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OIL SHALE DEVELOPMENT FROM THE PERSPECTIVE OF NETL'S UNCONVENTIONAL OIL RESOURCE REPOSITORY

Mark W. Smith[+], Lawrence J. Shadle[*], and Daniel L. Hill[+]

National Energy Technology Laboratory
U. S. Department of Energy
3610 Collins Ferry Rd.
Morgantown, West Virginia 26507-0880

[+]REM Engineering Services, PLLC
3537 Collins Ferry Rd.
Morgantown, West Virginia 26505

ABSTRACT- The history of oil shale development was examined by gathering relevant research literature for an Unconventional Oil Resource Repository. This repository contains over 17,000 entries from over 1,000 different sources. The development of oil shale has been hindered by a number of factors. These technical, political, and economic factors have brought about R&D boom-bust cycles. It is not surprising that these cycles are strongly correlated to market crude oil prices. However, it may be possible to influence some of the other factors through a sustained, yet measured, approach to R&D in both the public and private sectors.

1.0 INTRODUCTION

Shale development in the United States began in the late 1800's. The technology commonly applied was called retorting and the application was generally for domestic uses. However, as industrialization proceeded there have been economic cycles in which the required liquid fuels have been in short supply and entrepreneurs have turned to the vast proven oil shale reserves of the Green River Formation. The USGS estimates greater than 2 Trillion barrels of oil are available in the US in the form of oil shale with nearly 1.4 Trillion barrels being concentrated in the rich deposits of the Green River Basin (Dyni, 2003). The federal government has always played a critical role in oil shale research and development. This is understandable since more than 80% of the richest oil shale land in the U.S. is owned by the Federal government.

The first concerted government sponsored oil shale retorting project was in the development of the NTU process in Laramie, WY in the 1940's (Baughman, 1978). Since then there have been many different technologies considered and have been taken to various levels of development including both surface retorting and in situ recovery techniques. The development of a new technology proceeds through a common set of stages. These stages are represented in Figure 1 (Bartis, et al., 2005). The challenges to commercialization of any technology or industry include economics, politics and regulations, environmental issues, and technology readiness. Further, each of these challenges can compound the others. In recent decades these challenges have played a

[*] Corresponding author

significant role in slowing down oil shale technology development. One of the most significant challenges is simply the length of time required to navigate through the entire process from beginning to end. An industry-wide failure, such as the oil shale bust in the 1980's, when experienced in the midst of such a long term technology development process, results in long periods of inactivity with subsequent loss of knowledge.

Political issues also create additional economic challenges affecting technology development. Between 1971 and 1973 the Federal government decided upon and nominated oil shale leases. The tracts were dispersed over three states: Colorado, Wyoming, and Utah. The Federal government shares the lease royalties of 50% of that public land with the producing states (Johnson et al., 2004). In the 1970's, the three Western oil shale states needed additional support from other states to get funding passed. Some favorable factors have induced industries to begin shale oil processing such as the Arab Oil Embargo and the tripling of world oil prices by 1974. However, between 1973 and 1976 the estimated costs for an oil shale plant tripled. Costs for environmental protection increased. There were concerns about the high profits which oil companies had made during the Arab Oil Embargo, about federal subsidies for fossil fuel production, and the costs of extracting oil from oil shales. Pressures mounted to divest the major oil companies as a means of increasing competition in the energy industry (OTA, 1980). The lessees began having concerns about the uncertain economic feasibility of oil shale development. The leases did not allow for a suspension based on economic reasons. Therefore, many companies found reasons relating to resource recovery and conservation to justify suspending their leases in 1976. In 1982 Exxon suspended all oil shale operations at their Colony Project in response to continued and projected reductions in oil price.

Unfortunately, this is not the first time for oil shale development to experience a downturn. Certainly other challenges face the development of oil shale technologies; yet, none of these challenges are insurmountable when the need for shale oil is much more widely recognized. "Until recently the oil shales of the United States, particularly those of the Western States, have been referred to by the government geologists as a reserve available for extraction whenever the demand and the price shall become great enough to warrant the establishment of a new industry to supplement the supply of petroleum from the oil fields. *This time is now at hand.* The extraordinary demands of the war are already indicating the approaching insufficiency of the output from our petroleum fields, and experiments in the utilization of oil shale are already being made in Colorado. Plants are being erected, oil is being distilled, processes are being tested, and a steadily increasing output is soon to be expected" (Mitchell, 1918, p. 195, emphasis added). This statement was made in a National Geographic article in 1918. It is astounding that for roughly a century this sentiment has been echoed over and over in times of real, and artificial, energy crises. One question that could easily arise out of this observation is, "Why doesn't an oil shale industry exist in the United States in 2006?" The answers to this question are numerous and complex and widely disputed.

It is not the purpose of this paper to attempt to provide any additional commentary on this discussion; instead, it is to describe and demonstrate how the Unconventional Oil Resource Repository can be a useful tool in an approach to technology development that will be sustained in the presence of these challenges. The gathering of documents from previous research efforts is becoming more and more critical for preserving a technical knowledge base in the face of an aging group of experts in oil shale.

2.0 UNCONVENTIONAL OIL RESOURCE REPOSITORY

The Unconventional Oil Resources Repository (UORR) is an Access database with bibliographical information organized into records. The repository was created to provide a portable source of information related to unconventional oil resources, such as oil shale, oil sands, heavy oil, etc. Specifically, the repository began as a collection of government funded reports and publications, as well as other publicly available documents in electronic form. For items unrestricted by copyright the repository provides the full document in PDF format. The repository can be searched by title, abstract, and author. To further assist users, the repository can also be filtered based on a hierarchical structure created by the NETL staff.

The hierarchical structure has been developed to categorize the records entered into the database and is presented in Table 1. The categories include oil shale and tar sands, resource information, chemical and physical properties, mining and extraction methods, both above ground and underground process technologies, and products and applicable environmental clean-up technologies.

Currently the repository contains over 17,000 entries from more than 1,000 locations. Additionally over 800 full documents are available. Table 2 summarizes the sources from which the entries were obtained. In the future the repository will be updated with additional entries from current and new sources, as well as full documents. New sources will include university collections, additional government laboratory and agency libraries, as well as European and World patents.

The repository has been utilized by NETL staff for analysis of available experimental data and literature review efforts for process modeling. It has also assisted the United States Geological Survey staff in obtaining data on chemical and physical properties. The repository will soon be available for order from the NETL Strategic Oil and Natural Gas Reference Shelf on the NETL website. Figure 2 is a screenshot of the repository.

The repository has also been used to evaluate the development of oil shale technology. The investigation has revealed an up-and-down cycle between periods of vigorous, widespread research and development and times of very little interest in both the public and private sectors. This pattern is what we are referring to as the “boom-bust cycle” of oil shale R&D.

It should not be surprising that this cycle is most closely related to economic factors, specifically the price of crude oil. This effect is captured in Figure 3, where research activity is quantified by the number of publications and patents related to oil shale for the past 80+ years in the repository. The tentativeness of private companies to undertake major project efforts, even during peak periods of R&D when the risks were lowest, is due to the enormous capital investment and uncertainty in the value of the products.

A similar trend for research activity is presented in Figure 4, which is a plot of entries in the repository related to oil sands. It should be noted that the drop-off in research effort after the mid-80s is not as dramatic for oil sand as for oil shale. This is likely due to the commitment of the Canadian government to continue to fund research on their oil sands in spite of dropping crude prices.

3.0 HISTORICAL DEVELOPMENT OF OIL SHALE TECHNOLOGY

3.1 Above Ground Retorting

Over a dozen different above ground retorting technologies have been reviewed through the data and reports found in the repository (Tables 3-5). In general, above ground or surface shale retorting processes can be classified into four categories (OTA, 1980) differentiated by the manner in which heat is supplied to the shale. The four methods for supplying heat are conduction through the retort wall, direct heating, indirect heating, and hot solids mixing. The first of these categories, heat conduction through the retort wall is essentially the Fischer Assay.

Some of the more significant examples of the direct retort technology found in the repository are listed in Table 3. The numbers provided in the brackets represent the number of entries found in the repository from a key word search on each technology in the table. Examples include the NTU (Ruark, 1956; Harak, 1970), Union B (Atwood, 1977; Harney, 1983), USBM (Baughman, 1978), and Paraho (Atwood, 1977; Lukens, 1989). In a direct heat retort air is directly added to hot shale, and the hot products of combustion contact and heat the fresh shale being fed to the retort. This retort results in very high thermal efficiencies because the carbon is effectively consumed within the combustion zone. However, the products of combustion dilute the fuel oil and gas products producing a low BTU product stream. Oil recoveries of 80 to 90% of Fischer Assay are achievable. Additionally, direct heat processes produce a spent shale low in residual carbon attributed to the direct combustion of the residual carbon in the retorted shale.

In an indirectly heated retort pre-heated, oil shale-derived, fuel gases are recycled through the unprocessed shale. Examples of these retorts are listed Table 4 (along with the number of references found in the UORR upon a simple keyword search) and include Petrosix (Bruni, 1971; Uthus, 1985), Union B (Atwood, 1977; Jackson, 1983), Kivitier (Uthus, 1985; Yefimov, 1989), IGT (Lau, 1986; Mensinger, 1991), Paraho (Pforzheimer, 1974; Atwood, 1977), and Superior (Harney, 1983). Indirect retorts exhibit a heating method in which gases are heated outside the retort vessel and subsequently used in the retorting process. The product stream is not diluted and is therefore a high BTU product, but the thermal efficiencies may be low due to the residual carbon left on the spent shale. Oil recovery efficiencies are about 100% Fischer Assay. The specific use(s) of the preheated gases are unique to each design.

The solids heat transfer retort is also an indirect heating method in which pre-heated solids are mixed with fresh shale. Significant examples of the solids heat transfer retort technology are listed in Table 5 along with the number of references found in the repository upon a simple keyword search. Solids Heat retorts include Tosco II (Whitcombe and Vawter, 1975; Atwood, 1977), Lurgi-Ruhrgas (Schmalfeld, 1975; Marnell, 1976), Galoter (RSC, 1975; Tiagunov et al., 1976), Chevron (Tamm, 1981), Taciuk (Taciuk and Turner, 1988). In this type of retort the heat required to heat the solids is generated outside of the retorting vessel. These processes can exceed Fischer Assay oil recoveries because the heating rates are high. The thermal efficiencies vary widely from process to process as does the product quality. The result of this method is that since there is no combustion inside the retort a high BTU gas product is produced similar to indirectly gas heated retorts. Depending on the specific process or operational mode, the spent shale may or may not contain carbon. The principal factor is whether or not the spent shale is used as the heat carrier.

3.2 In-Situ Retorting

Two types of *in-situ* oil shale processing were tested in the time period of the 1950's through the 1980's. Both were characterized by having a step where at least some of the oil shale is heated underground. When this heating occurs underground, the kerogen is thermally decomposed, usually with heat produced from its partial combustion with air. The product oil must then flow to the production well(s).

True *in-situ* (TIS) involves no above ground recovery. Liquid oil and gaseous products are removed by wells from underground. The kerogen is upgraded at the surface to produce fuels and chemicals. Modified *in-situ* (MIS) involves many of the techniques described in TIS methods which are applied after some mining has occurred. Traditionally, the mining will involve recovery of oil shale and processing via above ground retorting. The motivation for selectively mining portions of the oil shale formation is to create an optimum void space to increase permeability, produce more uniform shale fragments, and provide a reservoir for the *in-situ* produced oil to gather. This is of great interest since most of the oil that gathers in the mined portion can be recovered, thus improving the overall recovery.

Once the formation is fractured, fluids such as hot inert gas, combustion products or superheated steam are injected into the formation to increase its temperature. Conceptually the heating and retorting front spreads horizontally from a TIS injection. This preheating is necessary for the next step in the TIS process, which involves partial combustion of the organic content of the oil shale. Once the formation reaches the temperature for pyrolysis, an oxidizer (such as air) is injected into the well for ignition. Upon successful ignition of the oil shale, the injection well is sealed to build up pressure in the rock formation.

A summary of the major research efforts in the repository related to TIS technologies is summarized in Table 6 including development by Sinclair Oil, Talley Energy Systems, Geokinetics (Henderson, 1984;), Equity Oil (Cha, 1982), and LERC (Carpenter, 1976). The most significant issues discovered during the first few decades of research related to heating efficiency, ignition success, and adequacy of rubblization. The heating process is very slow due the low thermal conductivity of the shale; the thickness of the overburden also affects the amount of heat lost. Because of the difficulty in raising the temperature of the rock, depth of the shale layers, and the presence of moisture, successful ignition is often challenging. Finally, increasing the permeability through fracturing and rubblizing is difficult to accomplish, and even more difficult to predict. Permeability issues include the resealing of fractures from the structural deformation and expansion of rich oil shale as it is retorted, and the collapsing of retorted particles under pressure due to loss of strength.

The Modified *in-situ* (MIS) process for oil shale recovery consists of constructing an underground, fixed-bed retort by a combination of mining and blasting. The mined portion is then retorted above ground. The earliest modified *in-situ* testing was conducted on Eastern oil shales. A summary of the major research efforts in the repository related to MIS technologies is summarized in Table 7 and include projects by

Dow (McNamara, 1980), Occidental (Ricketts, 1982; Stevens, 1983) and LLNL. The main advantages of MIS are that larger deposits can be retorted, oil recoveries per acre affected are high, and relatively few surface facilities are required. However, there are some drawbacks with MIS technology, including disposal of solid wastes on the surface and possible ground water pollution by burned-out materials. Both MIS and AGR require mining, while mining is not needed for TIS, therefore surface disturbance and waste disposal is minimal with TIS. MIS process has more recovery than AGR as indicated by Rio Blanco. On the other hand, the crude shale oil from MIS versus from AGR has better physical properties. Also, MIS requires more water for cooling, for raw shale disposal and for revegetation.

3.3 Current Activity Found in the UORR

In 2005 six companies submitted eight proposals for RD&D land leases to the Bureau of Land Management (BLM) in Colorado, Utah, and Wyoming (BLM, 2006). These companies were Chevron Shale Oil Company, EGL Resources, Inc., Exxon Mobil Corporation, Oil-Tech, Inc., Oil Shale Exploration, LLC, and Shell Frontier Oil and Gas. Six of the proposals were for *in-situ* processes; the remaining proposals were for above ground technologies. Three companies were awarded a total of five land leases in Colorado for *in-situ* RD&D projects and one was awarded in Utah for an above ground process. The five *in-situ* leases in Colorado were given to EGL Resources, Inc., Chevron, and Shell Frontier, which received leases for all three of its applications. The environmental assessments for each company are available on the BLM web site, and also in the UORR. The EGL project will be a "proof of concept" effort that will look at fracturing the oil shale formation and apply uniform heating via conduit pipes through and beneath the formation through which pressurized heating fluids would be pumped. The in-situ process proposed by Chevron is also a "proof of concept" aimed at studying conventional drilling methods and modified, horizontal fracturing technologies.

The most developed oil shale process contained in the repository is Shell's *in-situ* conversion process (ICP) (Vinegar, 2006). Three land leases were granted for RD&D of this technology. In this approach there is no attempt to speed up the heating process by fracturing the shale, injecting hot gases, or initiating a combustion front. Instead the shale resource is slowly heated over a long period of time through conductive heating methods. Much more detail of this process can be found in the more than 250 patents owned by Shell contained in the repository (Wellington, 2006).

One above ground RD&D lease application was approved for Oil Shale Exploration Company, LLC ("OSEC"). The process will utilize oil shale from the White River Mine, Uintah County, Utah. The above ground technology that will be utilized is the Alberta Taciuk Process (ATP).

One final technology to be identified here is the Chattanooga Process. Although it is not a part of the recent land lease RD&D activities, this above ground technology has been included in the repository in a number of patents. This technology is a modified version of an oil sands, hydroretort technology that was tested first on eastern oil shales, but has also run on Colorado shale.

Certainly, there is a great deal more research activity in the United States, and around the world, than has been mentioned here. This discussion has focused on publicly available information already contained in the repository. As more documents become available, they will be included in this valuable resource.

4.0 SUMMARY

The challenges facing an emerging oil shale industry in the United States are many, and complicated. Indeed, there is no clear formula or pathway to success in the current, global economic and political climate for a new commercial scale technology. Previous strategies and roadmaps offer valuable insight into today's challenges; however, a major key to successfully developing oil shale technologies is a sustained and measured approach to RD&D.

One tool to developing this type of approach is the NETL's Unconventional Oil Resource Repository. Continued development of this resource and study of the data it contains of previous and future oil shale research efforts can help reduce the impact of uncertain energy costs and supplies. The repository will help establish an information base and can facilitate dialogue among all willing research entities.

With over 17,000 entries currently present in the repository it is already a valuable resource for anyone interested in oil shale research. As new reports and publications become available, the number of entries will increase, including full text documents for many of the current entries. Additionally, collaboration with other existing and new repositories around the world will provide a powerful tool for technology developers in the public and private sectors. Finally, the repository will ultimately be transferred to an updatable web site housed among NETL's web resources for complete access to the public.

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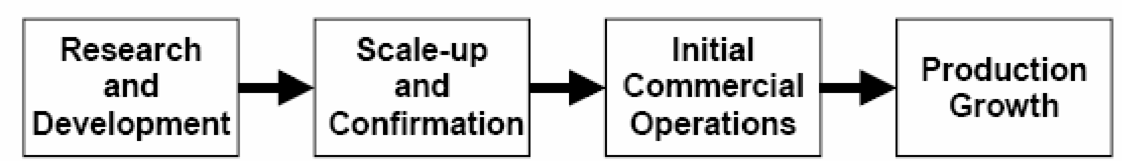
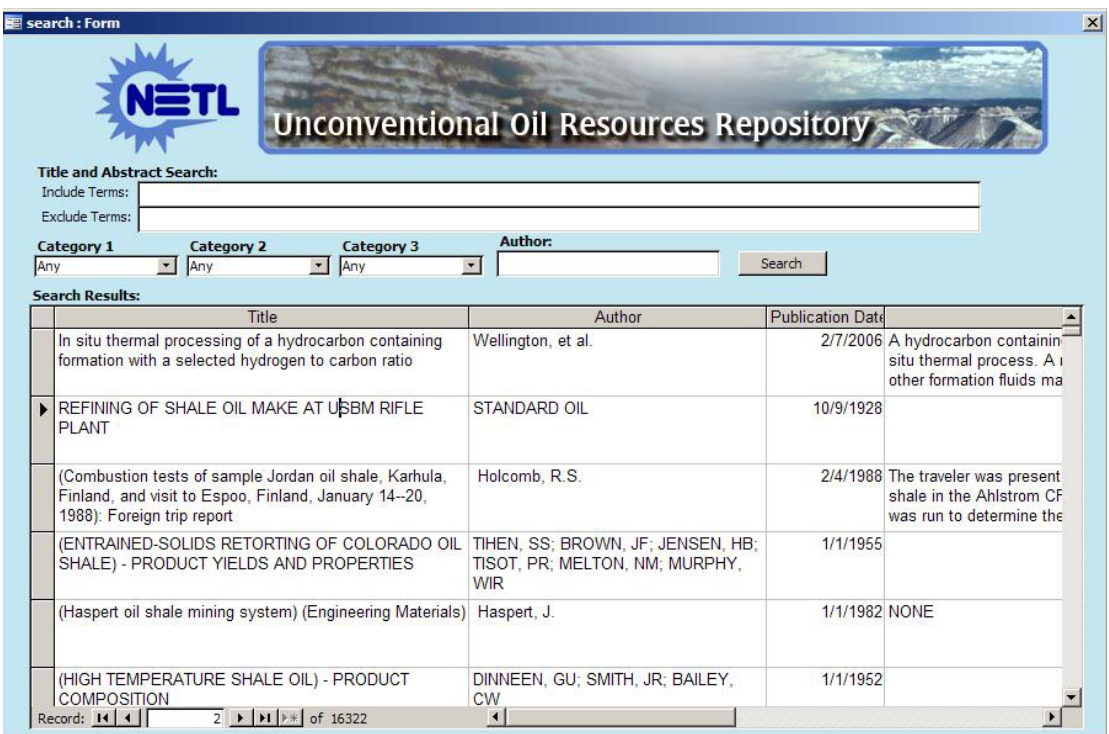


Development Stage	Research and Development	Scale-up and Confirmation	Initial Commercial Operations	Production Growth	Strategic Production
Facility Size	Laboratory to Pilot Plant	1000-5000 bpd	>50,000 bpd	>100,000 bpd	>100,000 bpd
Years to Transition*	--	0	6-8	14-20	25-30
Total Production (million bpd)		N/A	N/A	>0.1	>1

*Beginning with the transition from *Research and Development*

Figure 1. Stages of Technology Development and Commercialization (Bartis et al., 2005).



Title	Author	Publication Date	
In situ thermal processing of a hydrocarbon containing formation with a selected hydrogen to carbon ratio	Wellington, et al.	2/7/2006	A hydrocarbon containin situ thermal process. A other formation fluids ma
REFINING OF SHALE OIL MAKE AT USBM RIFLE PLANT	STANDARD OIL	10/9/1928	
(Combustion tests of sample Jordan oil shale, Karhula, Finland, and visit to Espoo, Finland, January 14--20, 1988): Foreign trip report	Holcomb, R.S.	2/4/1988	The traveler was present shale in the Ahlstrom CF was run to determine the
(ENTRAINED-SOLIDS RETORTING OF COLORADO OIL SHALE) - PRODUCT YIELDS AND PROPERTIES	TIHEN, SS; BROWN, JF; JENSEN, HB; TISOT, PR; MELTON, NM; MURPHY, WIR	1/1/1955	
(Haspert oil shale mining system) (Engineering Materials)	Haspert, J.	1/1/1982	NONE
(HIGH TEMPERATURE SHALE OIL) - PRODUCT COMPOSITION	DINNEEN, GU; SMITH, JR; BAILEY, CW	1/1/1952	

Figure 2. Screenshot of the Unconventional Oil Resource Repository.

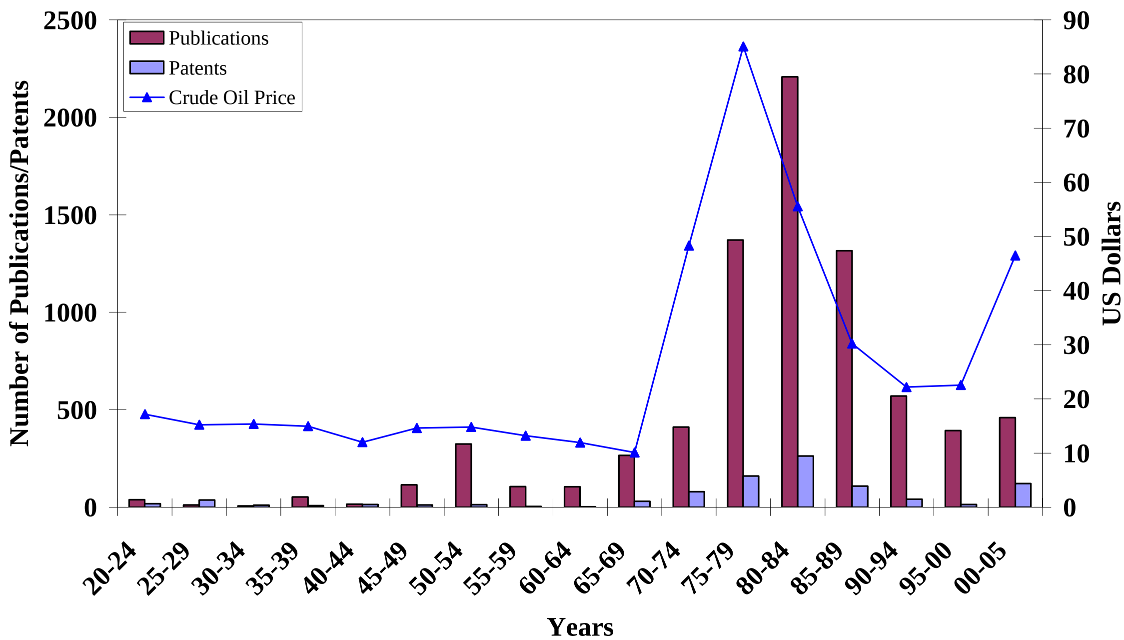


Figure 3. Effect of Crude Oil Prices (2006 dollars) On Oil Shale R&D (Maidment, 2006).

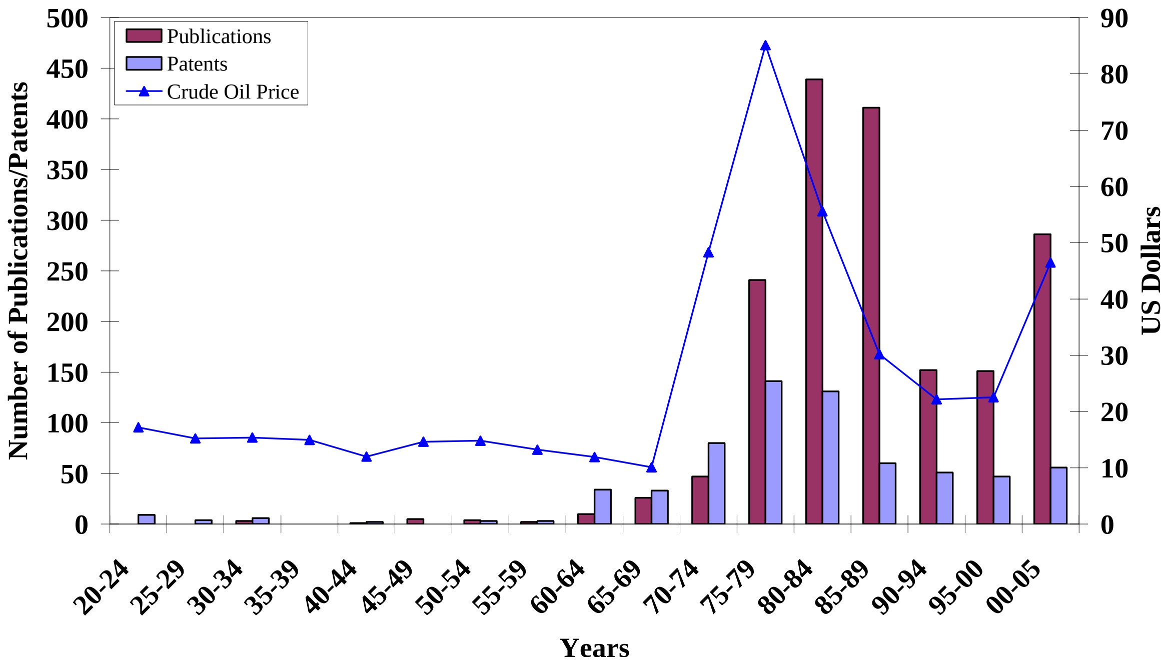


Figure 4. Effect of Crude Oil Prices (2006 dollars) On Oil Sand R&D (Maidment, 2006).

TABLES

Table 1. Unconventional Oil Resources Repository Categories and Keywords.

A. GENERAL AND CROSS-CUTTING INFORMATION

B. OIL SHALE

1. General and Cross-Cutting Information
2. Deposits, Resources, and Environmental Factors
   a. Western U.S.
   b. Eastern U.S.
   c. Other
3. Mining Methods & Associated Environmental Impacts
4. Chemical, Physical & Thermal Properties
5. Retorting Processes
   a. Aboveground
   b. In Situ
   c. Other
6. Products, By-Products, Environmental Emissions, and Waste Streams
7. Commercial Ventures

C. OIL SANDS

1. General and Cross-Cutting Information
2. Deposits, Resources, and Environmental Factors
   a. United States
   b. Canada
   c. Other
3. Mining Methods & Associated Environmental Impacts
4. Chemical, Physical & Thermal Properties
5. Recovery Processes
   a. Aboveground thermal
   b. Non-thermal recovery
   c. other
6. Products, By-Products, Environmental Emissions, and Waste Streams
7. Commercial Ventures

Table 2. Summary of UORR Entry Sources.

Source	Entries
Journal Articles (Web of Science)	7800
Government Funded Reports (ECD & Information Bridge)	3200
NETL Microfiche (LETC)	2800
Patents (US, CAN, & EUR)	2500
Eastern & Western Oil Shale Symposia	1000

Table 3. Summary of AG – Direct Retort Research in UORR.

Entity/ Process	Dates	Location	Description of Effort
NTU [168]	1920s, 1947-51, 1969	Anvil Points, CO; Laramie, WY	Batch, internal combustion retort; CO-Two 40-ton NTU retorts; 20,000 barrels shale oil produced; WY-150-ton retort
Union "A" [39]	1940s -1950s	Near Grand Valley, CO	Vertical kiln retort; "rock-pump" feed; 2, 50, and 350-ton retorts; 75% Fischer Assay; 800bpd for 6 weeks in 1200-ton retort
USBM [85]	1950-1956	Anvil Points, CO	Gas Combustion retorting process – 6, 25, and 150-ton retorts; low pressure and temperature – low capital investment; low oil recovery 85-90% Fischer Assay
Paraho [131]	1972-1982	Anvil Points, CO	Similar to Gas Combustion retort process – 30 and 300-ton retorts; low pressure and temperature; 80% Fischer Assay; 109,000 barrels shale oil

Table 4. Summary of AG – Indirect Retort Research in UORR.

Entity/ Process	Dates	Location	Description of Effort
Petrosix [12]	1950s-1970s	Brazil	Similar to Paraho except mechanical feed and spent shale handling; pilot plant constructed by Foster Wheeler Corp.(1950); demonstration near Curitaba, Brazil let to 43,000bpd design (1972)
Soviet Kiviter [6]	1920s -1941 1960s-1970s	USSR	Vertical kiln, cross- and counter-current gas heat transfer; two 1000 ton/day plants that co-featured the Kiviter process and the Galoter (fines); 75-80% Fischer Assay
Phillips & IGT [10]	1960s-1970s	Kentucky	Hydrogen Retorting – IGT operation of a Process Development Unit (PDU) to produce high BTU gas or middle distillates oil (1976); no large scale demonstrations reported
Paraho [131]	1975-1976	Anvil Points, CO	Demos at same facility used for Direct Retorting mode; 10,000 ton/day plant designed for US DOE
Superior [15]	1977	Cleveland, OH	Traveling grate system (doughnut shaped) – 250-ton pilot plant; designs based on Piceance Basin deposits
Union "B" [39]	Late 1970s	Near Grand Valley, CO	Similar to NTU but continuous with shale and gas flow countercurrently; Union A retort run in an indirect mode; 100% Fischer Assay; 69% thermal efficiency; 13,000 ton/day constructed only reached 50% of capacity

Table 5. Summary of AG – Solids Heat Transfer Retort Research in UORR.

Entity/ Process	Dates	Location	Description of Effort
TOSCO II [32]	1950s-1970s	Denver & Grand Valley, CO	Ceramic balls (¾ in) – 25-ton pilot plant, 1000-ton semi-works plant; >100% Fischer Assay; low thermal efficiencies, high crushing costs; 180,000 barrels of shale oil produced
Lurgi-Ruhrgas [25]	1950s-1960s	Europe & Asia	Ceramic balls replaced with fine-grained retort residual; feed stock included oil shale, oil sand, coal, and liquid hydrocarbons; 4000-ton plants built; 110% Fischer Assay; high crushing costs and shale dust problems encountered
Galoter [6]	1950s-1970s	USSR	Hot spent shale used as heat carrier – 1000-ton demonstration plant; 85-90% Fischer Assay; 1-1.3KBtu/scf product gases, lower electricity and steam than Kiviter; fine dust problems
Chevron [7]	1970s-1980s	Richmond, CA	Staged Turbulent Bed process – 10-ton pilot plant; high shale through-put, high thermal efficiency, wide range of shales; high crushing costs, pollution/control
Alberta Taciuk [8]	1970s-1980s	Calgary, Alberta, Canada	Rotary kiln process – two concentric horizontal vessels; hot spent shale utilized for preheating and mixed with raw shale feed; 120-ton pilot plant

Table 6. Summary of True *In-situ* Retort Research in UORR.

Entity/ Process	Dates	Location	Description of Effort
Sinclair Oil	1953 - 1966	Mahogany Zone, Piceance Basin	Field experiments; small amount of shale oil recovered; difficult but successful ignition; small fractures reseal as formation swells with retort.
USBM [97]	1960 - 1974	Rock Springs, Wyoming	Laboratory experiments, computer simulations, pilot plant and field fracture tests; low yields and recoveries, incomplete retort or large blocks of shale; inadequate and irregular fracturing allows heat carrier fluids to bypass large blocks of unretorted shale
Equity Oil Company [38]	1961 - 1977	Piceance Creek basin, Colorado	Field tests: heated methane/ nat.gas injected 547days; steam injected 4 months; small quantity of oil recovered w/ hot gas injection; no recovery w/ steam injection because of insufficient injection capacity; natural gas trapped in fractures and pores; improvement of steam injection capacity and operating cost needed
LERC [24]	1966 - 1977	Rock Springs, Wyoming	Fracture tests at 12 sites; burn tests at 5 sites: Site No. 2-One gallon recovered, Site No. 4-30,000gal produced, 8000 recovered, Site No. 6-no recovery, Site No. 7-Ignition test only – successful, Site No. 9-1080bbl retorted, 60bbl recovered; large energy losses in ignition – small amount of shale reached retort temperature; mechanical problems in production wells
Geokinetics (Sandia) [87]	1973 - 1982	Uintah County, Utah	Phase III & IV: commercial scale of 2000bpd; computer models developed; over 20 retorts burned in Utah; largest retort in 1979 130' x 180' x 30' thick; difficult to model extent of fracturing and retort with available field experiment data; challenges in scale-up of pilot studies
Talley Energy Systems	1977	Green River, Wyoming	Phase I: Multiple explosion fracturing; computer model; Phase II: Pilot demo; fracture tests under contract w/ LERC; multiple detonation fracturing methods unsuccessful; project terminated after initial testing

Table 7. Summary of Modified *In-situ* Retort Research in UORR.

Entity/ Process	**Dates**	**Location**	**Description of Effort**
DOW Chemical [129]	1950's-1970's	Midland, MI	Hydraulic fracturing, sand propping, chemical explosives; acid leaching, chemical explosives; Explosive under-reaming, well bore cleaning
Occidental [96]	1970's-1980's	Debeque, CO	20-25% of shale mined; ANFO used for detonation; air injected after ignition; 8 retorts varying from 32ft on a side by 70ft to 120ft on a side by 270ft in Piceance Creek basin
LLNL [80]	1970's-1980's	Livermore, CA	Rubble *In-situ* Extraction (RISE) – computer simulation and pilot scale retorts; AGR – hot recycled-solid retorting (HRS)