GEOLOGIC REPORT OF THE MAQUOKETA SHALE, NEW ALBANY SHALE,
AND BORDEN GROUP ROCKS IN THE ILLINOIS BASIN
AS POTENTIAL SOLID WASTE REPOSITORY SITES

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June 1976

This report was prepared by J. B. Droste and
C. J. Vitaliano under Consultant Subcontract 7062
and 7039 with Union Carbide Corporation, Nuclear
Division. The subcontracts were administered by
Oak Ridge National Laboratory and the Office of
Waste Isolation.

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OAK RIDGE, TENNESSEE

*prepared for the U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
under U.S. GOVERNMENT Contract W-7405 eng 26*

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Abstract

We have evaluated the Illinois Basin in order to select a "target site" for a possible solid nuclear waste repository. In the process we have been mindful of the following of the following: Geology (particularly stratigraphy and lithology and structure), terrane, population density, land use, land ownership and accessibility. After taking these restrictions into account we have singled out a strip of land in south central Indiana in which we have selected four potential sites worthy of further exploration. In three of the sites the geology, lithology, and depth below the surface are more than adequate for crypt purposes in two separate formations - the Maquoketa Shale of the Ordovician System and the New Albany Shale-Borden Group of the Upper Devonian-Mississippian Systems. The interval between the two is several hundred feet. The geology and associated features in the fourth site are undoubtedly similar to those in first three. In all four selections a sizeable proportion of the land is in public ownership and the population density in the non-publicly owned land is low. The geology, lithology, and position of the target formations have been projected into the sites in question from data provided by drill core records of the Indiana Geological Survey. Precise details would, of course, require exploratory drilling on the selected site.

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Introduction

Geologic Setting

The structural feature known today as the Illinois Basin occupies parts of the States of Illinois, Indiana and Kentucky (Fig. 1). The age of the rocks at the bedrock surface ranges from Cambro-Ordovician to Tertiary. Much of the bedrock surface in the basin, however, is covered by sediment whose origin is related to Pleistocene glacial events. The basin is surrounded by several named arches and the Ozark Dome. Shelf areas are found between the arches and the deep part of the basin, and in several places folds are located between the shelf areas and the center of the basin (Fig. 1). The rocks dip from the crest of these arches and the Dome toward the center of the basin which is located in southern Illinois (Fig. 2). Figure 3 shows the regional structure on top of the pre-Cambrian surface - the surface which forms the foundation of the Basin. Regional dips of this surface, as well as major folds on it and faults that cut it, are shown. The majority of the faults are concentrated in an east-west trending zone which traverses the entire basin in the latitude of the center of the basin. It should be pointed out, however, that although the faults in southern Illinois and western Kentucky are shown

on the map as a single line, they usually mark position of a fault zone and as a result the dislocation is not necessarily restricted to a single fault plain, but rather to a series of parallel to subparallel surfaces.

Stratigraphic sections for various parts of the basin are summarized in Figure 4. The geologic columns show the nomenclature, general thickness, and rock type for each area. Rocks with suitable characteristics for consideration as potential repository units are present in the Upper Ordovician, the Upper Devonian and the lower Mississippian segments of the column. Heterogenous lithologies or excess depth ranges, combine to rule out all other rocks in the basin as possibilities for repository development.

Surface and near surface bedrock units are the source of construction material and agricultural lime in many areas throughout the basin. Rock gypsum is being extracted by subsurface methods in Indiana and fluorspar and sulfide ores are being mined in the highly faulted and mineralized region of western Kentucky. Coal of Pennsylvanian age is being mined at present by surface and subsurface methods and the extensive nature of the reserves assures that coal will be exploited in the basin for many years to come. The Illinois Basin is also the locus of numerous oil and gas fields, and exploration for new fields will continue into the indefinite future.

Repository Site Requirements

Restrictions on site selection include sufficient thickness of the appropriate strata, area size, structure and seismic potential, mineral resources potential, and environmental sensitivity.

General

Rock sections of sufficient thickness, relative homogeneity, impermeability, and at depths between 1000 feet and 3000 feet beneath the surface are major prerequisites for repository locations.

Thickness. Impermeable rock sections one hundred or more feet thick that provide suitable transmissivity and insulation properties should be sought. In the Illinois Basin thick impermeable sections are composed of shale, siltstone and interbedded shaley carbonates. Sandstones and many of the carbonates proper are too permeable and often are water and oil or gas reservoirs. Ample thicknesses of impermeable rocks are found at two intervals in the column: 1) in the Maquoketa Group of the Ordovician System and 2) in the New Albany and Borden rocks of Upper Devonian-Lower Mississippian age (see Fig. 4). Both of these rock intervals exist at depths between

1000 and 3000 feet in certain parts of Indiana. Rocks older than Maquoketa age generally are too deep and, except for the New Albany Shale and Borden Group, rocks younger than Maquoketa are too thin, heterogeneous with respect to permeability, or occur at depths too shallow to be considered.

Area size. It is our understanding that an area of nine square miles (3 miles x 3 miles) is essential to provide suitable management of surface and subsurface use. If possible, an area of twenty-five square miles (5 miles x 5 miles) should be sought so as to provide an appropriate buffer zone. Even in rural areas of the Illinois Basin it may be more difficult to secure areas large enough for the purpose, as compared to less populated areas of the west where agriculture is not such an important factor. A nine square mile area (one section surrounded by its eight bordering sections) should be selected so that in addition to possession of the proper rock characteristics minimal relocation of population and highways, both State and Federal, as well as closing of County roads are required. Lands already under the control of the U.S. Forest Service, Department of Defense, or other governmental agencies should be utilized if they meet the overall prerequisites. Although the sixteen Sections surrounding the nine

Sections would produce a desirable buffer zone, twenty-five square miles of land in the midwest may be difficult to obtain. In a very short time a large group of people with diverse interests could be marshalled to oppose removing 25 square miles of good agricultural land from food production. In fact the problem of land acquisition may well be one of the most significant factors in site location.

Geologic Structure

Faults and folds. The repository site should be free from faults and tight folds. The fault zone areas in the southern part of the Illinois Basin would undoubtedly cause some serious engineering excavation problems. In addition fault zones serve to indicate possible areas of potential high seismic activity. In this connection, the Rough Creek area (southern Illinois) fault zone, the faulted mineralized area of western Kentucky, and the Wabash River fault system (Illinois-Indiana) have been designated as seismically active areas. These areas should be avoided. Other faults, for example the Mt. Carmel fault (central Indiana), are not known to be seismically active but even so should be avoided if possible. Finally the strongly folded area of the LaSalle Anticlinal belt (Fig. 1) would present engineering excavation

problems of considerable proportions. Despite these restrictions, sufficient fault- and fold-free areas exist in the Indiana portion of the Illinois Basin from which suitable repository sites may be selected without the complications associated with faulting and folding.

Mineral resources. Areas where known and potential mineral resources exist should be avoided. Mineral resources in the Illinois Basin include oil, gas, coal, construction material, agricultural lime, gypsum, and flourspar. The belt of oil and gas production in the Illinois Basin is shown in Figure 5. Exploration for additional supplies of oil is expected to continue into the indefinite future and the areas of major drilling should be avoided. Extensive surface and subsurface coal mining also occurs in the Illinois Basin. The area of interest for this mineral coincides roughly with the distribution of rocks of Pennsylvanian age (Fig. 6). The known reserves of coal in the Basin are very large and as a result coal will continue to be mined for many years to come. Selected repository sites should be sufficiently removed from areas of coal reserves. Consequently, the large commercial coal-bearing area in Illinois eliminates a significant part of that state from further considerations. In Indiana the eastern extent of commercial coal can be approximated by noting

the location of the 250 foot thickness line of the rocks of Pennsylvanian age in Figure 6.

Underground mining of gypsum is being carried on by the National Gypsum Company and the U. S. Gypsum Company in Martin County, Indiana. Other known potential gypsum bearing strata are generally located in areas where oil and gas fields exist and/or in areas underlain by coal reserves.

Mineralization associated with igneous activity have led to mining operations in the faulted and mineralized area in the southern part of the basin (see Fig. 3) but due to the structural complexities we have eliminated that area from any further consideration.

Environmental sensitive areas. Environmentally sensitive areas, such as surface water impoundments for water supply, recreational, and wildlife management uses should be avoided. Large to medium size multipurpose surface water impoundments serve as water supply, flood control, and recreation areas. Furthermore, recreation areas with smaller water impoundments are wildlife management areas. Opposition to repository site location near such areas would be intense. Natural areas, for example the Lost River karst area of Indiana and areas being considered under the Easter Wilderness Act should be avoided if possible.

Repository Formations

As mentioned above sections of strata at the proper depth below the surface, with appropriate thickness, permeability, and heat conductivity characteristics to meet specifications for a repository site are present at two horizons in the subsurface of Indiana -- the Maquoketa Shale in the Ordovician System, and the New Albany Shale-Borden Group in the Upper Devonian-Lower Mississippian Systems.

Maquoketa Shale

General Stratigraphy. The Maquoketa Shale forms the upper part of the Ordovician System (Fig. 4). It is underlain by limestones of the Ottawa Megagroup and overlain by limestones of the Silurian system. The structure on top of the Ottawa megagroup or the base of the Maquoketa shale is shown in Figure 7. The regional thickness and distribution of the Maquoketa rocks is given on Figure 8. The carbonates and shales of the Cincinnati Series are called Maquoketa Group in Illinois and Indiana and correlation of the formation between the two states is not difficult. Precise correlation of the Maquoketa group rocks into Kentucky is uncertain at this time, consequently the Group designation is not used there (Willman and others, 1975; Shaver and others, 1970; Gray, 1972).

The lower Maquoketa of Illinois and Indiana (Fig. 4-A and B) is a shale with intercalated beds of limestone--the limestone increasing in abundance upward. The Illinois Geological Survey (Willman and others, 1975) divides the Maquoketa Group into several formations, designated from base to top as: Scales Shale, Fort Atkinson Limestone, Brainard Shale, and Neda Formation. The Scales Shale averages 75 to 100 feet in thickness with the Elgin Shale Member below and the Clermont Shale Member above. The Elgin is predominantly shale and the Clermont consists of shale and thin limestones units - the limestone beds becoming more abundant upwards. The Ft. Atkinson Limestone averages 15 to 40 feet in thickness and the Brainard Shale is generally 75 to 100 feet thick except where it has been deeply truncated by pre-Silurian erosion. The Neda Formation, a red to green iron-bearing oolitic shale, is generally less than 10 feet thick.

Although the Indiana Geological Survey does not divide the Maquoketa into formal smaller units, Gray (1972) recognizes four informal units which he calls A, B, C and D. His lower two units, A and B, are combined in this report into the lower Maquoketa and correlated with pre-Ft. Atkinson beds in Illinois. The Ft. Atkinson, Brainard and Neda of Illinois combined are

equivalent to Gray's C-unit and herein called upper Maquoketa. The D-unit of Gray is not present in the area of this report. In summary the lower Maquoketa is the only portion of the Ordovician rocks containing a sufficient thickness of shale worthy of further consideration. In Indiana the thickness of the lower Maquoketa shale increases eastward from the Illinois-Indiana state line and therefore the best opportunity to find an interval of rock, in this formation, suitable to our purpose is in Indiana.

Figure 9 shows the structure on the top of the Trenton Limestone and base of the Maquoketa shale in Indiana. The structure on top of the Maquoketa shale in the same part of Indiana is shown in detail in Figure 10. The thickness distribution for lower Maquoketa Shale is shown in Figure 11. West of the dotted line on Figure 11 the Maquoketa is almost entirely shale. East of this line it contains sporadic thin limestone beds mixed with the shale.

The New Albany Shale - Borden Group Rock Units

Rock intervals suitable for repository purposes are also present in a younger group of rocks -- the New Albany Shale (Devonian System) and the Borden Group (Lower Mississippian System). They are parts of the Knobs and the Mammoth Cave Mega Groups.

The New Albany Shale

General Stratigraphy. According to Shaver, et. al., (1970) the New Albany Shale in Indiana (Fig. 3B) is typically a black shale containing much organic matter and minor amounts of dolomite and dolomitic-quartz-sandstones (Lineback, 1970; Shaver, et. al., 1970). The formation is about 104 ft. thick at the type locality, near New Albany, Indiana (see Borden, 1874, p. 158). The New Albany Shale is widespread west and southwest of the Cincinnati Arch in Indiana. It lies conformably on the North Vernon Limestone of the Devonian System and is conformably overlain by the thin, readily recognizable Rockford Limestone of the Mississippian System. It attains a maximum thickness of 307 feet in Posey County, in extreme southwestern Indiana, and it is correlative with the New Albany Group in Illinois (Collinson, 1967) and the Chattanooga Shale in Tennessee (Shaver, et. al., 1970).

In Indiana, Lineback (1970) has divided the New Albany Shale into five lithologically distinct members. They are in ascending order; (1) Blocher Member - brownish-black calcareous to dolomitic pyritic shale (Fig. D-5); (2) Selmier Member - greenish gray dolomitic mudstone; (3) the Morgan Trail Member - brownish-black shale containing many thin pyritic beds; (4) the Camp Run Member - interbedded brownish-black shale and greenish- to olive-gray mudstone and shale; and (5) the Clegg Creek Member, a massive brownish-black silty and dolomitic-pyritic shale.

The depth (below sea-level) to the top of the New Albany Shale is shown in Figure 12. The thickness and distribution of the New Albany Shale is shown in Figure 13. The unit thins in a northeasterly direction, but nowhere in Indiana is it less than 100 feet thick, and wherever noted it exceeds that figure. In general, the uniform lithology of the unit throughout its entire thickness provides an excellent index of the increment of the New Albany Shale available for use should later tests prove it satisfactory.

The Borden Group

General Stratigraphy. The Borden Group (Fig. 3B) known as the Knobstone or Knobstone Group, is part of the lower

Mississippian System. It is composed dominantly of gray argillaceous siltstones and shales and interbedded limestones. The Borden Group has a maximum thickness of 700 feet but thins in a southerly and southwesterly direction. On outcrop along, the Ohio River, it is 500 feet thick (Pinsak, 1957, p. 30). Its lower boundary is well marked by the top of the Rockford limestone. The upper boundary is gradational - the siltstones and shales grade imperceptibly by increasing carbonate content into the Harrodsburg Limestone. In Indiana the standard stratigraphic section of the Borden Group consists of the New Providence Shale at the base succeeded, in ascending order, by the Locust Point, the Carwood, and the Muldraugh Formations. In the subsurface stratigraphy of Indiana separation of the three upper formations on the basis of lithology alone is very difficult. For convenience, therefore, the lithology of the Borden Group is usually summarized in terms of two units - the New Providence Shale and the overlying formations.

The New Providence Shale is dominantly a greenish-gray, blue-gray, or dark lead-gray shale (almost a claystone). In southern Indiana a sequence of alternating sandstones and shales is present in the upper part of the formation and ironstone lenses or beds, generally less than 1 foot thick, are distributed throughout.

The strata overlying the New Providence Shale are composed of siltstone, shale, limestone, and cherts. The base of this unit is a coarse siltstone. It is overlain by finer-grained siltstone which in turn is overlain by shale, and coarse-grained siltstone. At the top of the sequence is a fine grained calcareous siltstone which contains intermittent crinoid-bearing limestones and varying amounts of chert. The limestones, however, appear at rather irregular intervals (Pinsak, 1957, p. 31) and in addition do not persist laterally for any great distance. The thickness and distribution of the usable portion of the Borden Group is shown in Figure 14.

In summary, the rocks that make up the New Albany Shale and the Borden Group have the low permeability desired for repository development. The lower unit of the New Albany Shale, the Blocher Member contains considerable organic matter and consequently will have to undergo testing in order to confirm its acceptability for the purpose. The remaining shales in the New Albany, along with the siltstones of the Borden Group provide ample thicknesses of rock with the necessary qualities to satisfy the requirements for repository purposes.

Site Selection

After considering all the above factors we have been able to select a strip of land near the eastern margin of the Illinois Basin in Indiana which contains one or more suitable repository sites. The area involved is shown in Figure 15 and consists of the U.S. Naval Ordnance Depot at Crane, Indiana and the southern segment of the Hoosier National Forest. Also shown in Figure 15 is the line demarking the eastern limit of possible sites in the New Albany Shale. That line, extending from northwestern Lawrence County to the southeastern corner of Crawford County would be slightly to the east of the usability limit of the Borden Group Rocks. The western edge of the target site bearing area is set by a line marking the eastern limit of major oil and gas exploration (Fig. 16). This line, incidently, also serves as the eastern limit of surface and subsurface coal mining. Also shown in Figure 16 is the major gypsum bearing area in southern Indiana.

In selecting our potential target sites we avoided the Lost River environmental area, the resort spas around French Lick in western Orange County and the upper Patoka River Basin with its new reservoir and recreational area in southern Orange and northern Crawford counties.

Portions of the Hoosier National Forest in Perry and Crawford Counties and the Naval Ammunition Depot at Crane, in northern Martin County, provide suitable areas and we herewith recommend for consideration as possible repository sites the areas shown in Figure 16 and marked A, B, C, and Crane N.A.D. Descriptions of sites A, B, and C follow:

Area A: Centered on Sec. 2, T. 6 S., R. 2 W., in Perry County is part of a dissected upland. The elevations in the deep valleys are at approximately 400 feet a.s.l. - the hilltop elevations are higher than 800 feet. The area is very sparsely settled and about two-thirds of the land is publicly owned (Forest Service). It is readily accessible by highway e.g., just east of Indiana Hy 37 and north and west of Indiana Hy 66. In addition several good county roads cross the area. Its southern boundary is adjacent to the German Ridge Recreation Area, Hoosier National Forest, and the German Ridge oil field is nearby.

In this area 350 to 400 feet of lower Maquoketa Shale is expected and the shales and siltstones interval of the New Albany-Borden units should be at least 200-250 feet thick. Data in the files of the Indiana Geological Survey indicate that oil and gas in commercial quantity has never been produced from the German Ridge field.

The major advantages of this location are:

1. Significant acreage is held by the Forest Service;
2. The area is very thinly populated;
3. A buffer zone of eight sections around Section 2 should not be difficult to obtain;
4. Lower Maquoketa and Borden-New Albany thickness is appropriate;
5. The area is low on structure and away from anticipated oil and gas exploration;
6. No coal reserves are known;
7. The area is distant from seismically active regions;
8. The Supervisor of the Hoosier National Forest has designated this area as one where subsurface use would not greatly interfere with planned surface use by the Forest personnel.
9. Transportation routes are near to the area.

The disadvantages of this location are:

1. The nearest well cutting Ordovician rocks are five to eight miles from Section 2;
2. Surface topography restricts the amount of level land available.

Area B: Located in Sec. 5 or 6, T. 4 S., R. 1 W., Perry County is in moderately dissected upland. Deep Valley elevations are less than 450 feet a.s.l. and the high ridge tops exceed 800 feet. The population density is low and located mainly on small farms which occupy the ridge tops. About 40 percent of the area is owned by the Forest Service. The western boundary of the area is delineated by Indiana Hy 37, the eastern boundary by Indiana Hy 66. Interstate Hy 64, U.S. 460, Indiana Hy 62 and 37 are just to the north.

In area B 300-360 feet of lower Maquoketa shale is expected - the shales and siltstones interval of the New Albany-Borden rocks should be between 200 and 250 feet thick. Three small fields (the Branchfield, the St. Croix, and the Bristol South) which have been prospected for oil and gas, are nearby. Data on file with the Indiana Geological Survey indicate that neither oil nor gas is known to have ever been produced from the Branchville field, about 500 barrels of oil were produced before 1973 from the St. Croix field, and that some production is probable, at this time, from the Bristol South field.

Advantages of Area B are:

1. Some acreage in Area B is held by the Forest Service;
2. The area is thinly populated;

3. A buffer zone of eight sections should not be too difficult to obtain;
4. Lower Maquoketa and Borden - New Albany thickness is appropriate;
5. The area is not structurally high;
6. No coal reserves are known;
7. The area is distant from seismically active areas;
8. The Supervisor of the Hoosier National Forest has designated this area as one that will not produce serious conflict with planned Forest Service surface use;
9. The area is close to transportation routes.

The disadvantages of the location are:

1. Less land (than Area A) is already held by the Government;
2. Only one deep well cutting Ordovician is within the area;
3. Although more level or gently sloping land is available than in Area A, the amount of level land is not high.

Area C: Sec. 9, T. 3 S., R. 2 W., is mainly in Crawford County and partly in Perry County. Its southern boundary is

approximately 2 miles north of the northern boundary of Area B. The area is in moderately dissected upland. Elevations in the deepest valleys are at about 500 feet a.s.l. - ridge top elevations exceed 850 feet. Population density in the area is low. The land, however, is mainly privately owned - only a small acreage is held by the U.S. Forest Service or by the state of Indiana as State Forest. In the interval between Areas A and B are several highway , including Interstate Hy 64 as well as a branch line of Southern Railroad. In addition the area is traversed by several good county roads.

About 300-350 feet of lower Maquoketa shale is to be expected in this site and the thickness of its shales and siltstones interval in the New Albany-Borden rocks should be between 300 and 350 feet. Three oil and gas fields in the proximity (the Eckerty, Birdeye, and Siberia) are not known to be in production of either oil or gas.

The advantages of this location are:

1. Some acreage is already held by the U.S. Government and the State of Indiana;
2. The area is thinly populated;
3. A buffer zone of eight sections should not be too difficult to obtain;

4. Lower Maquoketa and Borden-New Albany thickness is appropriate;
5. The area is not structurally high;
6. No coal reserves are known;
7. The area is distant from seismicly active areas;
8. The Supervisor of the Hoosier National Forest has designated this area as one that will not produce serious conflict with planned Forest Service surface use;
9. The area is close to transportation routes;
10. More land with gentler slopes is available.

The disadvantages of this location are:

1. Not as much acreage is already under government ownership;
2. Only one deep well cutting Ordovician is within one mile of the area limits.

Area D: Area D offers the greatest potential from the security point of view. This large area in Martin County is the U.S. Naval Ordnance Depot at Crane, Indiana. The same general advantages as A, B, and C apply to area D. The great additional advantage is that the entire area is already a military zone. No specific section has been selected for

Area D. We are not familiar enough with the surface land use in this area to select the least competitive site. Consultation with the Commanding Officer and his staff will be necessary before any meaningful recommendation can be made. With cooperation from the Department of Defense this area could be utilized with least difficulties. Throughout this area 230-300 feet of lower Maquoketa Shale is expected. The shales and siltstones interval of the New Albany-Borden rocks may be at least 300 to 350 feet thick.

Summary and Conclusions

All selected areas are located in maturely dissected upland. Much of the land is in the public domain. Agricultural acreage on private lands is generally small and somewhat marginal with respect to productivity. Large areas within the Hoosier National Forest are nonproductive land, abandoned, for economic reasons, by former owners.

The designated areas are also sufficiently removed from seismically "active" areas in southern Illinois, western Kentucky and southwestern Indiana along the lower reaches of the Wabash River. Geologists of the Indiana Geological Survey do not expect that large coal or rock gypsum deposits will ever be discovered in these areas. However, the U. S.

Forest Service data shows extensive leasing for oil exploration in much of the Hoosier National Forest, particularly on privately owned land.

Within areas A, B, and C a one square mile, "one section", area has been selected as a central area to contain the site for positioning an exploratory well. The sparsity of deep wells in Perry and Crawford Counties has limited the amount of detail with which to depict satisfactorily the local structure unless structure maps are drawn on rather shallow stratigraphic units, e.g. the structure of the region on top of the Cypress Formation of the Mississippian system as given by Sullivan (1972). The Cypress is a common target reservoir unit for oil and gas exploration in southwestern Indiana. The one square mile site designations we have selected are thought to be as far "off-structure" as can be ascertained at this time. Thus, they avoid areas where shallow oil and/or gas may be trapped.

Acknowledgements

We wish to express our thanks to the Indiana Geological Survey for permission to examine the records and the lithologic strip charts of wells drilled in Indiana, which are on file in the Geological Survey Building at Bloomington.

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Appendix

General Information Concerning the Gas Storage Facility of Texas Eastern Transmission, Jackson County, Indiana

The Texas Eastern underground gas storage facility in Section 27, Township 7 North, Range 6 East, Jackson County, Indiana is in the Maquoketa Group. Two storage vaults have been constructed; one is already in service and the second one will go into service very shortly. The prime contractor was the Fenix and Scisson Company.

The engineering data summarized below was provided by Mr. T. Thompson, Texas Eastern's project engineering superintendent. The total underground storage of the installation has the capacity of 668,000 barrels. The deepest elevation in the project is at the main sump 475' below the surface. The roof of the storage area is at the depth of 440 feet beneath the surface. Underground excavation produced room and pillar arrangement. The pillars are 40 feet by 40 feet; openings between pillars are 18 feet wide and 25 feet high.

The roof of the vault is a shaley limestone about five feet thick which occurs about 100 feet below the top of the

Maquoketa Group. After excavation the vault is pressurized with nitrogen (in order to purge oxygen) to 125 pounds per square inch, about four times the pressure to be used for gas storage. The water level in several peripheral observation wells are checked at the same time in order to determine possible vault leakage. Following this stage the nitrogen is purged with propane injected at a pressure of approximately 25 to 30 pounds per square inch. The second vault has now reached the propane injection stage.

The five foot limestone bed proved a very satisfactory roof and the entire Maquoketa sequence highly impermeable -- absolutely no water problems of any kind were encountered. A number of thin limestone beds of varying thickness encountered during the excavation caused no engineering problems whatever according to Mr. Thompson. Fenix and Scisson were the prime contractors for the project. Thompson was the Texas Eastern engineering superintendent and Fenix and Scisson the prime contractor for an underground gas storage project completed earlier north of Cincinnati, Ohio.

Samples of the roof rock, the shale below the roof, and the thin limestone beds within the shale were in Mr. Thompson's possession. The Petroleum Section of the

Indiana Geological Survey at Bloomington has on file samples from four wells drilled for the project. The Regional thickness pattern of the Maquoketa Shale suggested that it is about 700 feet thick in northeastern Jackson County. There the upper 100 feet of Maquoketa consists of interbedded shales and limestone. Below this level shales become the predominant lithology with thin and discontinuous limestone beds decreasing in abundance downward. It is estimated that about 220,000 cubic yards of rock, predominantly shale, was excavated to produce the underground vault.

Sample Study of Core Material

Two cores taken during development of the Texas Eastern underground vault are on file in the core library of the Indiana Geological Survey, Bloomington, Indiana.

1. Survey File Core #161. Texas Eastern Transmission
#1 Texas Eastern Transmission, completed 12-2-1957.
Elevation 650'. NE NE NW, Section 27, Township 7
North, Range 6 East.
2. Survey File Core #539. Texas Eastern Transmission
#7 Fenix and Scisson, completed 12-2-1975. Elevation
639'. SW NW, Section 27, Township 7 North, Range 6
East.

Samples from these cores have been studied by means of the microscope and x-ray powder methods. The shale and fine grained siltstone is light, medium and dark gray in color with lesser amounts of pale greenish gray shades. These rocks range from noncalcareous to moderately calcareous, mottled, thinly laminated to massive beds with very low permeability. Within the shales and along bedding planes horn corals, brachiopods, bryozoans, and echinodermal clasts are found. The dominant mineral of the shale/siltstone is quartz with dominant grain size in the fine to medium silt range. In the noncalcareous beds quartz usually makes up 70 percent or more of the bulk mineralogy. In the very clay-rich layers clay mineral abundance approximates 30 percent of the bulk mineralogy. X-ray studies indicate that illite is the predominant clay mineral present. Chlorite, another clay mineral, attains a maximum abundance of about 20 percent of the total clay mineral composition.

The shale/siltstones are interbedded with and grade into argillaceous limestones. The calcareous shales and argillaceous limestones both have acid insoluble residues ranging from 50 to 90 percent by weight. Quartz, clay mineral, very small amounts of pyrite, and organic matter of unknown composition comprise the acid insoluble residue.

The limestones are medium to dark gray in color and very fine grained. X-ray data indicate that the carbonate present is calcite; in only one sample was there a hint of dolomite. The calcite is present mainly as fossil clasts. Horn corals up to three inches in size are present as are branching bryozoans whose lengths approach two inches. Whole brachiopods up to two inches in long diameter form clasts embedded in a matrix of silt and sand sized fossil fragments mixed with terrigenous detritus. The limestones are tightly impermeable, a drop of acid on the split core sinks in very slowly. The purest limestone sample examined contained 20 percent by weight acid insoluble residue. This residue was composed of quartz and clay minerals.

A general description of the Ordovician rock in the cores follow:

Survey file core #539. Core recovery excellent.

Silurian. Sexton Creek (Brassfield) Limestone base at 332 feet.

Ordovician. Maquoketa Group.

Unit #1. 332 feet to 343 feet. 11 feet.

Siltstone, light gray to greenish gray, massive, faintly laminated and mottled irregularly, very tight.

Unit #2. 343 feet to 370 feet. 27 feet.

Siltstone/shale, medium to dark gray, slightly calcareous. Thin beds (1 to 3 inches) of argillaceous limestone interbedded and comprising about 30 percent of the unit. The entire unit is very tight.

Unit #3. 370 feet to 440 feet. 70 feet.

Alternating beds of shale/siltstone and limestone in approximately equal amounts. The shale/siltstone is medium to dark gray in color, is slightly calcareous to calcareous, contains single fossils surrounded by terrigenous matrix, and exists as intervals from less than one inch thick to one foot thick. The limestone is medium to dark gray biomicrudite, very argillaceous, and individual beds are from less than one inch thick to less than one foot thick. The entire interval is tight.

Unit #4. 440 feet to 450 feet. 10 feet.

Limestone, medium gray, biomicrudite. About 20 percent of the unit is comprised of thin (up to one inch thick) interbeds of calcareous siltstone/shale. The entire unit is tight. This unit probably forms the roof of the underground cavity.

Unit #5. 450' to total depth = 496 feet. 46 feet.

Shale/siltstone, medium gray, slightly to moderately calcareous. Thin (up to 2 inches thick) interbeds of very argillaceous limestone comprise about 15 percent of the unit's thickness. The entire unit is very tight. The storage cavity is within this unit.

Survey file core #161. Core recovery about 85 percent.

Silurian. Sexton Creek (Brassfield) Limestone base at 339 feet.

Ordovician. Maquoketa Group.

Unit #1. 339 feet to 342 feet. 3 feet.

Siltstone, light greenish gray to light gray, massive, mottled irregularly, very tight.

Unit #2. 342 feet to 350 feet. 8 feet.

(Unit #1 and Unit #2 in this core correlate with Unit #1 in SFC #539 above).

Shale/siltstone, medium gray, faintly laminated and mottled irregularly, slightly calcareous, very tight.

Unit #3. 350 feet to 379 feet. 29 feet.

Shale/siltstone, medium to dark gray, slightly to moderately calcareous. Thin beds (up to 3 inches) of very argillaceous limestone interbedded and comprising about 30 percent of the unit. The entire unit is very tight. This unit correlates with Unit #2 in the other core described above.

Unit #4. 379 feet to 440 feet. 61 feet.

Alternating beds of shale/siltstone and limestone in approximately equal amounts. The shale/siltstone is medium to dark gray, generally calcareous, contains single fossil clasts imbedded in terrigenous matrix and exists as intervals of less than one inch in thickness to less than one foot in thickness. The limestone is medium to dark gray biomicrudite, very argillaceous, and individual beds range from less than one inch thick to less than one foot thick. The entire interval is tight. This unit correlates with Unit #3 in the previously described core.

Unit #5. 440 feet to 460 feet. 20 feet.

Limestone, medium gray biomicrudite, argillaceous. About 20 percent of this unit is comprised of thin (up to one inch thick) interbeds of calcareous siltstone/shale. The entire unit is tight. The roof of the underground cavity is within this unit. This unit correlates with Unit #4 described in previous core.

Unit #6. 460 feet to 478 feet. 18 feet.

Shale/siltstone, medium gray, moderately calcareous, with about 10 percent of the unit made up of interbeds of very argillaceous limestone beds up to one inch thick.

Unit #7. 478 feet to 481 feet. 3 feet.

Limestone with interbedded shale/siltstone as in Unit #5 above.

Unit #8. 481 feet to total depth at 503 feet. 22 feet.

Shale/siltstone with thin interbedded limestone as in Unit #6 above.

The storage cavity is within the interval of Units #6, #7, and #8.

Summary

The shales and limestones of the Maquoketa Group are impermeable rocks and their distribution is predictable. The interbedded limestone and shales of the upper Maquoketa proved entirely satisfactory with respect to utilization for underground gas storage. Engineering problems are minimal and the mining operation is "dry". The lower Maquoketa which contains more shale with much less interbedded limestone is even less permeable than the upper Maquoketa and provides a rock with a very high potential for solid waste disposal development.

Figure 1. Diagram of the Central Interior lowland showing the location of the Illinois Basin and the surrounding geologic structures (after Bond et. al., 1970).

Figure 2. Cross section showing the structure, attitude, and distribution of the geologic formations in the Illinois Basin. The cross-section is oriented N.S. A similar section with E.W. orientation would show shallow dips on the east (Indiana) side and steep dips on the west (Illinois) side (after Willman, et. al., 1975).

Figure 3. The regional structure on top of the Precambrian basement of the Illinois Basin. The prominent alignment of faults crossing the southern part of the structure is actually of a series of fault zones (after Bond, et. al., 1971).

Figure 4. Stratigraphic columns showing the geologic formations and lithology to be encountered in different parts of the Illinois Basin (after Willman, et. al., 1975).

Figure 5. Planimetric map of the Illinois Basin showing the location of oil and gas producing areas. The abandoned Trenton gas field of northern Indiana is well removed from the proposed area for the repository sites (after Bond, et. al., 1971).

Figure 6. Planimetric map showing thickness and distribution of the Pennsylvanian System in part of southern Indiana (after Bond, et. al., 1970).

Figure 7. Planimetric map showing the structure on top of the Ottawa Megagroup in the Illinois Basin (after Bond, et. al., 1970).

Figure 8. Planimetric map showing the thickness of the Maquoketa group in the Illinois Basin (after Bond, et. al., 1970).

Figure 9. Planimetric map showing the structure on top of the Trenton Limestone in part of southern Indiana.

Figure 10. Planimetric map showing in detail the structure on top of the Maquoketa Shale for part of Indiana.

Figure 11. Planimetric map showing in detail the thickness and distribution of the Maquoketa Shale in part of Indiana. The dividing line between the shale rich western part and the limestone bed containing eastern part of the formation is shown.

Figure 12. Planimetric map showing in detail the depth to the top of the New Albany shale in part of southern Indiana.

Figure 13. Planimetric map showing the thickness and distribution of the New Albany Shale in part of southern Indiana.

Figure 14. Planimetric map showing the thickness and distribution of the shales and siltstones of the Borden Group in part of southern Indiana.

Figure 15. Planimetric map showing, in outline, the areas, in southern Indiana, containing the appropriate thicknesses of the useful lithologies.

Figure 16. Planimetric map of the area selected for possible repository sites in southern Indiana showing the eastern limit of major oil and gas exploration as well as the eastern limit of surface and subsurface coal mining.

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