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Review of the NURE Assessment of the U.S. Gulf Coast Uranium Province

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Historic exploration and development were used to evaluate the reliability of domestic uranium reserves and potential resources estimated by the U.S. Department of Energy national uranium resource evaluation (NURE) program in the U.S. Gulf Coast Uranium Province. NURE estimated 87 million pounds of reserves in the $30/lb U_3O_8 cost category in the Coast Plain uranium resource region, most in the Gulf Coast Uranium Province. Since NURE, 40 million pounds of reserves have been mined, and 38 million pounds are estimated to remain in place as of 2012, accounting for all but 9 million pounds of U_3O_8 in the reserve or production categories in the NURE estimate. Considering the complexities and uncertainties of the analysis, this study indicates that the NURE reserve estimates for the province were accurate. An unconditional potential resource of 1.4 billion pounds of U_3O_8, 600 million pounds of U_3O_8 in the forward cost category of $30/lb U_3O_8 (1980 prices), was estimated in 106 favorable areas by the NURE program in the province. Removing potential resources from the non-productive Houston embayment, and those reserves estimated below historic and current mining depths reduces the unconditional potential resource 33% to about 930 million pounds of U_3O_8, and that in the $30/lb cost category 34% to 399 million pounds of U_3O_8. Based on production records and reserve estimates tabulated for the region, most of the production since 1980 is likely from the reserves identified by NURE. The potential resource predicted by NURE has not been developed, likely due to a variety of factors related to the low uranium prices that have prevailed since 1980.

KEY WORDS: Uranium, assessment, Texas, reserve, resource, endowment.

INTRODUCTION

The uranium endowment of the United States historically was assessed by the U.S. Department of Energy (DOE). Since 1984, the U.S. Geological Survey (USGS) has been responsible for calculating the undiscovered uranium resources for the U.S., while the Department of Energy's Energy Information Administration (EIA) reports uranium reserves and production. A comprehensive review of previous estimates of undiscovered resources is in progress as part of a new USGS assessment of undiscovered domestic uranium resources. The last comprehensive domestic U.S. uranium assessment program, the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program, was formally completed in 1980; however, some assessments were completed through 1982. The new USGS assessment group is analyzing and georeferencing the results of the NURE program. The Gulf Coast Uranium Province, the western portion of the NURE Coastal Plain Uranium Resource Region, was selected for review of the assessment methodology used in the NURE program as part of the evaluation of potential assessment strategies to adopt for the new assessment (Fig. 1).

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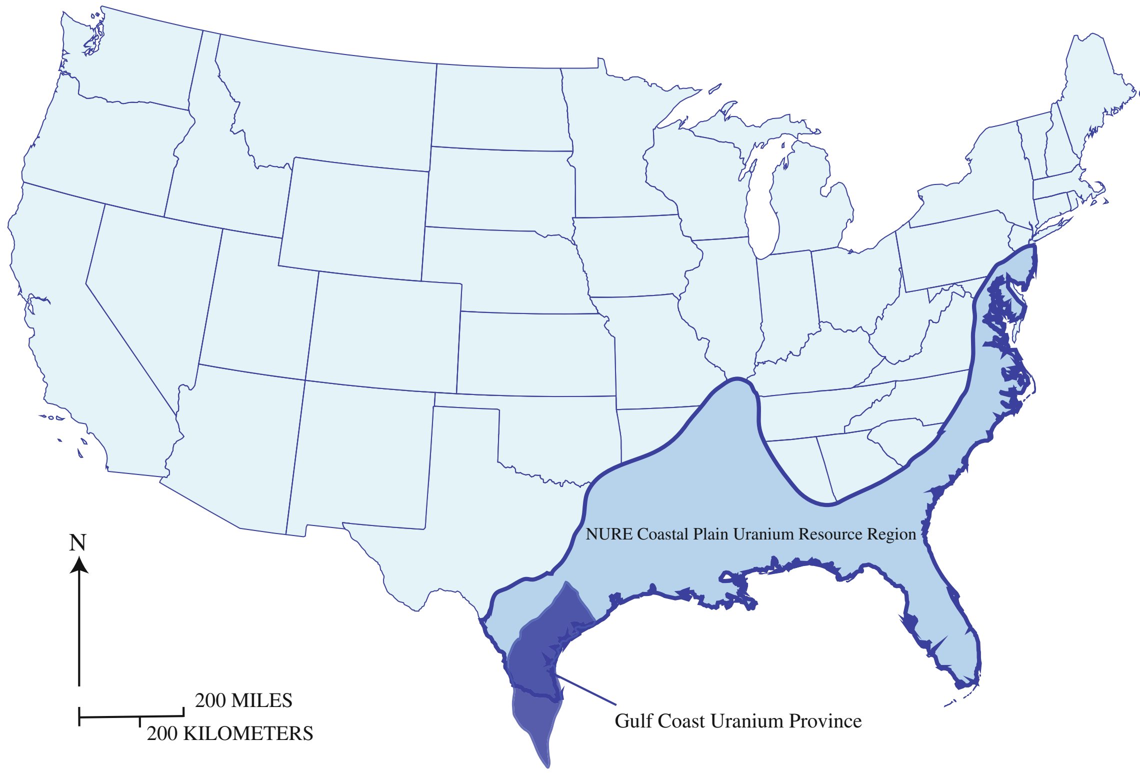

Figure 1. Location of the NURE coastal plain uranium resource region (U.S. Department of Energy 1980) and Gulf Coast Uranium Province (Finch 1996).

This province has been continuously explored and developed since the NURE assessment and this exploration and development data are used here to determine if the uranium in undiscovered resources and in place reserves estimated by NURE were accurate. The accuracy of resource predictions is critical if they are to be relied upon to guide public policy.

URANIUM DEPOSIT MODEL FOR THE GULF COAST URANIUM PROVINCE

Location

Uranium is found mainly in roll-front type deposits in the Gulf Coast Uranium Province in Eocene to Pliocene clastic rocks (Fig. 2). These sediments were deposited in two fluvial systems, the Gueydan system of the Rio Grande embayment in southern Texas and the Chita-Corrigan system in the Houston embayment in eastern Texas. The two systems interfinger at the San Marcos arch (Fig. 3) (Galloway et al. 1979).

Deposit Characteristics

Deposits are found in carbonaceous facies of the host formations or associated with faulting that may transport gases produced from underlying hydrocarbons into the host rocks. Both settings provide the reducing conditions that favor uranium precipitation from groundwater. Uranium ore bodies in south Texas typically deposit in a C-shaped roll, with individual variations controlled by local variations in sand facies and the location of reductants. Individual ore bodies are fairly small, usually less than 5 m thick and poddy. Ore bodies are discontinuous over several kilometers and stacked with "ghost rolls" found behind the relatively young and actively migrating mineralized fronts (Adams and Smith 1981; International Atomic Energy Agency 2009). Deposits range from about 70,000 to close to

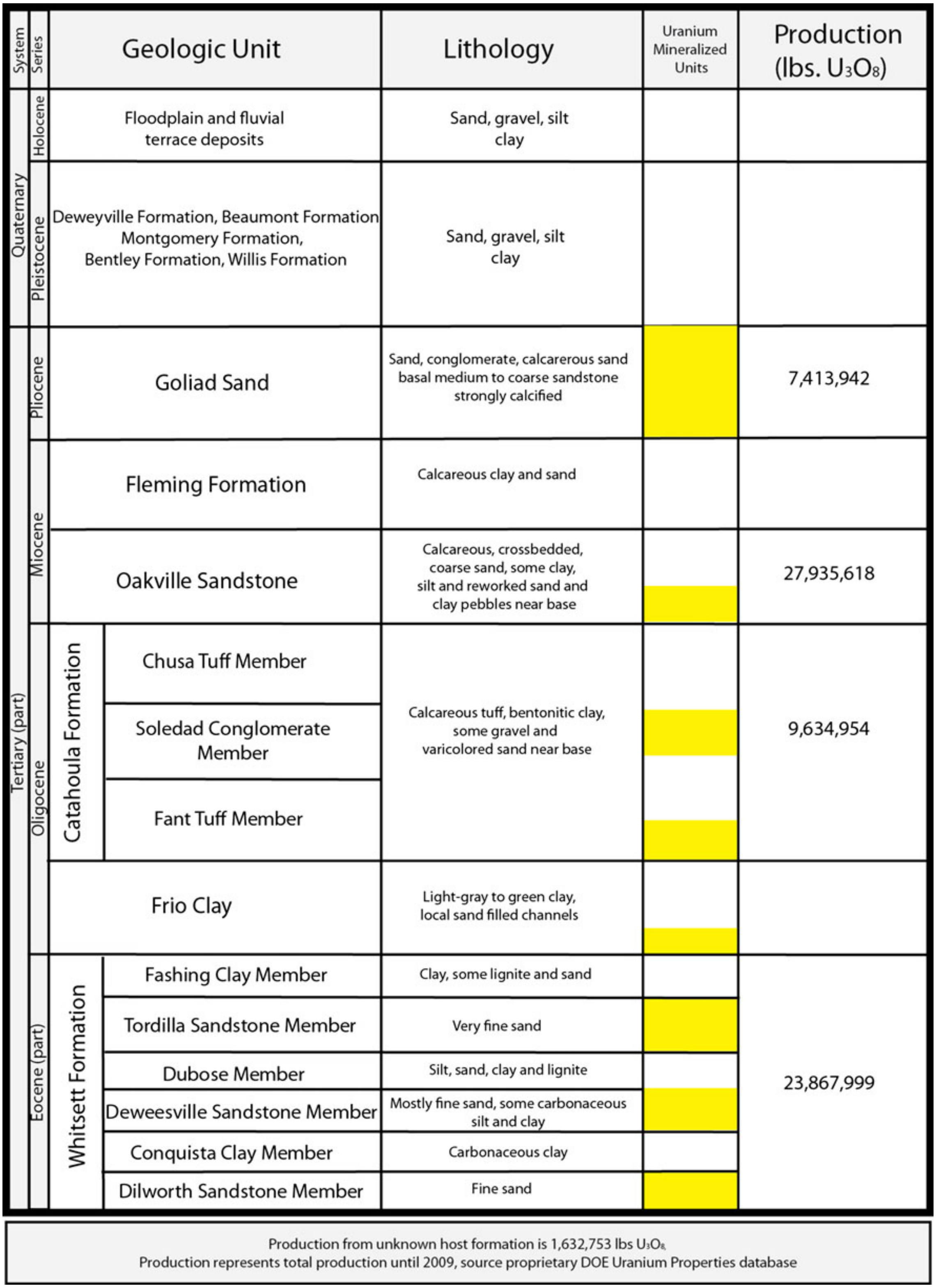

Figure 2. Tertiary units known to contain uranium mineralization (yellow highlights) in the Gulf Coast Uranium Province (after Galloway et al. 1979).

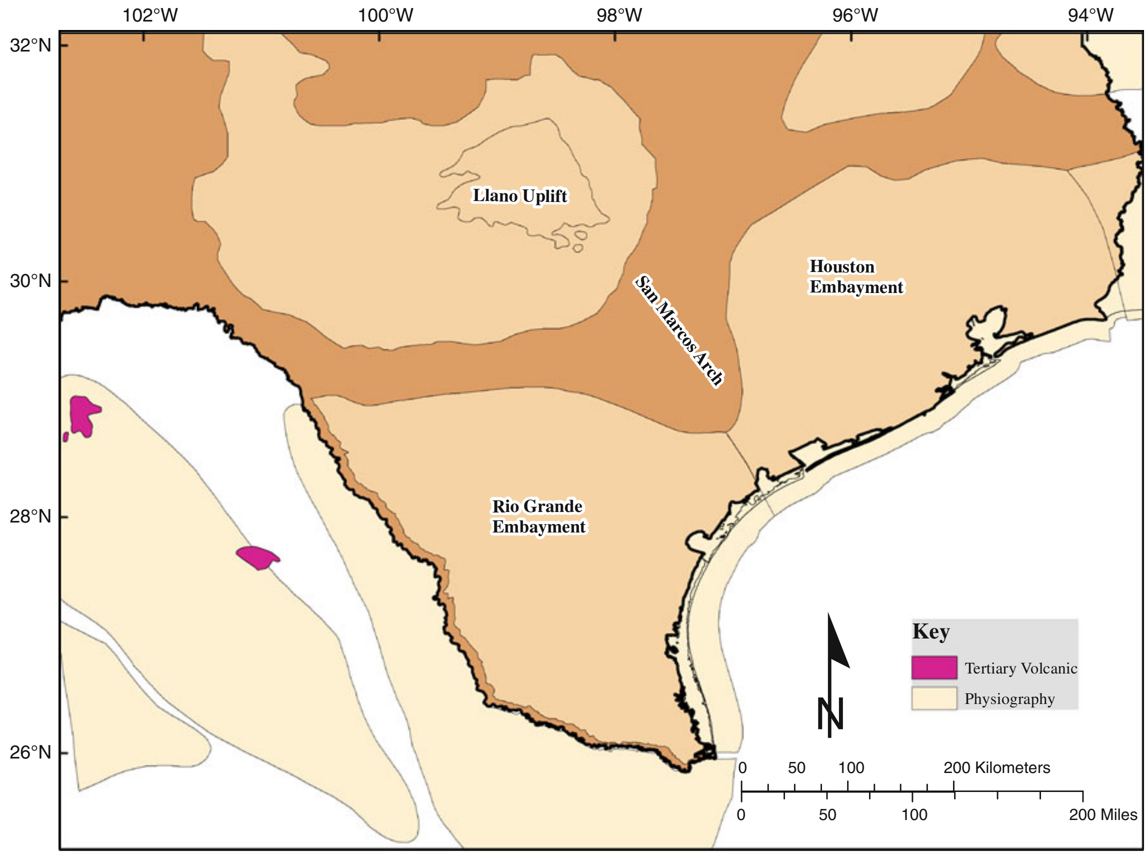

Figure 3. Location of major physiographic regions in the Gulf Coast Uranium Province.

10 million pounds of U_3O_8 in total size and average 0.09–0.10% U_3O_8 (International Atomic Energy Agency 2009; Dahlkamp 2010).

Deposit Model

The deposit model, developed by Adams and Smith (1981) and described below, has not changed significantly since the province was assessed during the NURE program. Exploration for deposits is still guided by these proposed source, transport, and trapping mechanisms.

Uranium Source

The source of uranium in Gulf-coast roll front deposits is poorly understood, but is thought to be tuffs interbedded with host sandstones derived from Tertiary volcanic centers in NE Mexico and volcanic rock fragments within sedimentary rocks sourced from southwest highland areas (Fig. 3) (Adams and Smith 1981; Eargle et al. 1975). The San Marcos arch may have controlled the easternmost distribution of these weathered sedimentary rocks and the volcanic ash effectively limiting the supply of labile uranium to west of this paleo-high (Baker 1979).

Uranium Transport

Groundwater leached uranium from source rocks, moving it down gradient through the sandstones with the highest transmissivity as reduction/oxidation reaction fronts (Galloway et al. 1979). During the Tertiary, west Texas was characterized by an arid to semi-arid environment (Galloway 1977; Galloway and Kaiser 1979). This environment was more favorable to the formation of economic uranium deposits than the more humid paleoenvironment in east Texas (Adams and Smith 1981; Eargle et al. 1975). A number of reasons for this association of arid environments with the formation of roll-front deposits have been advanced.

Uranium Trapping Mechanisms

The predominant control of uranium deposition in the Gulf Coast Uranium Province appears to be reducing conditions caused by methane or hydrogen sulfide gas that has moved up deep-seated structures, or along the edges of structural highs such as salt domes, from oil and gas fields that underlie the Tertiary section (Adams and Smith 1981; Arredondo 1991; Carothers 2008, 2010; Classen 1981; Goldhaber et al. 1978). However, some south Texas deposits formed in response to reduction related to lignite and other organic matter in the local sandstones (Reynolds et al. 1982). In places, deposits are richest where very permeable channel sandstones interfinger with muddy organic-rich overbank deposits along

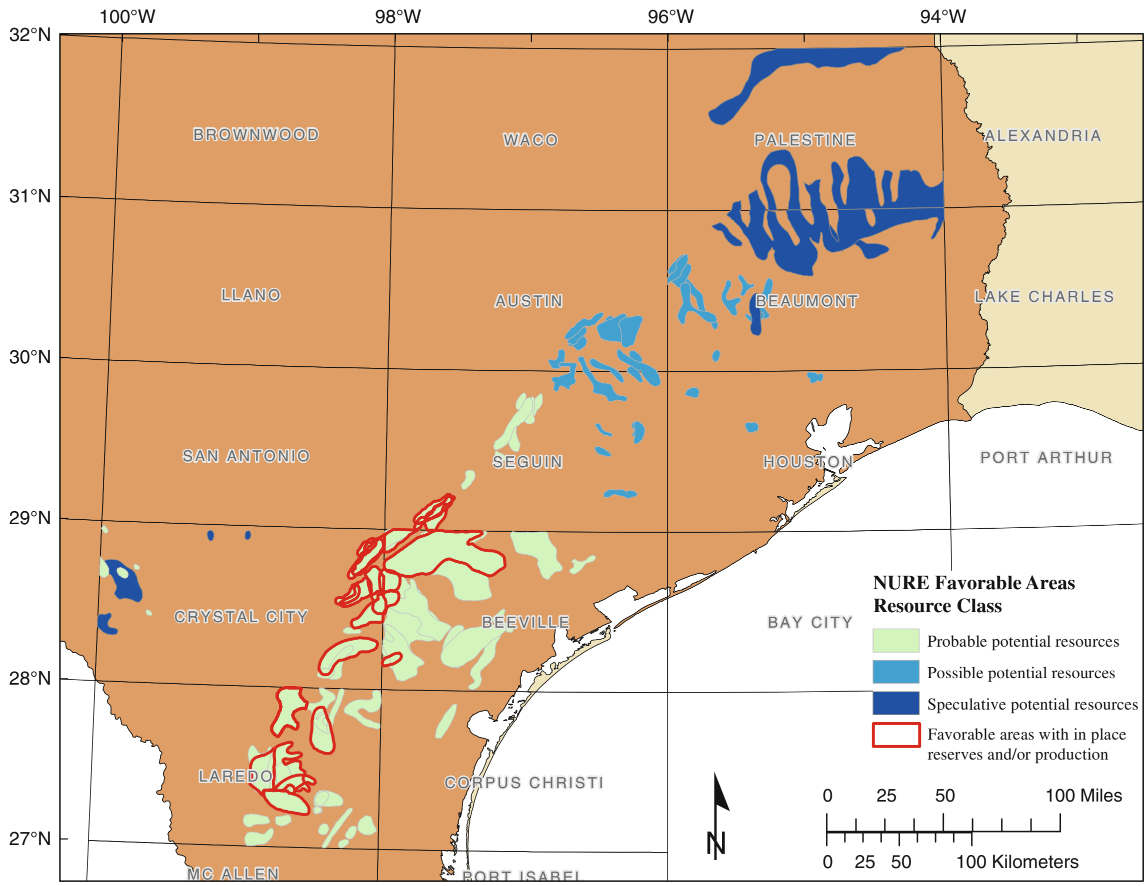

Figure 4. NURE favorable areas in the Gulf Coast Uranium Province. Not all favorable areas identified by the NURE program could be located.

Table 1. NURE Endowment, in Pounds of Uranium Oxide, for the Gulf Coast Uranium Province Portion of the Coastal Plain Resource Region

Potential Resource	Conditional Endowment (lb U_3O_8)	Unconditional Endowment (lb U_3O_8)	Conditional Endowment Cost Category \$30/lb U_3O_8 (lb U_3O_8)	Unconditional Endowment Cost Category \$30/lb U_3O_8 (lb U_3O_8)
Probable	950,340,400	924,289,200	443,124,368	431,870,813
Possible	497,612,600	414,948,400	190,527,835	163,541,266
Speculative	39,087,800	30,750,800	9,048,433	7,149,288
Total Endowment	1,487,040,800	1,369,988,400	642,700,636	602,561,367

the flanks of the channels. This distribution may be related to fluid flow, the concentration of organic matter in overbank deposits or both.

NURE COASTAL PLAIN RESOURCE REGION ASSESSMENT

The Gulf Coast Uranium Province was part of NURE's Coastal Plain Resource Region that extends along the Gulf and Atlantic coasts from southwestern Texas to New Jersey (Fig. 1). To determine if portions of the province were favorable for the formation of uranium deposits, geochemical and geophysical data were combined with geologic analysis by the NURE assessment team. Gamma-ray surveys of oil and gas drill holes were used to identify mineralized areas in the Beeville, Laredo, and Austin quadrangles (U.S. Department of Energy 1980). Regional aerial radiometric surveys were useful in identifying outcropping mineralization and positioning faults commonly associated with mineralization in the region (U.S. Department of Energy 1980). Geochemical analysis of stream-sediment and ground-water samples was also used to define permissive areas in the Tertiary Whitsett and Catahoula Formations, Oakville Sandstone and Goliad Sand (Fig. 2). Minor potential resources were identified in other Tertiary units including the Oligocene Dilworth Sandstone Member of the Whitsett Formation and other units stratigraphically

Table 2. Production from Mines in the Gulf Coast Uranium Province

Host Formation	Total Production (lb U_3O_8)
Whitsett Formation	23,867,999
Catahoula Formation	9,634,954
Oakville Sandstone	27,935,618
Goliad Sand	7,413,942
Unknown host formation	1,632,753
Total Production	70,485,266

Production data from U.S. Department of Energy (2009).

Table 3. Uranium Production Data from NURE Favorable Areas

NURE Favorable Area	1:250,000 Quadrangle Name	Production and Reserves by Locality (lb U_3O_8)[a]	NURE Conditional Endowment[b] (lb U_3O_8)	NURE Unconditional Endowment at \$30/lb[c] (lb U_3O_8)
14010011	Beeville	6,900,000	29,660,000	11,932,218
14010032	Beeville	1,504,970	2,600,000	969,540
14010038	Beeville	1,980,000	6,152,000	3,099,378
14011045	Beeville	5,990,903	34,760,000	15,767,136
14010030	Crystal City	19,052,784	53,600,000	30,117,840
14010034	Crystal City	8,585,950	32,360,000	18,419,312
14010035	Crystal City	901,520	8,112,000	4,543,531
14010040	Crystal City	2,360,640	9,848,000	5,218,455
14011036	Crystal City	1,355,213	2,584,000	1,301,819
14011037	Crystal City	691,508	8,092,000	4,134,203
14011041	Crystal City	6,663,695	5,704,000	3,059,626
14011042	Crystal City	7,350,775	2,568,000	1,392,626
14011043	Crystal City	4,607,447	524,400	311,494
14020021	Laredo	7,372,118	86,000,000	38,949,400
14020022	Laredo	567,505	68,900,000	32,865,300
14020026	Laredo	2,450,000	65,040,000	30,107,016
14020080	Laredo	477,166	11,222,000	5,572,845
14021024	Laredo	9,956,618	38,380,000	12,757,512
14030011	Laredo	100,000	77,900,000	38,763,040
14011046	Seguin	1,352,810	3,820,000	2,056,688
14011047	Seguin	1,200,000	4,998,000	2,672,930
14011048	Seguin	1,233,216	4,014,000	2,072,027
Production from mines not located within a known NURE favorable area		15,185,162		
Tailings Production		173,215		
Total		108,013,215	556,838,400	266,083,936

[a]Production from 1955 to 2009, reserves are those in place as of 2012.
[b]Unconditional potential endowment is the same as conditional endowment for these favorable areas.
[c]The \$30/lb uranium cost category was calculated in 1980 at current prices. Inflation would place this at approximately \$85/lb in 2012 prices (U.S. Department of Labor 2012).

below the Whitsett Formation including the Oligocene Manning Clay, Eocene Yegua Formation and Eocene Wilcox Formation. A DOE drilling project in the region tested for mineralization in the Oakville Sandstone and Goliad Sand. The 12 holes drilled in this area resulted in a reduction in area originally thought favorable for mineralization (U.S. Department of Energy 1980).

A series of subject quadrangle reports was prepared for the quadrangles assessed in Texas, the Austin, Beaumont, Beeville, Brownsville, Corpus Christi, Crystal City, Houston, Laredo, McAllen, Palestine, San Antonio, and Seguin quadrangles, and are published as the Department of Energy PGJ/F publication series. These reports describe the geologic setting, geochemistry, and geophysics of rock units in the quadrangles. This information was then combined to select areas that are favorable to host uranium deposits. Maps that accompany the reports show the location of uranium occurrences, water and stream sediment samples and their composition, formation thickness maps, structure contour maps to formation tops, total sandstone thickness maps, sandstone to shale ratio maps, land and culture maps and cross sections. Each subject quadrangle report contains a plate showing polygons considered favorable for the occurrence of uranium deposits. These polygons were defined by the assessment team following analysis of the geologic, geochemical, and geophysical data.

Near the end of the NURE program, the geology division of the data integration group within the BENDIX Field Engineering Corporation (DOE contractor) produced a series of reports summarizing NURE resource assessments. This was the 1980 Uranium Resource Summary Series, and included a volume for each resource region including the Coastal Plain regions that is the focus of this analysis (Bendix 1980). These reports contained assessment parameters organized by 1:250,000 quadrangles and a map of the polygons assessed during this phase of the NURE program. This series is available as a microfiche appendix to the final DOE NURE report (U.S. Department of Energy 1980). These reports include conditional and unconditional (see below) potential uranium resources estimates for the individual assessment localities. Also reported are cost factors used in the economic analysis that was applied to the estimated potential resource to calculate resources in the $30, $50, and $100 per pound cost categories. For each favorable area the depth to mineralization is estimated as well as the size of the favorable area, thickness of geologic unit, average grade, and density of mineralization. USGS has a complete copy of final reports for all the resource areas assessed by NURE, and has extracted key data from the favorable area reports into spreadsheets to use in analyzing NURE assessments.

There is a great deal of uncertainty in determining the location of polygons identified on quadrangle maps with favorable area reports tabulating resources within these polygons. The numbering system used in maps that accompany the favorable area reports cannot be used to correlate the polygons with corresponding estimated resources (U.S. Department of Energy 1980). Adding further confusion, maps showing the location of favorable areas found in the NURE subject quadrangle reports do not match those found in the summary resource assessment reports. Although the polygons are typically in the same general location, for instance the southeast corner of the map, the outlines of the polygons and the number of polygons varies significantly. Why these two products of the NURE program are not consistent is unknown. The area of the polygons identified in the BENDIX data integration group reports was used to correlate the polygons with the assessment reports. Using this method many, but not all, of the favorable areas could be located in those areas assessed by 1980. The location of favorable areas assessed after 1980, including those in the San Antonio and McAllen quadrangles, is unknown because no maps accompanied the assessment reports. In all, 74 of the 106 favorable areas were georeferenced for the region (Fig. 4).

NURE ASSESSMENT METHODOLOGY

The NURE assessment estimated conditional and unconditional potential resources for the favorable areas in the Gulf Coast Uranium Province (Appendix). Uranium endowment is estimated as summarized below, and is more completely described in the final U.S. uranium assessment report by DOE (U.S. Department of Energy 1980), in USGS Circular 994 (Finch and McCammon 1987) and in International Atomic Energy Agency Technical Document 344 (International Atomic Energy Agency 1992). Note that contrary to more common usage of endowment as including both reserves and undiscovered resources, in the NURE assessment methodology endowment refers to undiscovered resources only, and does not include reserves, which are considered separately:

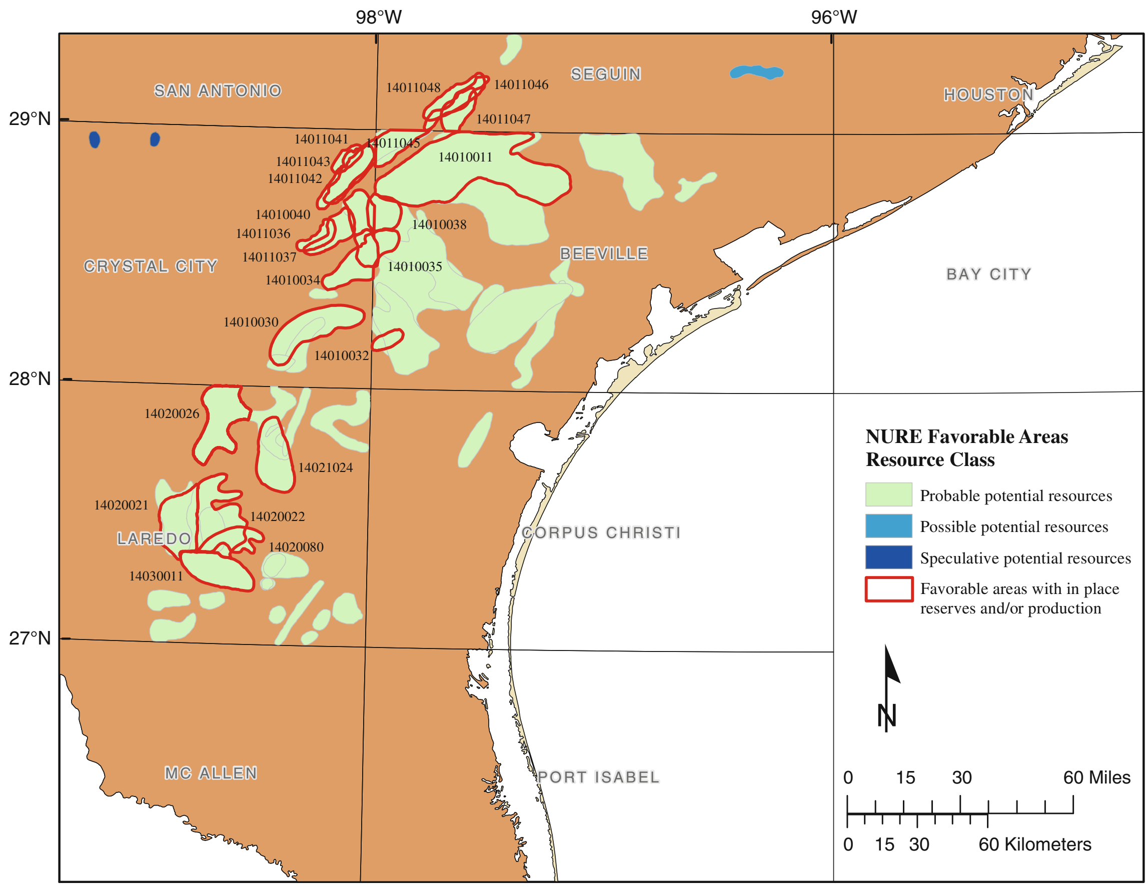

Figure 5. Areas favorable for uranium endowment identified during NURE that contain in place reserves or have produced uranium.

$$\text{Conditional Uranium Endowment (tons } U_3O_8) = A \times F \times T \times G$$

where A = projected surface area of favorable ground in square miles, F = fraction of A that is underlain by endowment, T = tons of endowed rock per square mile (thickness of mineralized unit × rock density), G = average grade of endowment (three grades were estimated: high/modal/low).

Unconditional endowment is estimated by applying a probability, elicited by the principal investigator from the resource appraisal group, that one or more deposits exist within the favorable area. The probability ranges from 1 (a 100% probability that one deposit will be found) to 0 (a 0% probability that one deposit will be found). Therefore, if an investigator is highly confident that at least one deposit will be discovered in a favorable areas, the unconditional and conditional endowments will be the same. With a decreased level of confidence on the part of the investigator, unconditional endowment will be less than conditional endowment. Conditional and unconditional potential resources are estimated at the mean, the 95th, 75th, 50th, 25th, and 5th percentiles. The mean endowment was selected for this analysis.

During NURE, economic filters were added to endowment to determine reserves and potential resources in the $30, $50, and $100 per pound cost categories (1980 prices). In the subsequent analysis, resources in the $30 per pound cost category were considered. This corresponds to approximately $85/lb in 2012 prices (U.S. Department of Labor 2012). Uranium prices have varied considerably, trending downward from 1980 and reaching a low in 1994 of about $7/lb U_3O_8. Prices then began to rebound until achieving a high of $136/lb U_3O_8 in 2007. In 2012 uranium prices have averaged about $50/lb U_3O_8 (Organisation of Economic Cooperation and Development Nuclear Energy Agency and

International Atomic Energy Agency 1996, 2012). Examination of uranium price trends indicates that the NURE \$30/lb U_3O_8 uranium price category is the most appropriate to use in an analysis of uranium production between 1980 and 2012.

Potential resources were also categorized as probable, possible, and speculative. Probable potential resources are in known districts as extensions of known deposits or new deposits within trends or mineralized areas that have been identified by exploration. Possible potential resources are found in formations or geologic settings that are productive elsewhere, but in which a deposit has not yet been identified within the considered favorable area. Speculative potential resources are located in formations or geologic settings that have not previously been productive but are within a productive province and share characteristics with the productive areas. The details of this analysis were stored in the Uranium Reserves and Data, URAD, database (Das and Lee 1991). Despite ongoing work to try to find this database by USGS and EIA, it has not been located therefore cannot be recreated or analyzed. Detailed descriptions of the NURE assessment methodology are found in Finch and McCammon (1987) and U.S. Department of Energy (1980).

URANIUM ENDOWMENT OF THE GULF COAST URANIUM PROVINCE

In the Gulf Coast Uranium Province, 106 favorable areas were defined in 11 1:250,000 scale quadrangle maps by the NURE program (Fig. 4). The conditional and unconditional potential uranium endowment was estimated for each of these areas (Appendix). NURE estimated a conditional endowment of about 1.5 billion pounds of U_3O_8, and an unconditional endowment of about 1.4 billion pounds of U_3O_8 in three potential resource classes in this province (Table 1; Appendix). Of this, about 643 million pounds of the conditional and 600 million pounds of the unconditional endowment are within the \$30/lb U_3O_8 cost category (Table 1). In addition, reserves of 86 million pounds of U_3O_8 were estimated for the entire NURE Coastal Plain Resource Region.

ANALYSIS OF NURE ENDOWMENT

Three decades of exploration and development provide information that can be used to place more practical limits on productive portions of the basin. Historic and current mining depths can be used to examine the depth limits considered during NURE. As well, favorable areas in regions where rigorous exploration has failed to identify reserves should be examined to determine whether continuing to include this endowment in the reported endowment of the region is appropriate. Updated reserve and production data can be used to examine whether or not reserves predicted for the region were accurate.

Production and Reserves

Uranium production has been ongoing in Texas since 1955 even through the interval of low uranium prices in the 1980s and 1990s. The DOE has tabulated cumulative uranium production in the United States, compiling a database of production and reserves which is the basis for this analysis of the uranium reserves and endowment calculated by NURE. In the current USGS study, DOE's reserve and production data were supplemented by information from the International Atomic Energy Agency world uranium deposits database (UDEPO), and NI 43-101 reports filed with Canadian securities administrators (International Atomic Energy Agency 2010; Carothers 2008, 2009, 2010). Deposits are those named in the DOE database, with no attempt at aggregation of smaller properties into larger deposit clusters. Deposits were located using a variety of resources including the original NURE geologic quadrangle reports, and exploration and production maps compiled by the Texas Commission on Environmental Quality and Texas Railroad Commission.

Between 1955 and 2009 approximately 70 million pounds of U_3O_8 were produced from 102 mines in the Gulf Coast Uranium Province (Table 2) (U.S. Department of Energy 2009). Thirty million pounds of U_3O_8 was mined prior to 1980, almost all from mines in Karnes County, Texas (U.S. Department of Energy 1980). Therefore, approximately 40 million pounds of U_3O_8 in production post-dated NURE. The NURE program calculated reserves of 87 million pounds of U_3O_8 in the \$30/lb cost category, for the entire Coastal Plain province, most, but not all, of which was in the Gulf Coast Uranium Province (U.S. Department of Energy 1980). Post-NURE production was a little less than half that predicted reserve. By examining the DOE uranium mines and production database and adding information from other sources, the current USGS study tabulated 38 million pounds of U_3O_8 of in place reserves identified for the province as of 2012.

Twenty-two of the 106 favorable areas in the Gulf Coast Uranium Province that we have been able to georeference report production or contain reserves (Table 3; Fig. 5). The potential endowment calculated by NURE for these favorable areas is included to illustrate their relative importance; however, reserves calculated by NURE cannot be reported by favorable area because this information has been lost. Five properties containing in all over 15 million pounds of U_3O_8 in total endowment are located outside the area of any of the known NURE favorable areas. Eight million pounds of produced U_3O_8 are estimated for properties that could not be located but are included in DOE database. The production from these properties was not considered in this analysis. A small amount of production is assigned to reprocessing of tailings, and is not considered here (Table 3).

DISCUSSION

In all, 108 million pounds of U_3O_8 in production or reserves were calculated for the Gulf Coast Uranium Province by the current study. Reserves in the \$30/lb cost category calculated by the NURE program for the entire Coastal Plain Region plus past production which was almost all from mines in the Gulf Coast Province were 117 million pounds of U_3O_8. The close correlation of total reserves plus production for this area as calculated by NURE and the current study indicates that the methodology used to calculated reserves during NURE appears to have been sound in predicting the identification of economic uranium deposits in the region. Considering the complexities of developing uranium mines and fluctuating, but low average price during the 30 years since the end of NURE, production (40 million pounds of U_3O_8) of approximately half the reserves predicted by the program (87 million pounds of U_3O_8) is reasonable.

All but two mines, the Kingsville Dome and Alta Mesa mines fall within a known NURE favorable area in south Texas. These two mines are within a quadrangle parts of which were assessed after 1980 and for which we do not have the location of favorable areas, therefore they may actually be included in areas that are not now locatable. The high correlation between production and favorable areas indicates the NURE program accurately predicted prospective ground.

In addition to reserves, between 600 and 640 million pounds of potential resources in the \$30/lb cost category were identified during NURE (Appendix). This analysis indicates that little of these potential resources has been produced or further delineated into reserves. Of the 106 favorable areas identified by NURE, only 22 produced uranium or contain in place reserves. This indicates that the number of favorable areas and their estimated potential resources as predicted by NURE may have been much higher than those reserves that are actually economically and technically recoverable.

A number of factors may have influenced the lack of production from the potential resources estimated for the region. One factor is the high cost category of \$30/lb that was used as a minimum for the NURE estimates. Uranium prices have been below this threshold for most of the past 30 years, with the exception of the price spike in 2007. So it is understandable that little of the potential resource estimated economic at the \$30/lb threshold has been identified or mined. A \$15/lb cost category was used early in the NURE program, but this information has been lost. A related factor is that uranium prices also drive exploration activity, and with the relatively low prices that have prevailed since 1980 uranium exploration activities have been relatively modest. Exploration expenditures usually closely correlate with the development of uranium resources (Organisation for Economic Cooperation and Development Nuclear Energy Agency and International Atomic Energy Agency 2010). This depressed level of exploration may explain the lack of discoveries. Another factor that may contribute to a lack of identified reserves is the high percentage of private land in Texas. Most of the uranium resources in Texas are located on private land to which access may be limited. In these scenarios, considerable resources may still remain to be discovered or fully defined as in place reserves in the region.

Other factors that may have influenced the lack of production from potential resources for the region may be inherent in the estimation methodology. The NURE minimum grade cutoff of 0.01% U_3O_8 used to calculate potential resources may have been too low a threshold such that it does not represent a realistic economic cutoff for mineable uranium deposits. This may have resulted in identification of a considerable resource in the region that is sub-economic. Also, as part of the NURE elicitation process the assessor considers the distribution of deposits from well understood control deposit areas. If this comparison is imperfect, the resulting estimated resource will be inaccurate. The underlying goal of the NURE program was to help guide exploration in the region. Early in the assessment program for the Gulf Coast, managers expressed a desire to provide the nuclear industry with possible target areas for uranium exploration (Olsen and Parker 1975). The emphasis guided analysis of the Gulf Coast to include areas that contained some favorable, but not all critical, attributes to support the NURE potential resource estimates. This emphasis at the outset of the program may have resulted in inclusion of more marginally favorable areas into the potential resource class, particularly those defined in the speculative potential resource category. As the program progressed, the speculative potential resource category diminished in importance, as some later compilations exclude this class of resource.

DISTRIBUTION OF POTENTIAL RESOURCES

Potential Resources in Non-productive Regions

Although exploration was slowed by low uranium prices, industry sources describe regional exploration programs that targeted all portions of the Gulf Coast Uranium Province, even the less prospective Houston embayment. Currently the UEC Corporation has an exploration project in the Houston embayment, the Carrizo project in Zavala County, Texas (Ux Consulting 2010). However, despite these efforts, no commercial deposits have been developed in the Houston embayment.

Southwest of the San Marcos arch in the Rio Grande embayment the NURE program estimated the potential endowment to be 1.3 billion pounds of U_3O_8 in the conditional, 1.2 billion pounds of U_3O_8 in the unconditional, and 530 million of U_3O_8 in the \$30/lb cost categories. East of the San Marcos arch in the Houston embayment, 27 favorable areas contain 232 million pounds of U_3O_8 of conditional, and 176 million pounds of U_3O_8 in the unconditional endowment category and 72 million pounds in the unconditional \$30/lb U_3O_8 cost category. The Houston embayment contains 16% of the conditional and 12% of the unconditional endowment of the Gulf Coast Uranium Province in any cost category, and 11% of the unconditional endowment in the \$30/lb cost category.

In the Rio Grande embayment, 95% of the conditional endowment was considered unconditional, and in the Houston embayment only 76% of conditional endowment was moved into the unconditional category. Of the 79 areas in the Rio Grande embayment, the resources in 46 were considered in the probable, 25 in the possible and 8 in the speculative potential resource categories. In the Houston embayment, of 27 areas three were classified probable and the rest possible. Both the lower percentage of potential resources and the few areas classified as probable indicate the lack of confidence assessors had that a deposit would be identified in favorable areas in the Houston embayment.

Many factors may contribute to the lack of uranium resources in the Houston embayment. Two aspects are the abundance of volcanic detritus that provided uranium and the pervasive reducing conditions in the Tertiary units likely to be host rocks. Volcanic tuffs, volcaniclastics, and other weathered sedimentary rocks thought to be the uranium source in the province derive from highland areas west of the region. At the San Marcos arch, and northeastward, the tuff content of the Oligocene Catahoula Formation drops markedly (Baker 1979). NURE assigned resources to increasingly more hypothetical resource classes the further the favorable areas were from the uranium source (Fig. 4). Although no narrative has been found that accompanies the NURE favorable area reports, the author speculates that assessors may have set this ranking to reflect the lack of source rocks in the northeastern portion of the province.

The arid to semi-arid conditions that favor weathering and transport of uranium in groundwater may not have developed in the more humid environment of the Houston embayment. In addition, a humid environment supports higher terrestrial biologic productivity, and as a result more abundant organic matter within a depositional sequence. In such an environment, uranium is expected to be retained in the broadly distributed organic-rich facies that are found throughout the Houston embayment. The resulting dissemination of organic matter throughout the stratigraphic section would sequester uranium within organics rather than allow the steep gradients needed to create an economic deposit.

Table 4. Percentage of the NURE Conditional and Unconditional Endowment Distribution by Depth in the Rio Grande and Houston Embayments

Depth (ft)	Rio Grande Embayment		Houston Embayment	
	Percent of Conditional Endowment	Percent of Unconditional Endowment	Percent of Conditional Endowment	Percent of Unconditional Endowment
<50	1	<1	3	2
50–150	6	6	9	10
150–250	8	9	10	11
250–350	16	17	10	12
350–450	18	19	9	10
450–750	25	26	14	13
750–1250	10	9	13	11
1250–1750	5	5	17	16
1750–2500	7	7	15	15
2500–3500	3	2	0	0
3500–4500	1	0	0	0

Table 5. NURE Estimated Endowment for the Western Gulf Coast Resource Region Reduced by Resources Estimated at Subeconomic Depths and that in Non-productive Portions of the Basin

	Conditional Endowment (lb U_3O_8)	Unconditional Endowment (lb U_3O_8)	Unconditional Endowment in the \$30/lb Cost Category (lb U_3O_8)
Endowment in the Texas Gulf Coast	1,487,040,800	1,369,988,400	602,561,368
Endowment in non-producing Houston embayment	232,928,600	175,931,400	72,208,664
Endowment below 750 ft in the Rio Grande embayment	311,008,760	264,711,308	131,649,237
Total endowment with sub-economic and non-producing regions removed	943,103,440	929,345,692	398,703,467

Potential Resource Distribution by Depth

The NURE program reported percentages of conditional and unconditional resources by depth from the surface. Sandstones in this region were assessed up to a depth of 4500 ft, whereas most historic and modern mining in Texas ranges from the surface to 500 ft. Resources below 500 ft may be difficult to economically recover in this region using technology that is currently available.

In the Rio Grande embayment, 26% of the conditional, and 23% of the unconditional endowment is assigned to depths greater than 750 ft (Table 4). In the Houston embayment, 45% of the conditional and 42% of the unconditional endowment is assigned to depths greater than 750 ft.

Resources estimated to exist deeper than historic mining depths of about 500 ft in the section have not historically been the target of exploitation by industry. Accordingly, including resources below depths that are subeconomic in the NURE assessment may be overly optimistic. To better represent the available endowment of the region, in this review, endowment below historically practicable mineable depths is removed from the regional endowment. For this analysis resources below 750 ft were chosen as subeconomic based on known exploration and production data.

Identification of Non-productive Areas of the Gulf Coast Uranium Province

Removing endowment estimated below mining depths of 750 ft that are currently subeconomic, and the endowment estimated for the Houston embayment, which has proved to be a non-productive region, the endowment for the Texas Gulf Coast is reduced to an endowment between 920 and 930 million pounds of U_3O_8 in the unrestricted cost categories, and to 399 million pounds in the $30/lb cost category. This is 37% less conditional, 32% less unconditional, and 34% less unconditional endowment in the $30/lb cost category than originally estimated by the NURE program for this region (Table 5).

CONCLUSIONS

The NURE program completed a comprehensive assessment of uranium resources in the U.S. Gulf Coast Uranium Province. The uranium is likely sourced in volcanic ash and volcaniclastic rocks interbedded in clastic Tertiary sedimentary rocks in the province. Uranium is leached from volcanic rocks by alkaline groundwater, and then concentrated adjacent to unconsolidated sediments and gases that emanate from hydrocarbon accumnlations deeper in the section.

An undiscovered resource of between 1.4 and 1.5 billion pounds of U_3O_8 in 106 favorable areas was estimated for the province. Of this, between 600 and 640 million pounds of U_3O_8 was considered economic in the cost category of $30/lb U_3O_8. Just over 20% of the favorable areas delineated by the NURE program contain resources and production of a total 108 million pounds of U_3O_8; 70 million pounds of production and 38 million pounds of in situ reserves. During NURE, 87 million pounds of reserves were identified in the Coastal Plain resource region, 40 million pounds of which were mined after the program ended. The remaining 47 million pounds remaining for the entire coastal plain region correlates well with the 38 million pounds calculated for this region by the current study. However, 600 million pounds of potential endowment in the $30/lb cost category remains unmined. This analysis demonstrates that the NURE undiscovered resource program estimated a larger undiscovered resource base than has been practically economically recoverable in the ensuing 32 years. Some factors that may have influenced this include the low grade cutoff of 0.01% U_3O_8 used in the NURE estimates and cost categories that are significantly higher than current or historic uranium prices. Using these cutoffs, much of the undiscovered resource is likely sub-economic. NURE was philosophically an exploration program focused on identifying potential resources. In this sense, NURE was a very effective program, as those reserves developed in the Gulf Coast Uranium Province are almost exclusively in favorable areas identified by the program. Other considerations are that low uranium prices that have typified the past 30 years may have discouraged the identification and exploitation of resources. In addition, the high percentage of potentially inaccessible private land in Texas can slow exploration because of the additional permissions necessary to explore in these areas.

The Houston embayment in the eastern portion of the province was ranked as a more speculative potential resource by the NURE assessment. This area has not proved productive and removal of resources assigned to the Houston embayment may be warranted. Although NURE assessed potential host rocks to 4500 ft depth, mining to date has not exceeded 500 ft. To more accurately estimate technically recoverable resources, it may be necessary to exclude resources below this practicable mining depth. When resources in the non-productive Houston embayment and those below practicable mining depths in the rest of the basin are excluded, the undiscovered resource endowment of the province is reduced to between 930 and 940 million pounds of U_3O_8 in all cost categories, and 399 million pounds in the $30 cost category.

This analysis could be applied to other uranium resource regions assessed by NURE to identify regions where the undiscovered resource endowment may be too high or too low. In some regions, uranium deposit models may have changed such that a reexamination of resources may be warranted. In other regions, significant exploration and production since NURE ended in 1980 may have identified uranium-rich areas not recognized during the last assessment, or condemned areas as non-productive.

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APPENDIX

Conditional and Unconditional Endowment Estimated by NURE for Favorable Areas in the Texas Gulf Coast Uranium Province

NURE Favorable Areas[a]	1:250,000 Quadrangle Name	Conditional Endowment (lb U_3O_8)	Unconditional Endowment (lb U_3O_8)	Conditional Endowment at \$30/lb U_3O_8 (lb U_3O_8)	Unconditional Endowment at \$30/lb[b] U_3O_8 (lb U_3O_8)	Resource Category
14040056	Austin	6,058,000	4,846,000	2,282,654	1,825,973	Possible
14040057	Austin	5,212,000	5,212,000	2,122,326	2,122,326	Possible
14040058	Austin	4,816,000	3,854,000	1,923,029	1,538,902	Possible
14040059	Austin	13,320,000	9,324,000	4,648,680	3,254,076	Possible
14040060	Austin	10,284,000	10,284,000	4,334,706	4,334,706	Possible
14040061	Austin	12,910,000	10,328,000	5,171,746	4,137,397	Possible
14040062	Austin	3,260,000	2,608,000	1,286,396	1,029,117	Possible
14040046	Beaumont	2,776,000	832,600	163,784	49,123	Possible
14040047	Beaumont	838,200	293,400	14,082	4,929	Possible
14040063	Beaumont	7,446,000	7,446,000	2,825,757	2,825,757	Possible
14040064	Beaumont	5,012,000	4,010,000	1,947,162	1,557,885	Possible
14040065	Beaumont	778,000	544,600	274,089	191,863	Possible
14040077	Beaumont	17,462,000	13,968,000	6,860,820	5,488,027	Possible
14040078	Beaumont	17,020,000	11,914,000	6,467,600	4,527,320	Possible
14010010	Beeville	2,296,000	2,296,000	1,083,712	1,083,712	Probable
14010011	Beeville	29,660,000	29,660,000	11,932,218	11,932,218	Probable
14010012	Beeville	22,620,000	22,620,000	8,100,222	8,100,222	Possible
14010013	Beeville	33,020,000	33,020,000	14,310,868	14,310,868	Probable
14010032	Beeville	2,600,000	2,600,000	969,540	969,540	Probable
14010038	Beeville	6,152,000	6,152,000	3,099,378	3,099,378	Probable
14010073	Beeville	35,320,000	28,260,000	13,057,804	10,447,722	Probable
14010085	Beeville	14,878,000	11,902,000	7,291,708	5,833,170	Possible
14011044	Beeville	18,160,000	18,160,000	8,224,664	8,224,664	Probable
14011045	Beeville	34,760,000	34,760,000	15,767,136	15,767,136	Probable
14011099	Beeville	24,580,000	24,580,000	9,335,484	9,335,484	Probable
14040066	Beeville	4,548,000	3,184,000	1,147,460	803,323	Possible
14020001	Corpus Christi	14,850,000	14,850,000	1,635,265	1,635,265	Possible
14020001	Corpus Christi	12,968,000	12,968,000	3,569,940	3,569,940	Possible
14020003	Corpus Christi	826,000	826,000	102,044	102,044	Possible
14020072	Corpus Christi	3,434,000	2,404,000	431,997	302,423	Possible
14010028	Crystal City	7,738,000	5,804,000	4,008,284	3,006,472	Probable
14010030	Crystal City	53,600,000	53,600,000	30,117,840	30,117,840	Probable
14010031	Crystal City	14,838,000	14,838,000	8,310,764	8,310,764	Probable
14010034	Crystal City	32,360,000	32,360,000	18,419,312	18,419,312	Probable
14010035	Crystal City	8,112,000	8,112,000	4,543,531	4,543,531	Probable
14010039	Crystal City	2,060,000	1,442,000	1,049,570	734,699	Probable
14010040	Crystal City	9,848,000	9,848,000	5,218,455	5,218,455	Probable

NURE Favorable Areas[a]	1:250,000 Quadrangle Name	Conditional Endowment (lb U_3O_8)	Unconditional Endowment (lb U_3O_8)	Conditional Endowment at \$30/lb U_3O_8 (lb U_3O_8)	Unconditional Endowment at \$30/lb[b] U_3O_8 (lb U_3O_8)	Resource Category
14010093	Crystal City	886,000	310,000	187,947	65,796	Possible
14010094	Crystal City	1,506,000	602,000	318,218	127,287	Possible
14010095	Crystal City	1,220,000	732,000	257,302	154,390	Possible
14010097	Crystal City	1,172,800	410,400	529,636	185,337	Possible
14010098	Crystal City	1,279,200	447,800	577,687	202,226	Possible
14010099	Crystal City	9,348,000	3,740,000	4,221,557	1,688,984	Possible
14011036	Crystal City	2,584,000	2,584,000	1,301,819	1,301,819	Probable
14011037	Crystal City	8,092,000	8,092,000	4,134,203	4,134,203	Probable
14011041	Crystal City	5,704,000	5,704,000	3,059,626	3,059,626	Probable
14011042	Crystal City	2,568,000	2,568,000	1,392,626	1,392,626	Probable
14011043	Crystal City	524,400	524,400	311,494	311,494	Probable
14011098	Crystal City	9,374,000	9,374,000	4,515,456	4,515,456	Probable
14040068	Houston	3,596,000	2,158,000	691,151	414,768	Possible
14040069	Houston	5,398,000	4,318,000	1,956,775	1,565,275	Possible
14040071	Houston	8,668,000	8,668,000	2,598,581	259,858	Possible
14020021	Laredo	86,000,000	86,000,000	38,949,400	38,949,400	Probable
14020022	Laredo	68,900,000	68,900,000	32,865,300	32,865,300	Probable
14020023	Laredo	17,516,000	17,516,000	8,045,099	8,045,099	Probable
14020026	Laredo	65,040,000	65,040,000	30,107,016	30,107,016	Probable
14020027	Laredo	11,652,000	11,652,000	4,822,763	4,822,763	Probable
14020080	Laredo	11,222,000	11,222,000	5,572,845	5,572,845	Probable
14020081	Laredo	9,450,000	9,450,000	4,771,305	4,771,305	Possible
14020082	Laredo	18,450,000	18,450,000	8,675,190	8,675,190	Probable
14020099	Laredo	24,000,000	24,000,000	11,402,400	11,402,400	Probable
14021019	Laredo	6,310,000	6,310,000	3,149,321	3,149,321	Probable
14021020	Laredo	18,136,000	18,136,000	8,696,212	8,696,212	Probable
14021024	Laredo	38,380,000	38,380,000	12,757,512	12,757,512	Probable
14021025	Laredo	30,200,000	30,200,000	13,034,320	13,034,320	Probable
14021099	Laredo	8,144,000	8,144,000	1,958,632	1,958,632	Probable
14030011	Laredo	77,900,000	77,900,000	38,763,040	38,763,040	Probable
14030012	Laredo	11,160,000	11,160,000	4,831,164	4,831,164	Probable
14030015	Laredo	30,040,000	30,040,000	14,094,768	14,094,768	Probable
14030017	Laredo	17,858,000	17,858,000	8,846,853	8,846,853	Probable
14030001	McAllen	26,600,000	21,280,000	11,374,160	9,099,328	Possible
14030001	McAllen	18,024,000	18,024,000	8,063,938	8,063,938	Possible
14030001	McAllen	5,936,000	5,936,000	2,711,565	2,711,565	Possible
14030002	McAllen	16,136,000	16,136,000	9,683,900	9,683,900	Possible
14030014	McAllen	15,594,000	15,594,000	259,741	51,948	Possible
14030014	McAllen	11,846,000	11,846,000	2,115,696	2,115,696	Possible
14030014	McAllen	3,454,000	690,800	7,977,890	7,977,890	Possible
14031004	McAllen	29,120,000	29,120,000	12,742,912	12,742,912	Possible
14031004	McAllen	19,750,000	19,750,000	10,503,050	10,503,050	Possible
14031006	McAllen	12,526,000	8,768,000	4,191,200	2,933,773	Possible
14031006	McAllen	31,460,000	31,460,000	10,831,678	10,831,678	Possible

NURE Favorable Areas[a]	1:250,000 Quadrangle Name	Conditional Endowment (lb U_3O_8)	Unconditional Endowment (lb U_3O_8)	Conditional Endowment at \$30/lb U_3O_8 (lb U_3O_8)	Unconditional Endowment at \$30/lb[b] U_3O_8 (lb U_3O_8)	Resource Category
14031008	McAllen	7,908,000	5,140,000	3,328,477	2,163,426	Probable
14031009	McAllen	6,710,000	2,012,000	2,828,936	848,259	Probable
14041010	McAllen	11,202,000	3,360,000	5,072,266	1,521,408	Probable
14040045	Palestine	19,124,000	4,782,000	885,441	221,407	Possible
14040048	Palestine	6,614,000	992,000	277,127	41,565	Possible
14010084	San Antonio	20,760,000	17,644,000	4,841,232	4,114,581	Speculative
14010086	San Antonio	2,230,000	1,449,600	528,287	343,410	Speculative
14010087	San Antonio	10,722,000	8,042,000	2,485,360	1,864,136	Speculative
14010089	San Antonio	335,200	268,200	79,476	63,590	Speculative
14010090	San Antonio	1,138,400	569,200	201,952	100,976	Speculative
14010091	San Antonio	553,600	276,800	98,209	49,104	Speculative
14010092	San Antonio	2,992,000	2,394,000	738,426	590,839	Speculative
14010096	San Antonio	356,600	107,000	75,492	22,652	Speculative
14010049	Seguin	2,082,000	1,664,800	1,003,524	802,434	Probable
14011046	Seguin	3,820,000	3,820,000	2,056,688	2,056,688	Probable
14011047	Seguin	4,998,000	4,998,000	2,672,930	2,672,930	Probable
14011048	Seguin	4,014,000	4,014,000	2,072,027	2,072,027	Probable
14040055	Seguin	7,868,000	7,868,000	4,021,335	4,021,335	Possible
14040067	Seguin	5,652,000	3,956,000	2,425,838	1,697,915	Possible
14040075	Seguin	14,930,000	10,450,000	7,803,911	5,462,215	Possible
14040076	Seguin	28,480,000	22,780,000	15,515,904	12,410,544	Possible
14041050	Seguin	3,568,000	2,854,000	2,144,368	1,715,254	Probable
14041051	Seguin	13,084,000	13,084,000	6,967,230	6,967,230	Probable
14041053	Seguin	8,096,000	8,096,000	4,242,304	4,242,304	Probable
14041054	Seguin	658,400	460,800	430,923	301,594	Possible
Total Endowment		*1,487,040,800*	*1,369,988,400*	*642,700,636*	*602,561,368*	

[a]In some favorable areas, identification numbers are repeated because they evaluate different geologic units in the same geographic area.
[b]\$30/lb uranium was calculated in 1980 prices. Inflation would place this at approximately \$85/lb in 2012 prices (U.S. Department of Labor 2012).

Conversion Factors, Definitions, Abbreviations

Conversion Factors

Inch/Pound to SI

Multiply	By	To Obtain
Length		
Foot (ft)	0.3048	Meter (m)
Mile (mi)	1.609	Kilometer (km)

Definitions

Favorable area (U.S. Department of Energy 1980; International Atomic Agency 1992): ''A geographic area in which the available data indicate the existence of geologic environments that are favorable for the concentration of uranium.'' Favorable areas exclude areas of mining or reserves.

Cost category: See potential resource below. Costs are calculated as forward costs per pound of U_3O_8. In the current study, $30/lb U_3O_8 was selected as the most appropriate economic cost category. Applying inflation, in 2012 dollars this economic cutoff would be approximately $85, which is almost twice the current uranium price of about $50/lb U_3O_8 (U.S. Department of Labor 2012). This is below the average historic price for uranium since 1980 (Organisation for Economic Cooperation and Development Nuclear Energy Agency and International Atomic Energy Agency 2012). This simple inflationary treatment does not take into account variations in mining costs since 1981 because the original parameters used in NURE are no longer reproducible so cannot be analyzed.

Possible potential resource (Finch and McCammon 1987): Estimates of undiscovered or partly defined uranium deposits in rocks or geologic settings productive elsewhere within the same geologic province or subprovince.

Potential resource (Finch and McCammon 1987): The portion of the uranium endowment, in tons of U_3O_8, that are estimated to be producible at selected forward costs in dollars per pound of U_3O_8.

Probable potential resource (Finch and McCammon 1987): Estimates within known productive uranium areas that are either extensions of known deposits or undiscovered deposits within known geologic trends or areas of mineralization.

Speculative potential resource (Finch and McCammon 1987): Estimated quantities in undiscovered or partly defined deposits in formations or geologic settings not previously productive with a productive geologic province or subprovince or within a geologic province or subprovince not previously productive.

Technically recoverable resources: Those resources that are mineable using currently known methods of extraction without regard for cost.

Uranium assessment (Finch and McCammon 1987): The economic evaluation of undiscovered resources.

Undiscovered uranium resources: Uranium resources expected to exist based on the application of the geologic knowledge of known deposits to geologically similar regions.

Uranium deposit (modified from Finch and McCammon 1987): A discrete concentration of uranium mineralization that is of possible economic interest and/or is above a lower cutoff grade and of a minimal size. For this paper, deposits were defined by the U.S. Department of Energy Producing Uranium Mines database. No aggregation of smaller deposits was considered here because there was not good enough information about the location of each deposit listed in the DOE database.

Uranium endowment (U.S. Department of Energy 1980): Uranium endowment is an estimate of all uranium-bearing material having a grade of at least 0.01% U_3O_8, postulated to occur in geologic settings favorable for undiscovered uranium deposits. The estimate is made previous to any consideration for the economics of exploration and exploitation, but it includes subsequent estimated potential resources, as well as associated additional material at or above the 0.01% cutoff grade within the area for which the estimate applies. Uranium endowment is the potential-related complement of the reserves-related uranium inventory.

Uranium reserves (U.S. Energy Information Administration 2012): Estimated quantities of uranium in known mineral deposits of such size, grade, and configuration that the uranium could be recovered at or below a specified production cost with currently proven mining and processing technology and under current law and regulations. Reserves are based on direct radiometric and chemical measurements of drill holes and other types of sampling of the deposits. Mineral grades and thickness, spatial relationships, depths below the surface, mining and reclamation methods, distances to milling facilities, and amenability of ores to processing are considered in the evaluation. The amount of uranium in ore that could be exploited within the chosen forward-cost levels are estimated in accordance with conventional engineering practices.

Uranium resources (Finch and McCammon 1987): A concentration of naturally occurring material in such form and amount that economic extraction is currently or potentially feasible.

Abbreviations

DOE	U.S. Department of Energy
NURE	U.S. Department of Energy national uranium resource evaluation program
URAD	U.S. Department of Energy ''uranium reserves and data'' computer program and database used to estimate potential uranium resources
USGS	U.S. Geological Survey

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