Energy Programs—A Contribution to Salt Dome Knowledge

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ABSTRACT

In recent years, several major federal energy programs involving salt domes have been initiated. An enormous amount of data has been accumulated concerning their occurrence, origin, character and utilization. This has resulted in an enhanced geological and technological understanding of salt domes. This understanding should aid in the planning and development of their use both in an economic and environmental sense.

Studies of the utility of salt domes for the isolation of high-level nuclear waste were initiated in the early 1970s by the U.S. Geological Survey and greatly expanded by the U.S. Department of Energy. Another program, the Strategic Petroleum Reserve Project, was mandated by Congress in 1975. Its ultimate goal was to establish a reserve of one billion barrels of crude oil. Man-made cavities in Gulf Coast salt domes are being utilized for this purpose. A third effort has been the study of compressed air energy storage underground. An evaluation of the use of man-made cavities in salt domes for this purpose has been a major focus of this program.

Enhancement of scientific knowledge related to salt domes has included such fields as structural geology, petrology, hydrology, rock mechanics, mining methods, failure modes of underground structures and potential environmental impact of salt dome utilization.

INTRODUCTION

The more than 500 salt domes in the U.S. Gulf Coast represent an enormous resource base both for the region and the nation. The characteristics as well as the existence of salt domes in the U.S. were unknown prior to the 1860s, although salt had been mined in Europe for over 1,000 years. Since that time knowledge concomitant with development expanded rapidly. Rock salt was discovered in 1862 followed by introduction of room-and-pillar mining in 1867. Sulfur was discovered in association with a salt dome in 1867 and was first successfully produced in 1894. Its commercial production was stimulated by the discovery in 1901 of oil on the Spindletop dome which provided the cheap energy to fuel the Frasch process (Hawkins and Jirik, 1966). Thus, in a relatively short period, three major resource developments associated with salt domes were begun.

In the years following Spindletop, petroleum became the dominant energy source that it is today. In the U.S. Gulf Coast region its occurrence continued to be largely associated with salt dome structures. According to Hawkins and Jirik (op. cit.), of the 329 domes proved by 1965, 195 yielded some petroleum by that time. The huge sums of money generated by this industry led to the employment of many thousands of highly trained petroleum geologists. Extremely sophisticated geological and geophysical exploration techniques were devised to locate and develop deposits of oil and gas. A consequence of this emphasis on science in petroleum exploration was the accumulation of vast amounts of data which led to a deeper understanding of the earth and its geological processes. These benefits were also realized in the Gulf Coast salt dome province.

The widespread occurrence of petroleum and the consequent involvement of landowners in its development led to legislation which generally required disclosures of its underground distribution and various details of its exploitation. This also created a climate that led to the documentation of the distribution and nature of petroleum deposits.

Therefore, both scientific involvement and political requirements led to an impressive documentation in public literature of the geology of petroleum. In the Gulf Coast area a great part of this record necessarily focused on salt domes. Their distribution, genesis and impact on the enclosing sediments were exhaustively investigated. This body of knowledge, however, was primarily concerned with the deformation of sediments into which the salt had intruded rather than with the salt stock itself. A minor exception was salt dome cap rock, which in some instances constituted hydrocarbon traps.

Salt dome cap rock also generated scientific interest and attention because it is the host rock for sulfur. Furthermore, because it represents a comparatively localized and erratic exploration target, an economic impetus was provided to develop an understanding of its geologic occurrence along with devising appropriate exploration techniques. This also led to enhanced scientific understanding that was recorded in published information.

Because salt stocks are of such high purity and are very large in size and their general locations well established, the need to apply scientific research, on a large scale, was not recognized in the early stages of rock salt mining and cavity development. Prior to the 1970s efforts along these lines were limited. A notable exception was mapping of the internal structure and details of rock salt mines by university affiliated geologists. The search for a deeper understanding of their internal structure and characteristics was also impeded by the relatively small size of the industry (compared with the petroleum business) and the small number of engineers and geologists actively employed. Furthermore, not a great deal of attention was given to these activities by either state or federal agencies. This was particularly true of the state governments that had little experience with the mining industry.

A major turnaround in research interest in salt domes resulted from the initiation during the 1970s of several major federal energy programs. The implementation of these programs has resulted in the accumulation of an enormous amount of data concerning the occurrence, origin, character and utilization of salt domes that has enhanced the geological and technological understanding of these structures. This should aid in the planning and development of their use by the private sector both in an economic and environmental sense.

PLANNING FOR SALT DOME UTILIZATION

Salt dome utilization consists of a variety of possibly competing developments. An array of current and potential demands for the use of salt domes is displayed in Figure 1 (Martinez and Thoms, 1978). The implementation of some, and possibly all, of this set of current and potential uses of domes can best be affected by viewing the dome and its surrounding environment as a system. This method may even be essential to the resolution of fundamental questions of salt dome tectonics and petrology. The three principal components of the salt dome system are: the salt stock, the cap rock and the intruded host materials. Figure 2 (Martinez, 1982) shows a model of these components along with the various materials that constitute them. In the growth and development of a salt dome, a dynamic interaction occurs between the three subsystems identified here. It is important to understand these interactions in order to resolve problems related to the various subsets of the system. The nature of this system and the interrelations between its components have been recognized in past studies. However, with the introduction of modern highly specialized studies into salt dome research, the value of interdisciplinary efforts focusing on the entire system becomes apparent.

Examples of benefits that may be derived from an understanding of properties of the salt dome system are given in Figure 3 and typical critical salt dome characteristics are listed along with operation-design parameters to which they are related. The typical path of feedback into a salt dome system analysis from a program of salt dome exploitation and the impact of such a study on exploitation is illustrated in Figure 4. It is self evident that this flow of information into the design process is inherent in any individual corporate enterprise of salt dome utilization. However, because of proprietary consideration, each individual system with its information feedback is isolated. Granted, some exchange of information has occurred, but it has not been widespread. With the advent of the federal government programs of the 1970s and 1980s, individual systems became interlocked to a greater or lesser degree, and publication along with widespread dissemination of data and research results became the general rule. A window was suddenly opened to a vast amount of knowledge.

The following sections will highlight benefits from these programs by a selective review of their research goals and accomplishments. An encyclopedic summary is beyond the scope of this paper.

STRATEGIC PETROLEUM RESERVE PROGRAM

The creation of a Strategic Petroleum Reserve (SPR) of up to one billion barrels of oil was authorized by the Energy Policy and Conservation Act of 1975. The original target was for 500 million barrels of crude oil and petroleum products to be in storage by the end of 1982. The goal of the Reserve was established at one billion barrels by 1985 by SPR Plan Amendment No. 2 submitted to Congress in 1978. This provided as well for implementation of a 750-million-barrel Government Reserve (U.S. Department of Energy, 1980). By the end of 1980 an oil storage capacity of 248 million barrels had been created and it was over 75 percent of that originally planned. Actual oil fill was only one-third of the goal (U.S. Department of Energy, 1981). Total crude oil in storage at the end of 1980 amounted to 107.8 million barrels; 105.9 million barrels of oil was in storage below ground in caverns in the salt domes shown in Figure 5 and about 1.9 million barrels in surface tanks and pipelines. The status of these individual salt dome facilities as of December, 1980, was as follows:

Salt Dome	Amount stored (million barrels)	Capacity (million barrels)
Bayou Choctaw	25.3	36.0
Weeks Island	4.4 (in mine)	75.0
Bryan Mound	38.6	60.3
Sulphur Mines	—	22.0
West Hackberry	38.6	50.6

All of the above sites are located in Louisiana except for Bryan Mound, which is in Brazoria County, Texas. Solution mined storage caverns constitute storage facilities of all of the domes except Weeks Island. The Weeks Island storage utilizes a conventional salt mine containing two levels of rooms and pillars.

Initial studies were required to select a list of candidate domes for near-term and long-term sites. "The search included a review of about 350 domes and bedded salt deposits of which 150 had some existing caverns. The search also included a review of about 300 existing conventional mines" (a few in salt). "Initially four domes with existing caverns, 13 undeveloped domes and 11 existing conventional mines were selected for detailed feasibility analysis" (Allen, 1976). Eight candidate sites were selected from these and included three salt domes with existing solution mined caverns and three salt domes with conventional mines. One of the early efforts in the SPR program was the preparation of a Programmatic Environmental Impact Statement and site specific Environ-

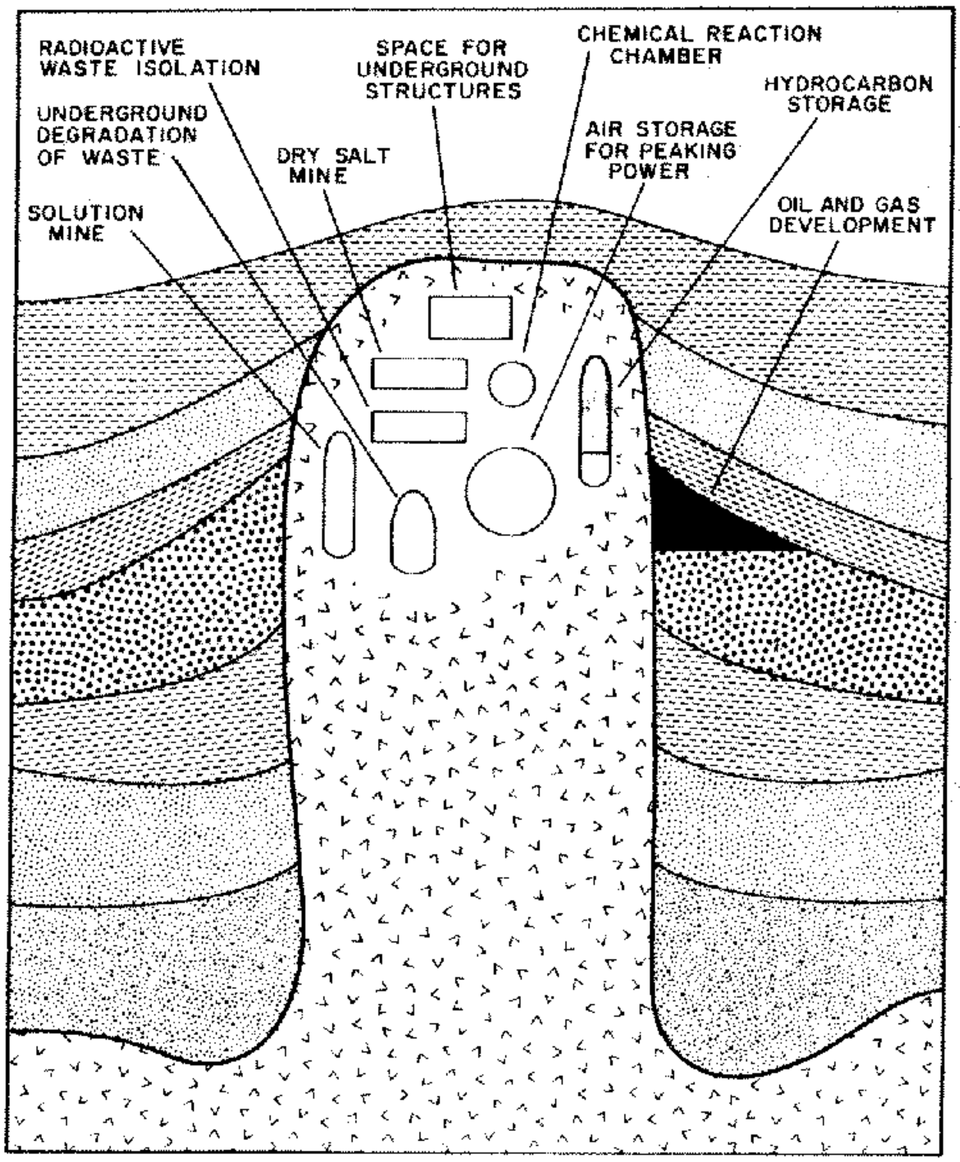


Figure 1. Potential demands for salt dome utilization. From Martinez and Thoms (1978).

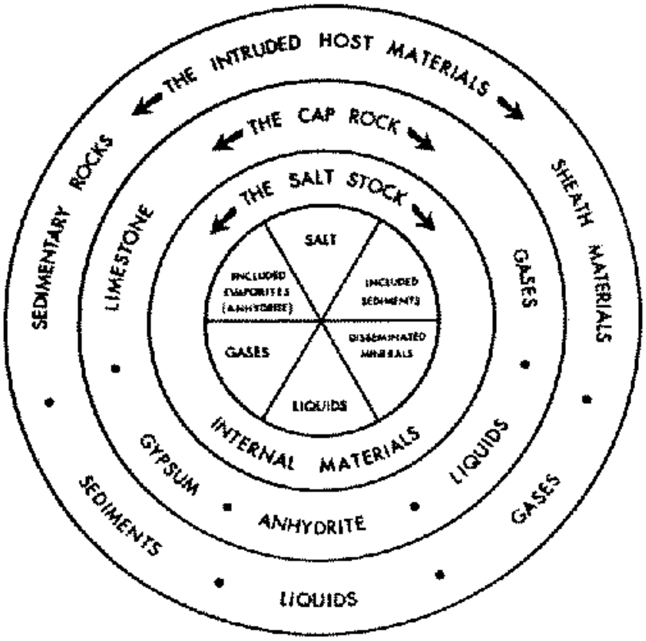
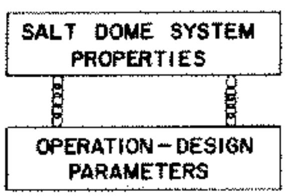


Figure 2. The salt dome system. From Martinez, in Martinez et al. (1978) and Martinez (1982).



EXAMPLE:

OPERATION—DESIGN PARAMETER	CRITICAL SALT DOME CHARACTERISTIC
• Rate of Cavity Development	Character of Salt and Included Material
• Shape of Cavity	Internal Domal Structure
• Stability of Cavity	Mechanical Properties of Domal Material
• Blowouts	Gas and Stress Conditions
• Contamination	Gas and Liquid Inclusions
• Optimization of Domal Use	Geometric Configuration and System Properties
• Future Adaptation	All Possible
• Environmental	Complete Geomechanical System

Figure 3. Salt dome system properties as a basis for operation-design parameters.

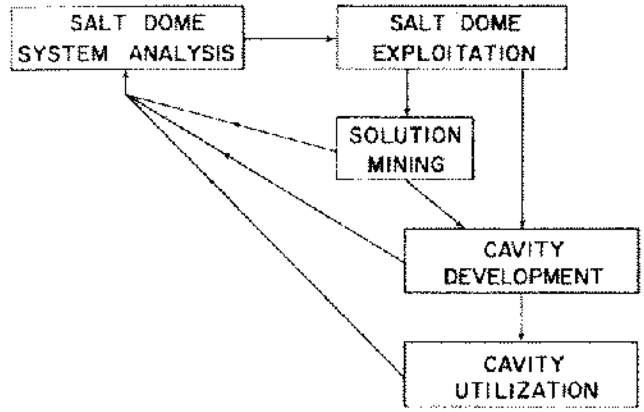


Figure 4. Information feedback in salt dome exploitation.

mental Impact Statements on these candidate near-term sites. Similar statements were prepared for other domes, one of which was selected for actual use. This represented a major new evaluation of the impact of solution mining and storage in salt domes on the environment. These reports are available to the public and can be used as source data for the evaluation of similar developments. Impact of the development of these caverns was considered localized and temporary (FEA, 1976).

Preparation of these environmental assessments and the need for a technical basis for engineering design led to more sophisticated and detailed studies. For those caverns developed by solution mining, the investigations were principally in the categories of rock mechanics and brine disposal both in the subsurface and in the Gulf of Mexico. Results of some rock mechanic studies were published in a series of reports by Sandia National Laboratories. Tillerson (1979) and Hilton et al. (1980) outline purposes of the program of geomechanics investigations. These included interaction effects between adjacent cavities, cavern spacing effects, depressurization effects and evaluation of salt creep rates. Hilton et al. (op. cit.) deal specifically with the question of interaction effects of storage caverns in salt. A Sandia report by Price et al. (1981) references some earlier Sandia reports on geomechanics. Sandia also did some work on the chemistry and mineralogy of samples from the Bryan Mound salt dome in Texas (Bild, 1980). Mechanisms and the ecological impact of the collapse of salt dome oil storage caverns were reviewed by Stanczuk et al. (1977). The U.S. Department of Energy (1981) contended that "the primary advancement in technology being undertaken by the SPR Program is that the leaching process will be performed at significantly higher rates than ever before attained."

One of the sites chosen for strategic oil storage was a room-and-pillar rock salt mine in the Weeks Island dome in south Louisiana. This site permitted much more detailed study of the characteristics and structure of the

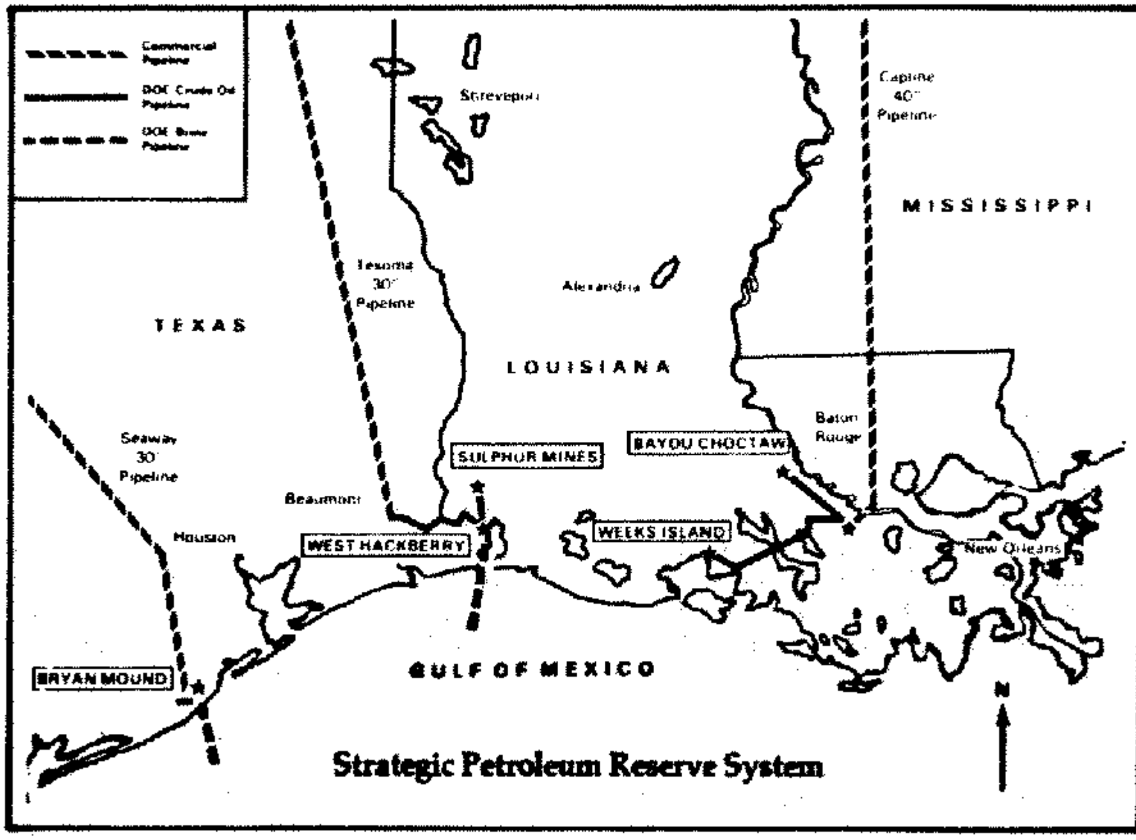


Figure 5. Location of SPR storage sites in salt domes in 1981. Modified from U.S. Department of Energy (1981).

salt. Geologic items of specific interest were deformation of visible layering in the salt, shear zones and brine oil and gas seeps. The geotechnical evaluation reviewed by Mahtab et al. (1978) considered the significance of these features along with blowouts, stability of the mine's roof, pillars and shafts (including pillar decay, exfoliation and slabbing), salt permeability, possible oil leakage and possible detonation of oil vapor. Hilton et al. (1979) prepared a structural analysis of Weeks Island Mine/Petroleum Repository.

In the course of planning the Weeks Island repository, some questions were raised about its suitability as a Strategic Petroleum Reserve Repository by the Comptroller General of the U.S. in a report to the Congress (1978). This served further to promote various technical studies of salt domes. The question of the effects of long-term storage on crude oil and potential losses was considered in this report for both salt caverns and mines (the report dealt with both). The significance of a water infiltration problem was also questioned. Investigative and corrective measures by DOE provided further information for the public domain in the problem of water leaks which is important in rock salt mining. Another item that was addressed in this GAO report was the occurrence of blowouts (also referred to as outbursts) (Thoms and Martinez, 1980). In this mine blowouts were considered to threaten the safety of a proposed new mine below the repository. A study by MSHA followed (Iannacchione et al., 1982, and Hyman, 1982). This research represented an important effort to understand an enigmatic phenomenon.

As alluded to earlier, much proprietary information resided in files of companies involved in the solution mining and conventional room-and-pillar mining of salt. Some interchange of information had been provided earlier by the Solution Mining Research Institute, but with the onset of the SPR program much of this proprietary information became available to government investigators.

Access to this data, coupled with the result of major new research programs, should provide major benefits in the future to the salt mining industry as well as to the general public.

NATIONAL WASTE TERMINAL STORAGE PROGRAM FOR MINED GEOLOGIC DISPOSAL OF NUCLEAR WASTE

The development and implementation of safe and environmentally acceptable nuclear waste disposal methods is a responsibility of the U.S. Department of Energy (DOE). The principal current emphasis of the program is on emplacement of nuclear wastes in mined geologic repositories located at a substantial depth below the earth's surface (U.S. Department of Energy, 1982). High-level waste, spent fuel and TRU (transuranic) waste are to be finally disposed of and isolated through implementation of the NWTS program. A safety criterion requires adequate isolation for at least 10,000 years to prevent releases of radionuclides that could result in unacceptable doses to individuals and the general public. There must be reasonable assurance that the combined capabilities of the waste package, repository and site will limit radionuclide mobilization and transport, and thereby meet the safety criterion stated above. It is a requirement of the program that "the waste package must control the release of radionuclides from within it into the surrounding rock after breach of package containment. This function must be maintained under the processes, events and environments expected in the repository, including mechanical, thermal and radiological effects, ground water flow conditions, and the in situ chemical environment as affected by ground water" (U.S. Department of Energy, 1982). Thus a high degree of sophistication is required in the planning and engineering of a repository. The final barrier is the host rock itself.

Salt has been recognized for a number of years as a particularly suitable rock type for the isolation of radioactive wastes, having first been proposed by a joint panel of the National Academy of Sciences and the National Research Council (Hess et al., 1957). Its advantages include its plastic behavior, which is responsible for its self-healing and impermeability, its relatively high thermal conductivity, its wide distribution and its ease of mining (Lómenick, 1977).

Early studies of the potential use of salt deposits for the isolation of radioactive wastes focused on bedded salt (Empson et al., 1970, and Bradshaw et al., 1970). In the early 1970s attention began to be directed to the possible utility of Gulf Coast salt domes for this purpose. Anderson, Eargle and Davis (1973) summarized the geology and hydrology of the salt domes of the U.S. Gulf Coast as a basis for considering the utility of these structures for containment of radioactive wastes. Their report was followed by an analysis, largely based on a review of the literature, by Ledbetter et al. (1975).

Initially, and for some time thereafter, the salt dome investigations were conducted and sponsored by Oak Ridge National Laboratories, first through Project Salt Vault and later through the National Waste Terminal Storage Program, which it managed. Oak Ridge National Laboratories was operated by the Nuclear Division of Union Carbide Corporation successively for the U.S. Atomic Energy Commission (AEC), the Energy Research and Development Administration (ERDA), the Federal Energy Administration (FEA), and the U.S. Department of Energy (DOE). All of these Federal agencies at one time had primary responsibility for the Nuclear Waste Isolation Program, which included the work on salt domes. Battelle Memorial Institute became responsible to DOE in 1977 for management of the waste program through its Office of Nuclear Waste Isolation, which continues to administer this effort.

The Institute for Environmental Studies (IES) at Louisiana State University initiated investigations into the utility of Gulf Coast salt domes in 1975 under a contract with Oak Ridge National Laboratory. For several years IES was the principal organization involved in such studies for the federal government through its National Laboratory at Oak Ridge. As the program expanded, a contract was awarded to Law Engineering Testing Company (LETCo) of Marietta, Georgia, in 1977 to serve as Geologic Project Manager of the salt dome program in the Gulf Coast, initially in that year through Oak Ridge National Laboratory but later through the Office of Nuclear Waste Isolation. Shortly thereafter, the Bureau of Economic Geology of the University of Texas was assigned responsibility for further studies of the Texas domes, and studies by IES were restricted to those in Louisiana. Work in Mississippi was to be done by the USGS, Mellen Geological Associates, Inc. and the University of Southern Mississippi. In the pursuit of its goals, ONWI began to involve others, and finally management of the Gulf Coast Salt Dome program was transferred from LETCo to ERTEC (ERTEC Western, Inc.).

It is obviously not feasible to review this entire complex program here. Some of the early work at LSU will be briefly summarized along with the thrust of some of the later participants. The LSU studies concentrated on the tectonics and hydrology of the salt domes and a determination of their stability in both of these categories. It was necessary to establish whether the domes were undergoing active movement and/or dissolution and what the rates of these activities might be. In the course of this study it became apparent that an evaluation was required of the effectiveness of a salt dome to provide hydrologic isolation of a mined opening.

The approach to evaluating tectonic stability was on a three-fold temporal basis (Figure 6, Martinez 1982). Thinning rates in Mesozoic and Tertiary sediments were used to evaluate stability during those geologic ages. Salt tectonic and cap rock studies also were a part of this effort. Salt dome growth during the Pleistocene was tested by a search for deformation of sedimentary strata of this age. Various instrumental arrays were used to detect possible current movement.

An assessment of the resistance of the salt stock to external dissolution provided a measure of its hydrologic stability (Figure 7, Martinez, 1979). Presence or absence of cap rock and its thickness, if present, constituted evidence of past dissolution and its relative amount. Current dissolution was evaluated by the presence and character

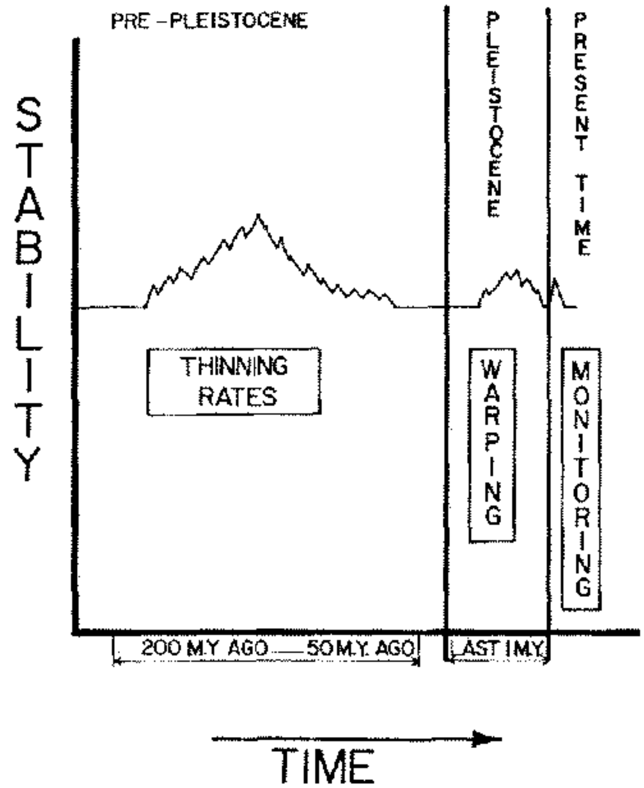


Figure 6. A temporal approach to the determination of tectonic stability. From Martinez, in Martinez et al. (1979) and Martinez (1982).

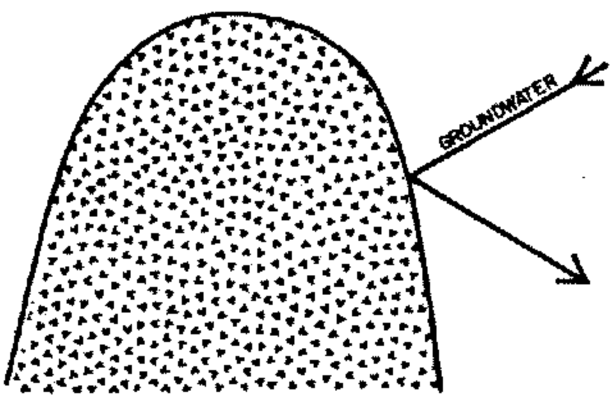


Figure 7. Hydrologic stability: resistance of the salt stock to external dissolution. From Martinez, in Martinez et al. (1978) and Martinez (1979).

or absence of saline plumes in the ground water and by the occurrence or absence of salt water springs over the dome and whether anhydrite sand at the cap rock salt interface is cemented or not (Martinez, 1978, 1982).

The incidence of water leaks in salt mines made an investigation of this problem a necessary part of the nuclear waste-salt dome evaluation. Figure 8 (Martinez, 1979) shows schematically the idea of hydrologic isolation, a

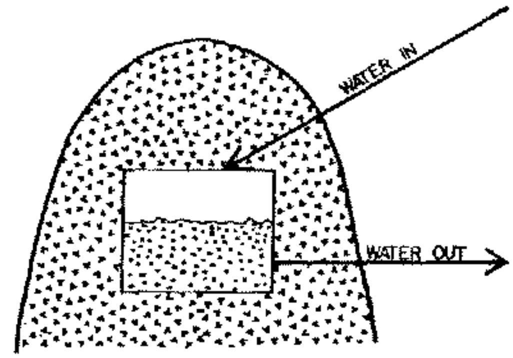


Figure 8. Hydrologic isolation: effectiveness of the salt stock to block inflow into and outflow of water from a mined opening. From Martinez, in Martinez et al. (1978) and Martinez (1979).

term used to indicate whether mine leaks if present can create a path for the release of radionuclides to the biosphere. Surveys of leaks in mines and geochemical studies were undertaken to address this problem. Some of the information required for the assessment of hydrologic isolation is given in Figure 9.

The IES-LSU studies were described in a series of reports to Oak Ridge National Laboratory and the DOE (Martinez et al., 1975, 1976, 1977, 1978, 1979).

In addition to the work described in the preceding paragraphs, the Office of Waste Isolation contracted with the Institute for Environmental Studies to arrange and manage the drilling of a deep core hole into each of two potential target domes in North Louisiana, Vacherie and Rayburn's. The cap rock along with 2,500 feet of underlying salt was continuously cored and then the wells were drilled to a total depth of 5,000 feet. Core recovery was 90.5 percent at Vacherie and 97.6 percent at Rayburn's (Hawkins, 1978). Nance and Wilcox (1979) prepared a report for DOE on the lithology at the Rayburn's core and Nance, Rovik and Wilcox (1979) prepared a report for DOE on the Vacherie core.

ORIGIN OF MINE LEAKS

1. FROM SOURCES EXTERNAL TO THE SALT STOCK
   A. METEORIC WATERS
   B. CONNATE WATERS (SUB-SURFACE BRINES)
2. FROM WATER TRAPPED WITHIN THE SALT

CHEMISTRY OF MINE LEAKS

1. MAJOR ELEMENTS
2. TRACE ELEMENTS
3. ISOTOPIC COMPOSITION

MECHANISM OF MIGRATION

1. THROUGH PERMEABILITY CHANNELS
2. BY BUBBLE MIGRATION
3. BY BUBBLE TRANSPORT THROUGH SALT DIAPIRISM

Figure 9. Information required for the assessment of hydrologic isolation.

More detailed summaries of the IES investigations are given by Martinez et al. (1980) and by Martinez (1982).

A major expansion of the Gulf Coast salt dome investigation followed the selection of Law Engineering Testing Company in 1977 as Geologic Project Manager for the Gulf Coast province. The Texas Bureau of Economic Geology undertook studies similar to those of IES-LSU. As previously stated, the USGS and groups in Mississippi also became involved. The work of the USGS was concerned with regional hydrology in areas of interest to the nuclear waste program.

A major accomplishment of the Law group was publication of a set of four volumes which constituted a geologic area characterization for the Gulf Coast Salt Domes Project. This report furnishes a geological and hydrological description of seven domes and their nearby surroundings, two of which are located in Texas, two in Louisiana and three in Mississippi. Volume 1 of this report (1981) provided an introduction, background and summary.

This work provides a recent summary of the geology of the Gulf Coast, reviews growth studies of salt domes, explores the state of knowledge of internal structure of salt domes, projects future earthquake experience in the Interior Salt Basins, estimates maximum future inundation and erosion at the candidate domes and appraises the prospects of mineral and other human resource development at these domes. A measure of information generated by the LETCo organization can be obtained from new data sources listed in Table 1.

Salt dome growth concepts were reviewed along with the various criteria for estimation of rates of growth. Some existing growth rate calculations were included in the report. The area characterization by LETCo included a summary of factual details and interpretative concepts of the internal structure of salt domes. Two related sections were devoted to a review of pertinent recorded observations from the only two room-and-pillar mines located in the Gulf Interior Region salt domes. In addition to the two salt cores obtained by LSU referred to earlier three other domes were cored through the efforts of others. Targets of these three core holes are as follows: a core hole in the Oakwood Dome in Texas penetrated 450 feet of cap rock and 193 feet of salt; a core hole in the Cypress Creek Dome in Mississippi penetrated 204 feet of cap rock and 513 feet of salt; and a core hole in Richton Dome in Mississippi penetrated 213 feet of cap rock and 508 feet of salt. Summaries of core descriptions from these holes are given in the LETCo document.

A seismic risk analysis was undertaken and it was concluded, as might be expected, that the Interior Salt Basin and Gulf Coast Regions are characterized by a low seismicity. One can infer from this report that these regions are subject to only sporadic earthquakes of low intensity.

The brief summary above of the LETCo effort is designed to give only an indication of the breadth and scope of this work. The various subcontractors involved as well as the many consultants who participated, while not identified here, are recognized in their report where applicable.

TABLE 1

Summary of New Data Sources*

Data type	Source
Hydrologic and geologic boreholes	Performed under subcontract to LETCo
Geophysical logs	Commercial logging companies, USGS, and LETCo
Lithologic data	Examination of cores, sidewall cores and drill cuttings by LETCo Consultants and Geologists
Paleontological data	Examination of drill cutting and sidewall cores by LETCo paleontological consultants
Near-dome gravity observations	Performed under subcontract to LETCo
Dome gravity modeling	Performed under subcontract to LETCo
Near-dome high-resolution seismic	Performed under subcontract to LETCo
Field geologic mapping	Performed under subcontract to LETCo
Ground-level resistivity	Performed by Law Engineering Geophysicists
Remote sensing analysis	Performed under subcontract to LETCo
Structure contour and isopach maps and cross sections	Constructed by LETCo Geologists

*From Law Engineering Testing Company, Vol. I, 1981.

The study by the Texas Bureau of Economic Geology, which proceeded somewhat on a parallel with the LSU investigation, provided input into the LETCo report and the scope of this salt dome symposium paper does not permit a detailed review of that work.

There has been a continuing interest in conceptual design of a repository in salt since the early demonstration of Project Salt Vault (Empson et al., op. cit.). This has involved rock mechanics studies from that time (Lomenick and Bradshaw, 1965; Bradshaw and Lomenick, 1970) to recent in-situ studies by RE/SPEC, Inc. in the Avery Island Mine (Van Sambeek, 1979). The dome-salt, brine-migration experiments also conducted in that mine (Krause and Gnirk, 1977) represented an extension of work sponsored by Oak Ridge National Laboratory more than a decade ago (Bradshaw and Sanchez, 1968; Anthony and Cline, 1971, 1974). Martinez and Kumar (1980) examined the possibility of brine migration through long periods of geologic time along natural thermal gradients as a source of water leaks in mines. Thus we see that the waste program has encompassed studies ranging from the character and movement of minute bubbles of encapsulated fluids to motion of the huge domes themselves.

The Paradox Basin, which is principally located in southeastern Utah and southwestern Colorado, also has been identified as a candidate for a waste repository in salt. Woodward-Clyde Consultants is the Geologic Project Manager for the Paradox Basin Study Region. Volume 1 of their Geologic Characterization Report (1982) provides a basis for the following comments. This report and other ONWI documents place the salt deposits of the Paradox Basin in the bedded salt category. However, the salt anticlines of that region are well known and are recognized in the Woodward-Clyde report as well. This author considers them to be salt structures, which despite their morphological and genetic differences from Gulf Coast domes, must be included in any general discussion of salt domes. The geologic characterization for this potential target included regional field studies in southeastern Utah and a literature review along with remote sensing, tectonic and seismologic studies in the entire Paradox Basin and surrounding areas. The report comprises sections on Physiography and Topography, Geomorphology and Quaternary Geology, Stratigraphy, Structural Geology, Seismicity, Tectonic History, Energy and Mineral Resources, and Hydrology. Investigative work conducted through this program included: a program of micro-earthquake monitoring, fault studies, an analysis of mining-induced seismicity potential within the Paradox Basin, an assessment of the potential for conflict between energy and mineral resources and repository siting, the acquisition and interpretation of hydrogeologic data, the gathering and evaluation of physiographic and topographic data which involved aerial reconnaissance and photography and map analysis, and localized structural geology studies within the Gibson Dome, Elk Ridge and Lisbon Valley areas and regional remote sensing lineament interpretations.

The Woodward-Clyde report also directed attention to problems associated with resource development in this region, including a methane gas explosion in a potash mine southwest of Moab, Utah, in which eighteen men were killed, and a loss of liquefied petroleum gas from a salt cavern just north of Moab.

The Paradox Basin investigation dealt with a much more complicated area than the Gulf Coast study because of the geologic history of that region. Therefore, emphasis on details was somewhat different.

COMPRESSED AIR ENERGY STORAGE PROGRAM

This program (CAES) represented a response by DOE to the need for peaking power to smooth out secular variations in the demand for electrical energy in the U.S. and thus reduce requirements in system capacity. A novel method to reduce energy requirements of gas turbines, used as peaking power components, was proposed by Professor Bozidar Djordjevitch of Yugoslavia and patented by him in Germany on March 22, 1956 under number 940683 (Martinez, 1974). His concept was to use stored air that had been compressed with surplus power in the operation of gas turbines for the production of power during periods of peak need. It was concluded after further study by the Deutsche Verbundgesellschaft e.v. and the Bundesanstalt für Bodenforschung (the Geological Survey, Federal Republic of Germany) that the proposal was technically and economically feasible, and that the cheapest and safest possibility was to utilize abandoned salt or potash mines as air storage cavities (personal communications from Professor Dr. H. J. Martini and Deutsche Verbundgesellschaft e.v.). A schematic diagram that compares the compressed air energy storage (CAES) system with a conventional gas turbine used for peaking power is shown in Figure 10 (Lang, 1977). This concept was eventually implemented with the construction at Huntorf in the Federal Republic of Germany of a 290-megawatt gas turbine, air storage peaking plant that uses two solution mined caverns, with a total capacity of about 10 million cubic feet, for air storage (Mattick et al., 1975). This plant became operational in late 1978 (Allen et al., 1982). These authors give the final details of cavern construction at Huntorf as follows: two cavities of about 150,000 m^3 (with a total capacity of about 300,000 m^3 [10,593,000 cubic feet]) were solution mined in a Zechstein salt structure. The top of the salt mass is about 500 meters deep and the cavity tops at least 600 meters below ground surface. Cavity height is approximately 180 meters and maximum diameter is 60 meters. The thickness of the salt between the two cavities is 160 meters and thickness of salt above the cavities is 100 meters.

A partial earlier background to the more recent CAES programs by DOE and the Electric Power Research Institute (EPRI) is given by Lang (op. cit.). His paper points out that the sponsorship of CAES programs by the federal government became active in 1976 through ERDA in cooperation with EPRI.

In the latter part of the 1970s DOE began studies in collaboration with EPRI on CAES utilizing storage reservoirs in salt deposits. DOE was assigned the role of managing a technology program to be implemented by Pacific Northwest Laboratory of Battelle Memorial Institute. Concurrently there was established a joint effort by DOE/EPRI to execute a CAES Demonstration Program. The brief discussion that follows recounts certain efforts of these programs and some of the benefits that have flowed from them.

The Battelle effort included a three-fold program of (1) field tests, (2) analytical modeling and (3) laboratory

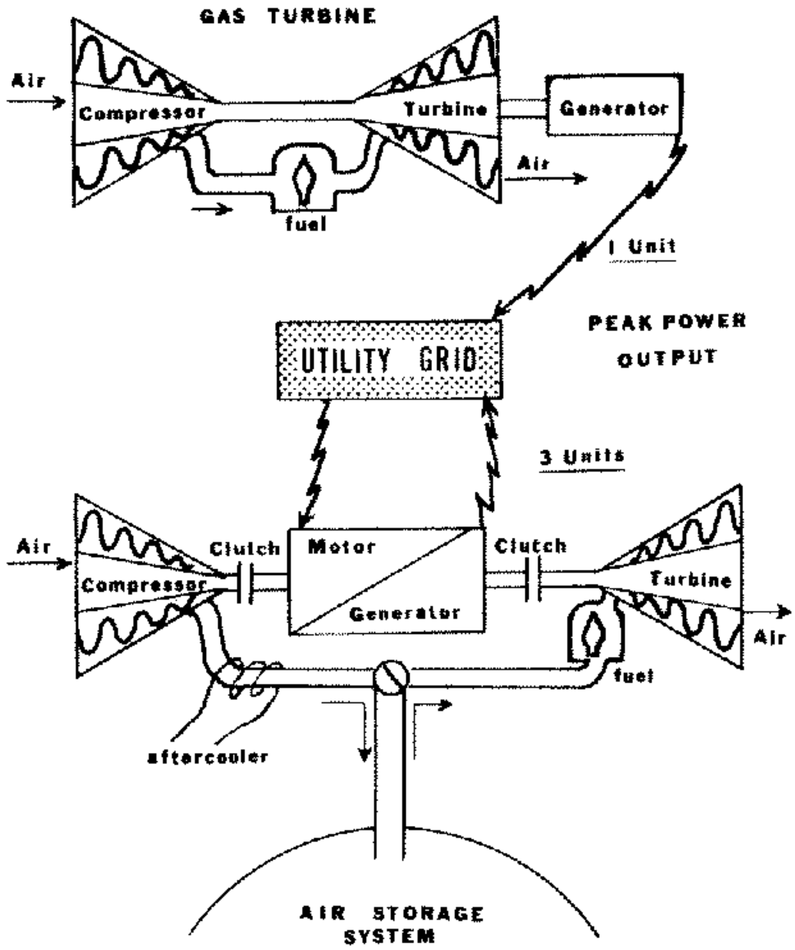


Figure 10. Comparison of a CAES system with a conventional gas turbine used for peaking power. From Lang, in Martinez and Thoms (1976).

modeling. Results from this program are compiled in a report by Allen et al. (op. cit.) which outlines the state of knowledge of solution mined salt cavities for CAES. The unique character of salt dome storage requirements in a CAES design is the cyclical nature of operation. This imposes daily changes of pressure, temperature and humidity that could damage a cavern and therefore must be controlled. The studies designed to explore such problems have added an extra dimension to knowledge gained from the use of caverns for storage of gaseous and liquid fluids, discussed earlier in this paper. Allen et al. (op. cit.) list topics evaluated in recent studies as follows:

- cavern geometry and size
- long-term creep and creep rupture of rock salt
- effects of pressure and temperature loading rates
- low frequency fatigue, coupled with cyclic pressure, temperature and wetting conditions
- progressive deterioration of salt fabric with possible air penetration
- cavern monitoring methods
- salt properties at non-ambient conditions.

The studies cited in the Allen et al. report resulted in the identification of design and operating criteria which these authors consider could serve as "guidelines for long-term stability of salt cavities." These criteria *for CAES cavern design* encompass establishment of:

- acceptable cavity floor and roof depths
- maximum cavity separation
- minimum thickness of salt between a cavern wall and the lateral salt dome boundary
- minimum thickness of salt above a solution cavity
- minimum ratio of overburden salt thickness to cavity span
- minimum value of cavern span
- acceptable range of ratio of cavity height to diameter
- maximum in-situ horizontal stress in terms of overburden pressure

- maximum rate of depressurization
- and others.

The topics evaluated and the criteria developed which are both listed above are largely addressed to the specific introduction of long continued cyclic effects already mentioned. According to Allen et al. (op. cit.) during a proposed 30- to 50-year operational lifetime of a CAES cavern, it could be subjected to between 15,000 and 20,000 loading/unloading cycles. The relative importance of this and other effects will depend significantly on whether the cavern is compensated through the maintenance of air pressure by a brine column extending from the cavern base to a surface pond or uncompensated, in which case there will be a variation in pressure through a cycle of operation (Allen et al., op. cit.; Thoms and Martinez, 1978). Numerical modeling of the behavior of salt caverns used for compressed air energy storage has been reported on by Serata and Cundey (1979) and Serata and McNamara (1980). Rock mechanic investigations involving both laboratory and in-situ field testing are summarized and discussed by Thoms (1980). A comprehensive survey of the geotechnical factors and guidelines for storage of compressed air in solution mined salt cavities is given in Allen et al. (1982).

The joint efforts by DOE and EPRI to execute a CAES Demonstration Program were furthered by a project to determine the design criteria and to develop preliminary engineering designs for a facility using a storage cavity constructed in a salt dome within the service area of Middle South Services, Inc. (United Engineers and Constructors Inc. and Middle South Services, Inc., Volumes 1 and 3, 1982). A comprehensive site-selection process identified a suitable site based on geology, proximity to electrical transmission lines, access to transportation and environmental impact (United Engineers and Constructors Inc. and Middle South Services, Inc., Volume 3, 1982).

This study to evaluate a CAES concept in the U.S. Gulf Coast, after evaluating 46 domes, selected the Carmichael salt dome in southwest Mississippi as the most desirable location, in Middle South Services' area, for a CAES facility. The preliminary design effort involved the efforts of many individuals and a substantial number of organizations. It provided another means of assembling salt dome data and utilization techniques from a variety of sources into a set of documents that are in the public domain. It is hoped some of this material will in the future be transferable to other studies having different goals. It certainly will form a basis for any new CAES projects.

Although the total CAES Program described in this section has a specific and unique goal, some of the information should be applicable to other more conventional developments in salt domes. For example, future storage of natural gas in solution mined caverns in salt may be carried out more efficiently as a result of information generated through this work. The studies of the effects of long-term stresses may be of some general application. Finally, any basic information developed about salt domes will serve to enhance the general state of knowledge about domes and perhaps to increase the accuracy of perceptions of details not specifically addressed here.

CONCLUSION

A review of the three major federal programs involving the use, or potential use, of salt domes gives a measure of the great amount of data accumulation that has resulted from them. This information concerning salt dome occurrence, origin, character and utilization has resulted in an enhanced geological and technological understanding. Planning and development required in salt dome utilization will be enhanced as a result of these programs.

Scientific knowledge of salt domes has benefited significantly from these activities in such diverse areas as: structural geology, petrology, hydrology, rock mechanics, mining methods, failure modes of underground structures and potential environmental impacts of salt dome utilization. In these times of intense public interest and involvement focusing on large-scale technological developments that interface with the environment and involve any measure of risk, it is well to recount benefits as outlined above. There is often a lack of understanding by the general public of the efforts by scientists and engineers involved in these kinds of projects to anticipate and evaluate hazards and weaknesses. Several major incidents in salt dome utilization—the Belle Isle Mine explosion of 1979; the West Hackberry well explosion, fire and oil spill of 1978; and the Jefferson Island mine inundation of 1980—have been investigated and reported on by appropriate federal authorities (MSHA, 1979, 1981; DOE, 1978). Due note has been taken of the significance of these and other incidents and problems in evaluations conducted under the programs described in this paper. One can only hope that future public interest will be able to operate from a thoughtful rather than an emotional background as a result of consideration of these benefits and governmental actions.

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