60°) is bisected by the greatest principal stress. This affords the guiding principle relating the orientation of common faults—normal, reverse, and transcurrent—to the associated stress fields.

Hydraulically induced fractures, whether by fluid pressure in wells or by the intrusion of igneous dikes, tend to follow surfaces parallel with the greatest and intermediate principal compressive stresses and perpendicular to the least stress. Therefore, the orientations of hydraulic fractures, or of igneous dikes and sills, are strongly influenced by the prevailing stress state in the ambient rocks. In particular, in tectonically relaxed regions characterized by normal faulting, the greatest principal stress is nearly vertical, and the intermediate and least principal stresses nearly horizontal, with the intermediate stress in the strike direction of the local normal faults. In such a region, the preferred orientation of hydraulic fractures is vertical and perpendicular to the least principal stress, and parallel with the strike of the local normal faults.

Hydraulic-fracture orientation may also be influenced by anisotropy or planar inhomogeneities in the rock such as bedding, schistose cleavage, or a system of parallel joints. If such a planar system does not depart too far from perpendicularity to the axis of least stress, hydraulic fractures may follow such a zone of weakness, across which the shear stress will not be zero. In this case, provided the rocks are also stressed tectonically, slippage along the fracture with possible resultant earthquakes is an expectable consequence of increasing the fluid pore pressure in the rock.

LEBLANC, RUFUS J., SR., Shell Oil Co., Houston, Tex.

Geometry of Sandstone Reservoir Bodies

Natural underground reservoirs capable of containing water, petroleum, and gases consist of sandstone, limestone, dolomite, and fractured rocks of various types. The character and distribution of sandstone and carbonate reservoirs are well known as a result of extensive research and exploration by the petroleum industry. Trends of certain sandstones are predictable because they are more regular and have been less affected than carbonates by postdepositional cementation and compaction.

The principal sandstone-generating environments are (1) fluvial environments such as alluvial fans, braided streams, and meandering streams, (2) distributary channel and delta-front environments of various types of deltas, (3) coastal barrier islands, tidal channels, and chenier plains, (4) desert and coastal eolian plains, and (5) deeper marine environments where the sands are distributed by both normal and density currents.

The alluvial-fan environment is characterized by flash floods and mud or debris flows which deposit the coarsest and most irregular sand bodies. Braided streams have numerous shallow channels separated by broad sand bars. Lateral channel migration results in the deposition of thin, lenticular sand bodies. Meandering streams migrate within belts 20 times their channel widths and deposit two very common types of sands. Bank caving and point-bar accretion processes result in lateral channel migration and the formation of sand bodies (point bars) within each meander loop. Natural cutoffs and channel diversions result in the abandonment of individual meanders and long channel segments respectively. Rapidly abandoned channels are filled with some sand but predominantly with fine-grained sediments (clay plugs), whereas gradually abandoned channels are filled mainly with sands and silts.

The most common sandstone reservoirs are of deltaic origin. They are laterally equivalent to fluvial sands and prodelta and marine clays and consist of two types: delta front or fringe sands and abandoned distributary channel sands. Fringe sands are sheetlike and their landward margins are abrupt (against organic clays of the deltaic plain). Seaward these sands grade into the finer prodelta and marine sediments. Distributary channel sandstones are narrow, with abrupt basal contacts and decrease in grain size upward. They cut into or completely through the fringe sands, and are also connected with the upstream fluvial sands of braided or meandering streams.

Some of the most porous and permeable sandstone reservoirs were deposited in the coastal interdeltaic realm of sedimentation. They consist of well-sorted beach and shoreface sands associated with barrier islands and tidal channels which occur between barriers. Barrier sand bodies are long and narrow, aligned parallel with the coastline, and characterized by a fine to coarse upward sedimentary sequence. They are flanked on the landward side by lagoonal clays and on the opposite side by marine clays. Tidal channel sand bodies have abrupt basal contacts, range in grain size from coarse to fine upward. Laterally they merge with barrier sands and grade into the finer sediments of tidal deltas and mudflats.

The most porous and permeable sandstone reservoirs are products of wind activity in coastal and desert regions. Wind-laid sands are typically very well sorted, highly crossbedded, and occur as extensive sheets.

Marine sandstones are those associated with normal marine processes of the continental shelf, slope, and deep, and those which are of density or turbidite current origin. An important type of normal marine sandstone is formed during marine transgressions. Although these sandstones are very thin, they are very distinctive and widespread, have sharp updip limits and grade seaward into marine shales. Two other types of shallow-marine sands (delta fringe and barrier shoreface) have previously been mentioned.

Many turbidites are associated with submarine canyons. These sands are transported from nearshore environments seaward through canyons and deposited on submarine fans in deep marine basins. Another type of turbidite forms as a result of slumping of deltaic facies occurring at shelf edges. Turbidite sandstones are usually associated with thick marine shales.

MACKENTHUN, KENNETH M., Environmental Protection Agency, Washington, D.C.

Magnitude of Wastewater Treatment and Disposal Program Facing the Nation

More than 300,000 water-using industrial plants in the United States discharge 3-4 times as much oxygen-demanding wastes as all of the sewered population of the United States. Many wastes discharged by industries are toxic to aquatic life and sometimes indirectly to man. An infamous example of the latter is mercury. The volume of industrial wastewater discharge before treatment in 1964 exceeded 13 billion gal. Indications are that over half of this wastewater volume comes from 4 major industrial groups including paper, organic chemicals, petroleum refining, and steel.

Industrial pollution problems are created by oxygen-demanding wastewater constituents, organic and inorganic settleable solids, suspended solids, flotable materials, toxic metals or substances, nuisance-stimulating nutrients, and waste heat. Treatment and control processes are now available for most industrial wastes. Some pollutants including complex chemicals, however, present difficult abatement problems.

The magnitude of the national industrial waste problem has remained relatively unknown. There has not been until the past few weeks a detailed inventory of industrial wastes. The Environmental Protection Agency within the past year embarked upon a three-pronged program to inventory, study, and regulate this vast waste complex.

Following a test mailing to refine the questionnaire and the instructions, a voluntary national industrial wastes inventory was begun in early August 1971. A comprehensive questionnaire has been mailed to 10,000 of the major water-using industries in the United States. The inventory questionnaire was designed to collect information on quantity and quality of wastewater constituents and discharge methods. Data from the inventory will be computerized to facilitate their use. These data will be extremely valuable in all governmental activities connected with the control of industrial wastes.

The Environmental Protection Agency is in partnership with the Corps of Engineers in the administration of the River and Harbor Act of 1899. Under the provision of this Act, each industrial waste discharge to the nation's waters will be regulated by a permit issued by the Corps of Engineers. The EPA will review, evaluate compliance with water quality standards, and recommend actions on the permit requests.

Comprehensive studies on 20 major industrial categories have recently been completed. These studies defined a feasible effluent level based upon production units for an industrial category. They present the best and most comprehensive compilation of data now available on wastewater management from these industrial categories.

MALINA, JOSEPH F., JR., Dept. of Civil Engineering, Univ. of Texas, Austin, Tex., and JOE C. MOSELEY II, Univ. of Texas, Executive Dept., Austin, Tex.

Disposal-Well Dimensions, Injection Rates, and Cost Responses

Deep-well injection as a means of liquid waste disposal is, at best, a costly and tricky operation. Nevertheless, despite the inevitable difficulties which occur, it has proven itself to be reliable, environmentally sound, and economically feasible for disposing of *certain* wastes in *certain* areas.

A mathematical simulation model has been developed for predicting the operational response of a disposal-well system. From the initial design parameters and the physical operating characteristics it is possible to estimate the cost of such an operation. Additionally, sensitivity analysis experiments can be performed to assess which design parameters, operational characteristics, or formation properties have the most significant impact on the overall system response.

Application of the model to date indicates that for favorable geologic conditions the cost of injection may range upward from \$0.25–\$0.40 per 1,000 gal; this figure includes O&M plus capital amortization, with the initial outlay ranging upward from about \$150,000. Even a ball-park cost estimate for a given injection system cannot be done until the key parameters (waste volume, well diameter, porosity, permeability, reservoir pressure, *etc.*) are known for that specific site.

Sufficient data are available from secondary sources to synthesize the basic characteristics of a "typical" injection well. (For this study, approximately 75 industrial disposal wells were considered.) Typical features include: (a) 90% of all wells in the U.S. are less than 6,000 ft deep with half between 2,600 and 4,200 ft, (b) only 10% operate with casinghead pressures greater than 1,050 psi, but 50% operate between 175 and 550 psi. These and other statistical characteristics were combined to create a set of fictitious—but representative—wells. It was upon this set of "standard" or "typical" wells that the following sensitivity experiments were performed. For our "typical well" designed to operate at 1,000 psi, an increase in wellhead pressure of 50% can be expected to raise the total unit cost from \$0.24 to \$0.32 per 1,000 gal. For a given flow rate, friction losses decrease rapidly as well diameter increases. For our well, an increase in diameter from 4 to 5 in., reduces the ratio of the pressure drop to driving pressure by 57%, thus substantially reducing energy requirements as a trade-off for a more expensive well. Responses to flow rate can be evaluated. For one of our "standard" wells, an increase in the flow rate from 400 to 600 gal/day increases the initial cost of \$224,000 by 53.5%, but lowered the unit cost by 21.2% from \$38.2 to \$30.1 per 1,000 gal. Formation impact can likewise be assessed. For our example, an unexpected drop in permeability from 60 to 40 md would increase the unit cost by 12.3%.

The above only begins to expose the type of information that simulation modeling can reveal. The modeling procedures and certain relations describing the basic processes are well understood. The weak link is data. The geologic—and other—uncertainties with which one must cope provide the real test. Only as more and better data become available will this approach reveal its true utility; hopefully it can be extended to include such things as probabilistic aspects of component failure, statistical reservoir analysis, *etc.*

McWILLIAMS, JACK, Amoco Production Co., Houston, Tex.

Large Saltwater Disposal Systems at East Texas and Hastings Oil Fields, Texas

The disposal of salt water produced with oil from the East Texas field has been successful in minimizing pollution of land areas and freshwater sources, and has been effective in maintaining bottomhole pressure. To date, 4.5 billion bbl of salt water have been returned to the producing reservoirs at a cost to the operators of approximately 2.5¢/bbl.

At Hastings field in Brazoria and Galveston Counties, Texas, Amoco is successfully disposing of 50,000–60,000 b/d of salt water by injection into saltwater-bearing formations below freshwater sandstones and above the oil-producing zones. The project is a "closed system," whereby the salt water produced is allowed no contact with air, thereby reducing corrosion attack on disposal facilities. To date, Amoco has injected approximately 500 million bbl of salt water.

OSTROOT, G. WARREN, and JOE RAMOS, Halliburton Services, Duncan, Okla.

Deep-Well Acid Disposal—Planning and Completion

Because of the magnitude of damage wrought to our natural resources, pollution control and environmental