Fermilab

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# Tunneling Beyond The Fermilab Site

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An accelerator that crosses the Fermilab site boundary must have a minimum effect on the surrounding environment and the people residing in the area. Unobstructed public access should be allowed above the ring except in relatively few areas such as the injection, dump, and experimental regions. The accelerator should be a benign and unobtrusive neighbor not only when it is completed but also in the construction period. For these reasons underground tunneling for all or most of the ring seems attractive. In this note we look into some questions raised by tunneling beyond the Fermilab site.

We note that construction of an underground tunnel does not require that one own the land above the tunnel. One is required only to purchase an 'easement' granting the use of a specific underground portion of the land. There is ample legal precident for such easements for gas and water lines, portions of the Chicago Deep Tunnel project, etc. Of course it will be necessary to purchase the property for access shafts, utility and experimental areas. This would tend to minimize the amount of land needed to be purchased compared to a cut and fill operation.

Most of our discussion is of general applicability. However, we will use as examples two specific ring configurations. The examples have not been optimized from the point of view of physics output or accelerator technology but are just specific examples which allow us to study questions of tunneling. One is a ring of 5 km radius (5 TeV) tangent to the Tevatron and entirely east of the Fox river. The second is ring of 20 km radius (20 TeV) west of the Fox river and fed by a beam from the Tevatron which crosses under the river. We assume that each of these machines will have 100 beam fills per year and we scale the maximum intensities with the accelerator radii. Thus we assume that there will be 1.0 E14 protons in each beam of the 20 TeV machine and 2.5 E13 for the 5 TeV machine.

We will stress only those safety problems unique to an off site tunnel, especially the radiation safety questions, and not explore the many other important safety questions common to other construction methods of a large cryogenic ring.

## Radiation Limits

The current radiation exposure limit for penetrating radiation is 170 mrem/yr for the general population. The Fermilab director has set 10 mrem/yr as a site boundary limit. The EPA has proposed a 10 mrem/yr limit for airborne radioactivity and has a regulation in effect for community water systems which sets a 4 mrem/yr limit. We assume in this paper radiation limits of 10 mrem/yr for penetrating radiation and airborne radioactivity, and 4 mrem/yr for all drinking water supplies. This translates to 20 pCi/ml for tritium and 0.2 pCi/ml for Na22. If the accelerator is to be a benign neighbor, we must be demonstrably within these limits. These EPA limits strictly apply only to community drinking water supplies defined as serving at least 25 people or 15 service outlets (taps, houses, etc.). We will apply these limits to all drinking water supplies.

## Beam Losses

In the consideration of the shielding required for the accelerator, we need consider three beam loss situations. The first is the shielding needed around the expected few high loss areas. These regions include beam dumps, scrapers, injection, etc. These areas will require special local shielding; the experience gained in designing beam dumps at Fermilab is directly applicable. Since these problems are manageable and common to any high energy machine, we do not consider them further here.

Secondly, we consider the effects of an approximately uniformly distributed loss around the ring during normal operation. Finally we must consider the effects of unexpectedly high beam losses at parts of the machine which have not been provided with special shielding. Alternatively we must be able to provide a convincing argument that the beam cannot be unexpectedly dumped in such regions.

## Hadron Radiation Shielding

Estimates of the hadron radiation field have been made (Thomas and McCaslin 1983, Van Ginneken 1983). In each of these it is found that the neutron component of the hadronic cascade gives the major contribution. One of these (Thomas and McCaslin 1983) uses a phenomenological model (the Moyer Model) whereas the other (Van Ginneken 1983) uses a standard Monte Carlo code (CASIM) (Van Ginneken 1975). Figure 1 (Thomas and McCaslin 1983) shows the dose at the shield surface as a function of the earth over burden. Note that the beam intensities assumed in this figure are four times larger than ours. These results are given as a function of a parameter, p, which is the fraction of the beam which is assumed to be uniformly lost around the ring. The rest would be disposed of in locally shielded areas. About 6 m of earth shielding is adequate (less than 10 mrem/yr) for the case of uniform 100% beam loss around the ring. In fact, we expect that most of the beam will interacted in the heavily shielded areas on the scrapers and dumps.

The case of an unexpected local loss of the total beam was also considered in the above papers. Van Ginneken 1983, considered the case of 20 TeV protons striking a magnet centered in a 1.0 m radius tunnel surrounded by wet Fermilab soil (density = 2.24 g/cm**3) using CASIM. Figure 2 shows the iso-dose contours for this case. The analysis is performed in a coordinate system where z is the distance along the central orbit and r is the distance perpendicular to the central orbit. The dose has been averaged over the 90 degree cone about the vertical plane. The numbers in parenthesis are the iso-dose contours scaled to a soil density of 1.80 g/cm**2 (dry sand). We see that the dose reaches its maximum about 25 m downstream of the initial interaction and 5-6 m of earth are adequate to reduce the surface dose to the required 10 mrem level. We assume that a person on the surface will receive at most one exposure to such an unexpected major beam loss. Such a loss would, of course, have a catastrophic effect on the machine and could not be tolerated.

## Muon Radiation Shielding

Figure 3 shows the radiation contours for muons (Van Ginneken 1983). This assumes the same geometry as for the above hadron calculation. Note that again we require about 6 m of earth shielding in order to keep the surface dose below 10 mrem if we were to have a local loss of the full beam.

The muons are highly concentrated in the forward direction. In order to keep within our radiation limits for the 20 TeV ring, the forward muons must remain underground for at least 1.8 km from the loss point. This translates into a requirement on the flatness of the site. The site should not have any substantial dips toward beam elevation along this tangent 1.8 km muon path. This translates to a strip within about 85 m of the outer perimeter of our 20 km ring. This strip should be kept free of subsurface dwellings; i.e., no deep cellars. This also sets a requirement on the nominal vertical radius of curvature for the accelerator; for a 6 m depth it must be greater than 270 km.

## Geology Of the Fermilab Region

The Fermilab site lies in western DuPage and eastern Kane counties. A major northern Illinois river, the Fox, lies about 2 km beyond the western boundary. The underground geology of DuPage county is well documented (Zeizel et al 1962) and Figure 4 shows a stratigraphic section. The surface layers are unconsolidated glacial deposits of tills, silts, sands, and gravel. Below these the bedrock consists of layers of cracked Dolomite (limestone). Figure 5 is a map showing the thickness of the glacial deposits. The Tevatron and our 5 km ring are also shown. There are many wells used for residential and public water supplies; Figure 6 shows the range of penetration of these wells into the bedrock. The geology of Kane county and the other western regions are less well documented. We assume that they do not differ significantly from that of DuPage county.

## Soil And Water Activation

A potential problem which must be given serious attention is the possible activation of residential drinking water in the neighborhood of the accelerator. Beam losses in the soil give rise to hadronic cascades which in turn form radiactive nuclei which are leached from the soil into an aquifer and then into residential wells. The only two nuclei which present a significant potenial hazard are tritium and Na22 which have half-lives of 12.3 and 2.6 years, respectively.

The existing Fermilab accelerator is located in glacial till, a clay soil through which water percolates slowly. Conservative estimates (Gollon 1978) are in the range of 3.6 to 7.2 vertical feet per year so that significant fractions of these radionuclides will decay before they reach the aquifers. The Na22 leached from the soil will decay to such a low level by the time it reaches the aquifer that it will be less of a hazard than tritium. However, if the new accelerator tunnel is placed on bedrock, i.e., in the aquifer, Na22 is the primary radionuclide of concern. Under these conditions, the migration times could be short compared to the decay time because water moves rapidly through the fractured limestone at the top of the local bedrock.

Two studies of ground water activation (Gollon 1978 and Cossairt 1980) done in conjunction with the design of beam dumps at Fermilab are useful in evaluating these effects. Following the approach of these papers, we can estimate the local ground water activity for each of our sample accelerator rings under the two beam loss conditions. For each of these loss conditions we assume the loss occurs in the aquifer or 12 m above it in a glacial till. For Na22 we assume that 2% is leachable if it is formed in rock and 7% if in a till.

The results of the two cases are based on Monte Carlo calculations. In the first, the proton beam strikes a string of magnets (point loss). In the second case, a uniform loss of the full beam for 100 fills is assumed (a full year's running).

For all cases we assume that the radioactive nuclei produced along a 0.4 km sector of the ring finds its way to a single local well. Decay losses appropriate for the drift times necessary to reach the aquifer are taken into account except for the cases where the beam is lost in the aquifer. Then we assume no decay losses. The material is then concentrated in 40 gallons of drinking water that is drawn each day from the well. The average concentrations of Na22 and tritium for all of these conditions for each of the two rings is shown in Table 1.

From Table 1 we see that in no case is tritium a problem. In the cases where the tunnel is located in the aquifer we exceed the Na22 limits and then by factors of 4-7 for the 20 TeV case. We believe that our production and collection model for Na22 is unduly conservative but at this point we do not have another creditable model. This should be an important topic of further study.

It is interesting to note that wells on the Fermilab site as close as 100 feet to the main ring have been carefully monitored for radioactivity. No radioactivity has been detected in over ten years of monitoring, and the measurements are sensitive to 0.02 pCi/ml of Na22 and 1.0 pCi/ml of tritium. The percolation model used (Gollon 1978) assumes rates which would permit radioactivity to reach the aquifer by now. A more realistic rate based on Fermilab soil measurements (Baker 1980) is one to two feet per year. Since the aquifer is 40 feet (about 12 m) below the present main ring, any radioactivity leached from the soil would not be expected to reach the aquifer yet, without a short circuit such as a sand lens would provide. However concentrations of tritium well above those allowed for public water systems have been detected in specially built collection systems under the neutrino area beam dumps. In these the ratio of tritium to Na22 has been higher than expected.

## Tunnel Size And Depth

Modern tunneling techniques utilize a rotary tunneling machine with a narrow gauge railway or a conveyor system to remove the debris to a shaft where it is carried to the surface. A minimum diameter for such a machine is about 6 feet and ones as large as 35 feet have been used. Tunnel experts tell us that between 7 and 10 feet costs do not depend strongly on diameter. A diameter of about 8 feet is considered nearly ideal. Since one would like at least 2-3 tunnel diameters of material between the tunnel ceiling and the surface, we are already providing at least 16-24 feet of earth shielding.

Radiation shielding as well as construction considerations indicate that a minimum conservative depth (surface to tunnel ceiling) of about 25 feet is reasonable. Constraints on tunnel depth are less clear. Keeping the tunnel above the aquifer is desirable to avoid the questions of ground water activation. Tunneling costs are not very dependent on tunnel depth for modest depths (a few hundred feet). On the other hand, the costs can increase substantially if one has to make transitions from the unconsolidated glacial debris to bedrock (soft versus hard tunneling). If ground water activation were not an issue placing the tunnel in bedrock would be attractive. The importance of a thorough knowledge of the local geology cannot be overstated. Soft tunneling costs are particularly dependent on changes of soil composition. Five to ten soil boring per mile of tunnel will probably be needed. Present soil boring costs are about $15 per vertical foot.

## A Sampling Of Tunnels

The Chicago 'Deep Tunnel' project has provided local construction firms with a great deal of experience in tunneling in glacial debris (soft tunneling) and in the limestone bedrock (hard tunneling). Describing some of these gives us a feeling for the magnitude of these recent projects.

The Calumet tunnel (Calumet Intercepting Sewer No. 19R2) in Cook county, Il. is a 11,512 foot tunnel made with an 8.5 foot diameter cutter and lined with concrete to a final diameter of 5.5 feet. Dug in glacial tills and having a ceiling to surface distance ranging from 20-40 feet, it was started in March 1974 (contract awarded July 1973). It progressed at 41 feet per 8 hour shift. The stated tunnel cost was $272 per linear foot but that is thought to be unrealistically low since it was part of a larger project (Kenny 1983).

The Des Plaines tunnel (Upper Des Plaines 22), also in Cook county is a 18,595 foot tunnel made with a 10.5 foot diameter cutter and concrete lined to a 7.5 foot diameter. It was a soft tunnel with a ceiling to surface distance varying from 20-40 feet. This contract was awarded in April 1980 at a cost of $563 per linear foot (Kenny 1983).

A 30,100 foot hard rock tunnel (Cal Sag Project) at an average depth of 200 feet will be dug with an 8.5 foot cutter. Tunneling speed is estimated at about 50 feet per 8 hour shift. The contract was awarded in November 1982 and construction was begun in April 1983. The cost is $498 per linear foot for the unlined tunnel. It was estimated that a concrete liner would cost an additional $125 per linear foot. This tunnel has 19 vertical shafts costing $200-225k each, or $134 per linear foot of shaft. The shaft cost is included in the $498 per linear foot cost (Malina 1983).

Two tunnels have been carefully costed (R. Bell, 1983) as part of the SLAC linear collider project. Each is an approximately semi-circular arc of 4700 feet in length and 10 feet in diameter. This pair of tunnels pass through sand, soft sandstone, and clays, while following the suface elevation. The changes of tunnel elevation require the use of rubber tired vehicles for the removal of tunnel debris rather than the more economical narrow gauge railway. This contributes to the estimated cost of about $1000/linear foot. This project is scheduled to be bid this summer (1983).

In our discussions it was clear that the cost differential between comparably sized soft and hard tunnels was not great, perhaps 25%. It was not even clear which was the more expensive. Both the dolomite bedrock and a uniform glacial till are considered good tunneling material. What was clear was that the transition between a hard and soft tunnel was expensive since the drilling techniques are different. In either case one could tunnel long distances between access shafts, a shaft every 2000-3000 feet seems near a shallow cost minimum.

Our technical problems seem well within the state of the tunneling art. Except for the tunnel being very long, it would present no new challenges. Multiple tunneling machines would most likely be used to reduce the construction time.

## A 5 km Ring In DuPage County (Mostly)

Figure 7 shows a 5 km radius ring tangent to the Tevatron at A0. Also shown is the Fermilab proposed Dedicated Collider ring. The 5 km ring, except for a small arc in the western portion, is entirely in DuPage county where the geology is well known. Note that all of Warrenville is within the ring, that it goes under the outskirts of Naperville, and that it crosses the West Branch of the DuPage river twice. The ring does not come near any obvious structures with deep foundations which might pose problems. Its location has also not been optimised to avoid any of these problems.

In Figure 7 the ring perimeter has been divided into 16 equal arcs by diameters (only 2 are shown) which have one end labeled A through H and their opposite end labeled A' through H'. Figure 8 plots the surface and bedrock elevations as a function of position on the ring. Also shown is the Tevatron elevation and the elevation of a possible accelerator ring. Note the positions of the two crossings of the West Branch of the DuPage river. At the southern crossing it may come close to bedrock.

We have selected a ring which slopes about 120 feet and is symmetric in depth about the AA' diameter. About half of the ring is in bedrock; it only enters bedrock once. We have the required amount of earth shielding above the ring to satisfy our radiation safety requirements.

Radioactivity in the ground water only becomes a concern when we are near or in the aquifer. No attempt has been made to estimate the number of wells so affected. A DuPage county regulation requires that all wells drilled in the county be registered but it is estimated that only about one half are. It would be straightforward to determine what fraction of this area is connected to a public water supply (hopefully its source is not near the ring!). By counting the residences not on a public supply (assume each has one well), a good estimate could be made of the number of wells affected. As an aside, the DuPage County Health Department is active in encouraging residents to switch from private to public water systems as they are extended and in filling in the old wells.

For the wells where there may be a radiation concern we might offer to drill them deeper (see Figure 6) so that they would not be affected by any possible contamination. It may also be desirable to drill a series of wells around the ring just for monitoring purposes since radiation levels could be detected long before the would pose a problem. We view this as a problem which needs a great deal more study, must be handled with great sensitivity, but one that is probably soluble.

The cost of the 5 km ring tunnel is probably between $500-1000 per foot. If we use $750 per foot, the cost of the ring tunnel would be about $75M. Note that this represents the cost of a bare tunnel. Utilities, access roads, drainage, suface service facilities, etc., are not included.

## Beyond The Western Suburbs - Crossing The Fox River

Figure 9 shows an extraction line from the Tevatron E0 area extending under the Fox river and deep into Kane county. The much lower population density of the western side of the Fox river makes it an attractive site for the 20 km ring. Although there is little published data on the underlying bedrock structure, some unpublished data is available (Gilkeson 1983).

Bedrock elevation maps for the Fox river region allow us to plot in Figure 10 the surface and bedrock elevations along the extraction line shown in Figure 9. Note that in contrast to the West Branch of the DuPage river, the Fox river has cut its way down to bedrock in most places. Also on Figure 10 is the extraction line sloping down about 5 mrad to cross about 30 feet under the Fox river. Note that the 5 mrad bend is very small and less than the 8 mrad capabilites of a main ring dipole. There seem to be no technical problems in tunneling underneath the Fox river athough the exact depth under the river needs detailed engineering study.

The radiation problems associated with this extraction channel do not appear serious for a number of reasons. The extracted beam has an energy of only 1 TeV and each pulse is of low intensity (about 10 E13 protons). Local shielding might be required just downstream of the downward bend magnet and near the aquifer just under the populated region of the Fox river valley.

## A 20 km Ring West Of the Fox River

The injection into a 20 TeV ring located on the western side of the Fox river does not seem to present a serious tunneling or safety problem. There is little or no published data on the bedrock elevations west of the Fox river; however, what data that does exist is being collected and forwarded to us. We are cautioned that most of these surveys were done a long time ago and are known to be unreliable in many instances (Gilkenson 1983). However we do know that the basic geology does not change in any drastic way as one goes from DuPage to Kane and on to De Kalb county. It still consists of glacial debris on top of a limestone bedrock. It is very likely that a site suitable for tunneling can be found. It is clear that the optimization of the site with respect to tunneling costs, enviromental impact (especially possible ground water activation) is a major effort that will require a considerable amount of geological field work. The much lower population density of Kane and De Kalb counties strengthen our feelings of cautious optimism that a suitable site can be found.

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Zeizel, A., Walton, W., Sasman, R., and Prickett, T., Ground-Water Resources of DuPage County, Illinois, State Geological Survey Cooperative Ground-Water Report 2, 1962.

Table 1. Worst-Case Radionuclide Concentrations in a Shallow Single-Person Well

| Proton Energy (TeV) | Tunnel Location (meters above aquifer) | Loss Point Information | $^{3}H$ Concentration (pCi/mℓ) | $^{22}Na$ Concentration (pCi/mℓ) |
|---|---|---|---|---|
| 20 | 0 | Point Loss | 16 | 1.4 |
| 20 | 0 | Uniform Loss | 10 | 0.88 |
| 20 | 12 | Point Loss | 12 | 0.15 |
| 20 | 12 | Uniform Loss | 7.4 | 0.10 |
| 5 | 0 | Point Loss | 1.3 | 0.12 |
| 5 | 0 | Uniform Loss | 3.4 | 0.30 |
| 5 | 12 | Point Loss | 1.0 | 0.01 |
| 5 | 12 | Uniform Loss | 2.5 | 0.03 |

Figure 1

Thomas and McCaslin 1983

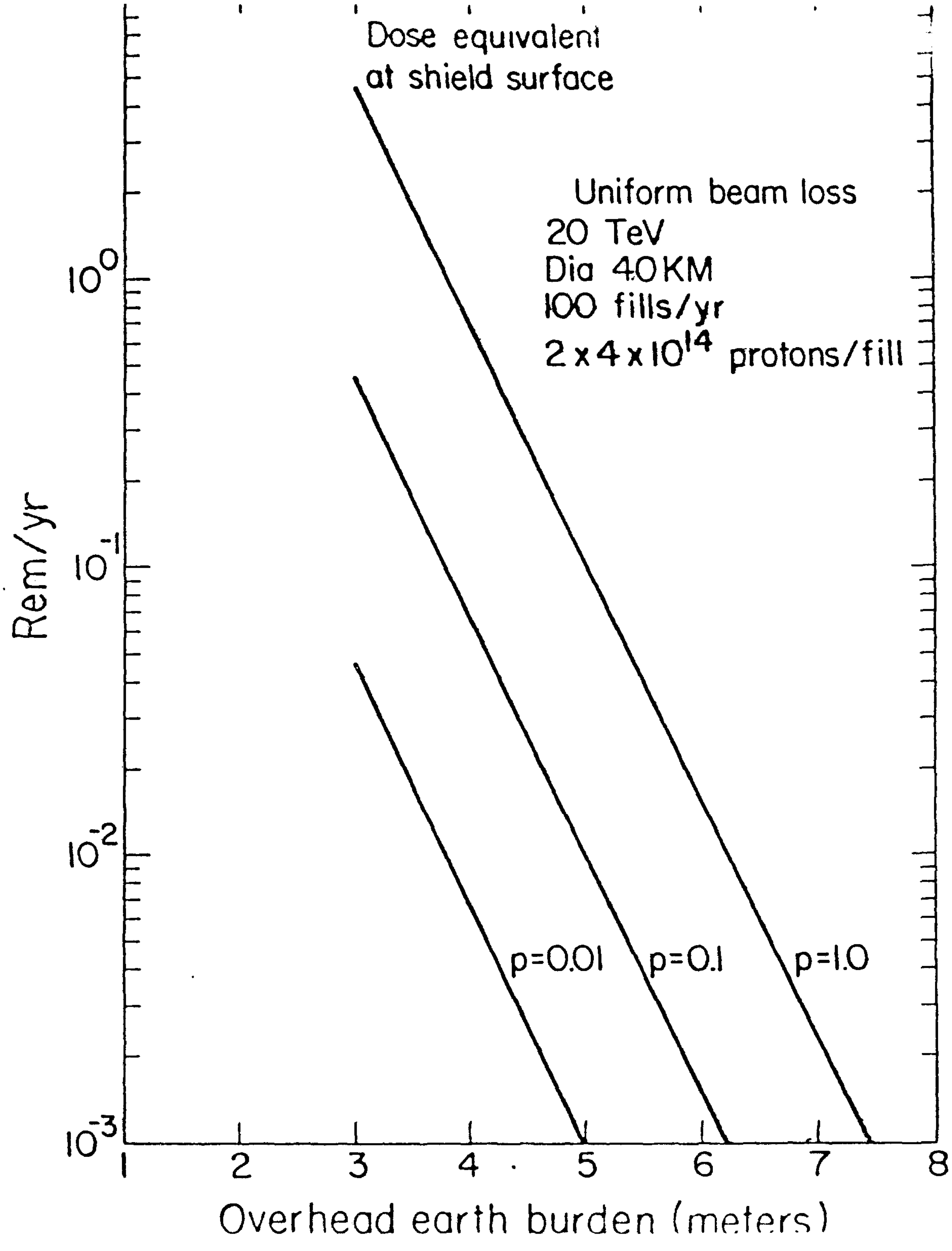
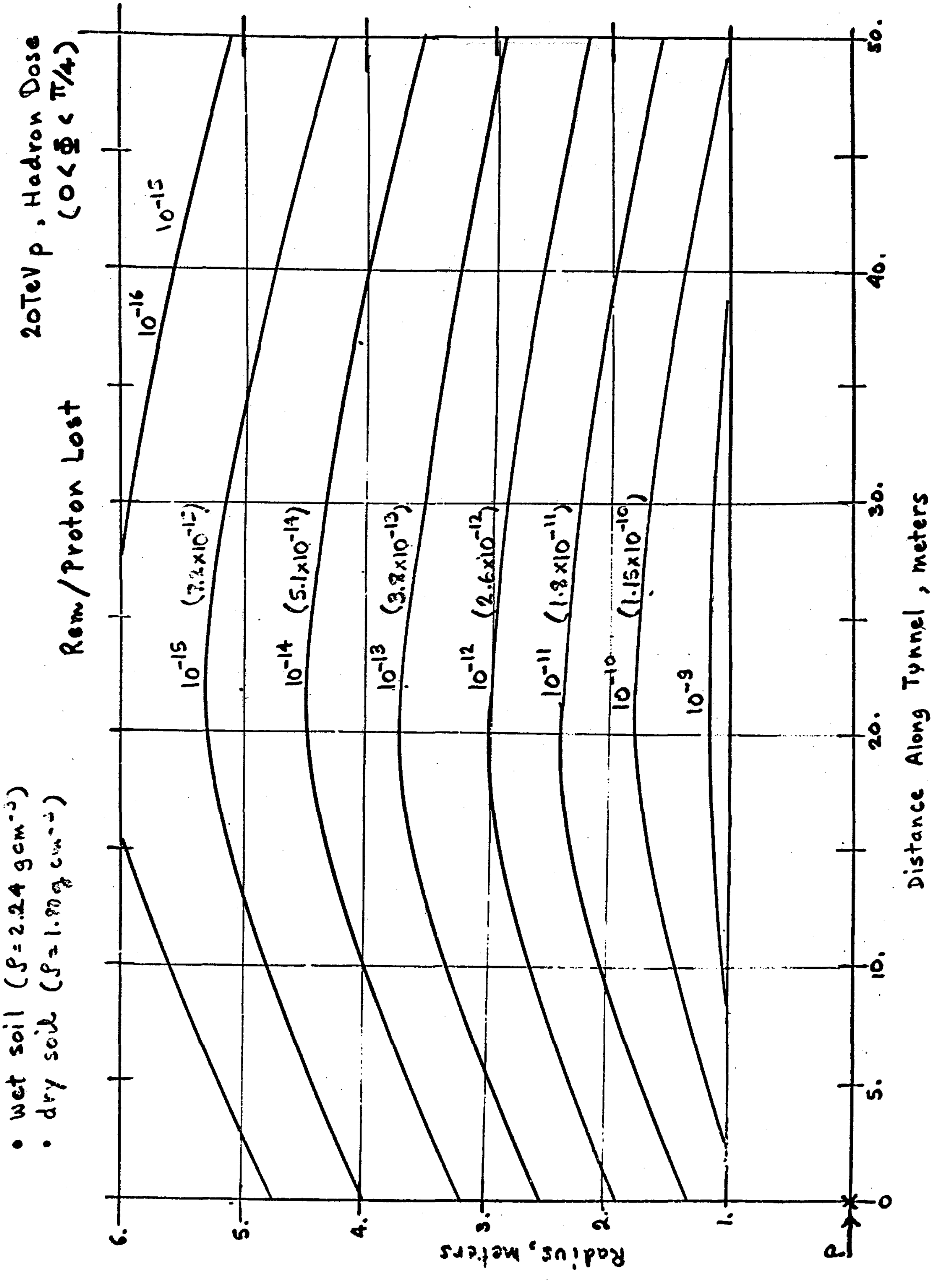
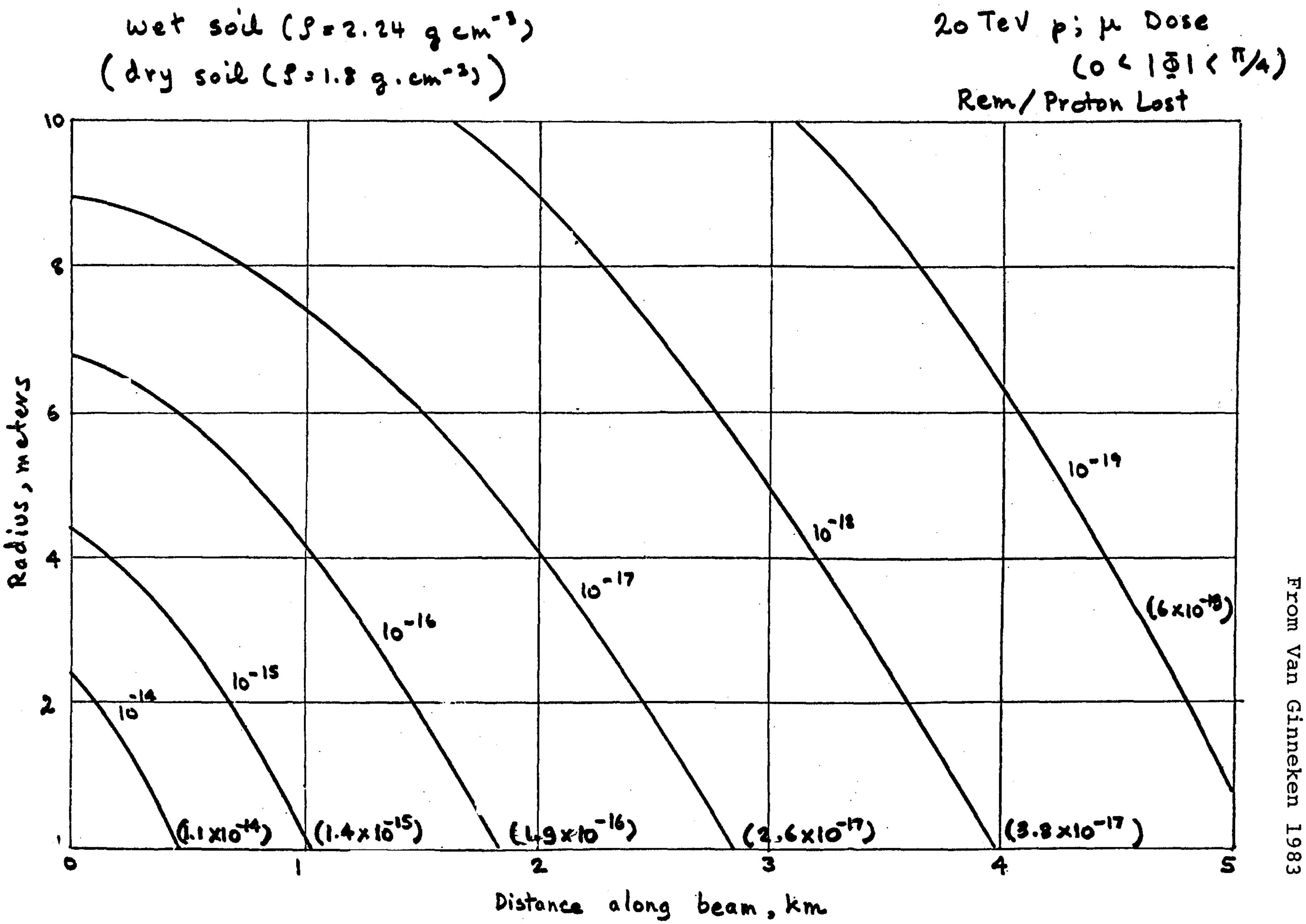


Figure 2

From Van Ginneken 1983



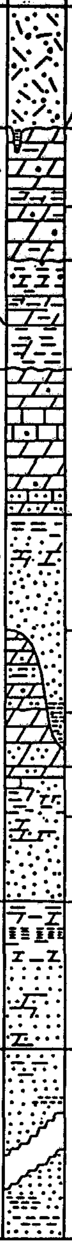


From Van Ginneken 1983

Figure 3

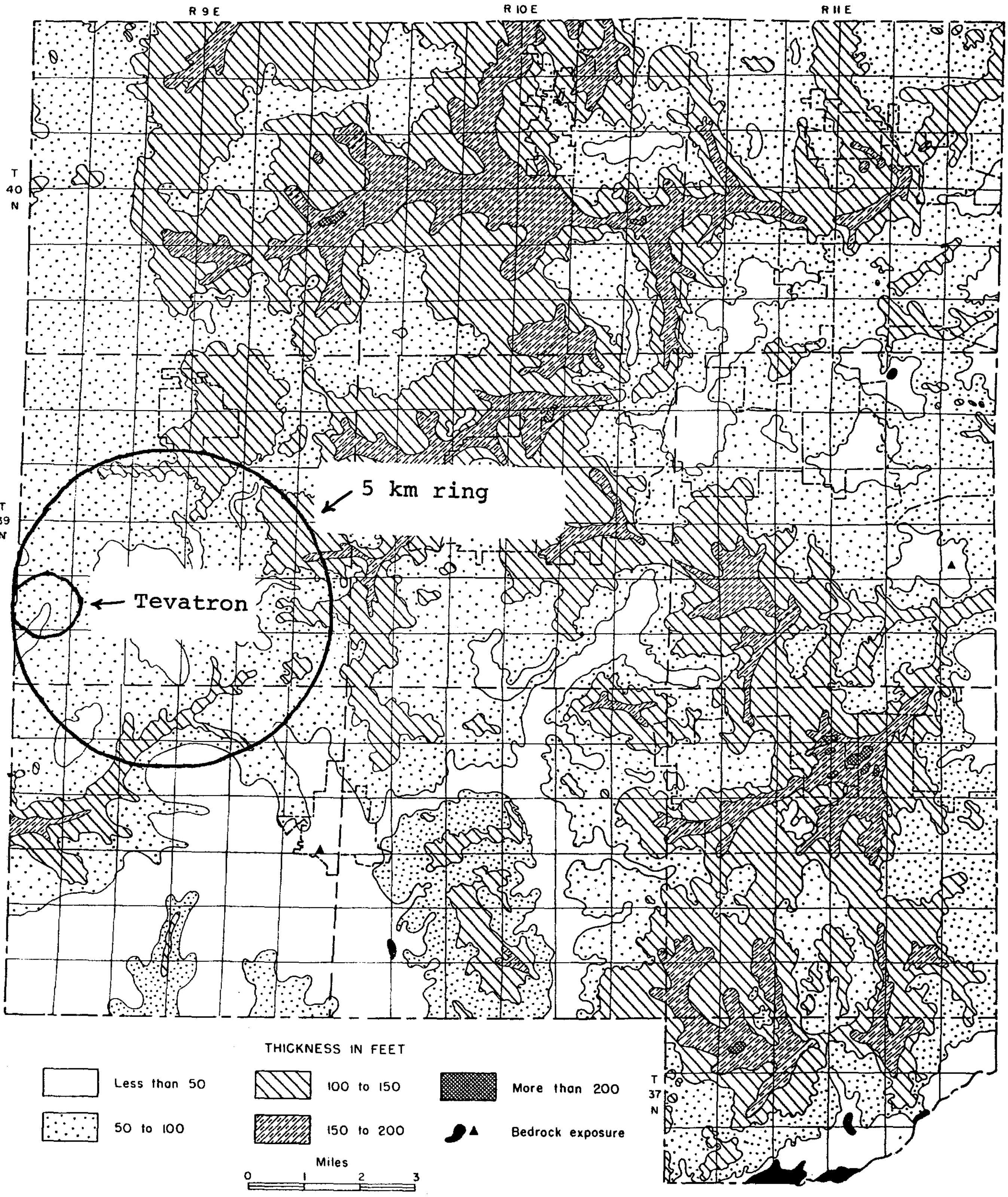
Figure 4

Zeizel et al 1962

| SYSTEM | SERIES | GROUP OR FORMATION | GEOHYDROLOGIC UNITS | | LOG | THICKNESS (FT) | DESCRIPTION | DRILLING AND CASING CONDITIONS | WATER YIELDING PROPERTIES | CHEMICAL QUALITY OF WATER | WATER TEMPERATURE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| QUATERNARY | PLEISTOCENE | | Glacial drift aquifers | |  | 0-200± | Unconsolidated glacial deposits-pebbly clay (till), silt, sand and gravel<br>Alluvial silts and sands along streams | Boulders, heaving sand locally; sand and gravel wells usually require screens and development; casing required in wells into bedrock | Sand and gravel, permeable<br>Some wells yield more than 1000 gpm; specific capacities range from 1.0 to 40.7 gpm/ft, av. 13.8 gpm/ft | Hardness from 387 to 596 ppm, av. 485 | 46° min.<br>52° av.<br>54° max. |
| DEVONIAN | | | | | | Fissure Fillings | Shale, sandy, brown to black | | | | |
| SILURIAN | NIAGARAN | Racine<br>Waukesha<br>Joliet | Niagaran aquifer | Silurian dol. aquifer | | 0-170 | Dolomite, very pure to highly argillaceous, silty, cherty; reefs in upper part<br>Dolomite, shaly, and shale, dolomitic; maroon, green, pink | Upper part usually weathered and broken; extent of crevicing varies widely<br>Chert layers slow drilling rate | Niagaran aquifer more productive than Alexandrian aquifer<br>Basal units of Niagaran aquifer locally may retard recharge<br>Specific capacities from 0.5 to 530 gpm/ft<br>Coefficient of transmissibility averages 114,000 gpm/ft | Variable hardness < 200 to >1000 ppm<br>Iron > 0.5 ppm in 60% of analyses | 49° min.<br>52° av.<br>59° max. |
| | ALEXANDRIAN | Kankakee<br>Edgewood | Alexandrian aquifer | | | 0-90 | Dolomite, glauc.; thin grn. shale partings<br>Dolomite, argillaceous, silty and/or sandy, cherty | | | | |
| ORDOVICIAN | CINCINNATIAN | Neda | Confining beds of the Maquoketa Formation | | | 0-20 | Shale, red; oolites | Shale requires casing<br>Dolomite units creviced | | | |
| | | Maquoketa | | | | 85-230 | Shale, silty, dolomitic, greenish gray, weak (Upper unit)<br>Dolomite and limestone, white, light gray, interbedded shale (Middle unit)<br>Shale, dolomitic, brown, gray (Lower unit) | | | | |
| | MOHAWKIAN | Galena<br>Decorah<br>Platteville | Galena-Platteville | Cambrian-Ordovician aquifer | | 300-350 | Dolomite, and/or limestone, cherty<br>Dolomite, shale partings, speckled<br>Dolomite and/or limestone, cherty, sandy at base | Top of Galena usually selected for hole reduction and seating of casing | Development and yields of crevices are small | Regionally hardness < 100 ppm<br>$H_2S$ often present<br>High alkalinity > 350 ppm | 54° to 55° |
| | | Glenwood | Glenwood-St. Peter | | | 200-375 | Sandstone, fine and coarse grained; little dolomite; shale at top<br>Sandstone, fine to medium grained; locally cherty red shale at base | Lower cherty shales cave and usually are cased<br>Friable sand may slough | Small to moderate quantities of water<br>Coefficient of transmissibility probably about 15% of that of Cambrian-Ordovician aquifer | Water similar in quality or slightly harder than that in Ironton-Galesville Sandstone | 53° to 56° |
| | CHAZYAN | St. Peter | | | | | | | | | |
| | PRAIRIE DU CHIEN | Shakopee<br>New Richmond<br>Oneota | Prairie du Chien | | | 0-200 | Dolomite, sandy, cherty (oolitic); sandstone<br>Sandstone interbedded with dolomite<br>Dolomite, white to pink, coarse grained cherty (oolitic), sandy at base | Crevices encountered locally in the dolomite, especially in Trempealeau<br>Casing not required | Crevices in dolomite and sandstone generally yield small to moderate quantities of water; Trempealeau locally well creviced and partly responsible for exceptionally high yields of several deep wells<br>Coefficient of transmissibility probably averages about 30% of that of total Cambrian-Ordovician aquifer | | |
| CAMBRIAN | CROIXAN | Trempealeau | Trempealeau | | | 80-190 | Dolomite, white, fine grained; geodic quartz; sandy at base | | | | |
| | | Franconia | Franconia | | | 70-100 | Dolomite, sandstone and shale, glauconitic, green to red, micaceous | | | | |
| | | Ironton | Ironton-Galesville | | | 175-200 | Sandstone, fine to coarse grained, well sorted; upper part dolomitic | Amount of cementation variable<br>Lower parts more friable<br>Sometimes sloughs | Most productive unit of Cambrian-Ordovician aquifer<br>Coefficient of transmissibility probably averages about 50% of that of total Cambrian-Ordovician aquifer | Iron usually < 0.4 ppm<br>Hardness av. 200 ppm | 55° to 58° |
| | | Galesville | | | | | | | | | |
| | | Eau Claire | Confining beds of the Eau Claire Formation (upper and middle beds) | | | 300-400 | Shale and siltstone, dolomitic, glauconitic; sandstone, dolomitic, glauconitic | Casing usually not necessary; locally weak shales may require casing | Shales, generally not water-yielding; act as a confining bed between Ironton-Galesville and Mt. Simon | | |
| | | Mt. Simon | Eau Claire (lower beds) and Mt. Simon Formations | Mt. Simon aquifer | | 2,000± | Sandstone, coarse grained, white, red in lower half; lenses of shale and siltstone, red, micaceous | Casing not required | Moderate amounts of water; permeability between that of Glenwood-St. Peter and Ironton-Galesville | Hardness from 247 to 544 ppm, av. 352<br>Chlorides increase at rate of 400 ppm each additional 25' depth below elevation -1275' | 66° at elev. -1300', increasing 1° with each additional 100' depth |
| | | | | | | | Precambrian | crystalline rocks | | | |

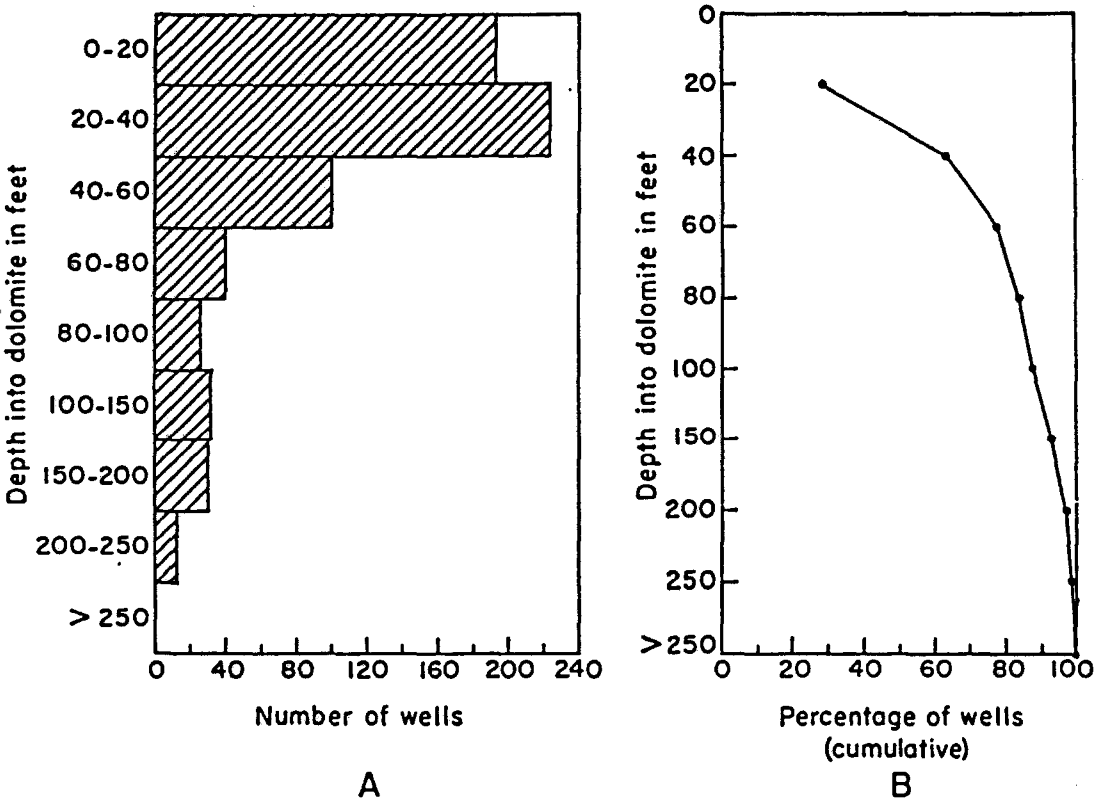
Stratigraphic section, geohydrologic units, water-yielding properties of the rocks, and character of ground water (modified for DuPage County from figure 17, Suter et al., 1959).

Figure 5



**Thickness of unconsolidated deposits.**

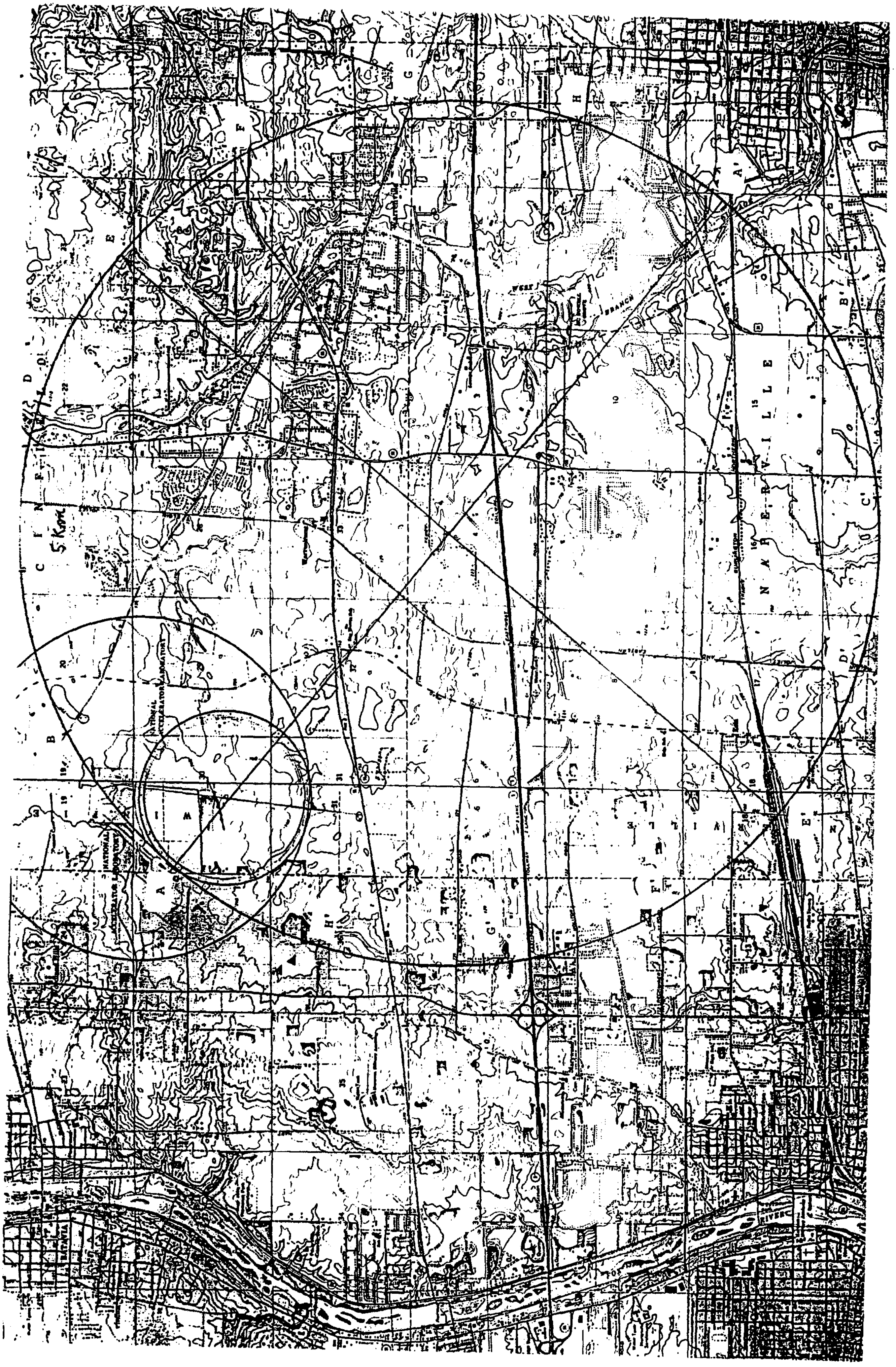
This figure taken from Zeizel et al 1962



**Number (A) and cumulative percentage (B) of wells versus depth of penetration into Silurian dolomite aquifer.**

This figure taken from Zeizel et al 1962

Figure 7



The Tevatron, Dedicated Collider, and 5 km Rings

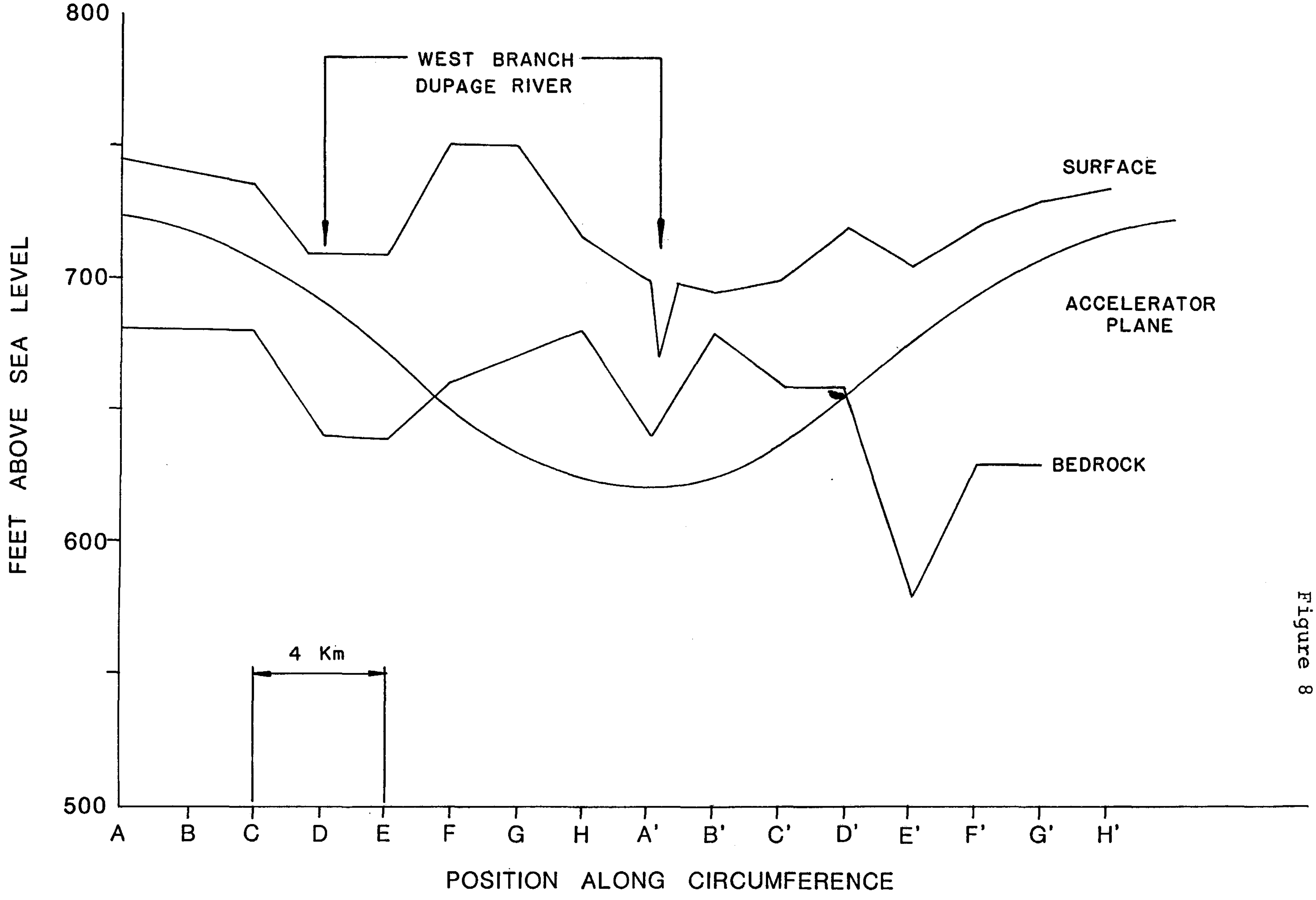

800
700
600
500
FEET ABOVE SEA LEVEL
WEST BRANCH DUPAGE RIVER
SURFACE
ACCELERATOR PLANE
BEDROCK
4 Km
A
B
C
D
E
F
G
H
A'
B'
C'
D'
E'
F'
G'
H'
POSITION ALONG CIRCUMFERENCE

Figure 8

Figure 9

Extraction Under the Fox River

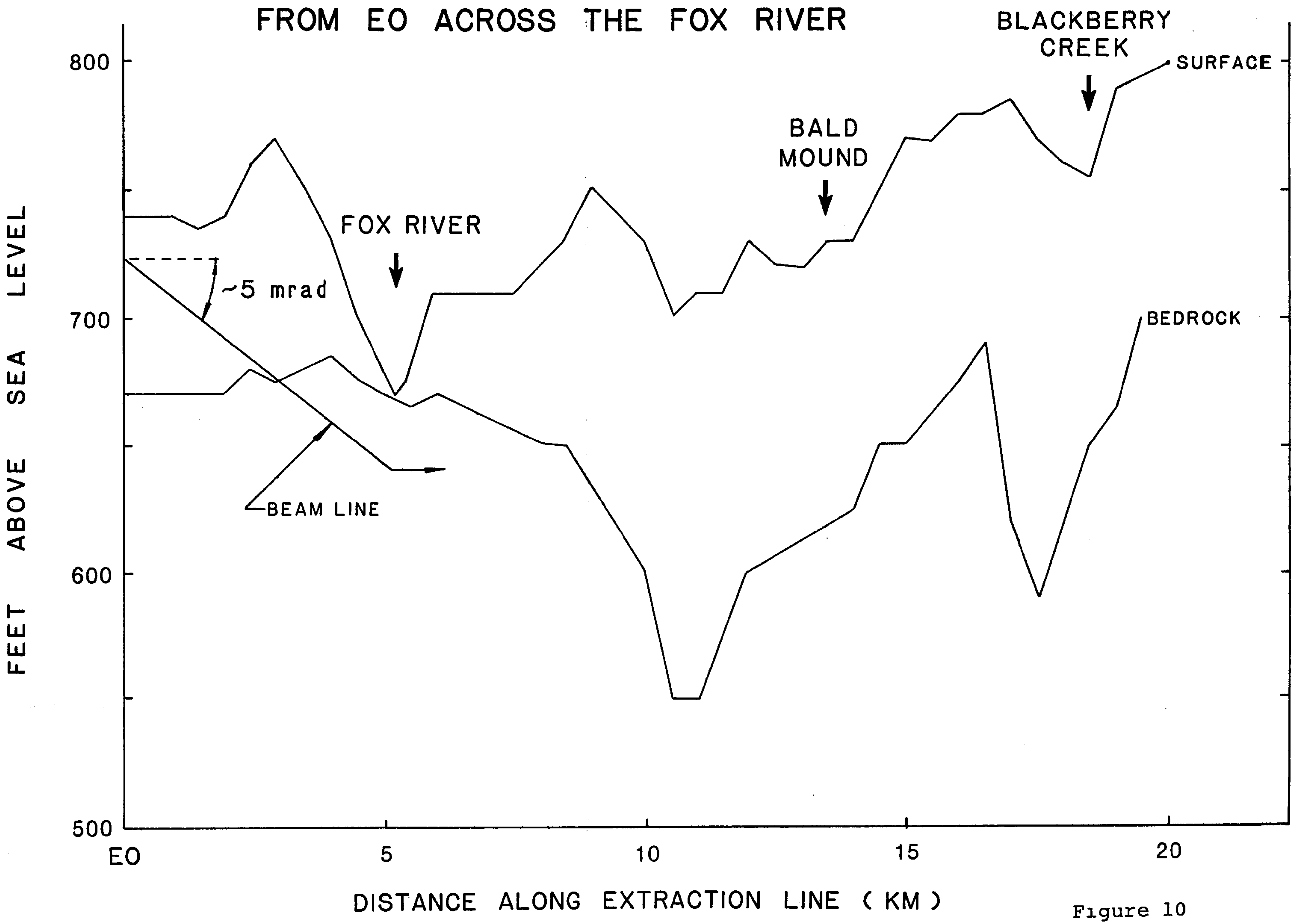

FROM EO ACROSS THE FOX RIVER
BLACKBERRY CREEK
SURFACE
BALD MOUND
FOX RIVER
~5 mrad
BEDROCK
BEAM LINE
FEET ABOVE SEA LEVEL
800
700
600
500
EO
5
10
15
20
DISTANCE ALONG EXTRACTION LINE ( KM )

Figure 10