THE POTENTIAL FOR UNDERGROUND COAL GASIFICATION IN INDIANA

Final Report

to the

Indiana Center for Coal Technology Research (CCTR)

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1 Project Description

1.1 Project rationale

Currently, Indiana mines over 35 million tons of coal a year, or about 3.5% of total U.S. coal production. The potential energy of Indiana coal reserves exceeds that of US oil and gas reserves. Indiana, however, generates only half of its coal-fired electricity using its own coals and imports over ten times the coal tonnage than it exports. Owing to some of the advantages that are inherent in the process, such as relatively easy sulfur removal, the gasification of coal is being assessed as one of the options for the future use of Indiana coals. The gasification process produces syngas (a mixture of CO, H_2, and other constituents), which can be used for the generation of electricity or for the production of liquid hydrocarbon fuels, natural gas surrogates and other valuable chemical products. Although CO_2 is also generated during the process, advanced coal gasification methods include solutions for carbon capture with lower costs than in conventional coal-fired power plants. It is expected that carbon sequestration will become a commercial technology, and become required in newly constructed power plants.

Earlier feasibility analyses focused on the construction of new coal gasification plants in Indiana (http://www.purdue.edu/dp/energy/CCTR/researchReports.php). Meanwhile, there exists an alternative method, denoted ***underground coal gasification*** (UCG), in which injection and production wells are drilled from the surface and linked together in a coal seam. Once linked, air or oxygen is injected and the coal is ignited in a controlled manner. Water present in the coal seam or in the surrounding rocks flows into the cavity formed by the combustion and is utilized in the gasification process. The produced gases (primarily H_2, CO, CH_4 and CO_2) flow to the surface through one or more production wells. After cleaning, these gases can be used to generate electric power or synthesize chemicals (e.g., ammonia, methanol and liquid hydrocarbon fuels).

The UCG process has several advantages over surface coal gasification such as lower capital investment costs (due to the absence of a manufactured gasifier), no handling of coal and solid wastes at the surface (ash remains in the underground cavity), no human labor or capital for underground coal mining, minimum surface disruption, no coal transportation costs, and the direct use of water and feedstock “in place.”

The UCG process, however, has areas of potential improvement and customization to local conditions that must be addressed through additional research and development. These improvements must advance the effectiveness of the gasification process while minimizing any potential detrimental effects on the setting. Some of the domains where improvements could optimize the process include the linking of injection and production wells within a coal seam, minimization of variation in the composition of the produced gas, and prevention of any degradation of potable groundwater supplies. There are a series of advances in drilling technologies that could be applied to address site specific circumstances. In addition, well-known accidents with uncontrolled underground coal fires, such as those near Centralia, PA, can cause public concerns about potential loss of control over the UCG process. Fortunately, it appears that all these problems can be resolved. For example, a reliable link between the multiple wells can be established by the appropriate application of specialized directional drilling technologies. The thickness, depth, composition and petrophysical character of coal seams can be determined based on geological data. To control the composition of the produced gas, the process parameters (e.g., injection pressure and flow rate, oxygen concentration) can be adjusted according to real-time surface measurements. Groundwater can be protected by appropriately siting a project and by conducting the UCG process at pressures well below lithostatic pressure and using the water that exists within the coal seam. Gas transportation costs can be decreased by optimizing the selection of potential UCG sites and by constructing power-generation or chemical plants near the UCG production facilities.

The purpose of this preliminary feasibility assessment is to analyze the potential for underground coal gasification within Indiana. A review of existing worldwide operations and geological requirements demonstrates that the application of UCG practices in Indiana has very significant potential benefits, but careful analysis of the specific geological conditions, physical and chemical properties of coals, water resources, coupled with an assessment of the state-of-the-art technologies must be conducted to identify potential UCG sites and to determine the feasibility of employing this technology in Indiana. Of particular importance is the relatively small number of active and successful operators of UCG projects around the world and that collaborations with one or two among them could be beneficial for all concerned. There are significant opportunities for economic development that will provide dividends for first movers in the Illinois basin.

1.2 Project phases

The project included three phases:

Phase 1 (April 1, 2008, - August 31, 2008)

Analysis of UCG current state of the science and technology and determination of criteria for site selection.

Responsibility: Purdue University, School of Chemical Engineering (PU)

Phase 2 (September 1, 2008, - November 30, 2008)

Analysis of Indiana's coal resources and determination of suitable UCG localities.

Responsibility: Indiana Geological Survey (IGS)

Phase 3. (December 1, 2008, - February 28, 2009)

Characterization of the most promising locations for potential UCG operations in Indiana.

Responsibility: PU and IGS

Phase 1: Analysis of UCG current state of science and technology and determination of criteria for site selection

The analysis of UCG state-of-the-science and most current technologies that are being employed globally was conducted based on extensive search of the literature, including journal articles, conference proceedings, patents and Internet publications. It should be noted that UCG has been used commercially in the former Soviet Union; thus, along with English language texts, the papers and patents written in Russian were also analyzed. Along with the literature search, it was expected to obtain useful information from active UCG experts. For this purpose, Drs. Varma and Shafirovich attended the 25th Annual International Pittsburgh Coal Conference, where UCG was among the symposium topics.

The UCG analysis was focused on the determination of selection criteria for available coal resources. The Indiana Geological Survey (IGS) in Bloomington, IN, has a defined set of criteria for underground mining, which include technological and land-use restrictions, but some

of the criteria for UCG are different. For example, the UCG process has specific requirements for the depth and thickness of coal seams that differ from those that constrain mining. In the conducted analysis, the quantitative thickness and depth criteria were established taking into account the specifics of the Indiana coals (shallow and thin coal seams). Based on the literature analysis, recommendations on some other criteria (coal properties, the seam dip, the amount of coal, groundwater availability, and land-use restrictions) were also given.

The Phase 1 Report, including the list of criteria for UCG (see Section 3), determined by the Purdue team, was forwarded to the IGS team and to the Indiana Center for Coal Technology Research (CCTR) on August 31, 2008. Later, additional review of modeling UCG processes was conducted. Also, valuable information on the history and advances of UCG technology was obtained from Dr. Michael Blinderman, Director of Ergo Exergy Inc.. In the Final report, Sections 2 and 3 were updated to incorporate these new developments. Thus, for information on the current state of UCG and the criteria for selecting potential UCG locations within the state, it is recommended that the Final report be used rather than the Phase I report.

Phase 2: Analysis of Indiana's coal resources and determination of suitable UCG locations

Based on the criteria that were determined in Phase 1 and using information on the nature and distribution of coals, the IGS analyzed the coals to determine potential locations within the state that could serve as candidate areas for possible UCG projects.. The principal sorting criteria used were coal seam thickness and depth. Only two coal seams, the Springfield and the Seelyville, that are the prime candidates for UCG were analyzed. Additional important information was considered secondarily, such as coal heating value, moisture, the distribution of mines and mined out areas, and the elements of infrastructure (power plants, gas pipelines, roads, etc.).

The Phase 2 Report, including the list and characteristics of suitable UCG locations, determined by the IGS, was forwarded to CCTR on December 1, 2008.

Phase 3: Characterization of the most promising locations for potential UCG operations in Indiana

Based on the maps generated during Phase 2, nine areas most suitable for UCG were identified. A list of various characteristics for each area, including the amount of coal present within the

given seam, was prepared, which allows for the comparison of different areas and selection of the best locations for UCG. These characteristics were analyzed and recommendations for the follow-up study were given.

In the Final Report, the current status of UCG development is described and the feasibility to use this technology in Indiana is evaluated, along with identification of the most promising locations and attributes that characterize each area. Some recommendations for future work are also given.

1.3 Deliverables

Interim Report (Phase 1). Responsibility: Purdue. Delivered on Aug. 31, 2008.

Interim Report (Phase 1) Presentation was made to Mr. M. Irwin and Dr. B. Bowen of the CCTR on Sep. 16, 2008.

Interim Report (Phase 2). Responsibility: IGS. Delivered on Dec. 1, 2008.

Interim Report (Phase 2) Presentation was made to the CCTR Advisory Board on Dec. 11, 2008.

Final Report. Responsibility: Purdue and IGS. Delivery Date: Jan. 15, 2009, extended to Feb. 28, 2009.

The Final Report presentation will be made at the Advisory Panel meeting on March 5, 2009.

2 Analysis of UCG Current State of Science and Technology

2.1 USSR (before 1991), Russia, Ukraine and Uzbekistan (after 1991)

In the former Soviet Union, an intensive research and development program on UCG was conducted from the 1930s, leading to the operation of several industrial scale UCG plants. In the 1960s, five UCG gas production stations were operating and as many as 3,000 people were involved in UCG research and development. In Yuzhno-Abinsk (Kuznetsk Basin, Russia), a UCG station produced combustible gas for 14 boiler plants in the city of Kiselevsk from 1955 until closing in 1996.[8] The only remaining commercial UCG site in the independent states formed after the FSU collapse is located in Angren, Uzbekistan. It is generally believed that UCG in FSU declined in 1970s due to the discovery of extensive natural gas resources in Siberia. Yet, over 15 Mt of coal have been gasified underground in the FSU generating 50 Gm^3 of gas. In comparison, only 50 Kt and 35 Kt of coal have been gasified in the US and Australia, respectively.

Gregg and Edgar[11] have provided a comprehensive review of UCG R&D in the USSR from the 1930s to 1970s. Later, detailed reviews were published in the Russian language.[9,12,13] Recent monographs[8,9] also review old Soviet UCG activity and, in addition, include information on recent work in Russia.

In particular, one problem of UCG technology is the necessity to *link the injection and production wells within the coal seam*. In many cases the coal seam has low permeability, and a linkage technology is necessary. After testing different methods for linking the injection and production wells, relatively inexpensive technologies have been developed in FSU, such as hydraulic fracturing of the coal seam by pressurized air (or water) (this technology is common in oil and gas industry) and the so-called *reverse combustion linking* (ignition near the production well and counter-current flame propagation towards the injection well). It should be noted that directional in-seam drilling has been successfully competing with these technologies for many decades. Nevertheless, hydrofraccing and reverse combustion linking remain attractive due to relatively low costs, and can be used either alone or in combination with directional drilling.

The results of UCG R&D in FSU are important for the selection of UCG sites in Indiana. For example, it was shown[8] that the UCG process based on injecting air produces fuel gas with heating value limited to 4.6-5.0 MJ/m^3 (123-134 BTU/cft), typically 3.3-4.2 MJ/m^3 (89-113

BTU/cft). Long-distance transportation of this gas decreases the economic effectiveness, thus, the best way is to use it (for power generation or for conversion to other products) near the UCG site. Note, however, that the heating value of the produced gas can be increased by oxygen enrichment of the injected air. This was demonstrated, for example, in UCG station in Lisichansk (Donetsk Basin, Ukraine) where cheap oxygen was available as a by-product of inert gas production.[8] Use of steam and O_2 injection may increase the heating value of the fuel gas to 10-12 MJ/m^3 (268-322 BTU/cft). Although the use of oxygen increases the costs, it may remain economically feasible. A careful cost/benefit analysis is required to evaluate different options, such as constructing a nearby power plant vs. long-distance gas transportation and using oxygen instead of air.

Another important result is related to the *coal seam thickness*. It was shown that a decrease in the seam thickness may reduce the heating value of the produced gas, which is associated with heat loss to the surrounding formation. For example, in one particular UCG plant, the gas heating value decreased significantly as the seam thickness fell below 2 m (Fig. 1). This example is important for analysis of UCG feasibility in Indiana, where most coal seams are thinner than 1 m. Note, however, that there are coal sites in Indiana with seam thickness more than 1 m and even more than 2 m. Thus, it is possible that there are Indiana sites where the coal seams are sufficiently thick and also satisfy the other UCG criteria. Identification of such sites is the goal of this project.

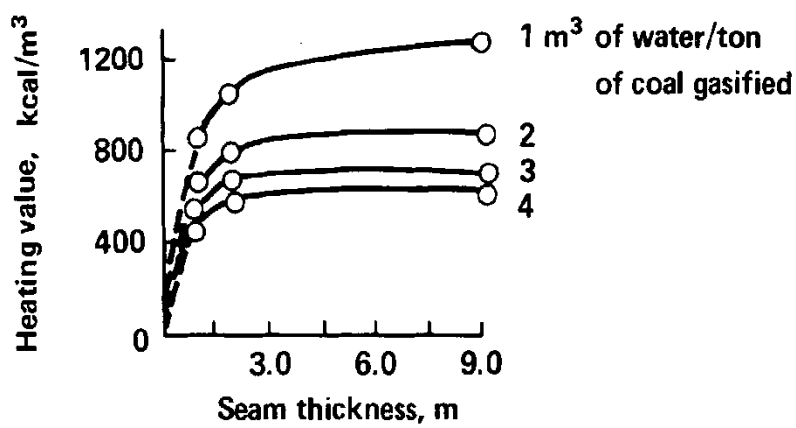

Fig. 1. Effect of seam thickness and the specific water inflow into gasification zones on the heating value of gas obtained by UCG.[11]

As mentioned above (Section 1.1), the UCG process usually consumes water contained in the coal seam and adjacent strata. Also, water can be pumped as steam, along with air or oxygen, into the injection well. In any case, some amount of water will remain unreacted, which potentially may lead to contamination of groundwater by harmful byproducts of the UCG process. To avoid this, environmental monitoring during and after the UCG process needs to be conducted. The results of environmental monitoring in FSU can be illustrated by the example of Yuzhno-Abinsk Podzemgaz station in the Kuznetsk Basin, where increases in phenol concentration in groundwater were observed, but it was concluded that water contamination during UCG was of a local nature and at admissible concentrations of harmful compounds. Specifically, phenol concentration in water samples from the UCG cavity achieved a maximum of 0.017 mg/L, but in the surrounding area, water sampled from 18 monitoring boreholes contained 0.0007-0.0042 mg/L phenol.[14] In three months after the completion of gasification operations, phenol concentration in water samples from the cavity became lower than the maximum allowable concentration of phenol in drinking water, 0.001 mg/L.[8] In addition, it was shown experimentally that coals are highly effective in removing phenols, thus ensuring self-purification of contaminated groundwater.[15] Note, however, that phenol is not a good indicator of contamination as it is water soluble and hence it can be washed away by regional groundwater flow. In contrast with phenol, compounds such as Benzene, Ethylbenzene, Toluene and Xylenes (BETX) and polycyclic aromatic hydrocarbons (PAH) are not soluble and are much more significant indicators of environmental performance. The monitoring of BETX, PAH and phenolic compounds along with inorganic contaminants has been prominent in recent UCG projects in Australia and South Africa[16], and it will be required in future UCG projects.

Research and development of underground gasification technology have been conducted in the FSU using *mathematical modeling* to simulate gasification processes and products. A steady-state model has been developed for coal gasification in a long channel with a constant cross section, where air and water flow into the channel and react with the coal.[17] This model involves heterogeneous chemical reactions:

$$C + O_2 \rightarrow CO_2 \tag{2}$$

$$2C + O_2 \rightarrow 2CO \tag{3}$$

$$C + CO_2 \rightarrow 2CO \tag{4}$$

$$C + H_2O \rightarrow CO + H_2 \quad (5)$$

$$C + 2H_2O \rightarrow CO_2 + 2H_2 \quad (6)$$

$$C + 2H_2 \rightarrow CH_4 \quad (7)$$

and reactions in the gas phase:

$$2CO + O_2 \rightarrow 2CO_2 \quad (8)$$

$$2H_2 + O_2 \rightarrow 2H_2O \quad (9)$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (10)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (11)$$

$$CO + 3H_2O \rightarrow CH_4 + H_2O \quad (12)$$

It is assumed that the flow is turbulent and the gas is radially well mixed (no gradients over the channel cross section). The model includes balance equations for gas species (O_2, CO_2, CO, H_2O, H_2, CH_4, and N_2), momentum and energy, as well as a thermal conduction equation for the coal. Kinetic parameters for the involved reactions are taken from the literature. Gas compositions and temperatures along the channel axis can be calculated for various parameters, such as the entrance pressure, air flow rate and water-to-coal ratio. In the published example, the channel cross section (area 1 m^2) was an isosceles triangle with the legs as the coal walls and the base as the inert wall. The calculations were made for the air flow rate 5,000 m^3/hr and pressure at the channel entrance 200 kPa. Figure 2 shows the calculated concentrations of the species (O_2, CO_2, CO, H_2 and CH_4) and temperatures of coal, T_c,and gas, T_g, as functions of the channel length, x, at 1 m^3 water vapor per ton of reacted coal. The profiles include three zones:

- Low-temperature oxidation zone ($x < 0.6$ m): the concentration of O_2 decreases while the concentrations of all other species increase.
- High-temperature oxidation zone ($0.6 < x < 1.0$ m): the concentration of CO_2 sharply increases while the concentrations of all other species decrease.
- Gasification zone ($1 < x < 40$ m): the concentrations of CO, H_2 and CH_4 gradually increase while the concentration of CO_2 decreases.

The obtained results demonstrate that the model describes adequately some important features of the UCG process and, according to the authors, correlates well with experiments. However, features such as coal pyrolysis and the cavity growth are beyond the scope of this model.

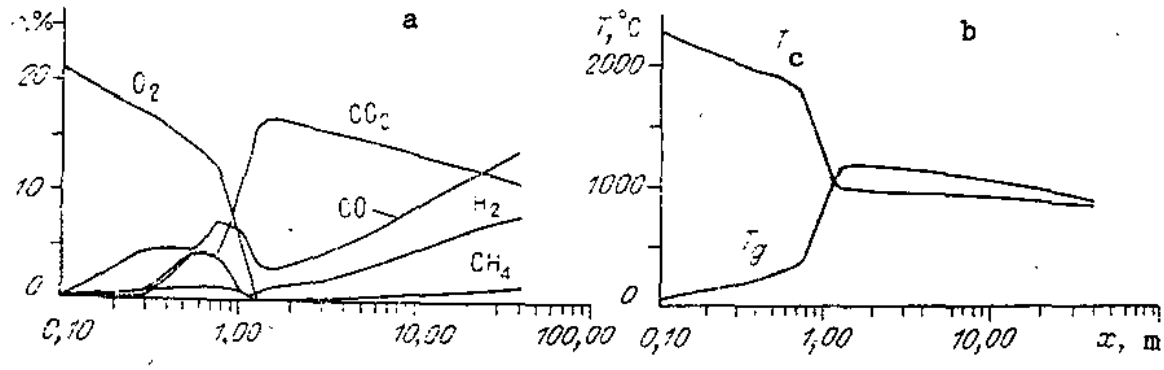

Fig. 2. Calculated (a) concentrations of the species (O_2, CO_2, CO, H_2 and CH_4) and (b) temperatures of coal, T_c, and gas, T_g, as functions of the channel length, x.[17]

Other research has assessed the effects of UCG on the strata that immediately adjoin the coal seam. Results indicate the pattern of roof deformation due to the UCG process and the filling of cavities with caved rocks is intimately linked with the physical, mechanical and thermal properties of the rock. At temperatures of 1000-1400°C rocks may deform, swell and expand.[18]

Models for interaction of gaseous products with groundwater have also been developed. Based on the monitoring data, a filtration-migration model for prediction of pollution migration from a pollution source to groundwater was developed.[19]

Currently, research and development of UCG continues in Russia and Ukraine. Figure 3 shows the number of patents in the UCG area for different countries issued from 1988 through 2007. This analysis was conducted using the database of the European Patent Office.[20] Using the database of the World Intellectual Property Organization (WIPO)[21] produced identical results. It is seen that after some period of inactivity, chronologically corresponding to the worst economic conditions in the FSU, UCG R&D is currently being reactivated in Russia and Ukraine. A search conducted in February 2009 for patent applications published in 2008, shows 5 patents taken by researchers in China, 3 in Russia, one in Ukraine and one in the US.

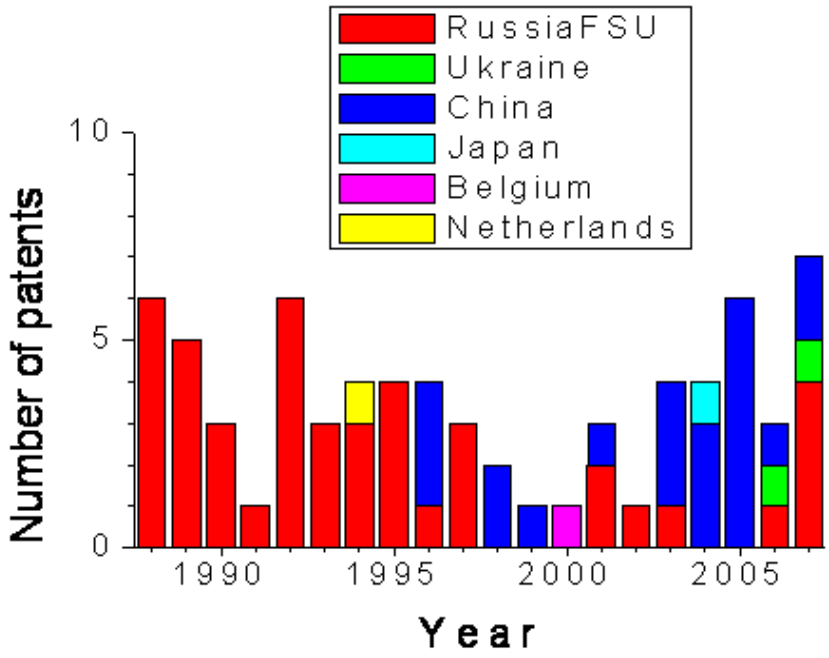

Fig. 3. Number of patents in the UCG area for the period from 1988 through 2007, where the year indicates the patent publication. Country indicates where the inventors worked ("RussiaFSU" means the former Soviet Union and, after its collapse, Russia).

2.2 United States

Initial UCG tests in the United States were conducted in Alabama in the 1940-1950s. Later, the UCG program was renewed and more than 30 experiments were conducted between 1972 and 1989 under various mining and geological conditions at various localities in the country including 4 in Wyoming, 4 in Texas, I in Washington and 1 in Virginia. Most of these were part of the DOE's coal gasification program, although some were funded by industry. The experiments included various diagnostics and subsequent environmental monitoring. A brief review of these trials has been provided by Gas Tech Inc.[5]

An important result of prior UCG work in the US is the development of the *Controlled Retracting Injection Point* (CRIP) process by researchers of the Lawrence Livermore National Laboratory (LLNL).[1,22] In the CRIP process, a production well is drilled vertically, and an injection well is drilled using directional drilling techniques to connect it to the production well

(see Fig. 4). Once the connection, or "channel," is established, a gasification cavity is initiated at the end of the injection well in the horizontal section of the coal seam. The CRIP technique involves the use of a burner attached to coiled tubing. The device is used to burn through the borehole liner or casing and ignite the coal. The ignition system can be moved to any desired location in the injection well. The CRIP technique enables a new reactor to be started at any chosen upstream location after a deteriorating reactor has been abandoned. Once the coal near the cavity is used up, the injection point is retracted (preferably by burning a section of the liner) and a new gasification cavity is initiated. In this manner, a precise control over the progress of gasification is obtained.

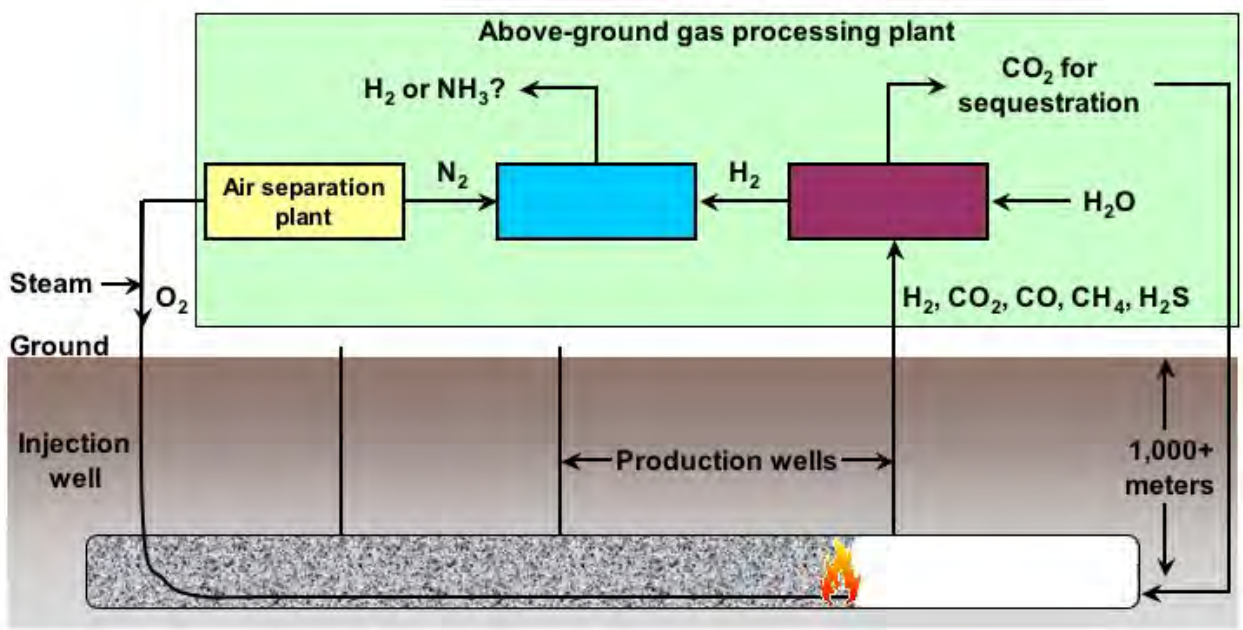

Fig. 4. Schematic of the CRIP process.[1]

The CRIP technique and clean cavern concept were used in the Rocky Mountain 1 trial, which is considered to be the most successful UCG test in the US. This trial was conducted from November 1987 to February 1988 in Carbon County, Wyoming. Oxygen and steam were injected into a sub-bituminous coal seam (thickness 10 m, depth 130 m). Along with CRIP, another linking technology, the so-called *extended linked well (ELW)* was tested. The ELW test

lasted 57 days, consuming 4,443 tons of coal and producing an average heating value of 9.7 MJ/m^3 (260 BTU/cft). The CRIP trial lasted a total of 93 days and gasified 11,227 tons of coal with average gas heating values of 10.7 MJ/m^3 (287 BTU/cft). It should be noted that pressure in the UCG cavity was maintained below hydrostatic to minimize the loss of organic laden gases and to ensure a small but continuous influx of groundwater into the gasification cavity. As a result, the environmental impact of UCG was minimal.[5]

In parallel to the trials, a number of mathematical models for UCG have also been developed in the US. A brief review of UCG models developed until the end of 1970s was provided by Gregg and Edgar.[11] Among later developments, analytical[23,24] and numerical models[25] should be mentioned. Britten and Krantz[23, 24] applied the method of activation energy asymptotics to analyze the dynamics of a planar combustion wave traveling in a porous medium in a direction opposed to the forced oxidant flux, similar to reverse combustion linking. The model assumes an infinite effective Lewis number and one-step, first-order Arrhenius kinetics for this two-phase, oxygen-limited combustion process. The fuel is modeled as a single component gas-phase species devolatilized from the medium ahead of the combustion zone. The obtained values of steady front velocity and front temperature agree well with results of numerical calculations. The analysis also determines conditions for the extinction of the steady reverse combustion front in terms of the heat loss strength and oxidant flux, and shows the existence of two solutions for heat losses below the extinction value. The predicted dependences of the steady front velocity and temperature on the heat loss intensity agree qualitatively with experimental observations.

Britten and Thorsness[25] have developed a model describing cavity growth and gas production during UCG in thick (~10 m) coal layers. It is applicable to UCG of shrinking coals in which oxidant injection is maintained at a fixed point low in the coal seam. The model is based on a few fundamental assumptions; namely that the cavity is axisymmetric about the injection point, all resistance to injected gas flow is through ash and overburden rubble that accumulates on the cavity floor, thermal radiation dominates in the well-mixed void space, and the coal and overburden spall or rubble on a small scale due to parameterized thermal effects. A unified model integrates the results of separate but interacting submodels which describe key phenomena occurring at different locations in and around the UCG reactor, as shown in Fig. 5. These submodels quantify water influx from the coal aquifer, flow dispersion through a rubble

bed at the bottom of the cavity, thermal degradation and chemical attack of rubble-covered coal sidewalls contacted by the injected reactants, and recession of cavity surfaces enclosing a void space in the upper cavity, caused by small-scale fragmentation and gasification driven primarily by radiative heat transfer. The model predicts recession rates of cavity surfaces and generation rates of major product species, which compare well with experimental data from two UCG field tests. For example, Figure 6 shows H_2 and CO production rates during first two CRIP reactors in the Rocky Mountain I UCG field test. It is seen that the model predictions are in accord with the measurements. The drop in flows around day 53 is due to purposely lowered injection flows immediately prior to and after the CRIP pipe-cutting maneuver which initiated the second reactor. Note, however, that the Rocky Mountain I field tests were conducted in a thick (7.6 m) seam, and the model may not be applicable for thinner seams (discussed later in Section 2.3).

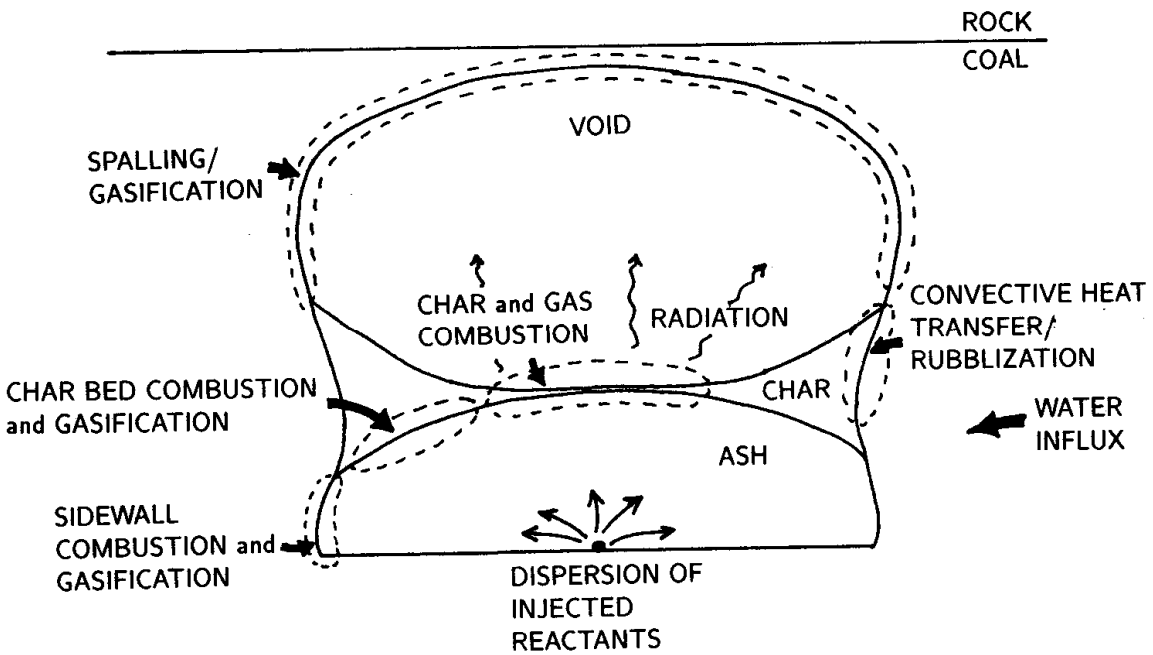

Fig. 5. Schematic of the UCG cavity and occurring processes.[25]

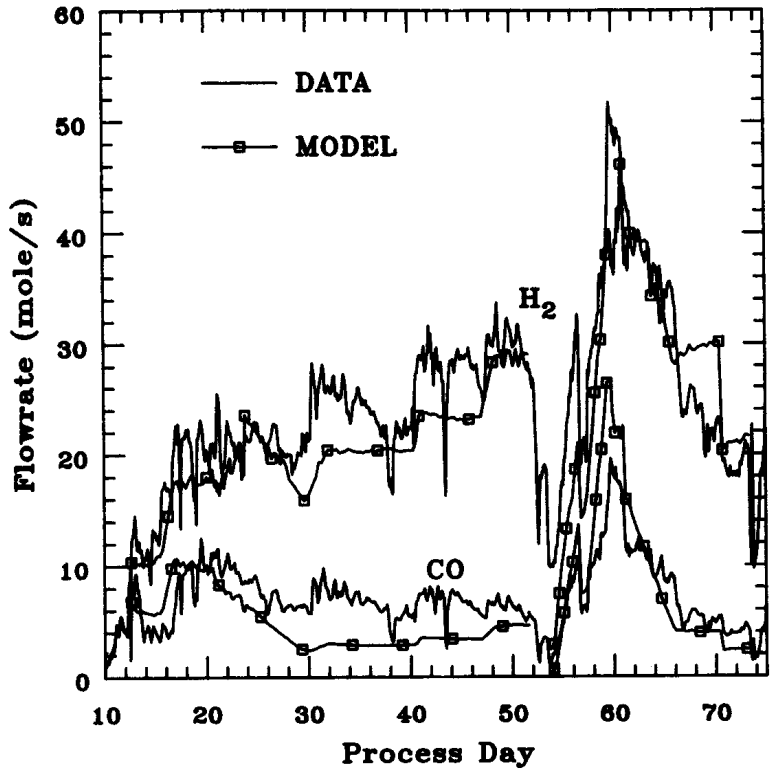

Fig. 6. Model predictions of H_2 and CO production rates compared with field data.[25]

The research in US has highlighted the importance of assessing the geological and hydro-geological settings for UCG. Recent investigation at the LLNL was focused on geomechanical processes in coal and surrounding rocks during UCG.[26] A suite of highly non-linear computational tools in both two and three dimensions was applied to a series of UCG scenarios. The simulations included combinations of continuum and discrete mechanical responses by employing fully coupled finite element and discrete element capabilities.

After declining oil and gas prices in the early 1980s, large-scale UCG projects were not conducted in the US. In recent years, due to growing energy needs, interest in UCG has been rejuvenated. BP and GasTech Inc. are developing an UCG demonstration project in the Powder River Basin (WY) that will be followed by a commercial-scale UCG project. In July 2007, BP and LLNL signed technical cooperation agreement on UCG. The initial two-year technical agreement will address three broad areas of UCG technology: carbon management to evaluate the feasibility of carbon dioxide storage underground; environmental risk assessment and

management; and numerical modeling of the UCG processes to understand pilot test results and match them with historical data. The technical objective is for LLNL to provide BP with expertise, model results, new capabilities and insights into the operation and environmental management of UCG.[27]

The importance of carbon management during the UCG processis an important aspect of UCG development in the US.[1,28] It is noted that all three main approaches to CO_2 capture in surface power plants (pre-combustion, post-combustion and oxy-fuel) can be combined with UCG. There are two options for using geological CO_2 sequestration with UCG. One option is to use separate cavities for CO_2 storage and the other is to use the cavities that were formed during UCG. The latter option is attractive (for example, due to reducing costs for drilling, etc.) but there are limitations and problems that require further investigation.[29] Note that the cavity should be located deeper than 800 m, so that CO_2 is stored in the supercritical state allowing for significantly higher utilization of the available pore space. The potential risks include sudden phase change during CO_2 injection, adverse geomechanical and geochemical responses, groundwater displacement, and CO_2 leakage.[1]

2.3 European Union

A number of UCG tests have been carried out in Western Europe. A significant difference of these tests is the large depth of coal seams (600-1200 m, as compared with <300 m in FSU and US).

In France, the first trial was conducted[30] at Bruay en Artois (the coal seam thickness 1.2 m, depth 1,170 m) in 1980-1981. Two technological and five monitoring wells were drilled. The distance between the injection and production wells was 65 m. Hydraulic fracturing (pressure 50.7 MPa) did not lead to satisfactory link between the wells. Attempts to use reverse combustion linking also failed because of coal self-ignition near the injection well. The main reason for the failure of this experiment was apparently a poor hydraulic connection between the wells, which led to the need for a very high pressure in the reverse combustion procedure and, as a result, to the coal self-ignition. The second trial was conducted[31] at La Haute Deule (the coal seam thickness 1.8 m, depth 880 m) in 1983. Two vertical wells were drilled (the distance

60 m). The hydraulic fracturing and reverse combustion linking were again unsuccessful. In both trials, gasification of the coal seam was not achieved.

In the framework of a joint Belgium-Germany project, UCG trials were conducted near Thulin, Belgium.[32-34] In 1982, four wells were drilled and an attempt to link them by reverse combustion was undertaken, which was, however, unsuccessful. A new attempt in 1984 also failed. Subsequent attempts to gasify coal resulted in producing small portions of gas with different compositions but hydraulic resistance between the wells remained large, indicating that the wells were not linked properly.

In the 1990's, a UCG project of the European Union was conducted by Spain, the UK and Belgium at "El Tremedal" in the Province of Teruel, Spain, which was chosen based on its geological suitability, coal seam depth (550 m) and the availability of extensive borehole data.[35,36] The objectives were to test the use of directional drilling to construct the well configuration and to evaluate the feasibility of gasification at depths greater than 500 m. The injection well, obtained by directional drilling, had vertical and horizontal parts as in CRIP technique (see Fig. 4). Three attempts to create the UCG process using oxygen were undertaken. During the experiments, continuous monitoring of pressure was conducted, and pressure was maintained close to hydrostatic pressure at the coal seam depth (5.3 MPa). The first attempt lasted 9 days and resulted in producing the following gas mixture: 24.9% H_2, 8.7% CO, 14.3% CH_4, 43.4% CO_2 and 8.3% H_2S, with the heating value 10.97 MJ/m^3 (294 BTU/cft). The second test lasted 3 days and produced a similar gas composition 24.7% H_2, 15.6% CO, 12.4% CH_4, 39.4% CO_2 and 8.8% H_2S, with the heating value 10.9 MJ/m^3 (293 BTU/cft). During the third test, technical problems resulted in the formation of volatile gas mixture and its explosion. The injection well was damaged and the decision was made to terminate the trial.

It should be noted that the high gas pressure used in the European trials led to higher concentrations of methane in the product gas.[35] This can be illustrated by comparison with the results of the UCG trial at 0.4 MPa (US), where oxygen was also used. The gas obtained at 0.4 MPa contained 38.1% H_2, 20.8% CO, 4.7% CH_4, 34.9% CO_2 and 1.5% H_2S. The effect of pressure is just a consequence of the methanation equation (12). Since the volume decreases during this reaction, according to Le Chatelier's principle, an increase in pressure shifts the equilibrium to the right, i.e. the yield of methane increases.

In the 1990s, along with experiments, numerical models of the cavity growth in thin coal seams were developed in Belgium[37-39] and the Netherlands.[40-42] For UCG in thin (< 2 m) European seams, the permeable-packed-bed concept used by Britten and Thorsness[25] (see Section 2.2) is applicable only during the initial stages of the gasification process. The researchers in Europe have developed channel-gasification models, based on a simplified description proposed by Wilks[43] and postulated two zones in the UCG gasifier: a low-permeability zone of rubble/ash around the injection well and a high-permeability, narrow and peripheral zone near the coal wall (Fig. 7). The Belgian group developed a two-dimensional model for UCG cavity growth in thin seams.[39] The model combines laminar flow through a porous medium around the injection point with the calculation of chemical processes in the peripheral zone adjacent to the coal wall. Figure 8 shows the calculated cavity shape and stream lines around the injection point. The bottom image corresponds to the situation where the low-permeability zone reaches the production well. This criterion can be used to define the end of the gasification process

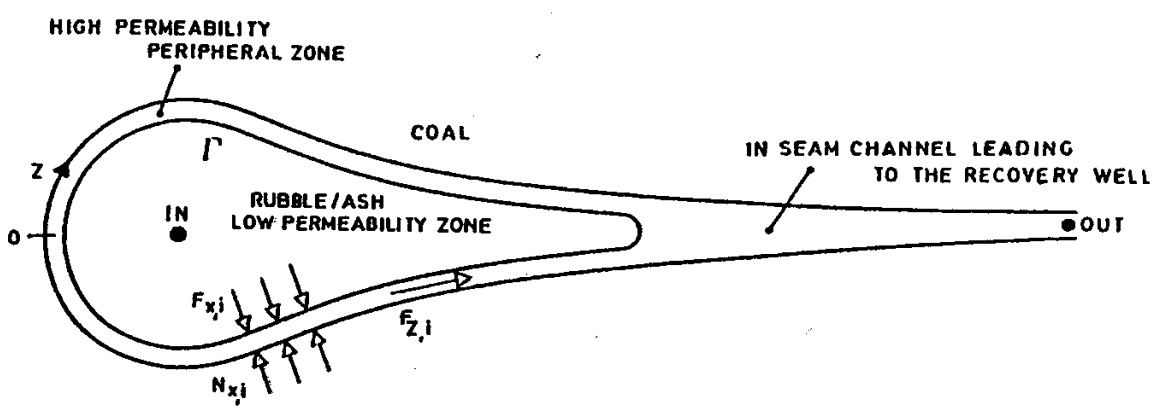

Fig. 7. Schematic of UCG reactor in thin seams.[39]

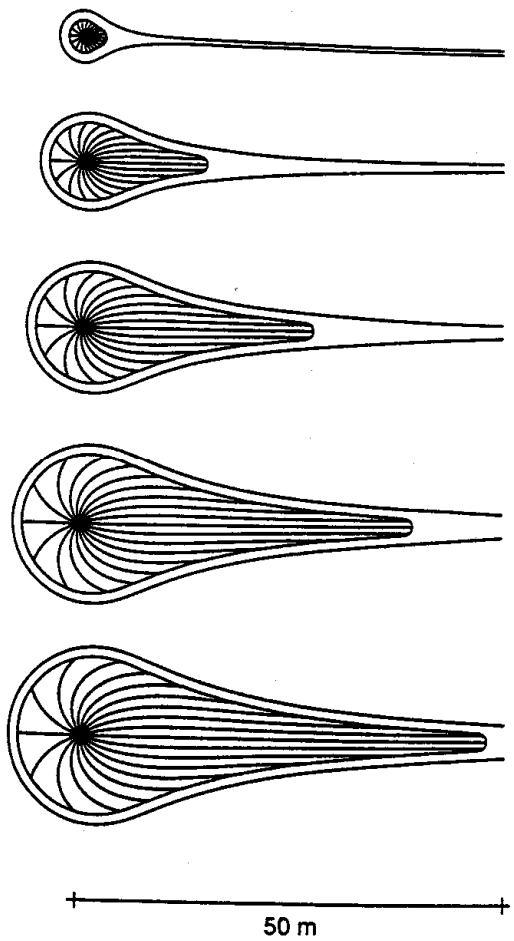

Fig. 8. Cavity shape and stream lines after 0, 5, 10, 15, and 18 days of gasifier development,[39] for 50 m distance between injection and production wells.

The Dutch group developed a two-dimensional, quasi-steady-state model of a laterally extending, partially collapsing gasification channel.[40] The model includes the chemistry of coal gasification, diffusional transport phenomena, pyrolysis of coal, and radiant heat exchange within the channel and with spalling cap rock. The quasisteady-state approach leads to relatively simple model equations in which only one single cross-sectional element of the channel needs to be considered. The model was used to demonstrate the influence of operating conditions such as pressure, air injection rate, and water injection rate on product gas composition. A comparison between observations from the UCG field test in Pricetown, West Virginia, (the seam thickness 2 m) and model predictions showed similar gas composition and process temperatures.

Later, the Dutch group developed a more comprehensive model[41,42] for studying the transport phenomena in UCG cavities based on a finite volume discretization of the Navier–Stokes equations and the k-ε turbulence model. Depending on the operating conditions, the fluid flow was dominated by either buoyancy due to temperature or concentration gradients. The predicted composition and heating value of the product gas were in good agreement with both the experimental data from the Pricetown field test and the results of simplified model.[40]

In the UK, The Department of Trade & Industry Technology (DTI) identified UCG as one of the potential future technologies for the development of the UK's large coal reserves.[4] An

initial pre-feasibility study was completed in January 2000 by the DTI in conjunction with The Coal Authority, and work then began on the selection of a U.K. site for a drilling and in-seam gasification trial. Detailed work was done on the geological and hydrogeological criteria for UCG, the evaluation of suitable sites, and the legislative policies that would apply to an onshore UCG scheme. This work emphasized the growing importance of environmental issues, and a thorough investigation of these issues will likely be undertaken before legislative approval of a test site. Sury et al.[6,7] provided a detailed analysis of the environmental aspects of UCG.

Currently, the Hydrogen Oriented Underground Coal Gasification for Europe (HUGE) project is conducted by research organizations of Poland and several other countries of the European Union.[44] Major attention in this project is paid to integration of gasification processes with heat and mass transfer phenomena occurring in geological multiphase systems of complex geometry. Valuable expertise from UCG, geological CO_2 storage, and enhanced oil recovery are compiled, critically assessed and used as building blocks in designing the hydrogen oriented UCG plant. The concept of a geo-reactor, which integrates UCG with geothermal heat exchange and with carbon capture and storage, is being investigated.

2.4 China

It is generally believed that China has the largest UCG program currently underway. This is confirmed by a relatively large number of patents in the UCG area, obtained by Chinese engineers (see Fig. 2). Since the late 1980s, many UCG trials have been carried out or are currently operating. Chinese trials utilize abandoned galleries of disused coal mines for the gasification. Vertical boreholes are drilled into the gallery to act as the injection and production wells.

Researchers at the China University of Mining and Technology investigated the two-stage UCG process proposed in the early 1930s in the USSR[45] for production of hydrogen, where a system of alternating air and steam injection is used. The experiments, conducted in Woniushan coal mine, Xuzhou, Jiangsu Province, prove the feasibility to use UCG for large-scale hydrogen production.[46]

Current technological projects include construction of a pilot industrial UCG plant at the Gonggou coal mine, Wulanchabu, Northern Inner Mongolia Autonomous Region. The $112

million project is a joint venture between the China University of Mining and Technology and Hebei Xin'ao Group.

2.5 Canada

In Canada, Ergo Exergy Technologies Inc., is a small but very active UCG development company. According to the information on the company's web site,[47] prior to founding the company in 1994, the principals of Ergo Exergy worked at the Angren UCG plant in Uzbekistan. Recently, Ergo Exergy experts have completed a UCG trial in Australia (see Section 2.6). They are working currently on a UCG pilot plant in South Africa (see Section 2.7). It should be noted that, according to Ergo Exergy, they use their proprietary εUCG™ technology. Burton et al.[1] suggest the εUCG™ may be based on the old Soviet UCG technology.

Laurus Energy Inc., an exclusive Canadian licensee of the εUCG™ technology, is developing a commercial project targeting power generation and supply of fuel and hydrogen for the local industrial markets near Edmonton, Alberta. The started project development includes regulatory and environmental approvals, site selection and pre-feasibility study, and site characterization program.[48] Note that coal gasification can be used to generate steam for oil recovery from tar sands, which are a major source of oil in Canada.[49]

In addition, Michael Blinderman, a director of Ergo Exergy, collaborates with researchers at the University of Queensland (Australia) in modeling the UCG process. Recently, they have developed new models for reverse and forward combustion regimes in UCG. [50-52] In contrast with the earlier model,[23,24] both oxygen-deficient and coal-deficient cases were analyzed. Hydrodynamic and pulsating stabilities were considered and special attention was paid to the vicinity of the stoichiometric point. Also, curved flames were analyzed in this work. Along with asymptotic techniques, in several instances simplified formulations were used and compact analytical representations were obtained. This approach resulted in an overall theory of reverse combustion linking during UCG that determines the relationships between key parameters of the process. Preliminary results of applying the theory to specific UCG conditions demonstrated reasonable conformity with the data obtained in practical UCG operations. For example, Figure 9 shows the speed of reverse combustion linking as a function of the supplied air flow rate. It is seen that the predicted values are in good agreement with the experimental data from the

Chinchilla trial. For forward combustion, a two-dimensional model was developed, assuming quasi-stationary flow of gas through a thin coal seam. It was shown that the speed and efficiency of forward combustion linking are significantly lower than for reverse combustion, which correlates with prior experimental results.

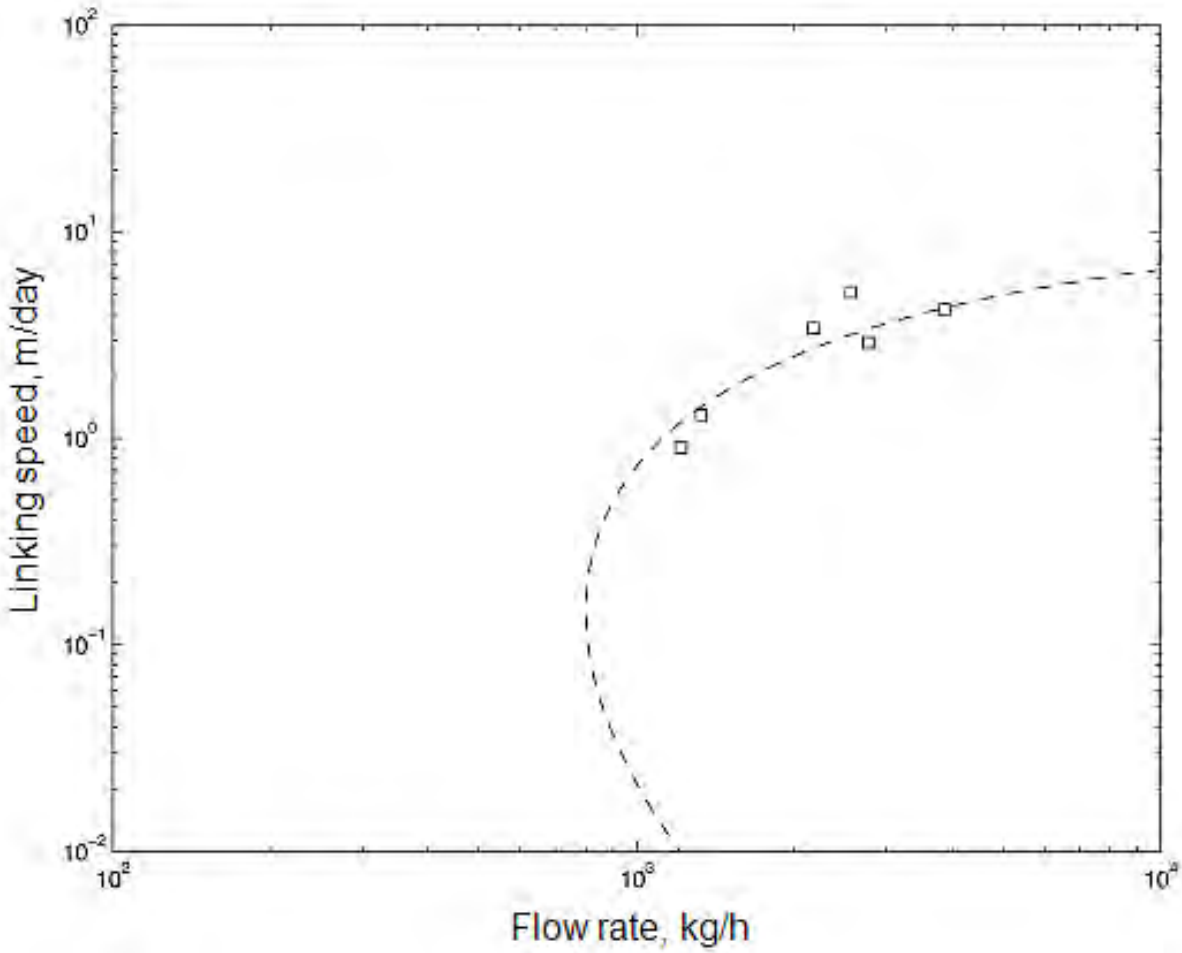

Fig. 9. The predicted (curve) and experimental (points) speed of reverse combustion linking as a function of the air flow rate.[50]

2.6 Australia

The development of UCG technology in Australia was advocated by Prof. Ian Stewart of the University of Newcastle. In 1983 his program of laboratory research was followed by a government funded feasibility study of UCG at the Leigh Creek coal mine in South Australia. The study concluded that the use of UCG gas as a fuel for combustion in gas turbines would be cost competitive with other sources of power.[53] Currently, commercial UCG projects are being developed by at least three Australian companies: Cougar Energy Ltd., Linc Energy Ltd. and Carbon Energy Ltd.

The Managing Director of Cougar Energy, Dr. Len Walker, has actively pursued an interest in UCG since 1982. In 1996, he formed an association with Dr. Michael Blinderman from Ergo Exergy. Together they initiated a UCG trial at Chinchilla in South East Queensland, conducted between 1999 and 2002.[54] Cougar Energy is planning to use Ergo Exergy's εUCG™ technology in the current projects. In Queensland, Cougar Energy has completed resource definition at its Kingaroy site, and is undertaking final site characterization prior to commencing the pilot burn for a 400 MW combined cycle power project. In Victoria, Cougar Energy's plan is to determine whether significant localized deposits of Victorian lignite exist which may be suitable for application of the UCG process.

The aforementioned Chinchilla trial was conducted by Linc Energy, using the technology provided by Ergo Exergy. The project involved drilling 9 injection/production wells and 19 monitoring wells to a coal seam at the average depth 140 m. During the project period, 35,000 t of coal were gasified, with 95% recovery of coal resource and 75% of total energy recovery. This resulted in production of $80 \cdot 10^6$ Nm^3 of gas (heating value 4.5 - 5.7 MJ/m^3, i.e. 121-153 BTU/cft). Results from an evaluation of the product gas composition showed that gas turbine units can operate satisfactorily on air blown UCG gas. A maximum capacity of 80,000 Nm^3/hr (675 t of coal per day) was reached and the availability of gas production over 30 months was demonstrated. The Chinchilla project has also demonstrated the feasibility to control UCG process, including shutdown and restart, and resulted in successful environmental performance according to independent audit reports. Specifically, no groundwater contamination was registered, no subsidence occurred, no surface contamination was detected, and no environmental issues were identified.

It should be noted that at the end of 2006 the collaboration between Linc Energy and Ergo Exergy was terminated. In December 2006, Linc Energy signed co-operation agreements with the Skochinsky Institute of Mining in Moscow, Russia, and its parent organization, the Scientific-Technical Mining Association. In October 2007, Linc Energy acquired a controlling interest in Yerostigaz, which owns the UCG site in Angren in Uzbekistan. With the additional experienced employees and expertise from Russia and Uzbekistan, Linc Energy plans to move forward on expanding UCG operations in Australia (a commercial UCG and coal-to-liquids plant) and other countries.[53]

Carbon Energy Ltd. is using CRIP technology and modeling packages for site selection, process design and process control, developed at the Commonwealth Scientific and Industrial Research Organization (CSIRO).[55] Carbon Energy plans a large-scale demonstration trial at Bloodwood Creek, in the Surat Basin in Queensland. In September 2008, Carbon Energy announced successful completion of the directional drilling program, which involved creating two parallel 850 m long in-seam wells and a vertical ignition well.[55] The trial will be performed as the first module of a commercial facility for generation of 1 PJ per year of syngas with a three-year module life. It is planned that each module will produce enough syngas to generate 20 MW of electricity in a combined-cycle gas-turbine power plant.

Along with the commercial developments described above, several research projects on modeling of UCG processes have been conducted at CSIRO, the University of Queensland[50-52] (see Section 2.5) and the University of New South Wales.[56-58] Perkins and Sahajwalla[56,57] developed a one-dimensional model of a reacting coal block to investigate the effects of operating conditions and coal properties on the local rate of cavity growth and energy effectiveness in UCG process. The investigation has revealed that the cavity growth rate is most sensitive to the operating temperature, water influx, and gas pressure. The coal properties that most affect the cavity growth rate are the thermomechanical spalling behavior, the behavior of the ash, and the amount of fixed carbon in the coal. Many trends observed in the field trials are reproduced by the model simulations, and predicted cavity growth rates for six field trials are comparable to those observed (Fig. 10).

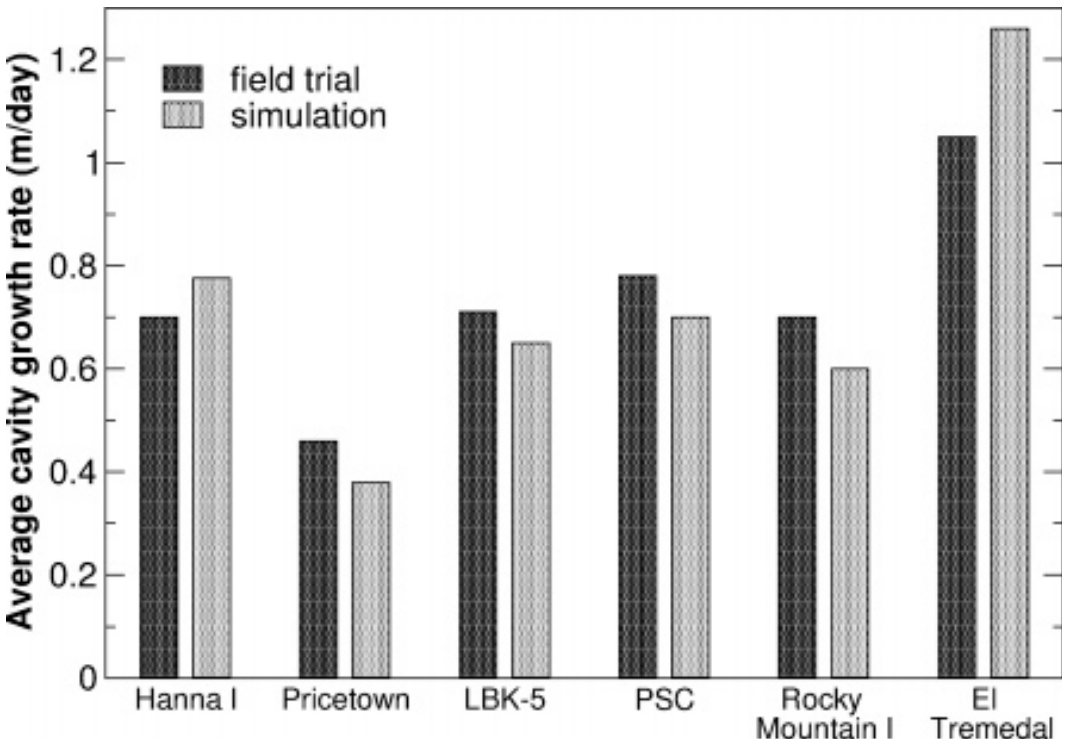

Fig. 10. Comparison of estimated cavity growth rates from six UCG field trials with model simulations.[57]

More recently, Perkins and Sahajwalla[58] developed a two-dimensional axisymmetric CFD model of an UCG cavity partially filled with an ash. Simulations have revealed that when bottom injection of the oxidant is applied, the flow in the void space above the ash bed is dominated by a single buoyant force due to temperature gradients established by combustion. Optimum oxygen injection rates can be found which maximize the production of chemical energy in the product gas. When the oxidant is injected into the cavity from the top, most of the valuable gasification products are oxidized leading to a product gas with a high temperature and a low calorific value. The simulations elucidate the important transport and reaction processes occurring in the underground cavity and the results are in qualitative agreement with observations from UCG field trials.

2.7 South Africa

Eskom, a coal-fired utility in South Africa, has been investigating UCG at its Majuba 4,100 MW power plant since 2001, using Ergo Exergy's εUCG™ technology. By the end of 2008, the project generated about 15,000 m^3/hr of flared gas.[16] The Eskom pilot project will be expanded in a staged manner, based on the success of the each preceding phase. The ultimate objective of the project is to fully evaluate the technology and produce a business case for co-firing of 1,200 MW of electricity at Majuba. The natural progression for UCG proceeds into Integrated Gasification Combined Cycle (UCG-IGCC), and into other unminable coal resources in South Africa. Eskom's preliminary estimates show that there is 45 Gt of coal in South Africa that is presently regarded as unminable with currently available technologies, but is still suitable for UCG. This will create a new energy source for Eskom that will enable the present generating capacity of 41 GW to be increased nine-fold.[59]

2.8 New Zealand

In 1994, a UCG project was undertaken in the Huntly coal reserve, 120 km south of Auckland. The test was carried out over a 13-day period and approximately 80 t of coal were consumed during reverse combustion linking of 5 vertical wells, which, however, was not followed by proper gasification.[16]

New Zealand is a tectonically active country which has resulted in the coal deposits being both faulted and folded and, in some cases, laid down on undulating basement topography. This geological complexity presents considerable technical challenges to the successful planning and extraction of coal. Solid Energy New Zealand Ltd., is planning to use UCG to complement currently employed mining methods, for low cost access to coal that is currently not technically or economically accessible. Solid Energy has exclusive rights to apply Ergo Exergy's εUCG™ technology within New Zealand and is currently investigating the potential for the application of UCG there.[60]

2.9 India

UCG is a promising technology for India, which has vast coal resources, primarily of low grade. India looks to utilize its coal reserves, which are the fourth-largest in the world, to reduce dependency on oil and gas imports. UCG is expected to be used to tap the reserves that are difficult to extract economically using conventional technologies. The Oil and Natural Gas Corporation Ltd. (ONGC) is planning to carry out pilot projects using recommendations of experts from the Skochinsky Institute of Mining in Moscow.[61] The Gas Authority of India Ltd. (GAIL) and AE Coal Technologies India Pvt. Limited, a company belonging to the Abhijeet Group of India, are implementing UCG projects using Ergo Exergy's ***ε***UCG™ technology.[62]

Recently, computational fluid dynamics studies of complex flow patterns in a growing UCG cavity were conducted by researchers of IIT-Bombay in collaboration with ONGC.[63] The main objective of this work was to understand the velocity distribution and perform residence time distribution (RTD) studies in the UCG cavity. Based on the RTD studies, the actual UCG cavity at different times was modeled as a simplified network of ideal reactors, which may offer a computationally less expensive and easier option to determine UCG process performance as a function of time.

2.10 Japan

Japan, which has substantial coal interests outside its borders, as well as continental shelf resources, has included UCG in its future research plans for coal exploitation, and has been maintaining a low level program for many years. The University of Tokyo and coal companies have been conducting technical and economic studies of UCG on a small scale and are considering conducting a trial in the near future. A feasibility study has been undertaken for a UCG trial and a 55 km^2 site area selected.[64] Predictions were based on analysis of field data from UCG trials in the USA. The study identified the largest cost elements as drilling and oxygen.

3 Criteria for UCG Site Selection

This feasibility analysis of UCG potential for the state of Indiana is based on the determination of selection criteria that were then applied to the coal resources located within the state. The Indiana Geological Survey (IGS) has performed a comprehensive assessment of those coal resources and defined them in terms of "available" or "restricted" for surface or underground mining. Much of the mapped resource is unavailable for mining based on technical and/or land use restrictions that remove the resource from the recoverable reserve base[65]. In some cases, the criteria for UCG are expected to be different from those needed for underground mining, while in others, the criteria are coincident. In all cases the locations determined as areas that could serve as potential sites for UCG in the state also fall in the available for underground mining category. An assessment was made of the coal seam criteria that have been applied for other UCG projects around the world.

3.1 Thickness of coal seam

The available information on the minimum seam thickness for UCG is somewhat contradictory. GasTech[5] indicates that the optimal thickness should be more than 30 feet (~ 10 m). However, that report considered coal seams of the Powder River Basin, Wyoming, which are mainly 30 to over 100 feet (10 to >30 m) thick. On the contrary, ErgoExergy states that UCG can be used in coal seams as thin as 0.5 m.[47] As mentioned above, the UCG work in the FSU showed that the heating value of the produced gas decreases significantly with decreasing the coal thickness below 2 m (see Fig. 2). The literature analysis allowed us to make recommendations for selection of Indiana coals based on the coal seam thickness, and are shown in Table 1.

Table 1. Coal seam thickness values used for determining the suitability of Indiana coals for UCG.

Thickness	**Suitability**
> 2.0 m	High
1.5 – 2.0 m	Medium
1.0 – 1.5 m	Low
< 1.0 m	Unacceptable

The coal seams in Indiana are mainly relatively thin (<1.5 m). For this reason, thickness is recommended as the first criterion to be used in the selection process. This will significantly reduce the amount of coal that could be further evaluated using other criteria. Of the seven major coal seams present in Indiana, only the Seelyville and Springfield Coals have a significant quantity of sufficiently thick sites (>1.5 m) to be considered for assessment of UCG potential.[65] Thus, the selection process focused on these two coal beds only. In conjunction with calculating those portions of these two seams that meet the thickness screening criteria, the associated tonnages of these thick contiguous blocks of coal were also determined (see Section 3.6).

3.2 Depth of coal seam

Our analysis of the UCG literature shows that the depth of coal seams is not a critical parameter. The depth varied from 30 to 350 m in the FSU developments and US experiments, while Western European trials were conducted in much deeper coals (600-1200 m). The LLNL experts indicate that the minimum depth should be 12 m.[1] On the other hand, the relatively shallow coal seams are generally used for surface mining. Sixty meters is the typically applied limit to depth of surface mining and therefore considered a bounding limit in this analysis. In particular, the Indiana Geological Survey has used 200 feet (~60 m) as the maximum depth for surface mining.[65] Taking into account the relatively low cost of surface mining, and assuming that use of

this technology will continue, it is reasonable to expect that coals with depth in the range from 12 to 60 m have low suitability for UCG in Indiana. Additionally the proximity of potable and potentially potable groundwater supplies (underground sources of drinking water or USDWs) at this shallow depth discourage further consideration of those coals that are located near the ground surface.

To decrease the risk of subsidence, Burton et al.[1] recommend operational depths of >200 m. Depth more than 300 m requires more complicated and expensive drilling technologies, but it also has advantages such as minimized risk of subsidence and the possibility to conduct the UCG process at higher pressure, which increases the heating value of the produced gas. Also, deeper seams are less likely to be hydrologically linked with potable aquifers, thus avoiding drinkable water contamination problems. Finally, if the product gas is to be used in gas turbines, additional compression may not be necessary. These considerations and our conclusions are summarized in Table 2.

Table 2. Coal seam depth values used to determine the suitability of Indiana coals for UCG.

Depth	**Suitability**
> 200 m	High
60-200 m	Adequate
< 60 m	Unacceptable

If potential UCG sites are found at different depths, further analysis should be made based on tradeoff between the higher cost of deeper wells and the advantages of UCG production from greater depths. As mentioned above (see Section 2.3), a major advantage of using deeper coals for UCG is the higher gasification pressure, which yields a higher methane content and hence a higher heating value. Of course, if the intent is to produce chemicals and/or liquid fuels from the gasified coal, then maintaining a high CO and H_2 content, rather than a high percentage of methane, is of interest.

3.3 Coal rank and other properties

With the present state of knowledge, low rank, high volatile, non-caking bituminous coals are preferable. UCG may work better on lower ranks coals because they tend to shrink upon heating, enhancing permeability and connectivity between injection and production wells.[1] Also, the impurities in lower rank coals may improve the kinetics of gasification by acting as catalysts for the burn process.[1] For coals of the same rank, the higher the heating value of coal, the higher the heating value of the UCG gas.

Indiana coals are characterized by high-volatile bituminous rank and have relatively high heating value, which makes them attractive for UCG. Although the heating value of Indiana coals is lower than for bituminous coals from the Appalachian Basin, it compares favorably with western coals[65].

The values of porosity and permeability within the coal seam may also be important factors, but it is difficult to use them as criteria at this point because of the scarcity of this type of data. Better cleated and more permeable seams allow for more effective connection between the injection and production wells, leading to faster transport of reactants and a higher rate of gasification. On the other hand, higher porosity and permeability increase the influx of water, and increase product gas losses.

Also, it is often recommended that coals should not exhibit significant swelling upon heating. In particular, Sury et al.[6] state that, in general, reverse combustion works well in shallow non-swelling coal but is not a recommended process for use at great depth and in swelling coals. This contradicts, however, the opinion of Burton et al.[1] who note that the FSU methods demonstrated minimum sensitivity to coal swelling: the large-dimension channels formed in the linkage process employed in that operation did not appear to be plugged by coal swelling. Areas of seams that are free of major faulting in the vicinity (<45 m) of the proposed gasifier, and which could potentially provide a pathway for water inflow or gas migration, should be preferentially targeted.[7]

3.4 Dip of coal seam

Sury et al.[7] indicate that shallow dipping coal seams are preferable. Such seams facilitate drainage and the maintenance of hydrostatic balance within the gasifier, and minimize potential

damage to the down dip production well from material that is moved in association with the UCG process. The report by GasTech[5] recommends dip angles of zero to twenty degrees and Indiana coals fall within this range. However, UCG has been successfully carried out in steeply dipping seams,[8] thus dip is not a critical constraining factor for selecting and operating UCG sites.

3.5 Groundwater

Water is an essential component of the UCG process, and thus its availability from either within a coal seam or from a source adjoining the seam is an important characteristic. The adjoining rocks must contain saline water (>10,000 ppm TDS, as per EPA regulations) and have a significant deliverable volume. Within Indiana, in many cases the coal itself serves as the principle aquifer within the stratigraphic section and is bounded by impermeable shales and low density rock. In some cases, permeable sandstones form the roof rock and therefore are in hydrological connectivity with strata outside of the coal seam. Sury et al.[7] recommend using coal seams with no overlying potable aquifers within a distance of 25 times the seam height. Trials have been successfully carried out in seams in closer proximity to potable underground aquifers, but the potential risk of contamination increases in such a setting.

3.6 Amount of coal

Gas produced by the underground gasification process can potentially be used in a series of applications. These applications range from supplying mobile units that could provide gas in agricultural areas to large power and chemical plants producing hundreds to thousands MW of electrical energy and vast amounts of hydrocarbon-based products. For this reason, the evaluation of potentially productive sites must include the determination of the amount of coal available in a gasification project in conjunction with a consideration of the potential applications of the produced gas. Additionally, for each potential site, the productive lifetime of the site must be determined as a function of required gas yield. For illustration, for 20-year continuous operation of a 300-MW UCG-based combined cycle power plant (efficiency 50%), it is necessary to produce $75.6 \cdot 10^9$ Nm^3 of syngas with a heating value of 5 MJ/m^3. Based on the

Chinchilla experimental data (see Section 2.6), $33 \cdot 10^6$ metric tons need to be gasified for this purpose. Note that this amount can be decreased in half by using oxygen and steam as injection gases which, however, increases the cost.

The volumes of coal available for gasification were determined by the IGS in Phase 3 of this assessment. Tonnages of coal present in each contiguous block were calculated for the two coal beds assessed, and these data are shown in Table 6.

3.7 Land-use restrictions

There is no indication in the literature that UCG needs to be located away from towns, roads and other surface features any more so than underground coal mines, assuming that the process design and environmental monitoring eliminate water contamination and air pollution. Thus, the land-use restrictions for underground mining determined by IGS[65] can be applied to potential UCG sites. The risk of subsidence of the ground surface is an important factor for siting of a project. Further work on the risk needs to be conducted in Indiana so that this factor can be addressed and any risk mitigated through appropriate siting and operational practices.

4 Analysis of Indiana's coal resources and determination of suitable UCG locations

4.1 Introduction

The review of UCG current status (Section 2 of this Report) indicates that in the coming years, this technology will likely be more frequently considered as a source of synthesis gas throughout many diverse locations in the world. It is clear, however, that to determine the feasibility of employing this technology within Indiana using Illinois basin coals, an analysis of details of Indiana's subsurface geology, coal properties, underground water resources, and subsidence risk must be conducted.

The main purpose of Phase 2 of this feasibility assessment was to analyze Indiana's coal resources and determine the presence of locations that could potentially serve as suitable UCG project sites. This analysis used geologically-related criteria identified and selected in Phase 1 (see Section 3 of this Report). Depth of the coal seam and its thickness were identified as the most important parameters for determination of site suitability for UCG, and the values for these criteria are given in Tables 1 and 2.

4.2 Methodology

In this study, two coal beds, the Springfield and the Seelyville, were analyzed for their potential use in UCG. These two coal beds have the largest available resources in Indiana (Table 3). The Springfield Coal has been of economic importance from the beginning of mining history in the state. In contrast, the Seelyville Coal has not been mined because of inferior quality (high ash, high sulfur, presence of splits), but could possibly be a good candidate for UCG.

Table 3. Summary of available and restricted coal resources for main economic coal beds in Indiana.[65] *Values are in billion short tons.*

Coal bed	Original	Mined -out	Remaining	Restricted for mining	**Total available** (Remaining minus Restricted)	Available as % of original	Available for surface mining	Available for underground mining
Danville	6.55	0.36	6.19	5.33	**0.83**	**13.89**	0.35	0.52
Hymera	5.53	0.55	4.98	4.10	**0.87**	**17.47**	0.15	0.81
Springfield	13.31	1.31	12.00	4.65	**7.35**	**61.25**	0.82	6.94
Houchin Creek	5.92	0.0022	5.92	5.56	**0.36**	**6.08**	0.18	0.17
Survant	8.47	0.31	8.17	6.86	**1.31**	**16.03**	0.22	1.10
Colchester	5.14	0.001	5.14	4.95	**0.19**	**3.70**	0.11	0.10
Seelyville	14.61	0.33	14.28	7.68	**6.60**	**46.22**	0.30	6.30
Total	**59.53**	**2.8632**	**56.68**	**39.13**	**17.54**	**30.95**	**2.13**	**15.94**

For these two coal beds, a set of maps were generated, using data from the IGS's publicly available stratigraphic database[66] and coal quality database.[67] For each coal, the following maps were generated:

1) Map showing the extent of the coal and distribution of surface and underground mines and mined out areas (Appendix, Figures 1 and 15);
2) Map showing suitability of the coal for UCG, based on seam thickness (Appendix, Figures 2 and 16);

3) Map showing suitability of the coal for UCG, based on coal seam depth (Appendix, Figures 3 and 17);
4) Map showing moisture content of the coal (Appendix, Figures 4 and 18);
5) Map showing heating value of the coal (Btu/lb, dry basis) (Appendix, Figures 5 and 19).

Additionally for the Seelyville Coal, a map of the lithologies that occur immediately above the coal was created (Appendix, Figure 20). This map, together with moisture content map, helps to address the issue of water availability for the UCG operation. Because seam thickness and depth are considered the most important criteria in the selection of potential UCG sites, the two layers representing these parameters were overlain in a geographic information system to derive outlines of the most promising sites.

4.3 Identification of areas most suitable for UCG

Maps generated for the Springfield Coal are presented in the Appendix as Figures 1-14, while maps for the Seelyville Coal are presented in the Appendix as Figures 15-29. For the Springfield Coal, the most suitable areas for UCG are in Knox and Gibson Counties (Appendix, Figures 6-8). These areas reflect the coal seam thickness larger than 1 m (Table 1) and adequate depth to the coal (deeper than 60m, Table 2). For these most promising areas, Figures 9-12 in the Appendix show infrastructure, including roads, railroads, gas pipelines, etc. These surface features are important for planning UCG operations and future markets for the gas and, in addition to the geological factors, are critical for making the selection of the UCG sites. Further, maps of availability of the Springfield Coal for surface mining (Appendix, Figure 13) and underground mining (Appendix, Figure 14) are also included in this report. These maps will be helpful at the stage when decisions about traditional mining versus UCG need to be made.

For the Seelyville Coal, areas in Vanderburgh, Warrick, Gibson, and Posey counties are the most suitable (Appendix, Figures 21-23). For these areas, Figures 24-27 in the Appendix show roads, towns, pipelines, and other elements of infrastructure. Figures 28 and 29 in the Appendix show the availability of this coal for surface and underground mining.

5 Characterization of the most promising locations for potential UCG operations in Indiana

5.1 Introduction

The Phase 2 study identified the most promising areas in Indiana (see Section 4 of this Report). The main purpose of Phase 3 was quantitative characterization of the most promising zones, including the amount of available coal and various properties and parameters. This characterization will serve as a basis for subsequent analysis and decisions on the initiation of UCG development in Indiana.

5.2 Identification and characterization of zones most promising for UCG

Based on the maps generated in Phase 2 for the Springfield and Seelyville Coals, and consideration of geological and infrastructure criteria identified in Phases 1 and 2, four zones in the Springfield Coal (numbered 1-4) and five zones in the Seelyville Coal (numbered 5-9) have been outlined as the most promising for UCG (Figures 30 and 31 in the Appendix). These zones represent areas where there is coal seam thickness greater than 2 m and an adequate depth to the coal bed. Each of those zones is surrounded by coal 1.5 m to 2.0 m thick, which could also be used for UCG. In this study, however, these surrounding zones were not included in the analysis and calculation of available coal volumes.

The zones have been outlined in such a way that they are not located close to the existing mines or sandstone bodies (for example, the Galatia channel in the case of the Springfield Coal), and half a mile buffer was used around them.

For each of the proposed zones, the amount of the available coal was calculated. The calculations utilized the area of the zone and the thickness of the coal obtained from grids created based on the available thickness data points. Density of 1.38 g/cm^3 was used as an average for the coal. These values, together with the ranges of other important parameters, are listed in Tables 4 and 5. Table 6 summarizes the data on the available amounts of coal in the selected zones.

Table 4. Characteristics of zones selected for the Springfield Coal Member.

	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
Area [km^2]	8.67	30.36	14.11	9.83
Area [ft^2]	93,285,125	326,752,816	151,906,925	105,774,118
Area [acres]	2,141	7,501	3,487	2,428
Volume [m^3]	18,192,618	67,844,800	34,901,024	21,339,823
Volume [ft^3]	642,466,257	2,395,916,517	1,232,518,036	753,608,728
Mass [Metric tons]	25,105,813	93,625,825	48,163,413	29,448,955
Mass [Short tons]	27,674,138	103,203,747	53,090,531	32,461,584
Thickness range [ft]	6.56-7.9	6.56-8.6	6.56-10.3	6.56-7.9
Thickness range [m]	2-2.4	2-2.6	2-3.1	2-2.6
Depth range [ft]	197-656	197-656	197-656	197-656
Depth range [m]	60-200	60-200	60-200	60-200
Moisture range [ar,%]	5-10	5-10	5-7.5	7.5-12.5
Ash range [dry, %]	7.5-12.5	10-15	10-15	5-10
Sulfur [total, dry, %]	3-4	2-4	3-5	1-3
Heating value [dry, Btu/lb]	12,500-13,000	12,000-13,000	11,500-12,500	13,000-14,000
Distance to nearest power plant [miles]	14	9.5	10	3
Distance to nearest pipeline [miles]	1	0	0	7
Distance to nearest town [miles]	3	0	6.7	5.5

Table 5. Characteristics of zones selected for the Seelyville Coal Member.

	Zone 5	**Zone 6**	**Zone 7**	**Zone 8**	**Zone 9**
Area [km^2]	10.56	21.48	11.68	6.56	44.88
Area [ft^2]	113,666,894	231,208,828	125,722,474	70,611,252	483,084,300
Area [acres]	2,60	5,307	2,886	1,621	11,090
Volume [m^3]	23,548,810	49,618,092	30,369,915	15,491,992	120,256,072
Volume [ft^3]	831,618,367	1,752,246,390	1,072,503,422	547,094,529	4,246,803,094
Mass [metric tons]	32,497,357	68,472,967	41,910,483	21,378,949	165,953,379
Mass [short tons]	35,821,837	75,477,752	46,197,925	23,566,015	182,930,410
Thickness range [ft]	6.56-9.4	6.56-9.2	6.56-11.4	6.56-9.4	6.56-11.3
Thickness range [m]	2-2.9	2-2.8	2-3.5	2-2.9	2-3.4
Depth range [ft]	197-656	197-656	> 656	197-656	197-656
Depth range [m]	60-200	60-200	> 200	60-200	60-200
Moisture range [ar,%]	< 7.5	5-7.5	5-7.5	7.5-10	7.5-10
Ash range [dry, %]	10-15	10-15	7.5-12.5	12.5-15	12.5-20
Sulfur [total, dry, %]	3-5	2-4	3-4	3-4	2-4
Heating value [dry, Btu/lb]	11,500-12,000	11,500-12,000	12,000-13,000	11,500-12,500	11,500-12,000
Distance to nearest power plant [miles]	18	17	18	17	17
Distance to nearest pipeline [miles]	0	2	3	5	0
Distance to nearest town [miles]	3	2.5	2.2	1.6	2.5

Table 6. Amounts of available coal in the selected zones.

Zone number	**Coal bed**	**Mass,** metric tons	**Mass,** short tons
1	Springfield	25,105,813	27,674,138
2	Springfield	93,625,825	103,203,747
3	Springfield	48,163,413	53,090,531
4	Springfield	29,448,955	32,461,584
5	Seelyville	32,497,357	35,821,837
6	Seelyville	68,472,967	75,477,752
7	Seelyville	41,910,483	46,197,925
8	Seelyville	21,378,949	23,566,015
9	Seelyville	165,953,379	182,930,410
	TOTAL	**526,557,142**	**580,423,937**

5.3 Analysis of characteristics of the selected zones

Since each of the selected nine zones is characterized by a relatively large set of parameters, it is difficult to compare them. Depending on which parameter is considered to be the most important, different decisions on the site selection for UCG operations can be made.

If the goal of UCG is to provide syngas for direct burning in the available power plants, owing to its highest heating value, Zone 4 (the Springfield Coal) is apparently the best. This zone is located only 3 miles from a power plant (Gibson). Note that Zone 4 is also characterized by the highest moisture, the lowest ash content and the lowest sulfur content.. This zone is also located sufficiently far from towns (5.5 miles to the nearest town).

On the other hand, all selected zones, except Zone 7 (the Seelyville Coal), are characterized by depth between 60 and 200 m. Coals at such depths can be recovered using conventional underground mining. If the goal is to use only unminable coals, Zone 7 (depth more than 200 m) attracts attention. In this case, however, the distance to the nearest power plant is 18 miles. Thus, a careful economical analysis must be conducted to compare the cost of gas transportation with the costs of constructing a new power plant near the UCG site.

In this analysis, the amount of available coal should also be taken into account as this characteristic obviously affects the potential duration of UCG-based power generation (see Section 3.6). From this point of view, Zone 9 (the Seelyville Coal) is a clear winner. This zone contains about 183 million short tons of coal. Zone 9 is located, however, 17 miles from a power plant. On the other hand, its closeness to a pipeline (0 miles) could be considered an advantage provided an economical method is available to transport the UCG gas to this pipeline. One solution of the transportation problem could be construction of a plant for production of natural gas surrogates near the UCG site.

5.4 Recommendations for future work

The brief analysis presented in Section 5.3 illustrates difficulties that have to be overcome during the final selection. Besides the characteristics shown in Tables 4 and 5, there are other important factors that influence UCG. One important factor is the availability of aquifers. To provide water for the UCG process, a non-potable aquifer should be available near (above) the UCG site. Simultaneously, to prevent contamination of drinking water, a potable aquifer must be located as

far as possible. Another important problem is the possible influence of partings, splits and other characteristics of the coal seam on UCG process. Such features are common for Indiana coals, particularly for the Seelyville Coal Member. Another factor that must be assessed is the risk of subsidence. How the modules in the gasification cell are designed in response to the overlying stratigraphy is a key to mitigating subsidence of the ground surface.

Information on the aforementioned issues could be obtained in a follow-up detailed characterization of sites that meet the screening criteria used in this report.

This follow-up study should include an evaluation of the hydrology of the coals, the character of the surrounding or enclosing rock within which the coal resides, and the details of the petrophysical characteristics of the coals, as they control the kinetics of the combustion process.

Specific investigations related to gasification kinetics of the selected Indiana coals are needed because Indiana coals, although of similar rank, may have significantly different chemical and petrographic compositions[65]. These variations are accompanied by differences in porosity and permeability of the coal, and understanding the influence of this variability on gasification kinetics may turn out to be critical for the success of the UCG operations.

Site specific modeling of the UCG process also needs to be undertaken in a follow-up investigation. Such modeling, in addition to coal properties, would include various aspects related to the surrounding rocks and their hydrological regime. In this modeling, special attention should also be paid to environmental aspects, including evaluating the risks of groundwater pollution and subsidence as gasification occurs.

Finally, the possibility of coupling CO_2 capture and sequestration with the UCG project should also be considered. Although the use of cavities formed in the coal seam as a result of the UCG process for CO_2 sequestration is not likely in Indiana (due to the relatively low depth of coal beds), CO_2 could be stored in other, deeper locations. The IGS researchers have conducted a study of the potential for CO_2 sequestration in Indiana, so they are in a good position to explore the potential of combining UCG and CO_2 sequestration. Ultimately, an economic analysis, including capital, operational and environmental costs, will also need to be conducted.

Some operators of UCG projects perform detailed site characterization prior to initiating a pilot project. The drilling, coring and logging of an extensive array of bore holes is a favored technique to ascertain technical features. The design and characteristics of such a detailed

assessment program is site specific and such a program will need to be designed for assessing the coals of Indiana for a possible project. The initial project will require more data collection than subsequent ones. Once the key factors have been determined for projects within the state, they can be optimized for subsequent projects.

In light of the expertise within the Lawrence Livermore National Laboratory (LLNL), and companies such as Ergo Exergy and Linc Energy, it is advisable to make cooperative arrangements with one or more of these organizations to proceed forward with a site characterization for a pilot project. The aforementioned characterization along with kinetic and modeling studies should continue in parallel to refine our understanding of the conditions that will constrain UCG in Indiana and will further sharpen the potential for applying the technology within the state.

6 Summary

A review of current status of the global development of underground coal gasification shows that this technology has great potential to grow and replace/complement traditional methods for coal mining and surface gasification. New commercial UCG projects have started recently in several countries and more projects will probably start soon. Selection of the best UCG technology is a complex process, and a variety of technical and geological factors must be taken into consideration for each site being evaluated.

Some basic screening criteria for selecting UCG sites in Indiana have been formulated in this report. Taking into account both operational experiences at UCG projects and the geological characteristics of Indiana coals, the thickness and depth of coal seam were recommended to be used as the primary screening criteria. Based on the available information on the characteristics of coal seams in Indiana, it was recommended to focus on the Springfield and Seelyville coal beds. For these coals, maps were generated that show thickness, depth and other characteristics, such as moisture content and heating value for these two coals. Based on the analysis of these maps, two areas meet the optimal values in the screening criteria: (1) Knox and Gibson Counties for the Springfield Coal and (2) Vanderburgh, Warrick, Gibson, and Posey counties for the Seelyville Coal. For these areas, more detailed maps, which also show available infrastructure (power plants, pipelines, towns, etc.) were generated. Maps of availability of the Springfield Coal for surface and underground mining are also included in this report. These maps will be helpful at the stage when decisions about traditional mining versus UCG need to be made.

Analysis of the generated maps and additional information identified nine promising zones for UCG in Indiana (four for the Springfield and five for the Seelyville Coal). For these zones, the lists of characteristics, including the amounts of available coal, were prepared. Based on these data, we have made preliminary recommendations on the future selection of a suitable location for UCG operations. Available information, however, is insufficient to select individual sites and begin a front end engineering and design study for the construction of a UCG plant. A follow-up study will be required which will include more detailed characterization of the selected zones, and involve various geological, chemical and engineering evaluations of the selected zones.

Concurrent with the follow-up studies, which are required to refine understanding and further sharpen the potential of Indiana coals for UCG operations, it is recommended that cooperative agreements with the Lawrence Livermore National Laboratory (LLNL), and a company such as Ergo Exergy or Linc Energy, be made to initiate discussions on a future pilot project to be located in Indiana.

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Appendix: Maps

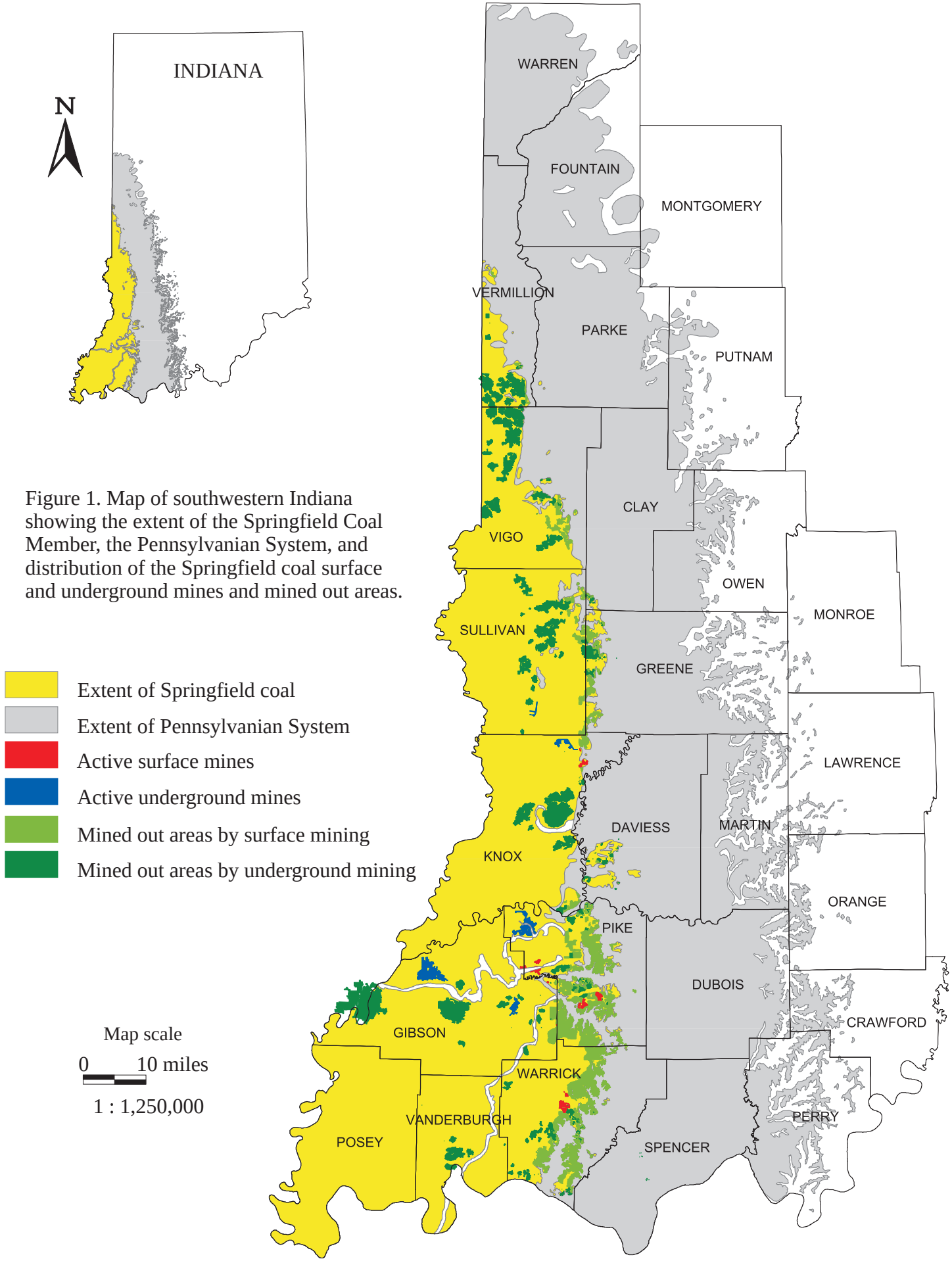


Figure 1. Map of southwestern Indiana showing the extent of the Springfield Coal Member, the Pennsylvanian System, and distribution of the Springfield coal surface and underground mines and mined out areas.

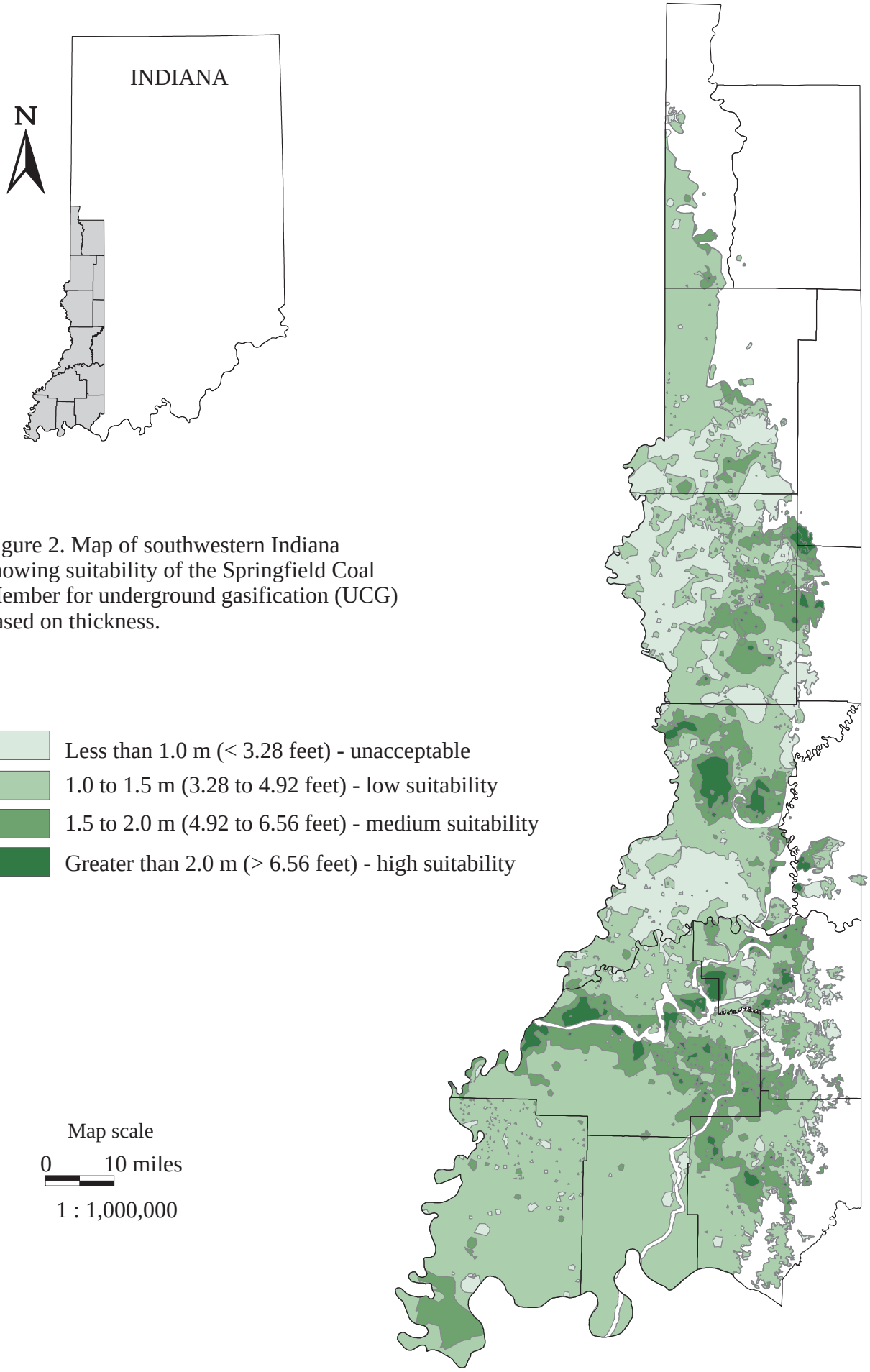


Figure 2. Map of southwestern Indiana showing suitability of the Springfield Coal Member for underground gasification (UCG) based on thickness.

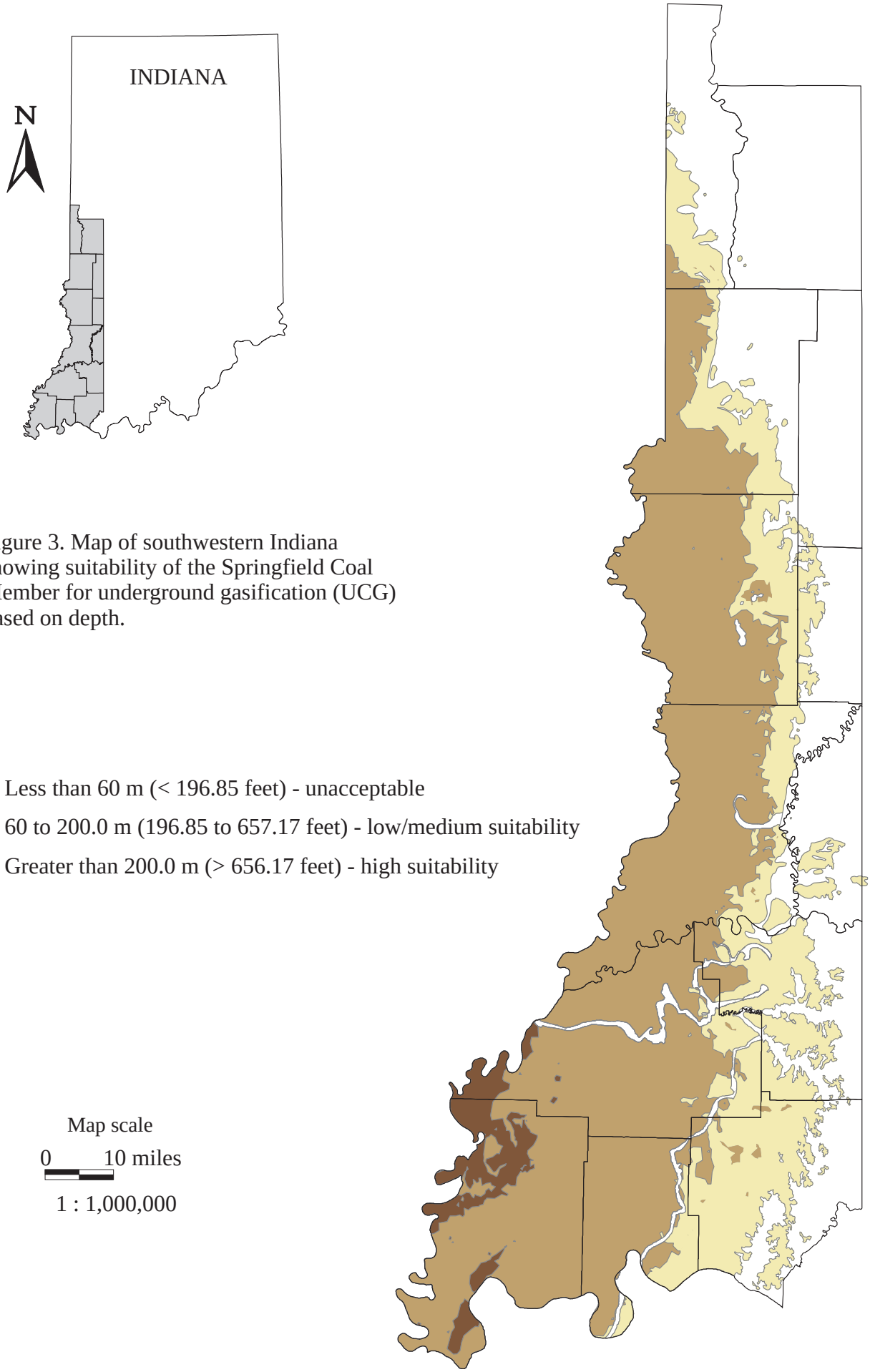
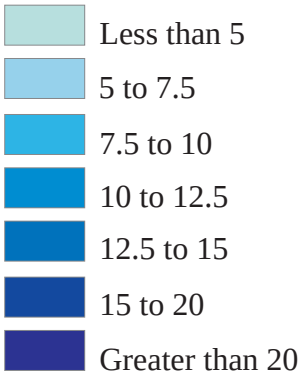
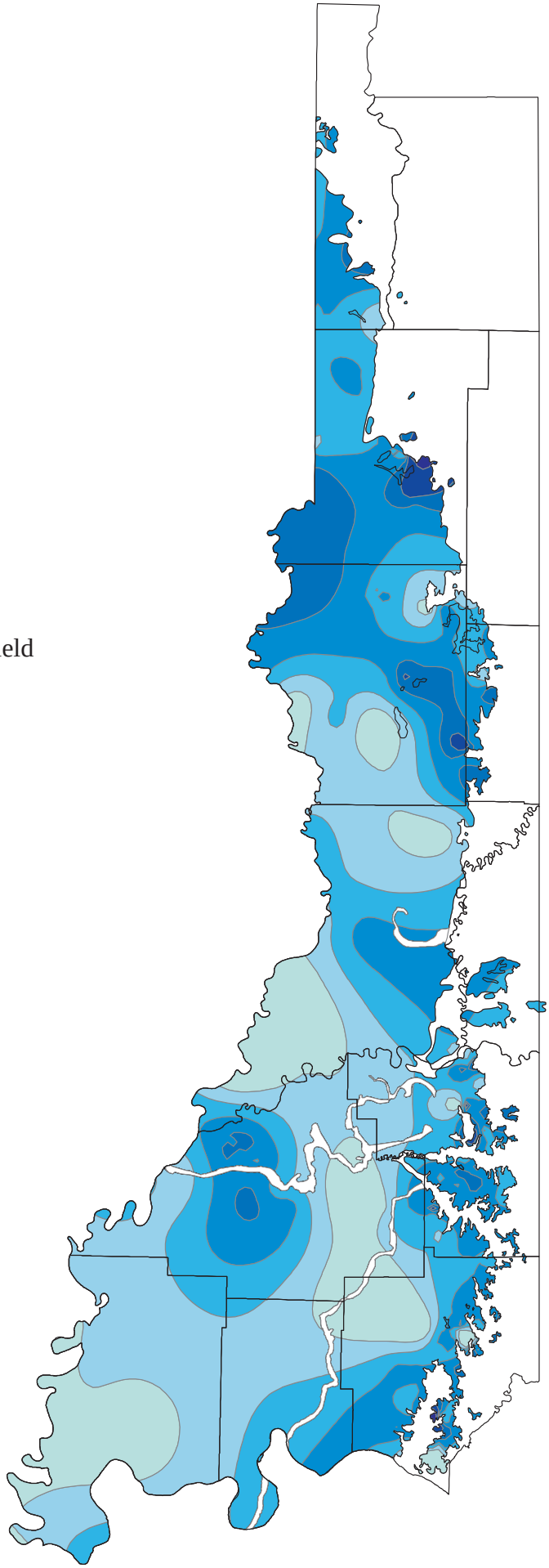


Figure 3. Map of southwestern Indiana showing suitability of the Springfield Coal Member for underground gasification (UCG) based on depth.

Figure 4. Map of southwestern Indiana showing moisture content [%] of the Springfield Coal Member.



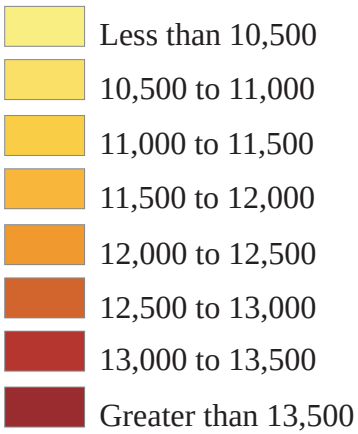


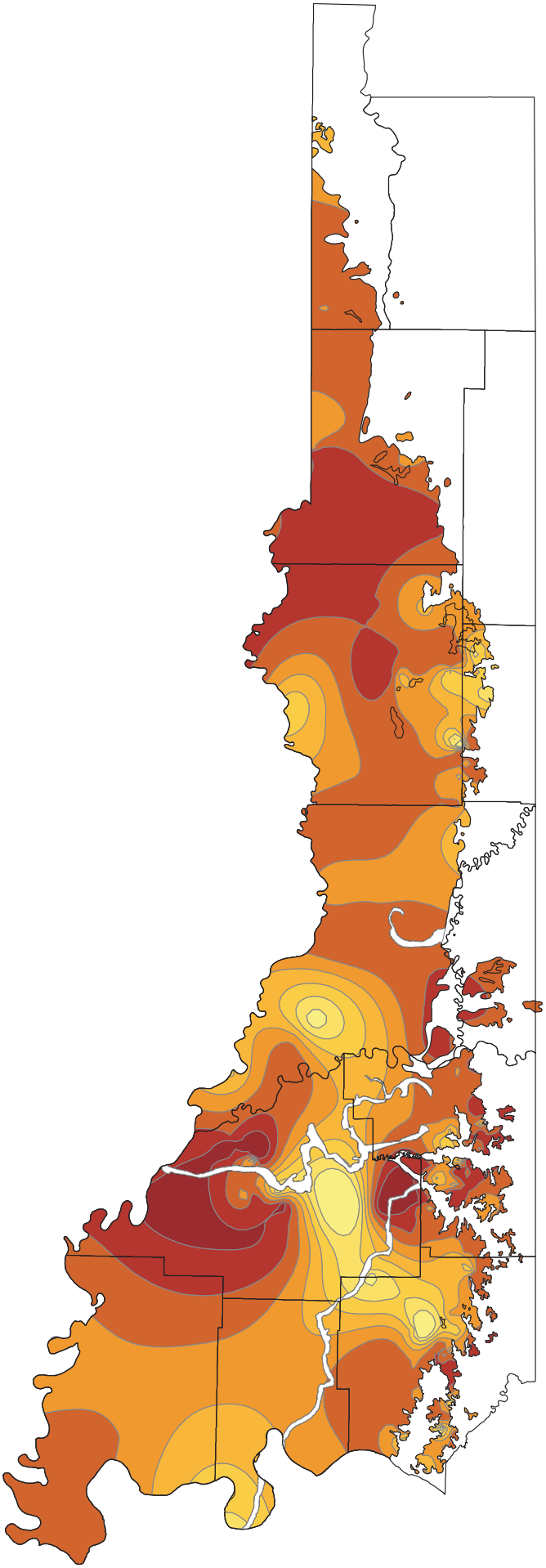
Map scale

0 10 miles

1 : 1,000,000

Figure 5. Map of southwestern Indiana showing heating value [Btu/lb, dry] of the Springfield Coal Member.





Map scale

0 10 miles

1 : 1,000,000

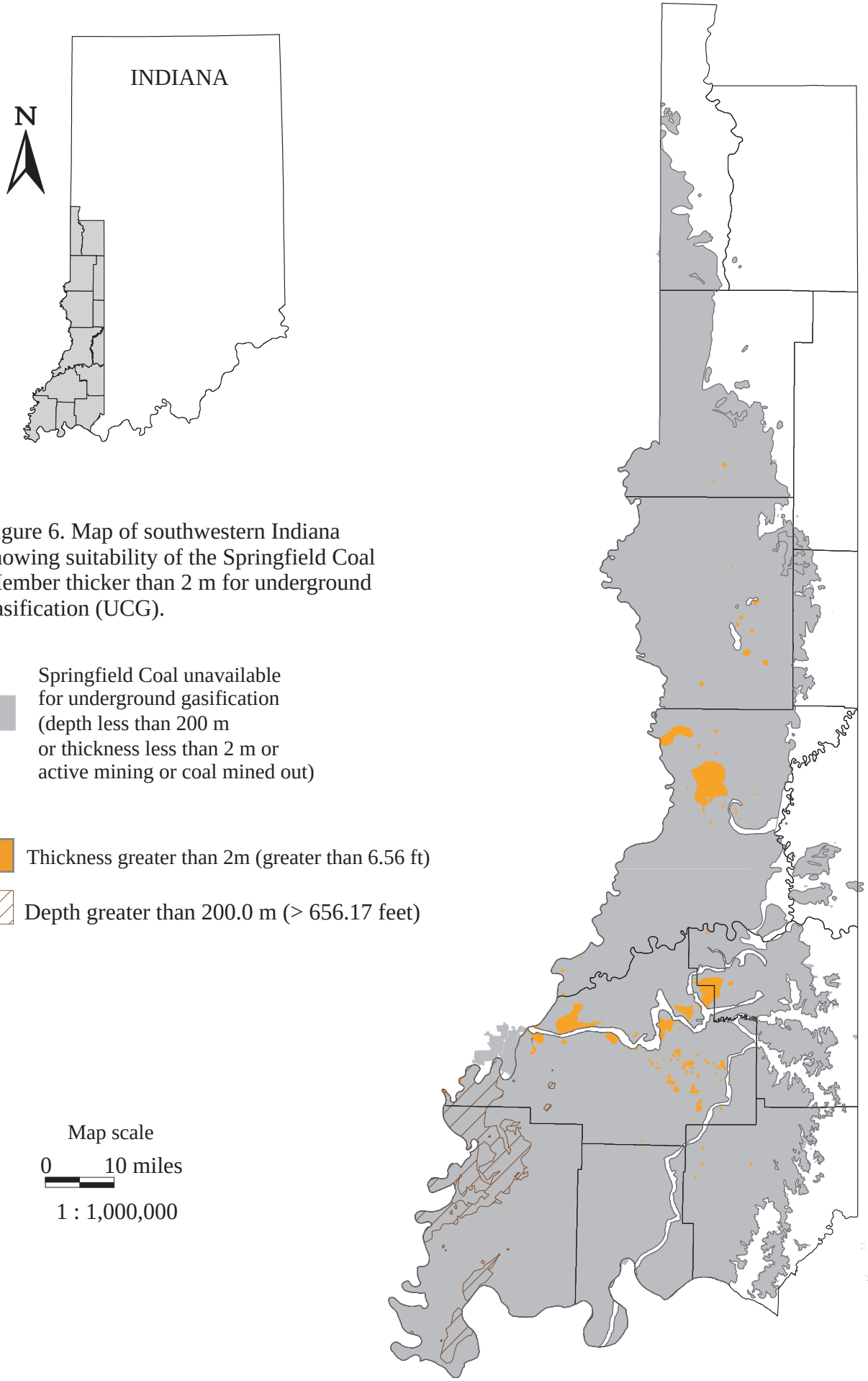


Figure 6. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 2 m for underground gasification (UCG).

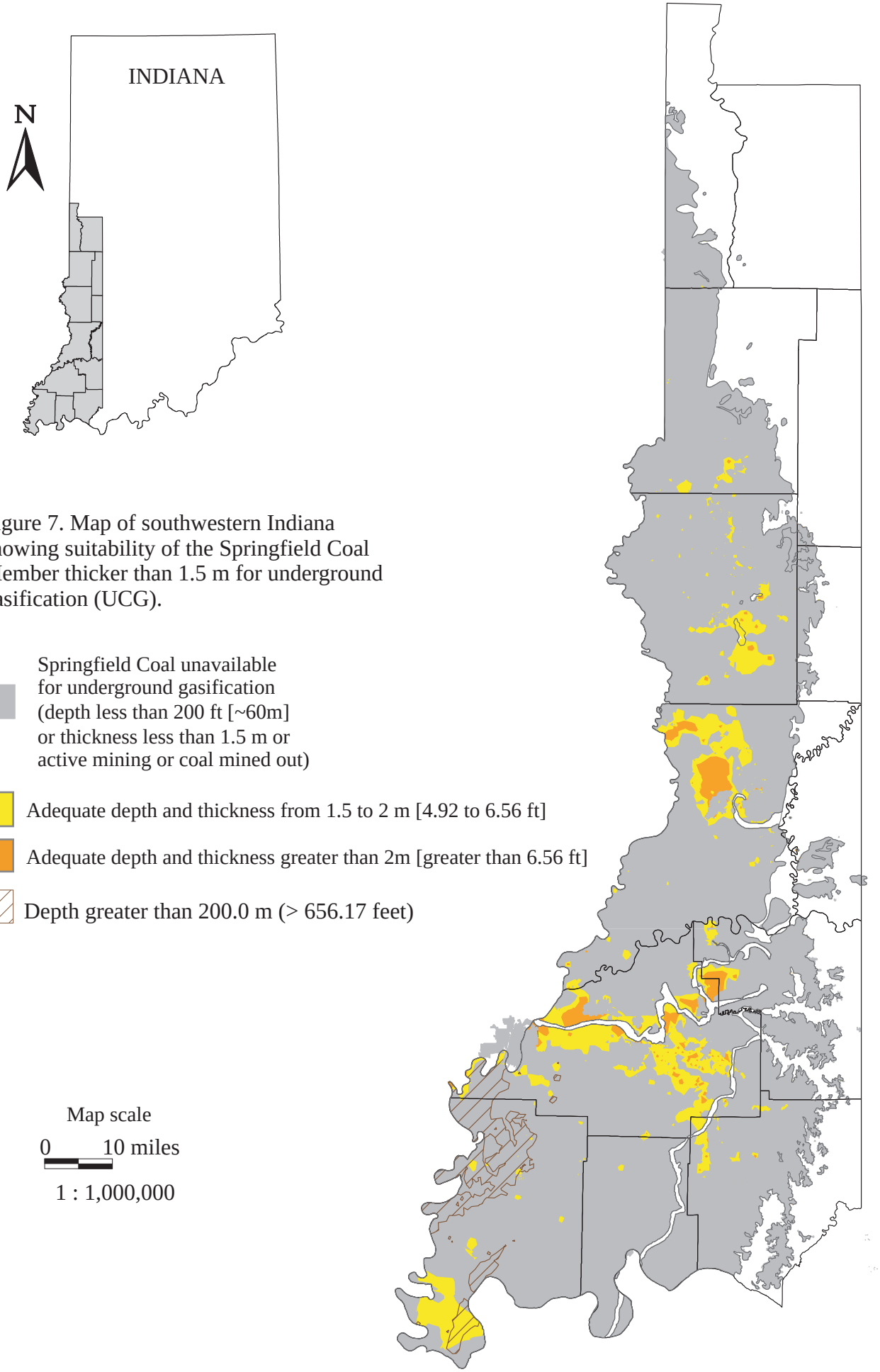


Figure 7. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 1.5 m for underground gasification (UCG).

Figure 8. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 1 m for underground gasification (UCG).

Springfield Coal unavailable for underground gasification (depth less than 200 ft [~60m] or thickness less than 1m or active mining or coal mined out)

Adequate depth and thickness from 1 to 2 m [3.28 to 6.56 ft]

Adequate depth and thickness greater than 2m [greater than 6.56 ft]

Depth greater than 200.0 m (> 656.17 feet)

Map scale

0 10 miles

1 : 1,000,000

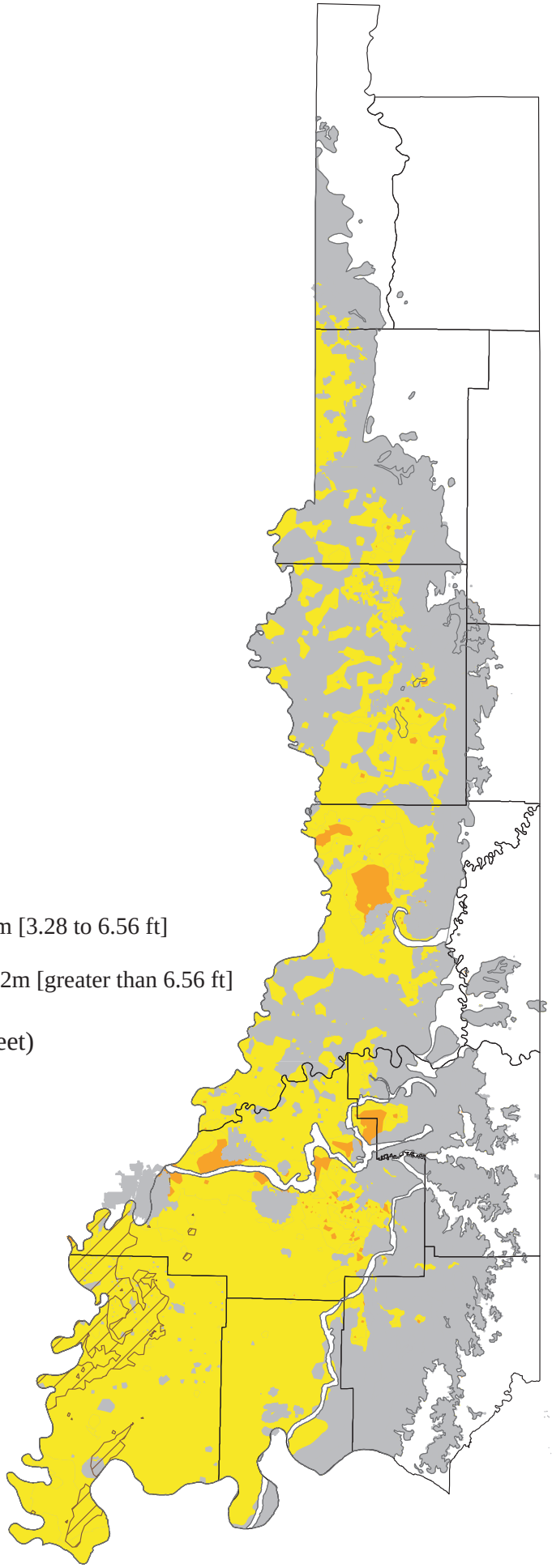


Figure 9. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 1.5 m for underground gasification (UCG) and infrastructure in Knox, Pike, and Gibson Counties.

Springfield Coal unavailable for underground gasification (depth less than 200 ft [~60m] or thickness less than 1m or coal mined out)

Adequate depth and thickness from 1.5 to 2 m [4.92 to 6.56 ft]

Adequate depth and thickness greater than 2m [greater than 6.56 ft]

Depth greater than 200.0 m (> 656.17 feet)

County boundary

Coal burning electric power plant

Highway

Active railroad

The approved I-69 corridor

City

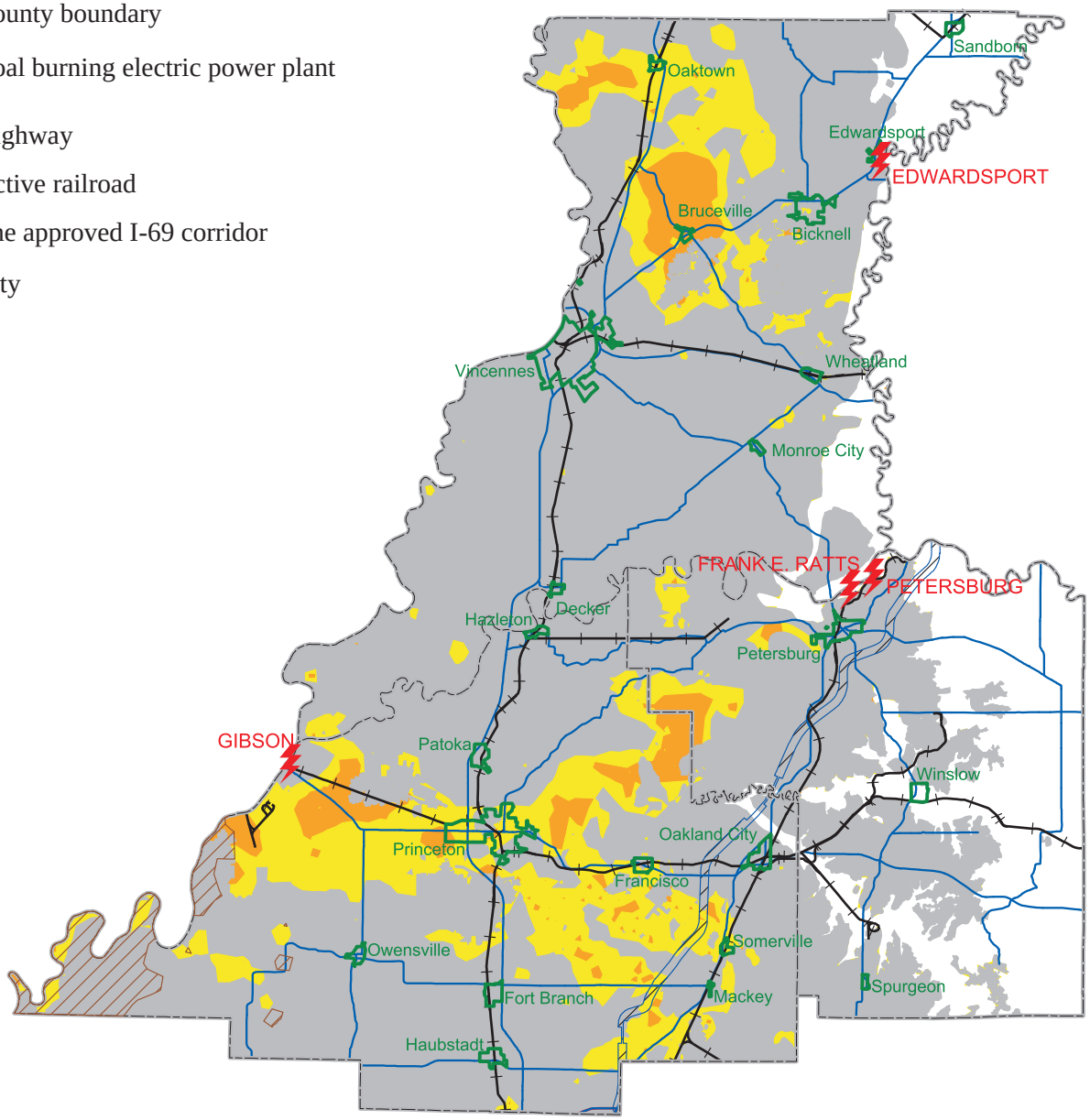


Figure 10. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 1 m for underground gasification (UCG) and infrastructure in Knox, Pike, and Gibson Counties.

Springfield Coal unavailable for underground gasification (depth less than 200 ft [~60m] or thickness less than 1m or coal mined out)

Adequate depth and thickness from 1 to 2 m [3.28 to 6.56 ft]

Adequate depth and thickness greater than 2m [greater than 6.56 ft]

Depth greater than 200.0 m (> 656.17 feet)

County boundary

Coal burning electric power plant

Highway

Active railroad

The approved I-69 corridor

City

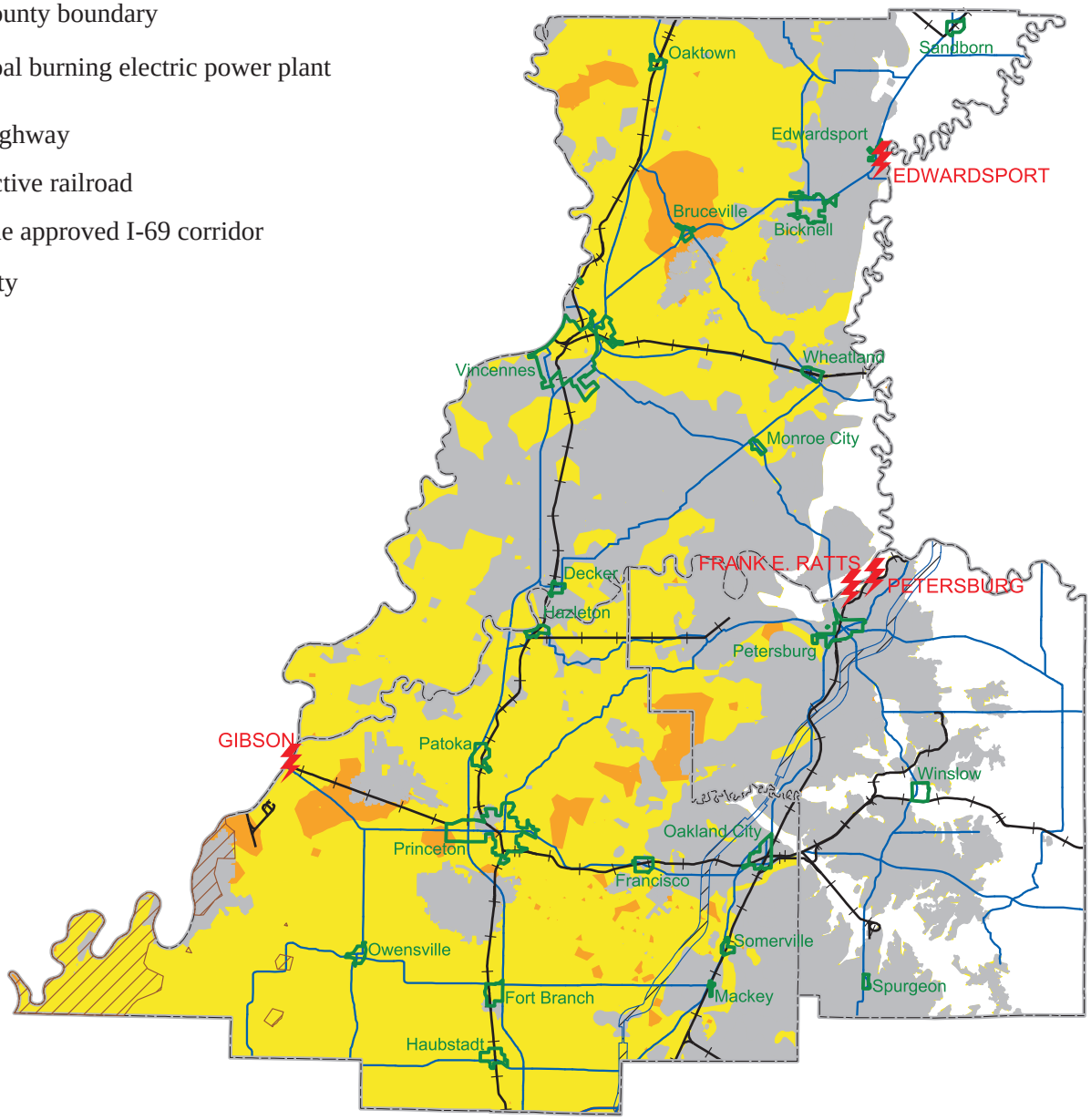


Figure 11. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 1.5 m for underground gasification (UCG) and natural-gas pipelines in Knox, Pike, and Gibson Counties.

Springfield Coal unavailable for underground gasification (depth less than 200 ft [~60m] or thickness less than 1m or coal mined out)

Adequate depth and thickness from 1.5 to 2 m [4.92 to 6.56 ft]

Adequate depth and thickness greater than 2m [greater than 6.56 ft]

Depth greater than 200.0 m (> 656.17 feet)

County boundary

Coal burning electric power plant

City

Natural gas pipelines

Less than 10 in.

10 to 20 in.

More than 20 in.

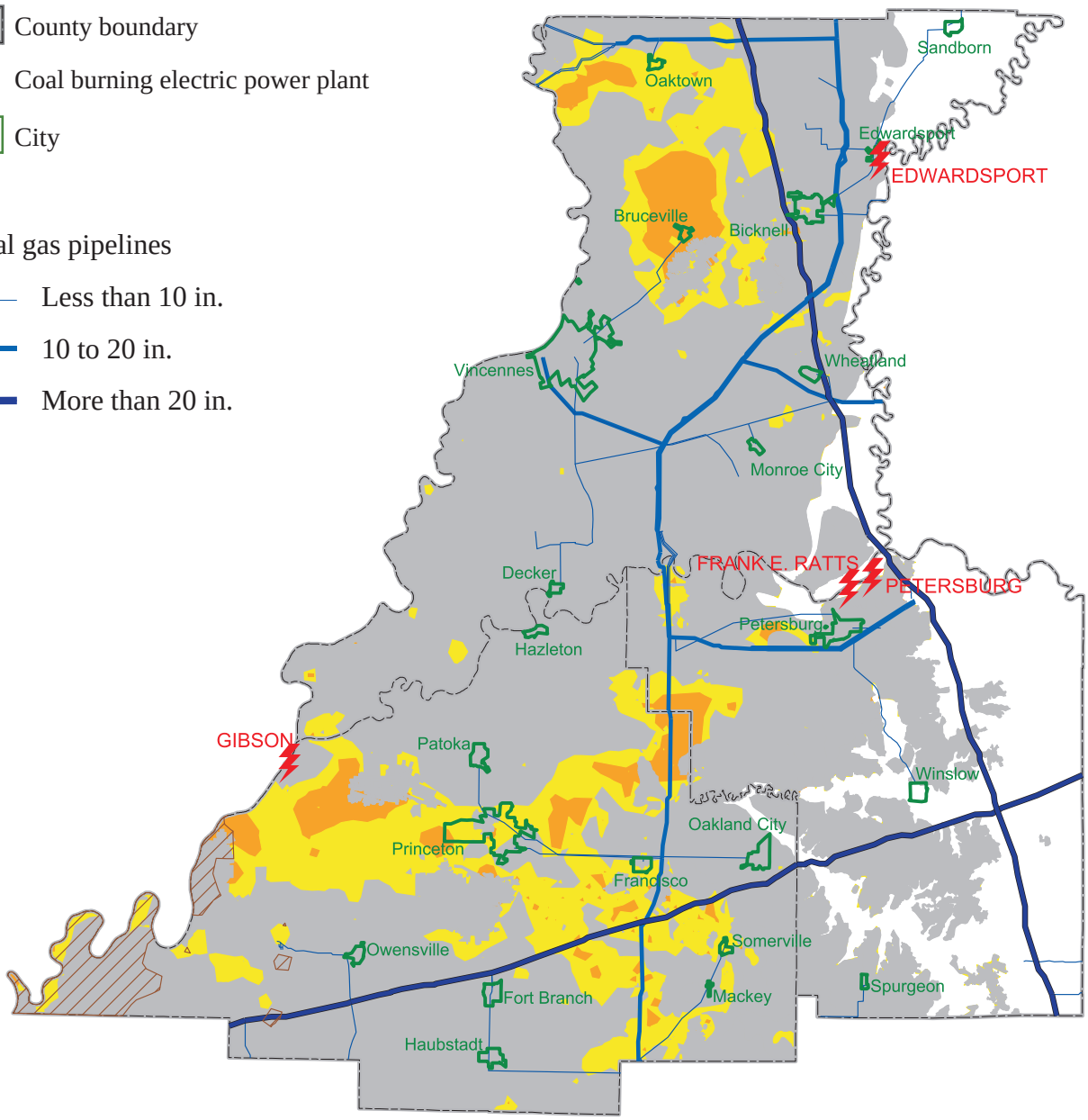


Figure 12. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 1 m for underground gasification (UCG) and natural-gas pipelines in Knox, Pike, and Gibson Counties.

Springfield Coal unavailable for underground gasification (depth less than 200 ft [~60m] or thickness less than 1m or coal mined out)

Adequate depth and thickness from 1.0 to 2 m [3.28 to 6.56 ft]

Adequate depth and thickness greater than 2m [greater than 6.56 ft]

Depth greater than 200.0 m (> 656.17 feet)

County boundary

Coal burning electric power plant

City

Natural gas pipelines

Less than 10 in.

10 to 20 in.

More than 20 in.

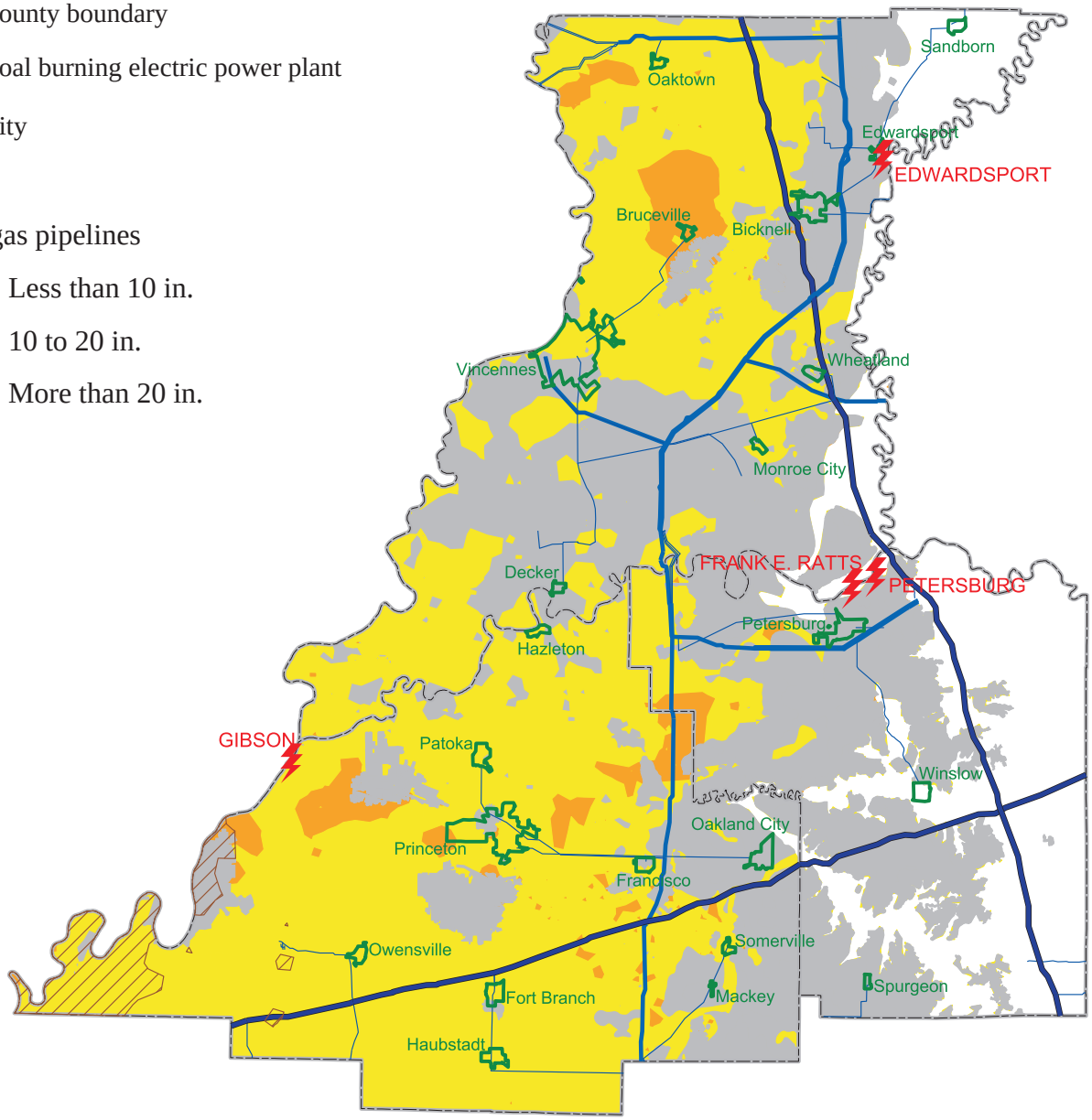
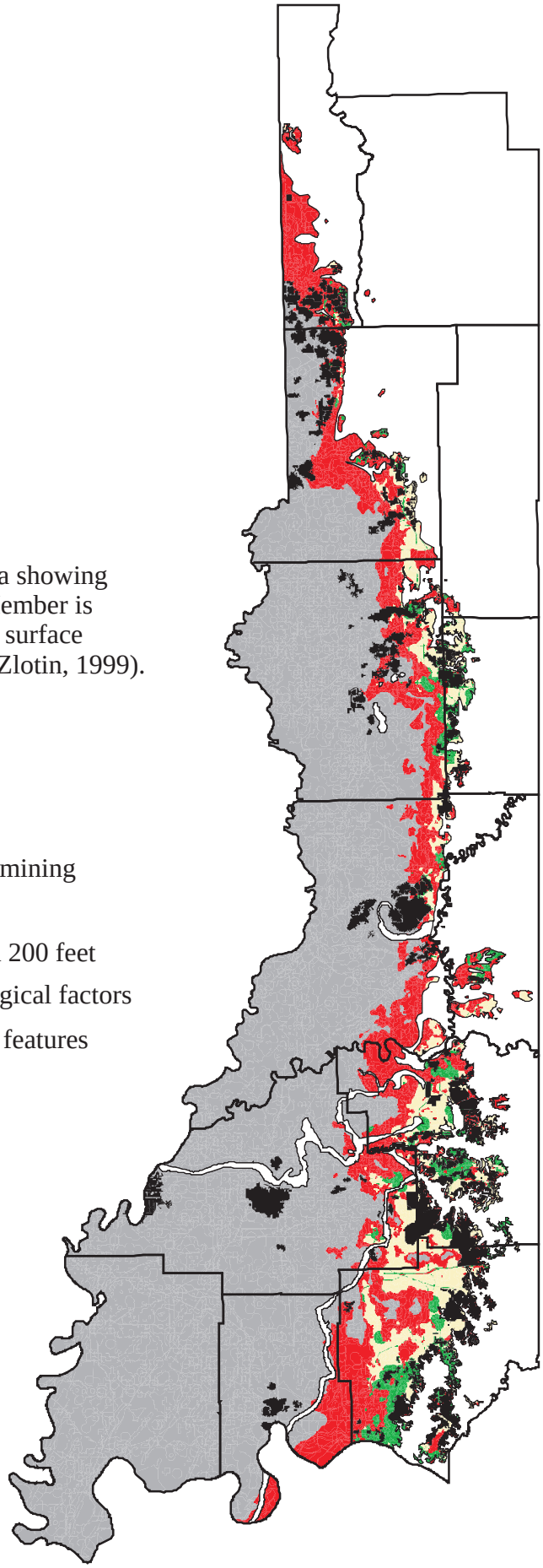


Figure 13. Map of southwestern Indiana showing the areas where the Springfield Coal Member is available for surface mining and where surface mining is restricted (after Conolly and Zlotin, 1999).



Springfield coal available for surface mining

Springfield coal mined out

Depth to Springfield coal greater then 200 feet

Surface mining restricted by technological factors

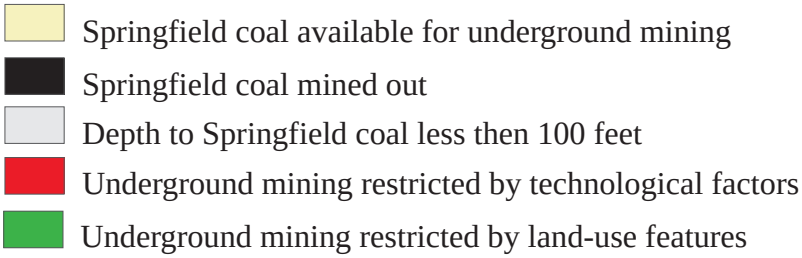
Surface mining restricted by land-use features

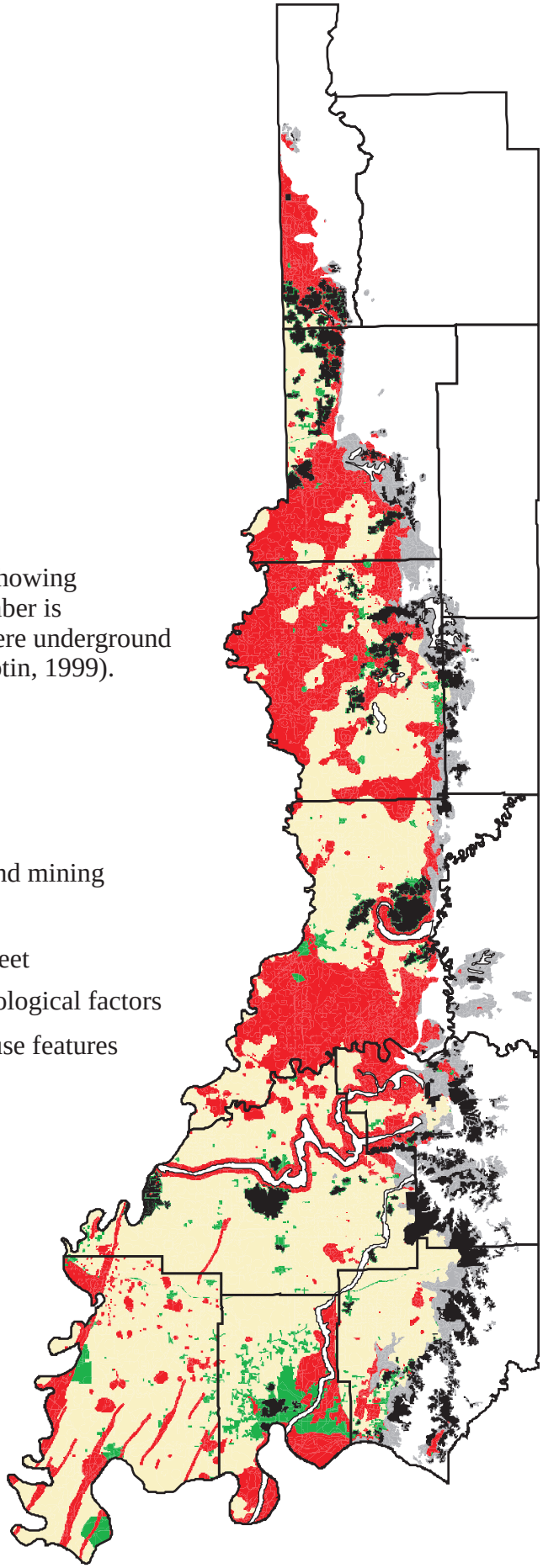
Map scale

0 10 miles

1 : 1,000,000

Figure 14. Map of southwestern Indiana showing the areas where the Springfield Coal Member is available for underground mining and where underground mining is restricted (after Conolly and Zlotin, 1999).





Map scale

0 10 miles

1 : 1,000,000

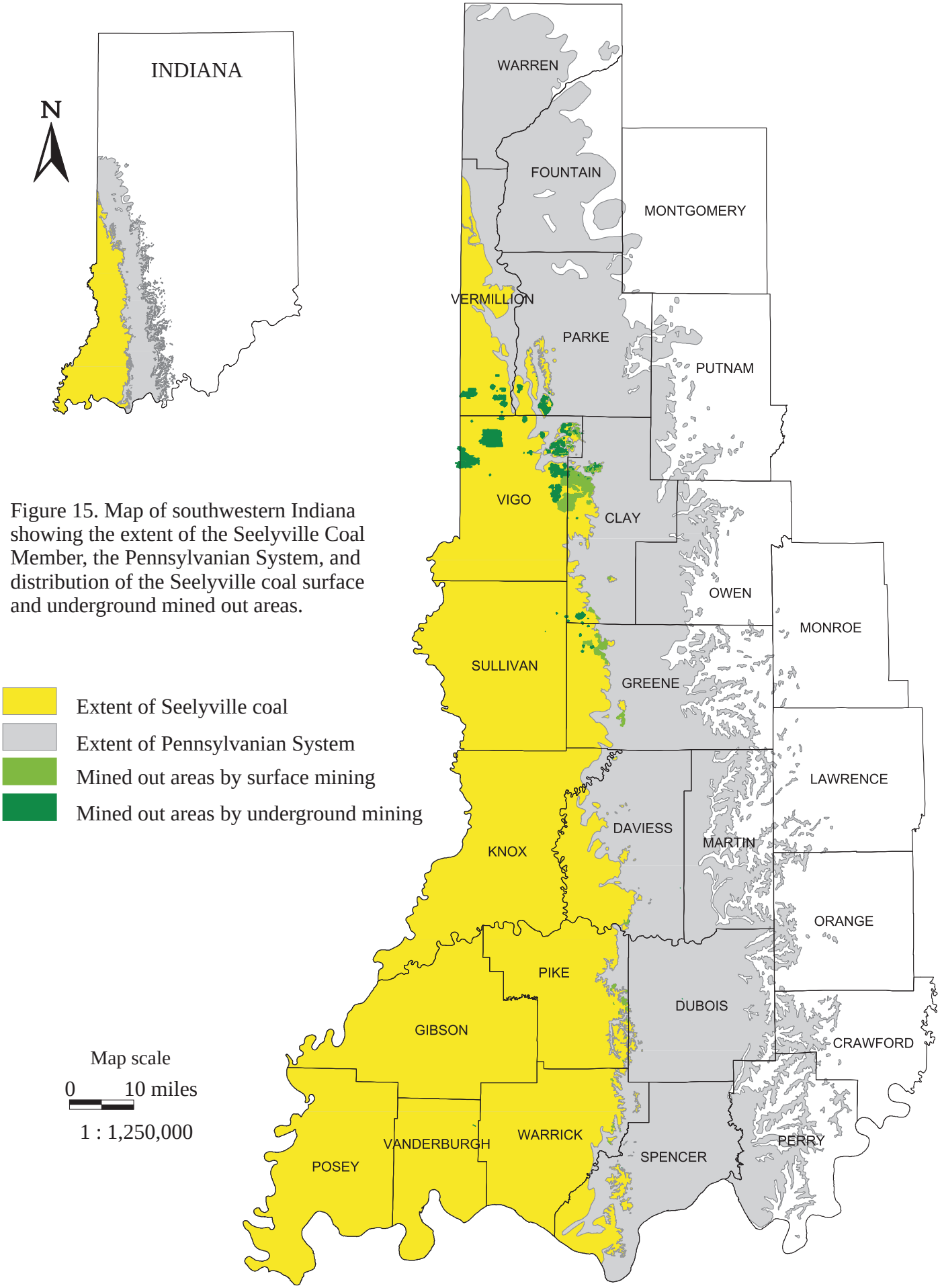


Figure 15. Map of southwestern Indiana showing the extent of the Seelyville Coal Member, the Pennsylvanian System, and distribution of the Seelyville coal surface and underground mined out areas.

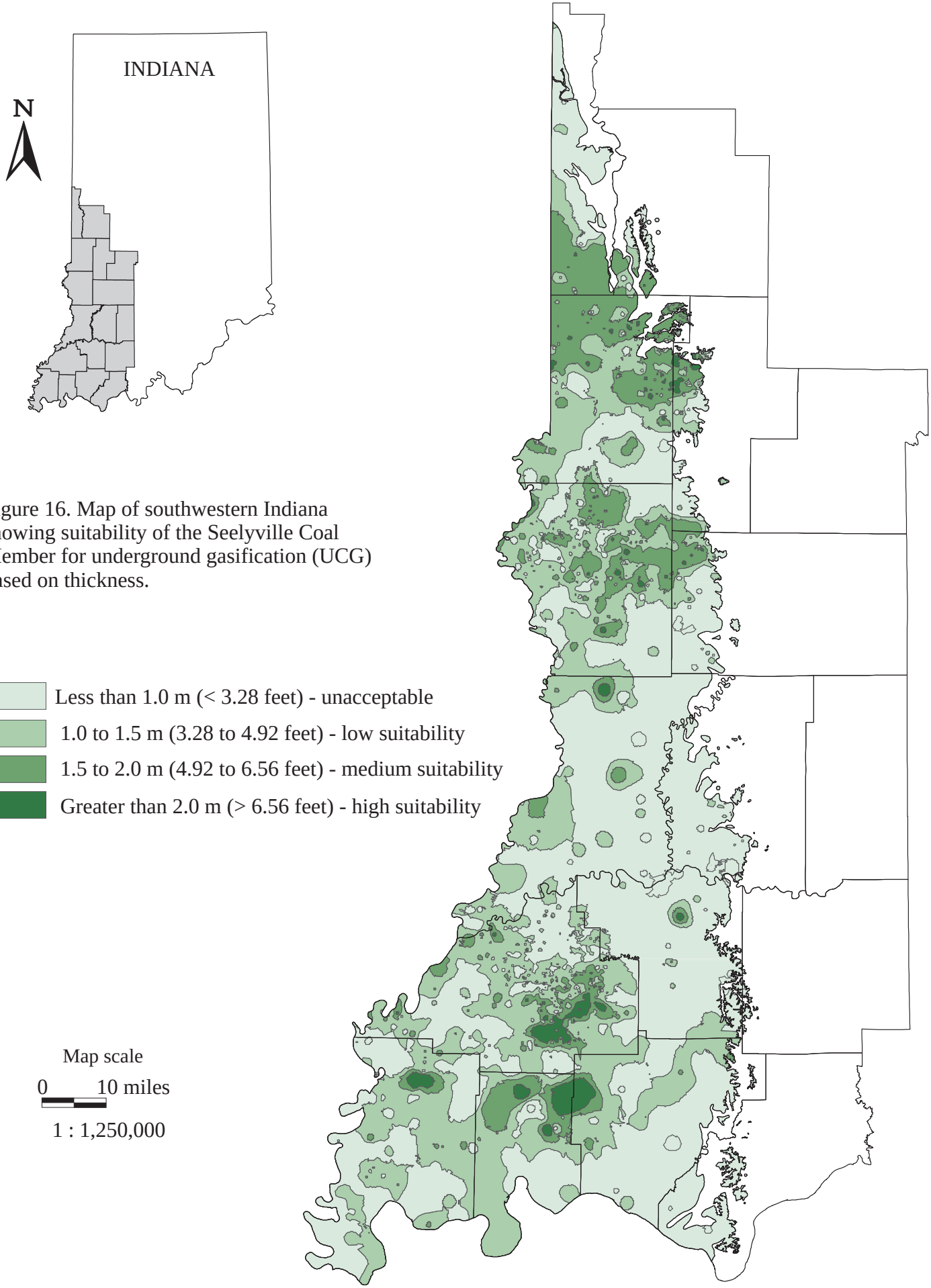


Figure 16. Map of southwestern Indiana showing suitability of the Seelyville Coal Member for underground gasification (UCG) based on thickness.

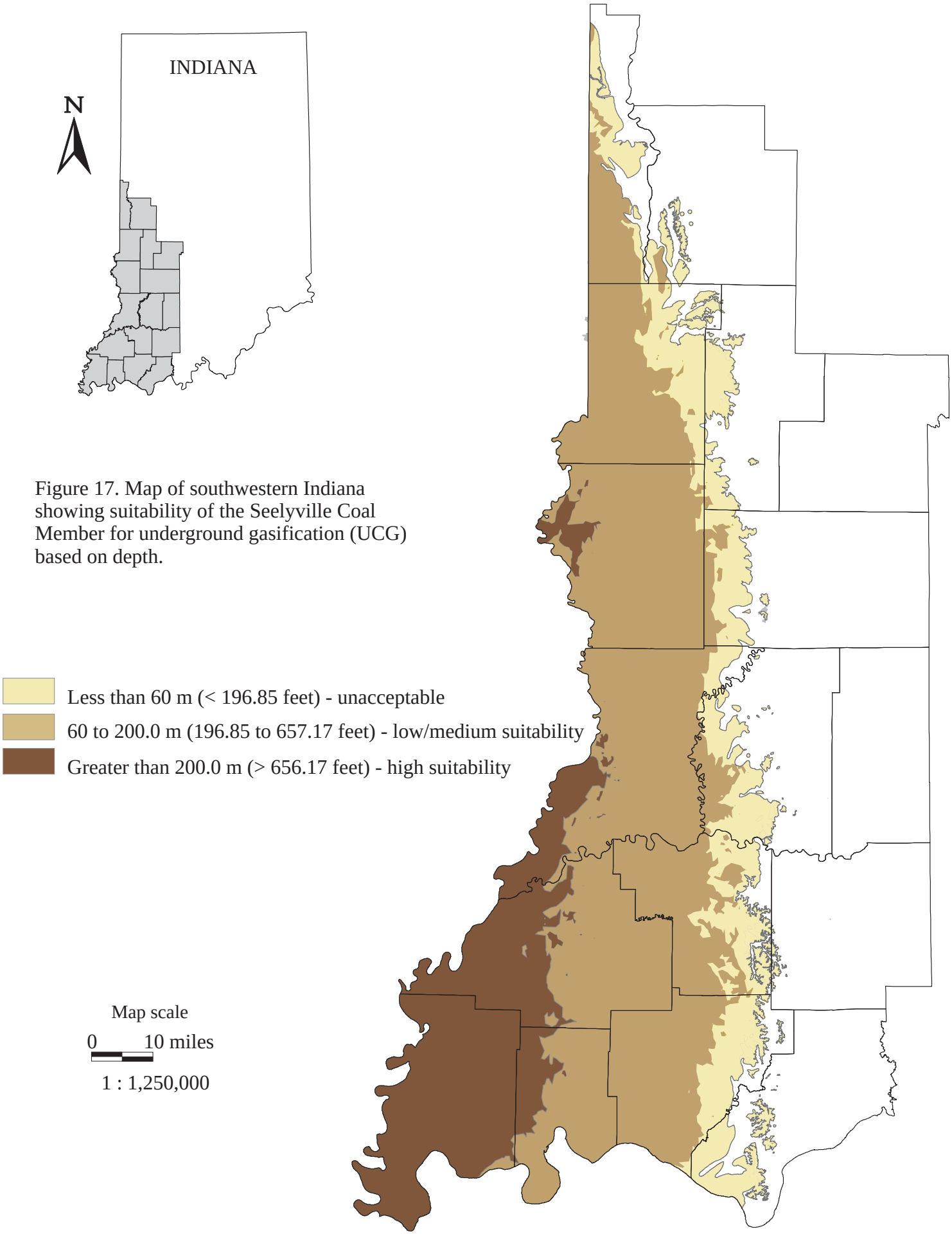


Figure 17. Map of southwestern Indiana showing suitability of the Seelyville Coal Member for underground gasification (UCG) based on depth.

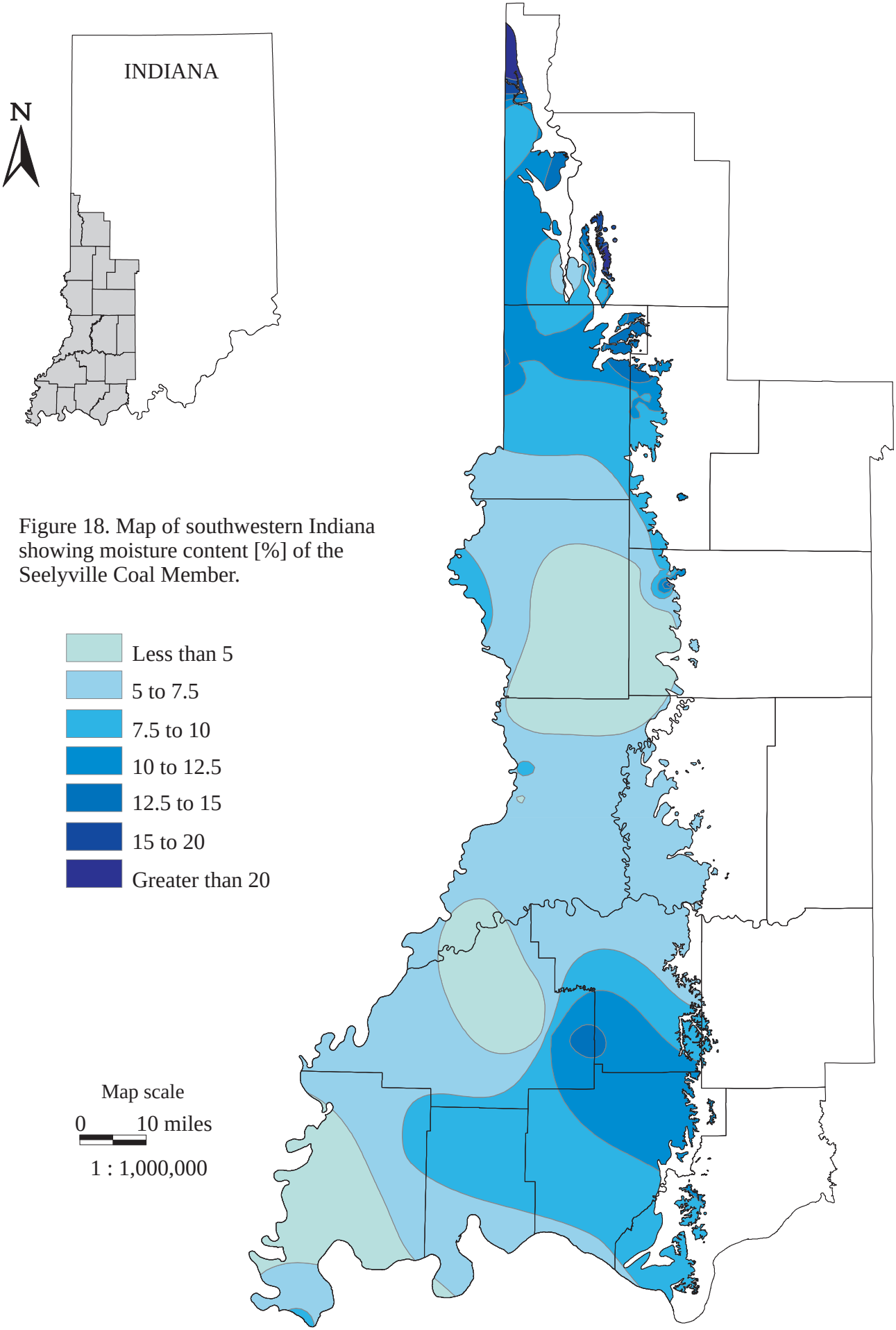


Figure 18. Map of southwestern Indiana showing moisture content [%] of the Seelyville Coal Member.

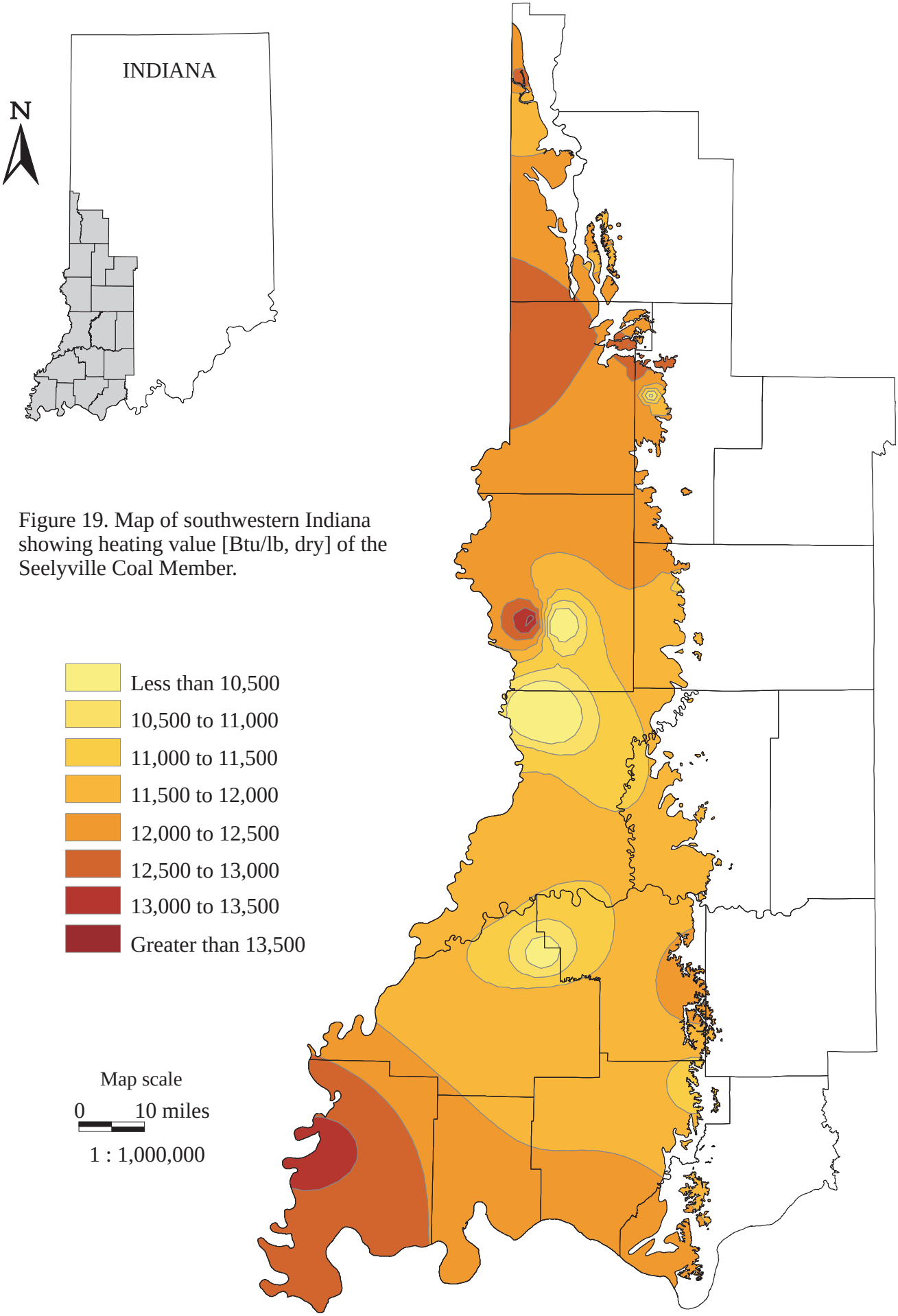


Figure 19. Map of southwestern Indiana showing heating value [Btu/lb, dry] of the Seelyville Coal Member.

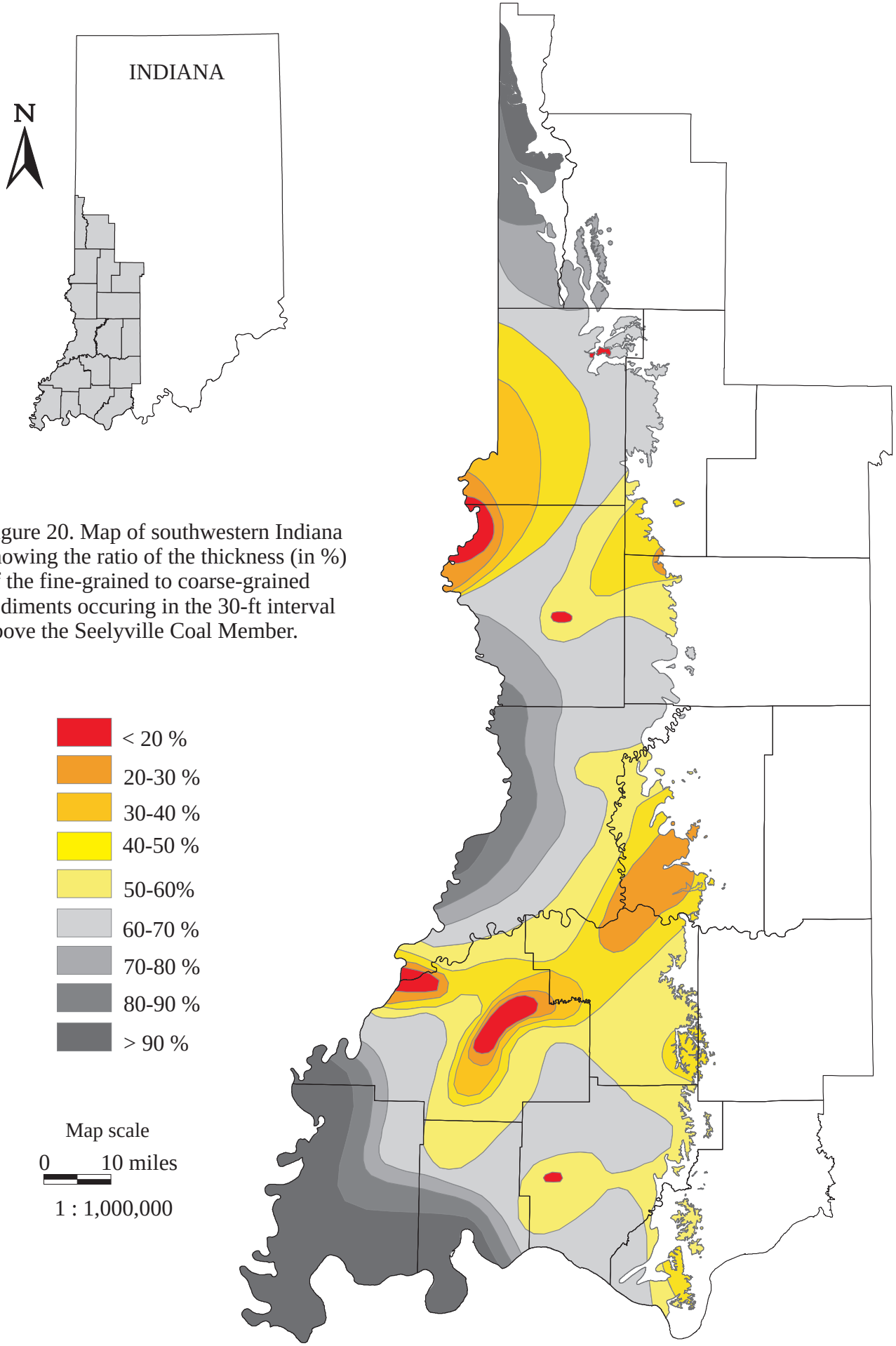


Figure 20. Map of southwestern Indiana showing the ratio of the thickness (in %) of the fine-grained to coarse-grained sediments occuring in the 30-ft interval above the Seelyville Coal Member.

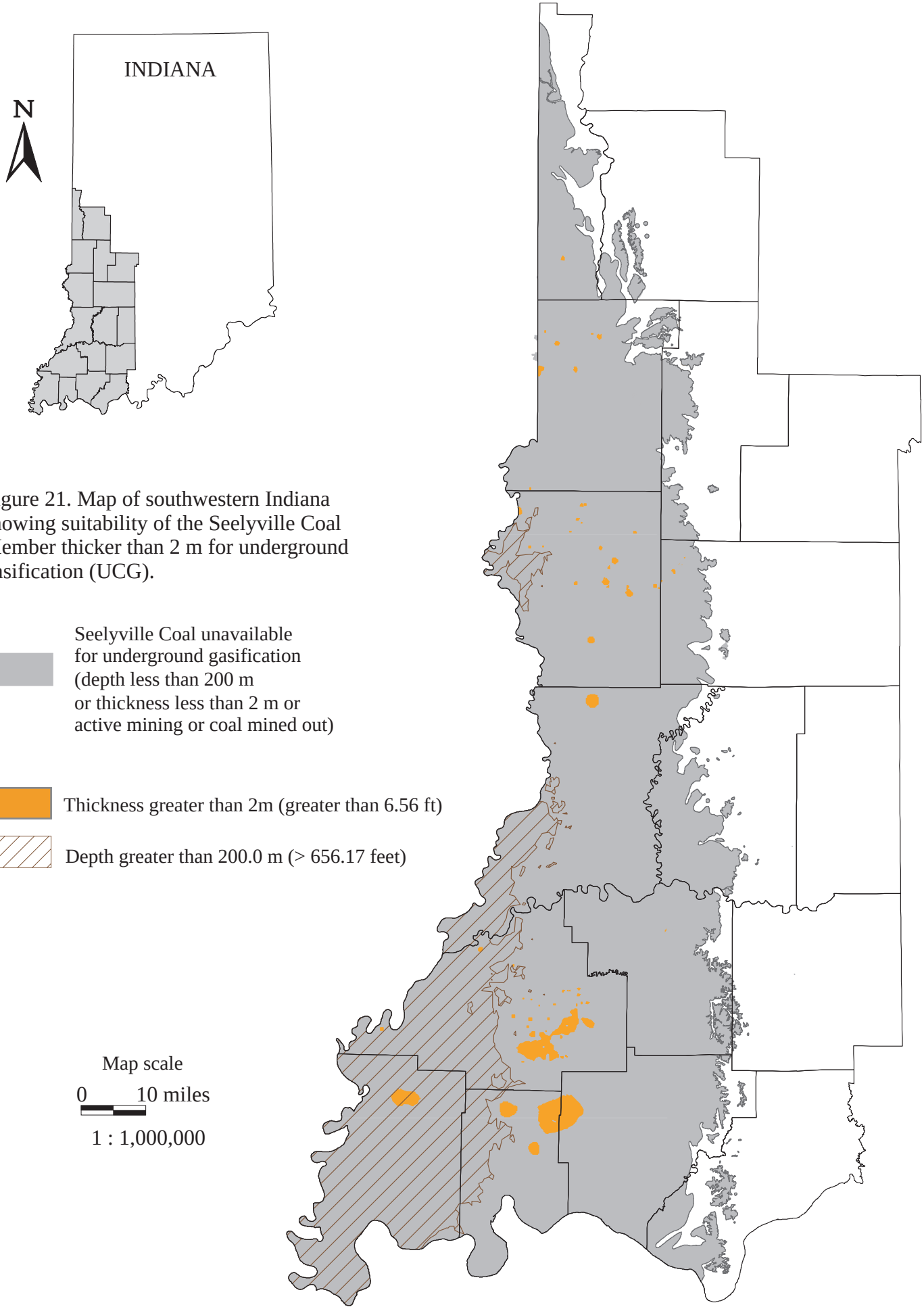


Figure 21. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 2 m for underground gasification (UCG).

Figure 22. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 1.5 m for underground gasification (UCG).

Seelyville Coal unavailable for underground gasification (depth less than 200 ft [~60m] or thickness less than 1.5 m or active mining or coal mined out)

Adequate depth and thickness from 1.5 to 2 m [4.92 to 6.56 ft]

Adequate depth and thickness greater than 2m [greater than 6.56 ft]

Depth greater than 200.0 m (> 656.17 feet)

Map scale

0 10 miles

1 : 1,000,000

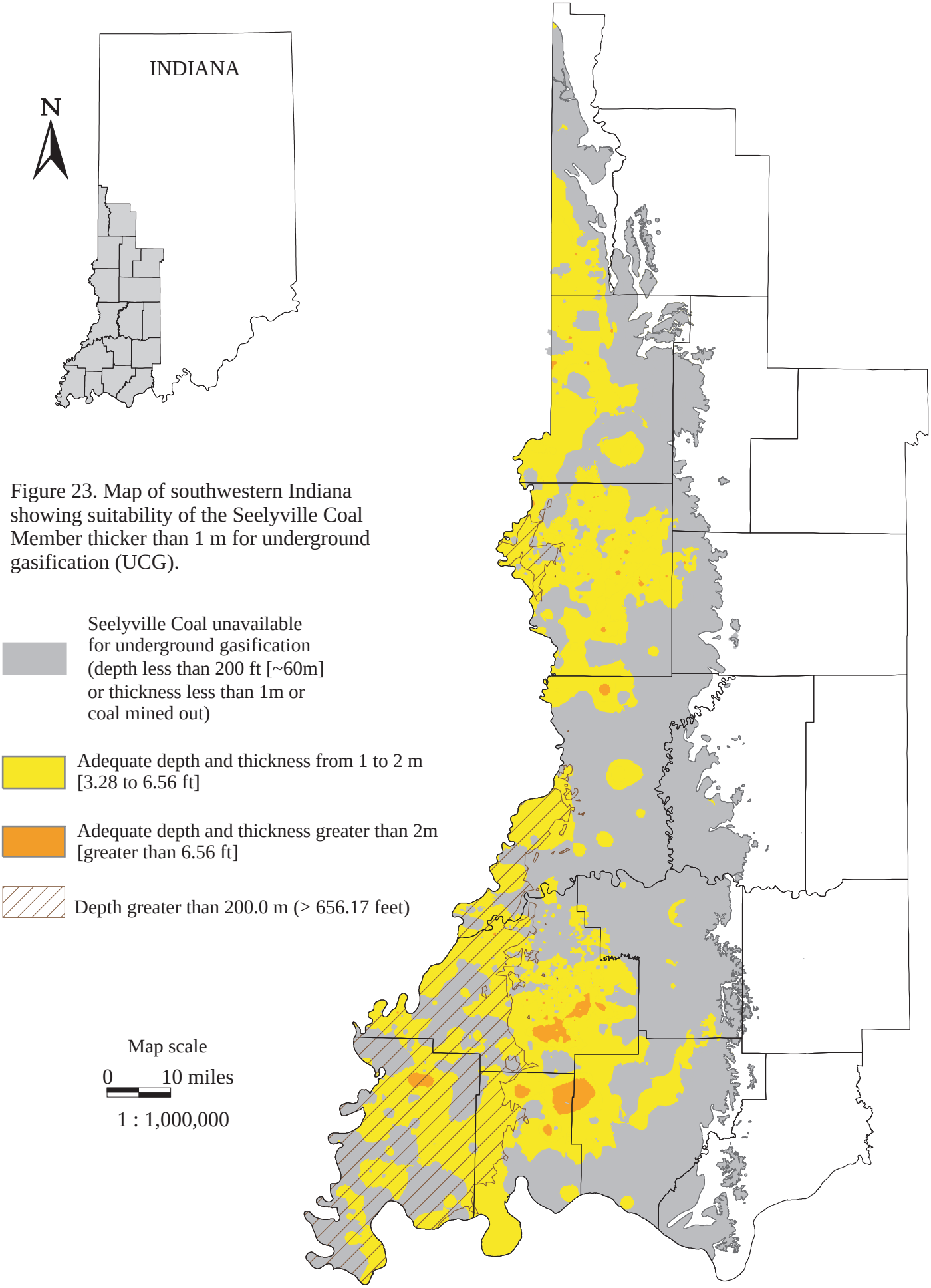


Figure 23. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 1 m for underground gasification (UCG).

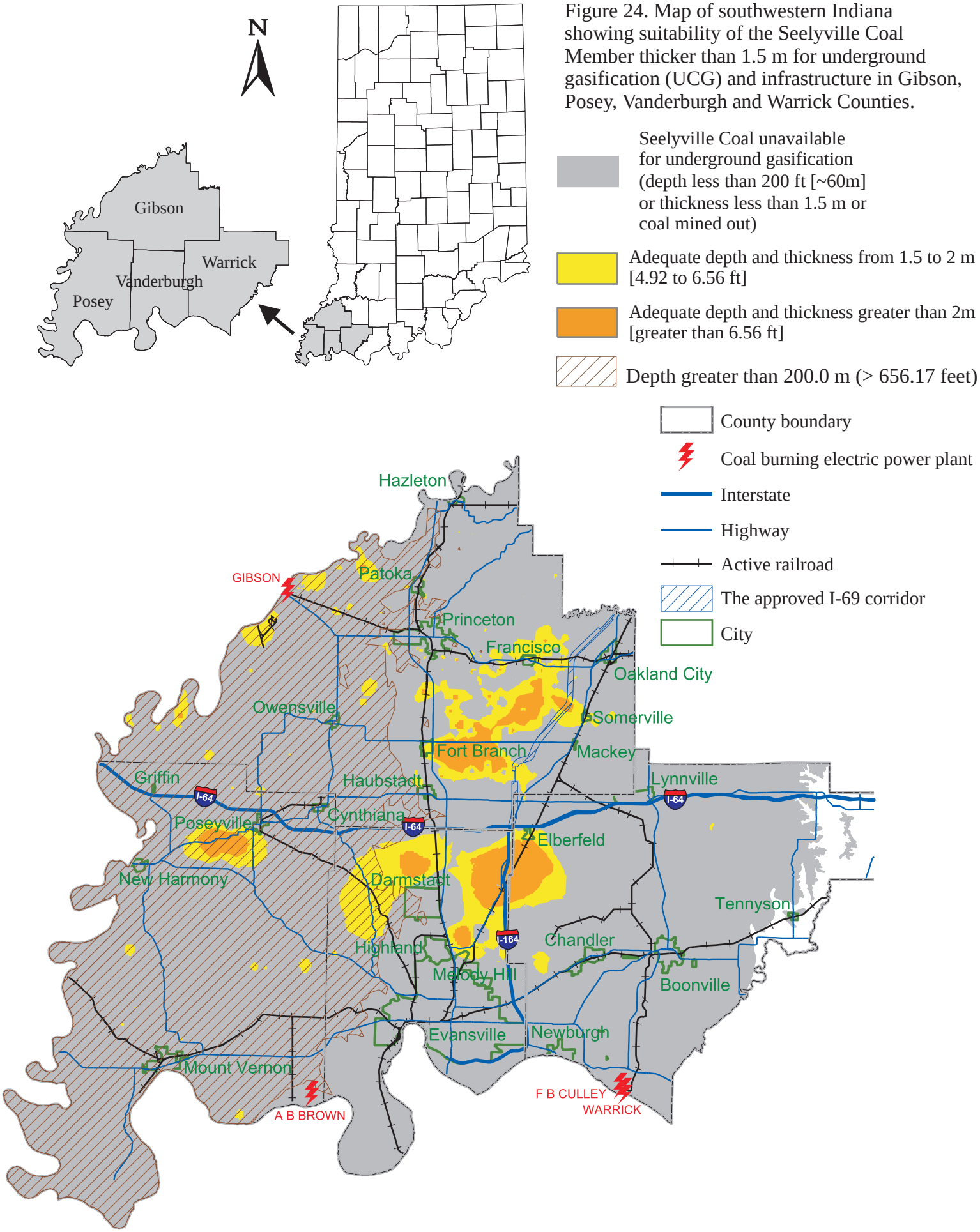


Figure 24. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 1.5 m for underground gasification (UCG) and infrastructure in Gibson, Posey, Vanderburgh and Warrick Counties.

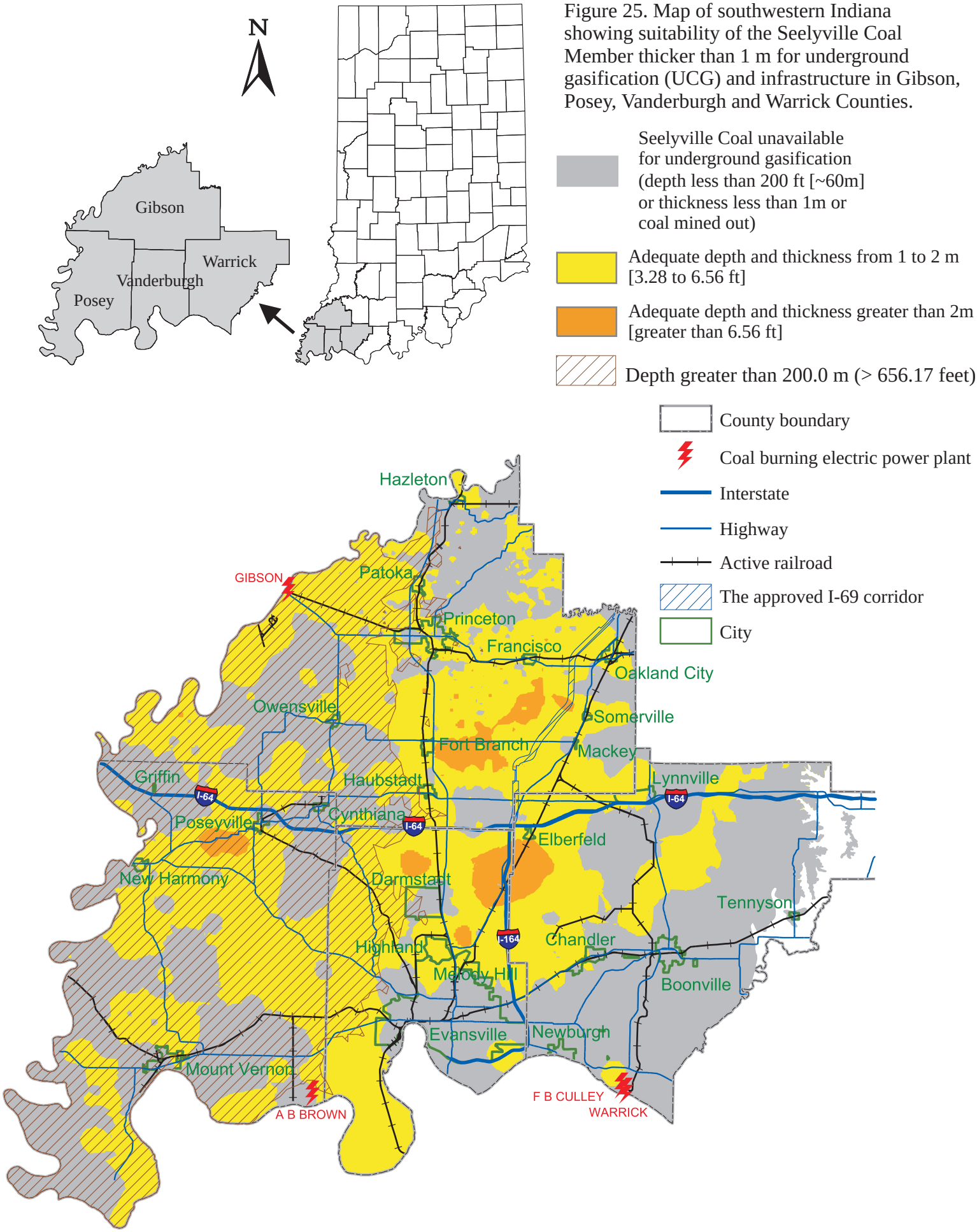


Figure 25. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 1 m for underground gasification (UCG) and infrastructure in Gibson, Posey, Vanderburgh and Warrick Counties.

Figure 26. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 1.5 m for underground gasification (UCG) and natural-gas pipelines in Gibson, Posey, Vanderburgh and Warrick Counties.

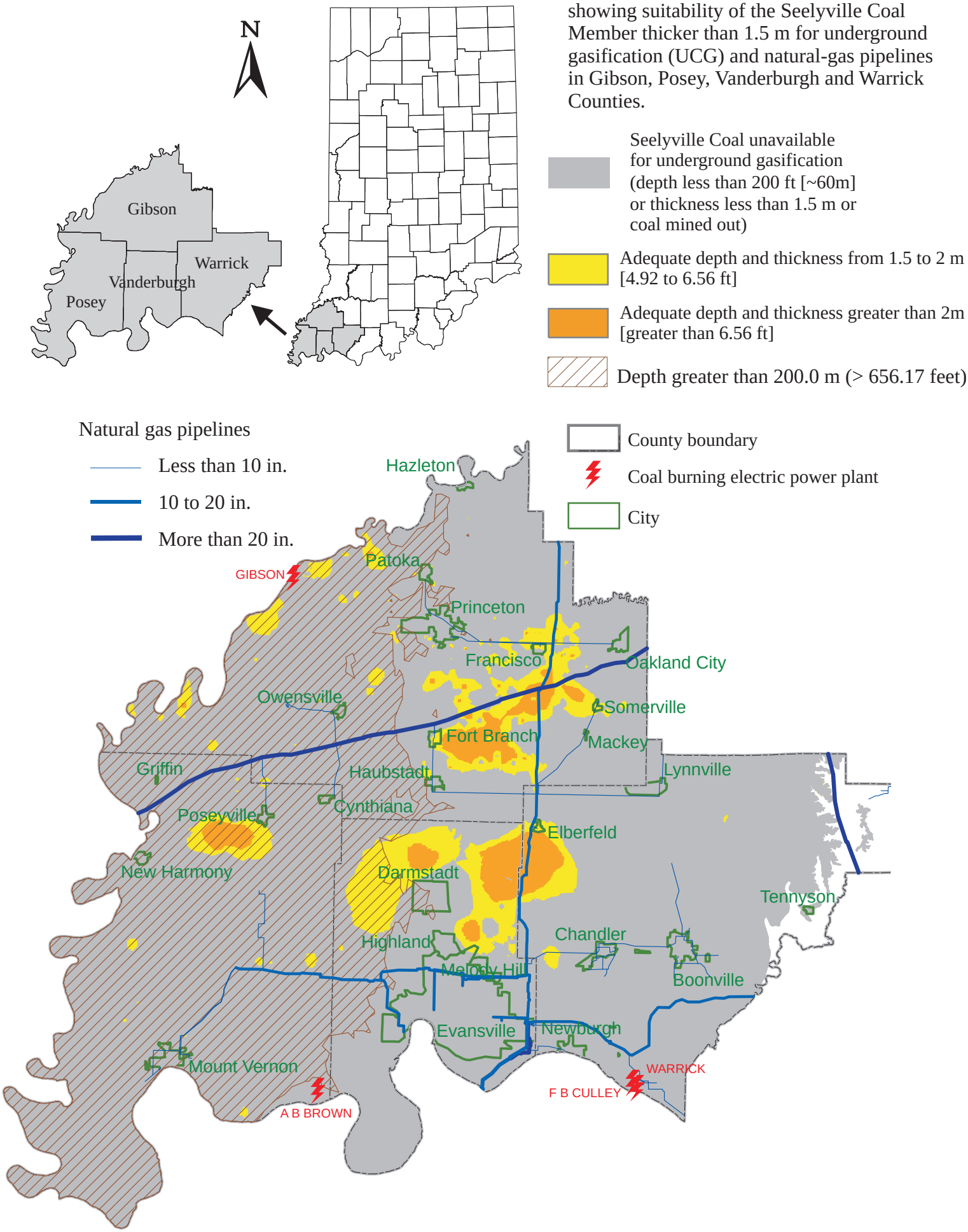


Figure 27. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 1 m for underground gasification (UCG) and natural-gas pipelines in Gibson, Posey, Vanderburgh and Warrick Counties.

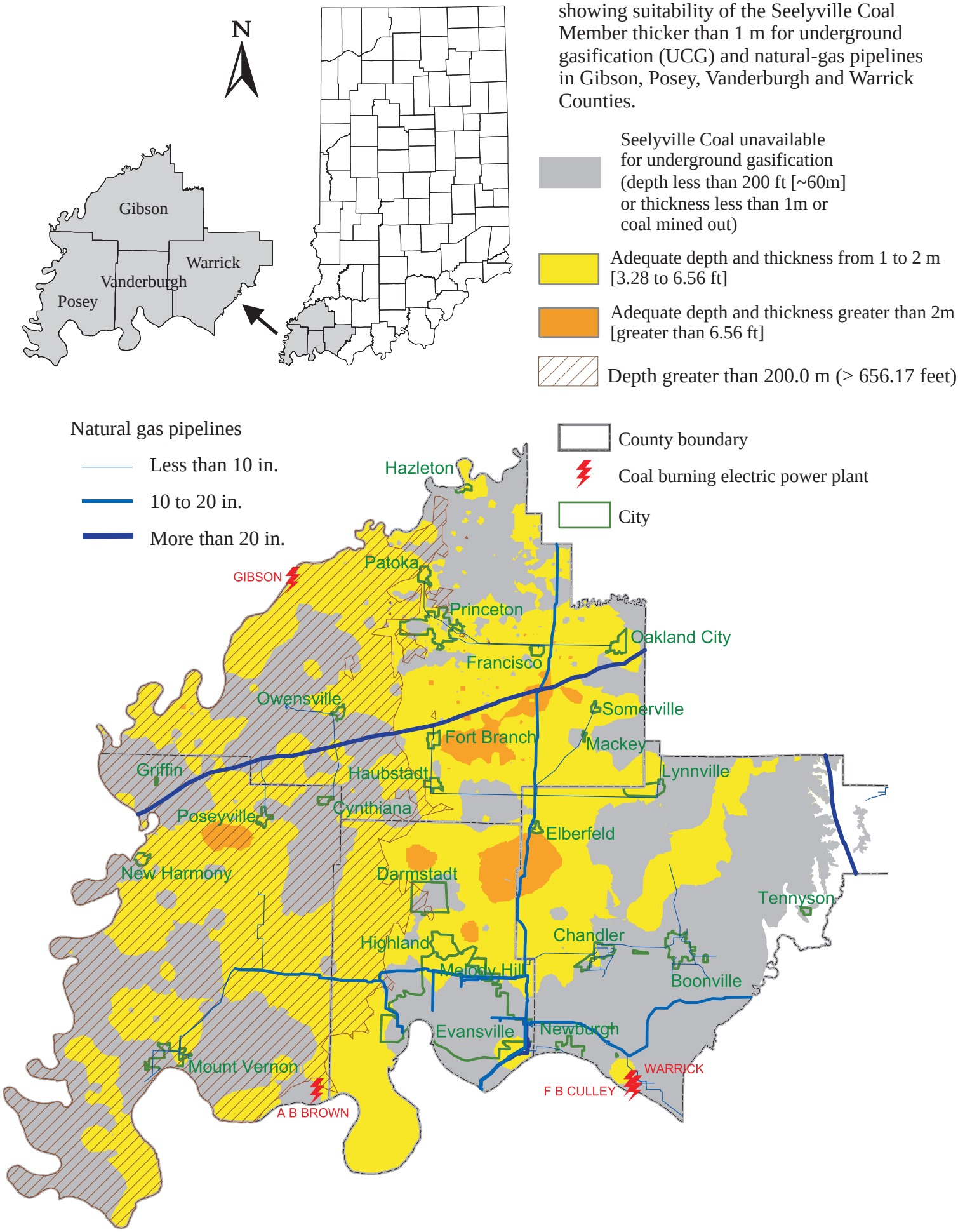
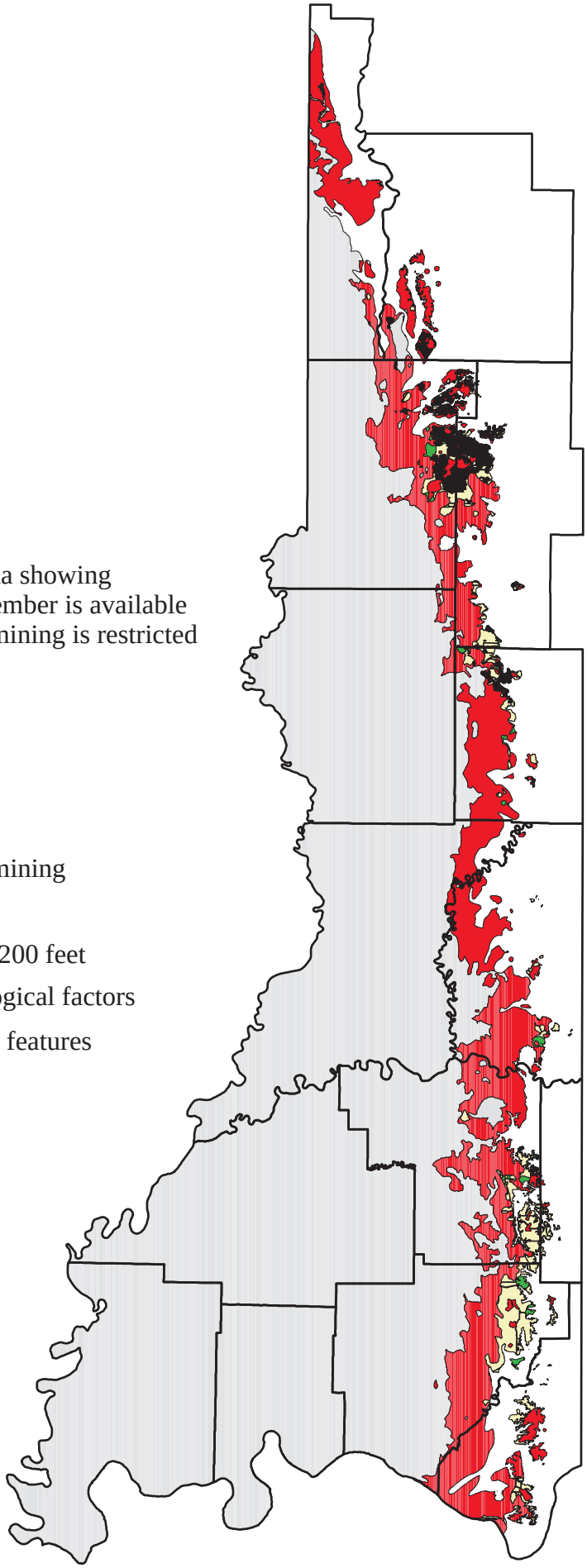


Figure 28. Map of southwestern Indiana showing the areas where the Seelyville Coal Member is available for surface mining and where surface mining is restricted (after Conolly, 2001).



Seelyville coal available for surface mining

Seelyville coal mined out

Depth to Seelyville coal greater then 200 feet

Surface mining restricted by technological factors

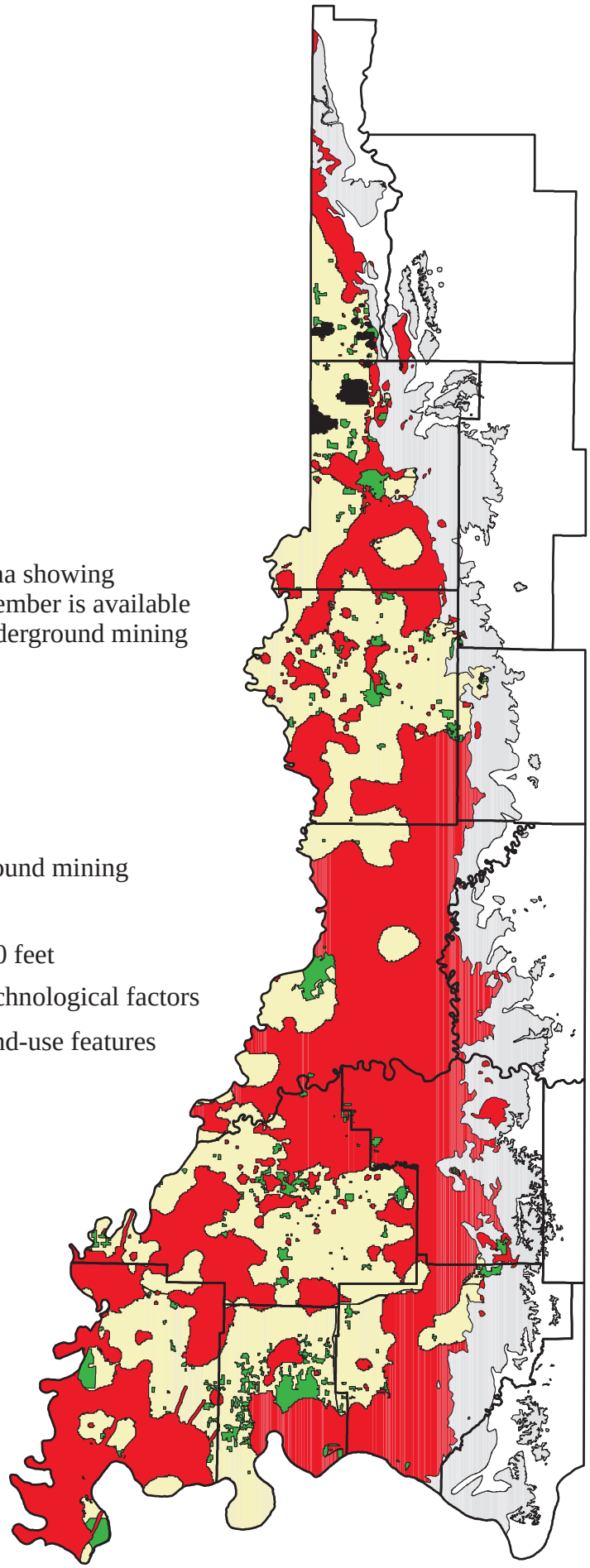
Surface mining restricted by land-use features

Map scale

0 10 miles

1 : 1,000,000

Figure 29. Map of southwestern Indiana showing the areas where the Seelyville Coal Member is available for underground mining and where underground mining is restricted (after Conolly, 2001).



Seelyville coal available for underground mining

Seelyville coal mined out

Depth to Seelyville coal less then 100 feet

Underground mining restricted by technological factors

Underground mining restricted by land-use features

Map scale

0 10 miles

1 : 1,000,000

Figure 30. Map of southwestern Indiana showing suitability of the Springfield Coal Member thicker than 1.5 m for underground gasification (UCG) and selected zones in Knox, Pike, and Gibson Counties.

Springfield Coal unavailable for underground gasification (depth less than 200 ft [~60m] or thickness less than 1m or coal mined out)

Adequate depth and thickness from 1.5 to 2 m [4.92 to 6.56 ft]

Adequate depth and thickness greater than 2m [greater than 6.56 ft]

Depth greater than 200.0 m (> 656.17 feet)

No coal

County boundary

Coal burning electric power plant

City

Natural gas pipelines

Less than 10 in.

10 to 20 in.

More than 20 in.

Selected zones

10 miles

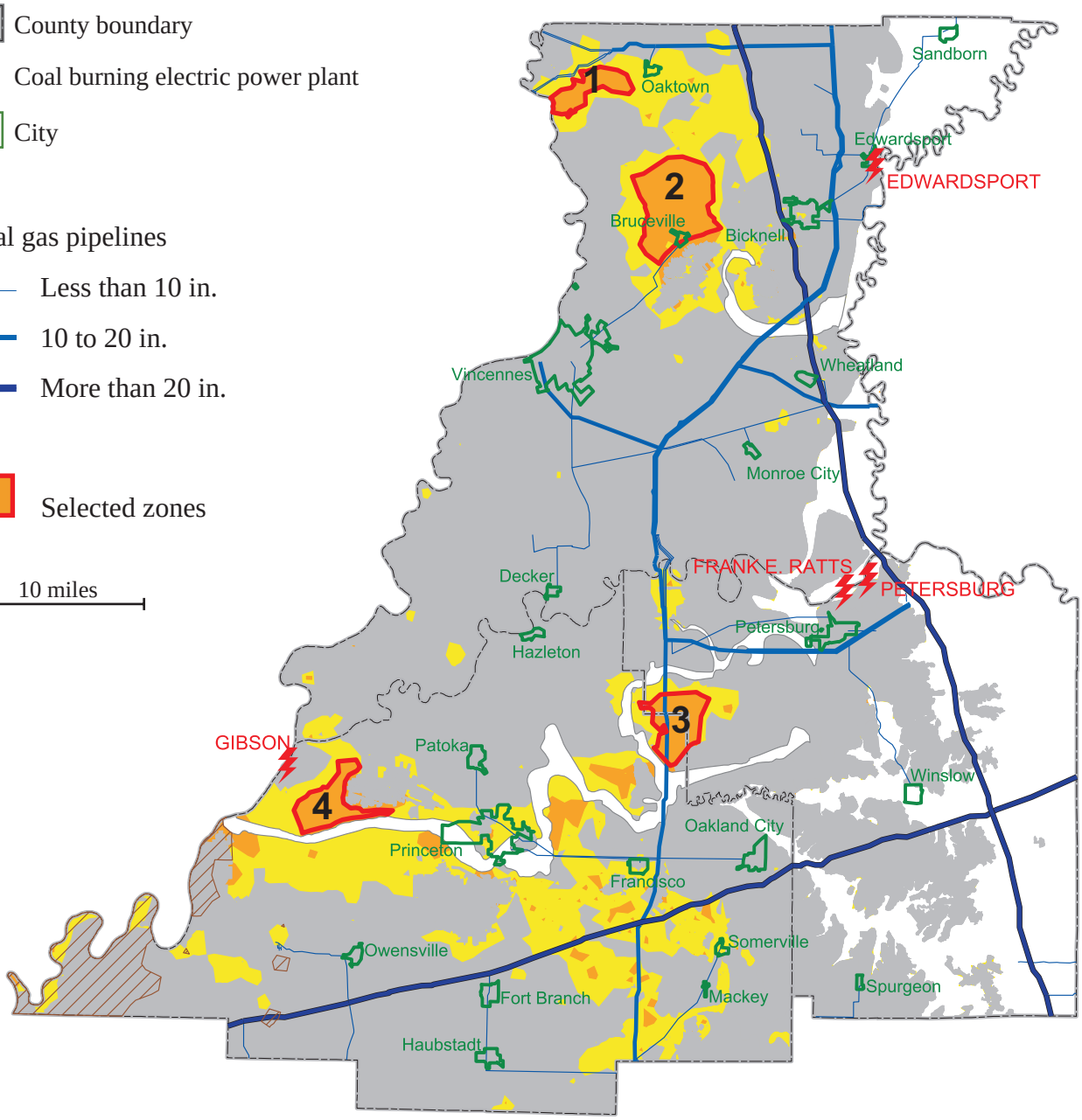


Figure 31. Map of southwestern Indiana showing suitability of the Seelyville Coal Member thicker than 1.5 m for underground gasification (UCG) and selected zones in Gibson, Posey, Vanderburgh and Warrick Counties.