Fine brown loamy sand	5	12
Medium to fine sand and trace of gravel	2	14
Medium to fine sand	6	20
Fine sand with trace of gravel	9	29
Medium to fine sand and gravel	4	33
Medium to coarse sand and trace of gravel	3	36
Medium to coarse sand and gravel	2	38
Medium to fine sand and gravel	2	40

See footnotes at end of table.

TABLE 4.—*Logs of soil borings* [1]—Continued

Material	Thickness (feet)	Depth (feet)
ACF 3		
Fine sand with trace of gravel	3	3
Fine loamy sand	4	7
Fine sand with trace of gravel	1	8
Fine loamy sand	16	24
Fine loamy sand with veins of fine sandy loam	2	26
Medium to fine sand	2	28
Fine sand with trace of gravel	12	40
AMF K-14 [3]		
Concrete	0. 5	0. 5
Tan and brown coarse loamy sand (moist) with a little gravel	2	2. 5
Light-brown sand (moist) with a little gravel and lens of brown sand at 3½ ft and a lense of sandy loam at 11 ft	14. 5	17
Light-brown coarse sand (moist to 41 ft then water bearing) with some gravel	27	44
Grayish-brown sandy loam (moist) with a little gravel and lenses of clay loam	2	46
Gray clay loam (rather stiff) with a little gravel	2	48
Brown sandy loam (moist) with a little gravel	11	59
Gray clay loam (very stiff) with a little gravel	6	65
Gray fine sandy loam (moist)	1	66
Gray clay loam (hard)	3	69
Gray sandy loam (moist)	8	77
Gray clay (hard) with a little gravel	7	84
Gray sand with a little gravel	1	85
Gray clay (hard) with a little gravel	10	95
Dark-gray clay (hard)	2	97
Gray clay (hard) with a little gravel	3	100

See footnotes at end of table.

TABLE 4.—*Logs of soil borings* [1]—Continued

Material	Thickness (feet)	Depth (feet)
AMF J-13		
Concrete	0. 2	0. 2
Tan and brown sandy loam (moist)	1. 8	2
Tan and brown coarse loamy sand (moist)	. 5	2. 5
Tan and light-brown sand (moist)	2	4. 5
Light-brown sand (moist) with a little gravel and a few lenses of sandy loam from 10 to 12 ft	9	13. 5
Tan fine loamy sand (moist)	1	14. 5
Tan sand (moist)	4. 5	19
Light-grayish brown coarse sand (moist) with some gravel, a few lenses of sandy loam	23	42
Brown sandy loam (moist) with a little gravel and boulders	5	47
Grayish-brown sandy loam (moist) with a little gravel	12. 5	59. 5
Gray clay loam (very stiff to hard) with a little gravel	10	69. 5
AMF J-15		
Concrete	0. 5	0. 5
Light-brown coarse loamy sand (moist)	2	2. 5
Light-brown sand (moist)	2	4. 5
Brown coarse sand (moist) with a little gravel	1. 5	6
Light-brown sand (moist) with a little gravel to about 9 ft, then with some gravel	8	14
Grayish-brown coarse sand (moist) with some gravel	4	18
Light-brown coarse sand (moist) with gravel to about 22 ft, then with some gravel	1	29
Dark-brown coarse sand (moist) with some gravel and a lens of clay loam at 31 ft	3	32
Grayish-brown sandy loam (moist) with a little gravel and a few boulders below 57 ft	27. 5	59. 5
T 1 [4]		
Reddish-brown loamy sand and gravel	1. 5	1. 5
Reddish-brown sandy loam	24. 5	26
Gray clay loam (very stiff)	2	28

See footnotes at end of table.

TABLE 4.—*Logs of soil borings* [1]—Continued

Material	Thickness (feet)	Depth (feet)
T 2		
Brown sand and gravel	15	15
Dark-brown sandy loam	1	16
Gray gravel (dense)	2	18
Gray gravel (very coarse)	2	20
Brown sandy loam	11	31
Gray clay loam (stiff)	3	34
T 3		
Brown sand and gravel	6	6
Dark-brown sandy loam (moist)	20. 5	26. 5
Blue clay loam (very stiff)	1. 5	28
T 4		
Brown sand, some gravel	12	12
Gray coarse sandy loam	3	15
Coarse sand, some gravel	3	18
Gray sand	1. 5	19. 5
Gray sand and gravel	5. 5	25
Brown sand and gravel	10	35
Gray clay loam (stiff)	15	50

[1] See pl. 2 for location of soil borings.
[2] Borings designated "ACF" made by Caswell Engineering Co., Minneapolis, Minn., July 1958.
[3] Borings designated "AMF" made by Twin City Testing and Engineering Laboratory, Inc., St. Paul, Minn., March 1957.
[4] Borings designated "T" made for R. D. Thomas and Associates, Minneapolis, Minn.

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