Energy and Environment Subcommittee of the Energy and Commerce Committee 06/09/10 Briefing

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1 Preamble

Horrible things happen, see **Figure 1**, when complex technologies and procedures overtake humans, who service the technologies falsely assuming complete control. In this briefing I attempt to explain the blowout of the BP exploratory well Mississippi Canyon Block 252-01 in terms of complexity, technology, and science. I argue that organizational structures and human behavior have not kept pace with the complex technologies we – the engineers and scientists – have created. Given the structural changes in the industry, academia, and government, this tragedy has been at least twenty years in the making.

Given our current work on the BP well blowout, there is nothing in the science and engineering of this tragedy that baffles us. It seems that the human inability to grasp and execute the complex steps of a deepwater drilling procedure led to the tragic outcome. A separate discussion is warranted of an almost universal lack of preparedness by the industry and government to deal with the aftermath of this blowout. This general failure of organizational structures should also be understood in the context of complexity.

2 Background

Among the 50 largest oil companies in the world, the North American companies control a mere 3.5 percent of the producible oil equivalent reserves, see **Figure 2**.

The U.S. Gulf of Mexico (GOM) activities were compiled by Eileen O'Grady and edited by by Walter Bagley of Reuters, *FACTBOX–Gulf of Mexico oil and gas activity*, 04 Jun 2010 20:30:53 GMT, www.alertnet.org/thenews/newsdesk/N04128424.htm.

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2.1 U.S. Gulf of Mexico Oil and Gas Production

- Drilling and leasing activity:
  - A total of 331 wells were drilled in federal waters in the Gulf of Mexico (GOM) in 2009; more than 50,000 wells have been drilled in federal water in the gulf since 1947. Federal water can vary by state, but is generally at least three miles (4.8 km) offshore.
  - GOM has 7,000 active leases, 64 percent of which are in deepwater, defined as greater than 1,000 feet (330 meters).
  - Currently, 33 wells are being drilled in GOM.
  - In March 2010, there were 3493 GOM platforms in water depth less than 200 ft, 21 between 200 and 400 ft, 9 between 400 and 800 ft, 7 between 800 and 1000 ft, and 25 in water depths above 1000 ft (www.offshoresresource.com).
  - The 2009, GOM production in state and federal water was 1.6 million barrels per day[2] and accounted for 31 percent of total domestic oil production. GOM natural gas production equaled 11 percent of 2009 domestic gas production.
- Deepwater statistics:

[2] In April 2010, the GOM oil production exceeded 1.7 million barrels per day.

Figure 1: This cannot happen again. Ever! Source: conservationreport.files.wordpress.com/-2008/05/oil-spill-birds1.jpg.

- Nearly 4,000 wells have been drilled in GOM water depth in excess of 1,000 feet and 700 wells in all federal water 5,000 feet or greater;
- 80 percent of offshore oil production and 45 percent of natural gas production came from deepwater in 2009;
- Deepwater offshore oil production surpassed shallow water production in 2001.

- Economic impact:
  - In 2009, federal offshore leasing revenue was $6 billion.
  - All U.S. offshore operations provide direct employment estimated at 150,000 jobs.
  - Since 1953, the federal government has collected $200 billion from lease bonuses, fees and royalty payments from all offshore operators.
- Offshore spills and blowouts:
  - Over the past 45 years, 17.5 billion barrels of crude oil and condensate have been produced in federal offshore waters, while 532,000 barrels have been spilled; meaning 30.3 barrels have spilled per 1 million barrels produced;
  - The number of spills jumped during the 2000-2009 decade to 72 from 15 in the 1990s and the amount of oil spilled jumped to 18,000 barrels from 2,000 barrels in the 1990s.
  - Seven offshore blowouts occurred in federal waters from 1964 to 1970 that resulted in spills exceeding 1,000 barrels. Since 1971, blowout events have resulted in only 1,800 barrels of spilled oil.

2.2 Global Offshore Oil and Gas Production

Worldwide, deepwater offshore oil production now exceeds 5 million barrels per day, according to IHS CERA. In April 2010, world production of all liquid fuels was 86.62 million b/d, according to the International Energy Agency (IEA). Thus, deepwater offshore oil production currently constitutes 6 percent of global production. Offshore oil is expected to make up some 40 percent of world production at the end of this decade so the regulations and delays that stem from the Deepwater Horizon accident could eventually have a significant impact on world production.

The three largest offshore spills in the world were:

1. 26 January 1991; terminals, tankers; 8 sources total; Sea Island installations; Kuwait; off coast in Persian Gulf and in Saudi Arabia (240.0 millions of gallons);
2. 03 June 1979; exploratory well Ixtoc I well; Mexico; Gulf of Mexico, Bahia Del Campeche, 80 km NW of Ciudad del Carmen, Campeche (140.0 millions of gallons);
3. 19 July 1979; two supertankers collided off the Caribbean island of Little Tobago during a tropical rainstorm (84 million gallons).

It should be noted that all but two of the largest marine spills of petroleum occurred at the ocean surface, see **Figure 3**, as a result of war sabotage and tanker accidents.

3 Problems

As shown in the background section, offshore drilling and production are of utmost importance to the energy security of the United States. Roughly 1/5 of U.S. oil production originates from deepwater. Given the strategic importance of the offshore hydrocarbon resource, there have been unsettling trends in its development:

1. The federal government has virtually abandoned all offshore technology-related research, while the oil and gas industry has eliminated most of its research capabilities, which three decades ago allowed it to rapidly expand deepwater production.

2. Large service companies have been unable to satisfy the ever-growing research needs of the industry.

3. Academic research has been important but small in scale and permanently starved of funding. Within academia, petroleum engineering departments have generally been viewed as less important and glamorous than, for example, biomedical departments. This attitude has resulted in an almost uniform understaffing of petroleum engineering departments in the U.S.

4. The depletion of industry research capabilities, and the starvation of academia that educates the new industry leaders[3], have resulted in a scarcity of experienced personnel that can grasp the complexity of offshore operations and make quick and correct decisions.

5. The industry has replaced the educated, knowledgable people with software that is usually written by programmers with computer science degrees, but with little knowledge of the domain physics. This increasingly complex software often gives answers that are difficult to interpret or plainly false, see the discussion below of complexity, technology and science.

6. To make things worse, a vast majority of the current industry engineers and scientists, are above 50 years of age and will retire soon.

7. Oil companies no longer have sufficient in-house manpower that would allow them to be unequivocally in charge of complex offshore operations. Instead, they rely on multiple contractors, who independently perform the various tasks related to the drilling and completing a deepwater well. The individual contractors have different cultures and management structures, leading easily to conflicts of interest, confusion, lack of coordination, and severely slowed decision-making. The lack of a clear line of authority is particularly damaging in extreme situations, like the Deepwater Horizon explosion and sinking.

8. Similar observations apply to the government agencies involved in spill management. They suffer from extreme bureaucracy, overlapping authorities, and the absence of clearly delineated chains of command.

[3] Jon Stewart asked recently: "Anybody here majored in oil leaks? Anybody? Anybody?"

The current situation is a product of two decades of research capability deterioration in the face of an increasing demand for high quality research and complex engineering applications.

4 Why Are These Problems Important?

At the core of the current problems are complexity, technology, and science.

4.1 Complexity

Here is an exchange that took place in Paris in the 1920s. It illustrates well a serious problem with the Earth sciences (and most engineering disciplines), as they are currently practiced:

Fitzgerald: The rich are different than us.

Hemingway: Yes, they have more money.

The problem is that bigger systems are *essentially* different than smaller ones, but we tend to ignore this profound truth.

Since the time of Newton, most modern scientists have come to believe that nature works like clockwork. Study each of the planets revolving around the sun and their moons, they said, and you would be able to predict the future of the entire solar system for eternity. Study living creatures, they said, and you would be able to predict the future fate of all living systems and their interactions. It is true that a clock can be taken apart and reassembled. We then have the same clock with perfectly predictable future rotations of its gears. It is not true however that a frog can be dissected into parts and when these parts are reassembled, the same living frog jumps off the table. A living organism displays complex autonomous features - emergent behavior - that cannot be predicted by studying its parts in separation.[4] Therefore, our ability to predict the future behavior of complex living and inanimate systems is *never* perfect or complete.

Earth sciences, like the natural sciences, are steeped in emergent behavior. For example, the fast flow of aqueous chlorine 36 could never be predicted by the complex numerical models of the Yucca Mountain that missed altogether the discrete fractures in the overburden. A multiphase fluid flow in a large geologic stratum is never an extrapolation of the microscopic fluid displacement events that occur at the pore level. Detailed images of rock and fluid properties centimeters away from a wellbore never tell us a complete story of the distribution of these properties at a scale of tens of meters or kilometers[5].

Complexity, i.e., impossibility of splitting a large system into smaller parts, studying each part in separation, and putting the parts together to build a whole is at the core of problems with modern science and engineering, see **Figure 4**. Complexity is an essential feature of deepwater petroleum and natural gas production systems.

[4] I cringe when I hear the otherwise prominent scientists boasting how they can put together the living cells by assembling simple elements like Lego blocks, or transistors and wires. See the discussion below of technology.

[5] And current upscaling methods for geologic systems are far less than ready for a splashy premiere.

4.2 Technology and Science

In 1954, the German philosopher, Martin Heidegger, warned us about the negative impacts of technology that molds our world view to the exclusion of all other views. Heidegger showed that technology is no mere means to satisfy human ends; paraphrasing somewhat his words: "Technology is a way of revealing nature as a standing reserve of energy that is on call waiting for us to be used at will. As such technology shapes us as much as we shape it. Humans are but a part of a modern technological system. Man in the midst of technology is nothing but the orderer of the standing reserve, and he may easily be consumed as a part of it. Meanwhile man, precisely as the one so threatened exalts himself to the posture of the lord of the earth. This illusion gives rise to one final delusion: It seems as though man everywhere and always encounters only himself." This is the supreme danger of technology, said Heidegger, because man loses ability to see anything outside the realm of technology, nature for example. Modern technology must use exact physical science and it is erroneously equated with it. "This illusion can maintain itself only so long as neither the essence of modern technology nor indeed the essence of modern science is adequately found out through questioning."

It is needless to say the a thorough understanding of technology and science have been lacking among the public and government in the United States, which also happens to be the most technologically and scientifically advanced country on the earth.

5 Research Recommendations

When left to the industry, applied research tends to be short-term and focused on the core mission of the industry: oil and gas production. Therefore, industrial research is limited to increasing oil and gas reserves by finding new reservoirs (exploration geophysics and drilling), and/or increasing ultimate hydrocarbon recovery from the existing reservoirs by better reservoir access (drilling and completions) and better production methods (production geophysics and improved oil&gas recovery methods).

Crucial research on the understanding of behavior of complex systems in reservoir exploration and production has been neglected because of insufficient resources. A comparison to NASA is appropriate, because deepwater drilling and production occur in an environment which is generally harsher than outer space, using engineered systems that are more complex than the space shuttles and satellites. NASA has received massive federal funding to arrive at the procedures of handling unexpected extreme events. These procedures still failed to protect the space shuttles Challenger (1986) and Columbia (2003). The time elapsed between these two disasters was shorter than the blowouts of exploration wells Ixtoc I (1979) and the Mississippi Canyon Block 252-01 (2010).

Given the number of respective missions (132 space shuttle flights and 53,000 offshore wells drilled and completed in the Gulf of Mexico), the offshore oil and gas industry in the U.S. still has a better safety record[6] than NASA. Nevertheless, the human and ecological

[6] In 2003, the riser pipe snapped when the drill pipe was pulled out of the hole upon the completion of drilling of the 24,000 ft Mississippi Canyon 822 No. 6 well in 6,000 ft of water. The well belonged to BP, the BOP worked, there was no blow out, and no one was hurt on the drill ship.

impacts of a serious accident in deepwater oil production far exceed those of even the most serious disaster in space. Therefore, federal government would be well-advised to start funding[7] academic research that would ensure the long-term viability of deepwater production in the U.S. and worldwide. This was done in France through a small tax on gasoline, and in Norway through a government mandate on industry research and research-specific tax write-offs for foreign corporations that operate in Norway. Australia spends lavishly on research in mineral extraction and oil&gas production.

What follows are the short sketches of the best ideas pertinent to the safety and lesser environmental impacts of deepwater production of oil and gas. There are many other ideas at UT Austin and elsewhere.

5.1 Cementation

This idea comes from Dr. Paul Bommer, PGE, UT Austin.

Clearly obtaining a satisfactory cement seal in a well between the cement and the hole, and the cement and the pipe is difficult. The standard practice is to concentrate first on the removal of mud from the area to be cemented through mechanical action, the use of a chemical mud flush, and fluid flow regime. This exposes the rock face to the cement as well as a cleaner pipe surface. Complete mud removal eliminates the possibility of a mud filled channel remaining when the cement is pumped. Mud removal also eliminates the possibility of mud contamination of the cement whereby the cement properties could be altered.

The second problem is to use cement that does not allow the percolation of reservoir fluids into the cement where they may form a channel. This is a particular problem with gas due to the large density difference between gas and the cement. Numerous studies have shown that cement shrinks slightly in all dimensions as it sets. Cement also passes through a gel stage where it is thought the cement no longer provides hydrostatic pressure against the reservoir to control flow, but at the same time has not developed sufficient compressive strength to resist gas percolation through the gelatinous cement. The current industry standard is to use the minimum amount of cement to cut down on hydrostatic pressure loss and to use cement with the shortest possible gel time. More ductile cements are also used thinking the cement may expand rather than contract during setting. Clearly these ideas are not uniformly successful.

It is clear that in spite of these difficulties gas wells are successfully cemented, yet some experience failures. This dilemma points out a serious need for a more complete understanding of the cementing process.

> It is recommended that we develop an experimental apparatus that allows for the measurement of cement properties when subjected to a simulated gas reservoir at high temperatures and pressures. The apparatus will also allow for the study of the entire cementing process, including mud effects.

[7] I do not know what the funding sources in the U.S. should be.

5.2 Safety Analysis of Complex Systems in the Offshore Environment

This idea comes from Dr. Chris Jablonowski, with participation of Drs. Paul Bommer, Larry Lake, Emilio Nùñez, Tad Patzek, and Kamy Sepehrnoori. All are at PGE, UT Austin.

For everyone:

Task 0: Conduct a publicly sponsored, government mandated, post-mortem analysis of past mishaps in the offshore operations related to well drilling, completion, and production. Include subsea pipelines and production platforms.

> Prior accident analysis will provide a baseline for Tasks 1 and 2, and tell what lessons and organizational changes have resulted from offshore accidents.

For operators:

Task 1: Conduct an independent, third-party expert review of corporate safety management systems of other technically and operationally complex sectors (e.g. construction, airlines, nuclear), and consolidate best practices of existing systems. Also, identify remaining gaps and define new processes for safety management.

> Currently, the degree of sophistication and quality of implementation of safety management systems varies widely across oil and gas operators. This leads to large differentials in performance (in both the occurrence of incidents and in the likelihood of reporting). A new baseline expectation must be defined. This review must extend beyond IADC's existing Health, Safety and Environmental Case Guidelines for Mobile Offshore Drilling Units (2009).

For regulators:

Task 2: Similar to the review in Task 1, conduct an independent, third-party expert review of best practices in regulation and enforcement of other technically and operationally complex sectors (rule-making, inspections, enforcement, punishment), and consolidate best practices of existing systems. Identify remaining gaps and define new processes for regulation.

> Instead of waiting for violations, or hoping to catch violations during an inspection, it is probable that the offshore regulator will need to be more intrusive and take on the additional step of reviewing operators' technical review process and safety management systems if a step-change in performance is to be achieved. A process for how such reviews are to be conducted, who will do them, what the metrics will be, and other components of the review process are needed. The basis of the assessment will derive in part from the results of Task 1.

There are two well known techniques for the safety analysis of complex systems. The first one, Failure Modes and Effects Analysis (FMEA) is a deductive technique that consists of failure identification in each component of a complex system, its causes and consequences on the equipment and on the whole system. The second one, Fault Tree Analysis (FTA) consists of a construction of a logical diagram (fault tree), through a deductive process that, from a predefined undesired event, searches the possible causes of such event. The process follows investigating the successive combinations of failures of the components until reaching the so called basic failures. FMEA and FTA complement each other and can form the basis for a comprehensive safety analysis of complex systems.

5.3 Development of "Ocean Cleaner" – High Capacity Offshore Oil Reclaiming Vessel

This idea comes from Mr. Russell Covington, President of Beacon Maritime, Inc., a marine/offshore construction company located in Orange, Texas, with the participation of Sembcorp Marine.

Objective: Our short-term objective is to deploy existing vessel(s) that have been modified to efficiently reclaim large amounts of floating oil in offshore conditions in an effort to help contain the current spill. Long term, such vessels can be permanently modified or purpose-built for strategic, ready-deployment in various coastal regions to serve in the event of future occurrences at/or near the site of origination.

Background: To date, oil reclamation vessels (commonly referred to as skimmers) have been constrained in their capacity and operating parameters by two (2) major factors. First, design of these vessels typically began with the premise that 100% retention of reclaimed pollutant would be a defining characteristic. This required that either the reclaiming rate or the rate of discharge of treated water was strictly limited by the ability to mechanically and completely separate the oil from the water. Second, economic constraints have limited capital investment in such vessels to relatively small units capable of managing regional spills primarily in inland waters, bays and estuaries. Due to the unprecedented nature of the current spill our fundamental priorities have necessarily shifted. As a result, the benefits from the ability to reclaim huge amounts of oil outweigh the risks that smaller amounts of contaminant might escape during the process. These escaped contaminants will remain subject to existing, secondary means of defense at or near the shore. It is also clear that the historic economic model has shifted, and what was once deemed too costly is now an obviously efficient response.

Task Requirements: Combining existing technologies, we believe we have developed a simple means of converting a typical petroleum tanker (∼300,000 bbl capacity) to a vessel ("Ocean Cleaner") that will effectively reclaim oil in the aforementioned conditions. Modifications required for this conversion are relatively simple (economical), can be affected in a short time frame and are entirely reversible, allowing for return of the vessel to its original purpose if required. Tad Patzek adds that help might be needed in the treatment of oil/water emulsions to accelerate separation of oil from seawater.

Proposed Development: The "Ocean Cleaner" concept should be fully developed on a "fast-track" schedule and conversion of at least one existing vessel completed in time for use on the current GOM spill. Beacon Maritime, Inc. will lead this effort with the technical support of Sembcorp Marine. For the marine operation, companies including Seacor Holdings, Inc., or Overseas Shipholding Group, Inc., both of whom have substantial double-hull U.S. flag vessels may provide the vessel and operation thereof. Initial conversations with Seacor have commenced. Information developed during the design and operational phases of this project may be applied to the improved, future development of purpose-built, standby vessels.

We propose that this project be quickly developed in three phases including: 1) Preliminary Design (Cost estimation–$500,000; time estimation–3-weeks), 2) Construction Engineering and Modifications to Vessel (Cost estimation–$< \$5,000,000$; time estimation–6–8 weeks); 3) Vessel Charter and Deployment (Cost estimation–$50,000/day). Beacon Maritime, Inc. will manage the initial design project with the support of Sembcorp Marine key technical personnel. Construction engineering and modifications to vessel will be performed by Beacon and coordinated with the ship owner. Modifications will be performed at Beacon's facility located in the central Gulf of Mexico at Orange, Texas and Calcasieu Parish, Louisiana. If, in the Preliminary Design phase, it is determined that this concept will meet or exceed expectations, multiple vessels may be similarly modified nearly concurrent with the prototype.

5.4 Oil Spill Capture At and Beneath Seawater Surface

This idea comes from Mr. Robert Pendzick, an adjunct instructor in Physics and Astronomy, at Mount Union University in Alliance, Ohio; and Drs. Tad Patzek and Kishore Mohanty, PGE, UT Austin.

Objective: In a small scale test, it was possible to capture and redirect a plume of oil back into a small surface area and this approach could be scaled up to the real world. Just like contractors move debris down a building by using a bucket chain, large subsea funnels can be envisioned that capture and refocus the oil plume as it rises. Using funnels of 20 m in diameter at the base and a 4 m top opening, it might be plausible to restrict the oil at the surface to a relatively small area. These dimensions can be adjusted to meet the real world measurements at different depths. The funnels could be cheap (e.g., rebar with tyvek[8]), neutrally buoyant, and steerable with ROV's or from surface tethers. This means that the funnels do not have to form a continuous chain, and – if icing were a problem – they could be raised and lowered to allow melting. The separation of oil from seawater and water disposal back to the sea would occur on surface vessels to which the funnels are connected. One vessel could be connected to several (4 or 6) funnels.

Background: The inundation of Louisiana coast with spilled oil, see **Figure 1**, is unacceptable. It is now obvious that neither the oil industry nor federal government have technical capabilities to quickly intercept spilled oil from a subsea blowout, while the oil is still rising and/or when it floats on the ocean surface close to the blowout site. The oil-skimming tech-

[8]Flashspun high-density polyethylene fibers, a synthetic material; the name is a registered trademark of DuPont.

nology and inflatable booms are clearly insufficient. "This is a war," said[9] U.S. Coast Guard Admiral Thad Allen, the federal government's point man for the recovery effort, on ABC's "This Week." "This is an insidious war because it's attacking four states at one time and it comes from different directions depending on the weather." Allen said wind and currents had broken up the slick formed by the leak into thousands of smaller oil formations over a 200-mile radius from the well site, which is about 50 miles off the Louisiana shore. "One of the problems with this entire spill is it's not a monolithic huge spill," Allen said. "It is literally hundreds of thousands of smaller spills." Capturing an oil plume before it surfaces, or just after it has would prevent many of these problems from occurring.

Task Requirements: The oil/gas plume shape and dynamics could be modeled both analytically and numerically, and for deep plumes the funnels should be placed at the break in the water thermocline around 500-1000 ft to prevent formation of hydrate crystals. The principles of fluid mechanics and mechanics of shells should be used to devise the properly scaled experiments.

Proposed Development: Quick experiments with the funnel geometry and spatial deployment must be conducted first. In parallel, research is needed to better understand the complex behavior of multi-component oil and solution gas droplets moving through a temperature and pressure gradient. There is a dire need to better understand oil interactions with cold water, possible separation of heavier oil components from the lighter ones (leading to the neutrally buoyant subsurface plumes that spread horizontally). The knowledge of the dynamics of ascent of oil droplets that are initially saturated with dissolved gas and lose mass as they rise is needed. The presence of mass transfer and a "dirty," chemically active oil/water interface must also be studied. As an oil/gas droplet moves through seawater, bacteria attack and eat its lighter, preferably paraffinic components. We need to understand the kinetics of bacterial action. Finally, the use of surfactants to manipulate oil droplet coalescence and the velocity of their ascent may be important. Today we do not understand well what these surfactants do, and what their environmental impacts are.

> We recommend that the funnel models be designed as soon as possible and carefully scaled experiments performed. Separately, plume dynamics must be studied and methods of subsea level plume observation developed and tested. The immediate outcome would be the development and deployment of a full-scale plume refocusing and capture system.

5.5 Technological Base Development for Deep Sea Robot Operations

This idea comes from Dr. Del Tesar, Director, Robotics Research Group, UT Austin, with participation of Dr. Tad Patzek, and other PGE faculty, UT Austin.

Objective: The goal is to pursue long-term tech base development for robot operations for deep sea functions (especially those for emergencies) based on requirements derived from ten

[9] WSJ website: June 6, 2010, *5th* Update*: BP Says 10,500 Bbl Oil Collected From Gulf Leak Sat*, Mark Long and Nicholas Winning Of Dow Jones Newswires.

distinct applications. The resulting technology must be cost effective, easily repaired (even remotely), and it must be rapidly refreshed.

Background: The on-going oil release in the Gulf of Mexico strongly suggests that existing robot technology is inadequate to treat the complex set of tasks associated with this event. That this complexity would be unexpected is incorrect. Present sub-sea robot technology uses hydraulic actuation, a simplified tool set, and archaic levels of man-machine interface. In other words, it is essentially several decades removed from technology that could be developed today. None of the present technology can be repaired on the ocean floor. The end-effector tools can only perform simple pick-and-place handling, and dexterous dual manipulator operations are rarely performed. Lessons learned for the repair by NASA of the Hubble telescope or those obtained from remote maintenance of nuclear reactors are not applied on the ocean floor. Increasingly complex remote operations are being carried out for hazardous tasks in the battlefield. Clearly, the present oil spill will generate some clear lessons on what would be necessary for the next "unexpected" event. We propose here to combine the research expertise of the top ranked department of petroleum engineering in the U.S. with the longest standing robotics development group to treat this tech base development opportunity.

Task Requirements: Lessons learned from robot development for remote operations in space (say, a lunar base) and for nuclear reactors (say, maintenance of a 4700 tube steam generator) points the way to develop operational requirements. The petroleum engineering faculty at UTexas will classify ten distinct operations to be performed remotely on the sea floor. Each of the ten operations will be broken down into ten or more physical subtasks. The reality is that any robot must be able to perform all of the subtasks of a remote operation or it will be considered a failure (i.e., 9 out of 10 is not enough). Generally, each subtask will require the development of one or more specialized tools (to form a library of tools). These task-dedicated tools must perform with exceptional certainty and reliability (the lesson for the tools used by astronauts to repair the Hubble telescope). Perhaps 50 to 100 tools should be made available for any deep sea operation with perhaps 10 to 20 to carry out a given operation.

Proposed Robot Development: As with personal computer technology, the envisioned deep sea technology must be modular (open architecture) with standardized quick-change interfaces to enable rapid repairs and tech mods to occur on a continuing basis. This, then, requires a finite number of self-contained, intelligent electro-mechanical actuator modules to drive any mobile platform or manipulator (including any specialized power tools). These fully integrated modules must be developed in a minimum set (no more than 10) in order that they can be fully certified yet populate all envisioned deep sea robot systems. Given this set of intelligent actuators, it becomes necessary to create a universal system level operating software system for all robots composed of these actuators and tools. This software must automatically adapt to any assembly of actuators, tools, and links. It must permit a high level of human supervision (be stiff, watch out, go slowly, pick up tool 15, etc.). Present technology does not enable the application of two tools simultaneously on a given task by using dual manipulators. Given that twenty tools are necessary to carry out a total deep sea operation, these should be contained in a closed water tight volume with a hatch to enable the remote manipulators to quickly exchange tools with modest oversight by the operator (either in a submarine or remotely at a sea surface station).

The objective is to carefully define the task requirements, use lessons learned for remote operations in other application domains, create a highly certified modular and system level technology, enable the training of a new class of technical operator, require that tech mods can occur seamlessly on a continuing basis, and to do so in the shortest feasible time for development and deployment.

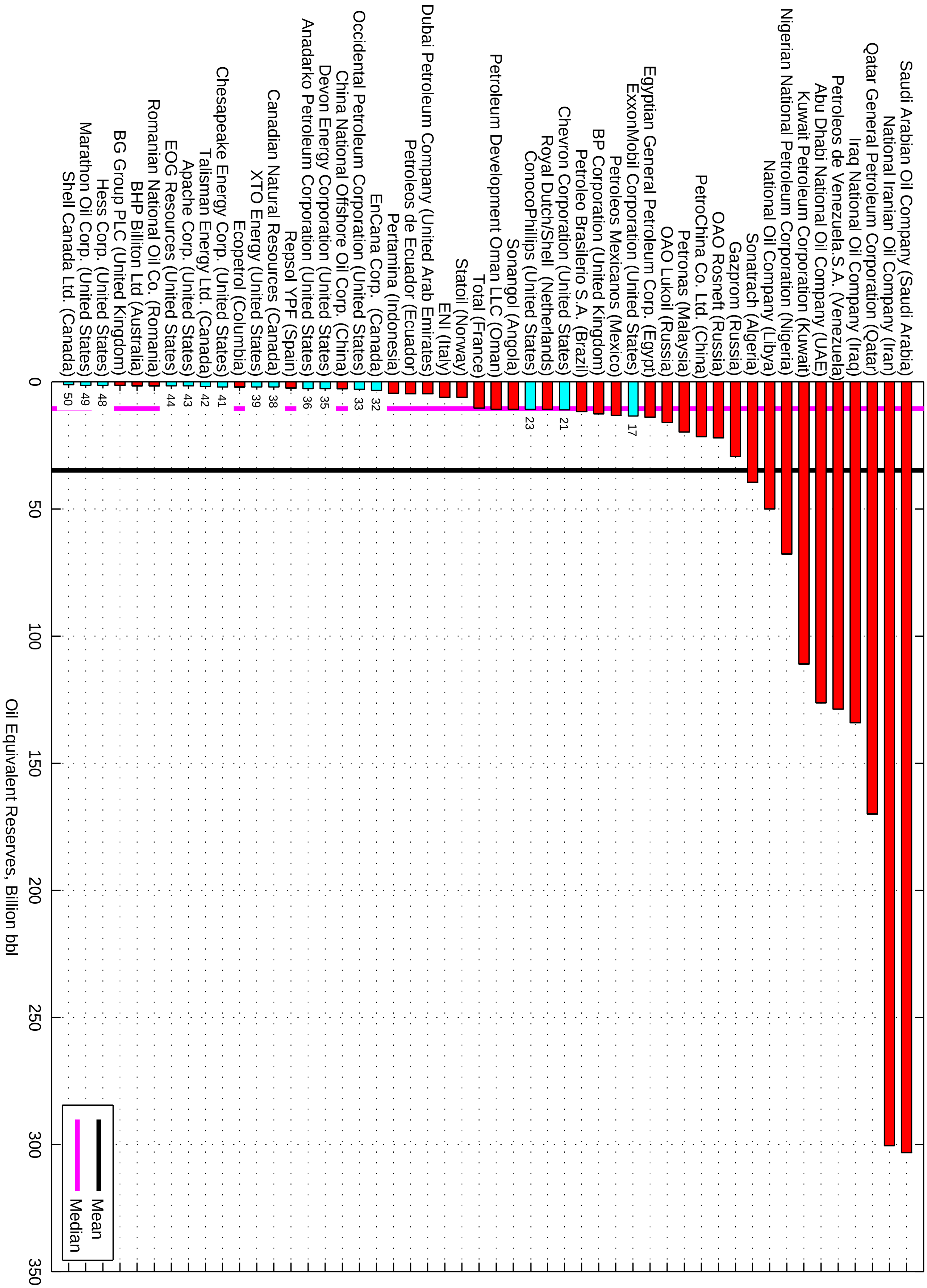

Figure 2: The ranked producible reserves (oil and natural gas) of the 50 largest oil and gas companies in the world. Source: *OGJ 200/100*, Oil & Gas Journal, September 15, 2008.

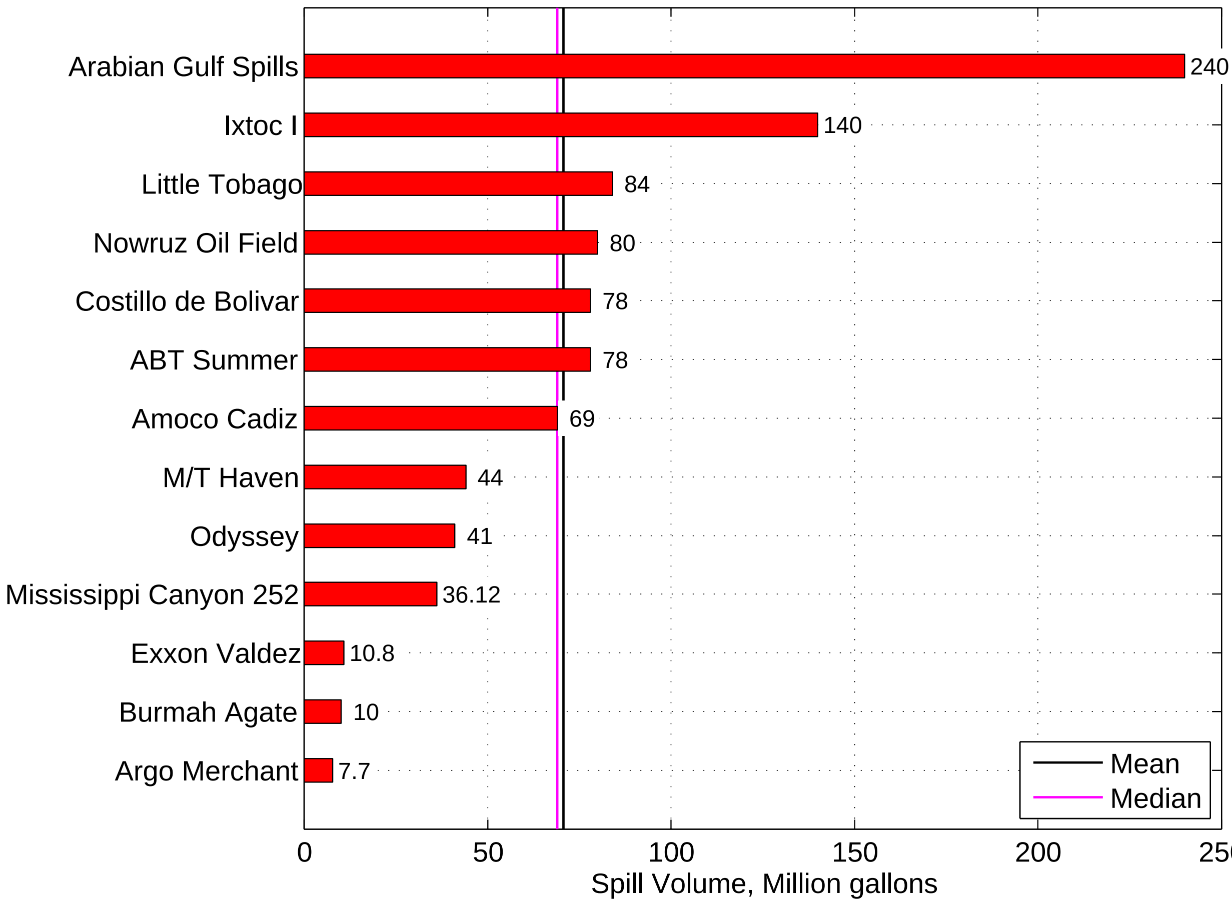

Figure 3: Except for the Pemex Ixtoc I and the BP Mississippi Canyon Block 252-1 exploratory wells, all largest offshore spills of crude oil occurred at the ocean surface as a result of sabotage or tanker accidents. In terms of its environmental impact, the 1989 Exxon Valdez spill in Prince William Sound, Alaska, is regarded as the most harmful one to date. This ranking may be changed by the still unknown environmental impacts of the BP spill. Various sources, e.g., www.history.com/topics/oil-spills.

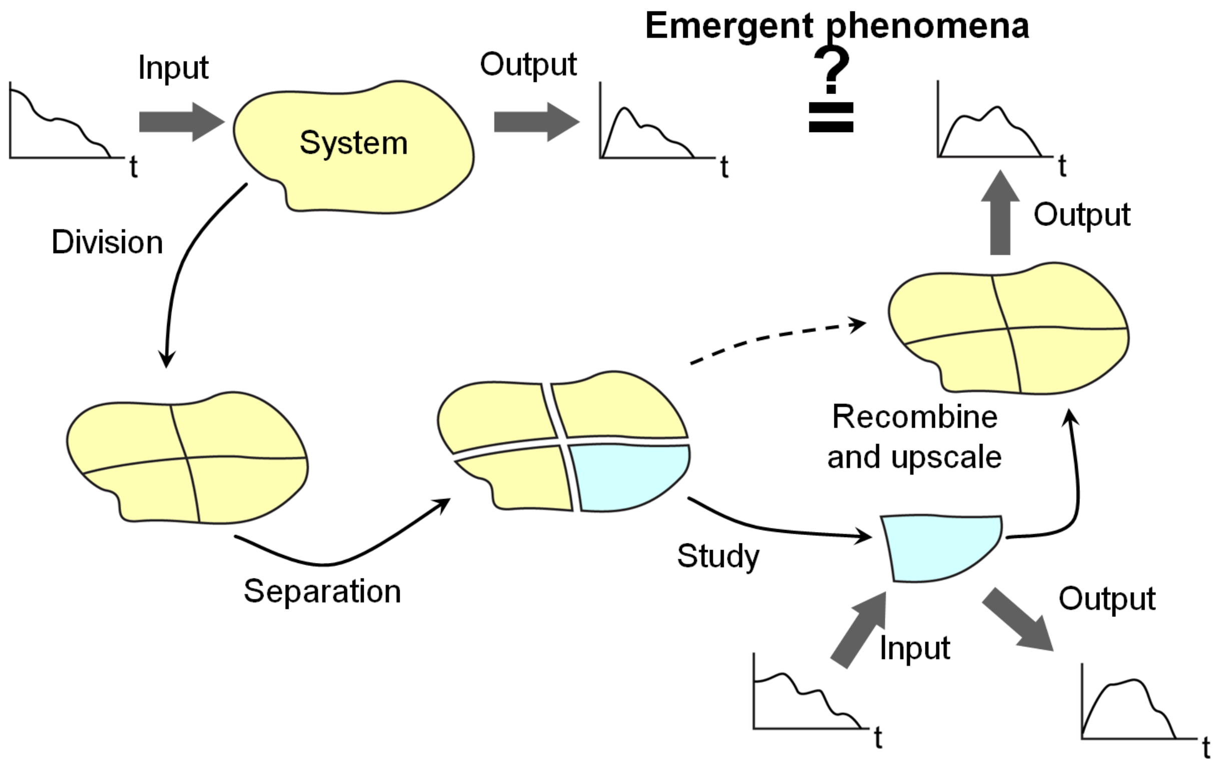

Figure 4: Reductionist approach customarily applied to all systems does not work for complex systems. New science, engineering, anthropology, sociology, political science, and psychology are needed. Source: Dr. Larry Lake, PGE, UT Austin.