Earth Resources Engineering

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Introduction

The year 2016 marked the 60th anniversary of the First Rock Mechanics Symposium, held at the Colorado School of Mines, April 23-25, 1956.[1] The Symposium has been held on a regular basis ever since.[2] The 50th US Rock Mechanics Symposium was held June 26-29, 2016, in Houston, under the auspices of the American Rock Mechanics Association (ARMA).

1956 was also the year that the writer arrived in the United States – to begin a career in rock mechanics that has lasted to the present day.

In a discussion with the writer at the 50th US Symposium, Dr Ali Daneshy, Editor-in-Chief of the *Hydraulic Fracturing Journal* (HFJ), kindly offered to dedicate this issue of his journal to the general topic of the status of US rock mechanics today. He invited me, together with a number of distinguished colleagues, to contribute to this special issue.

The recent draconian reductions in staff at petroleum companies, due to the severe economic downturns in both the petroleum and mining industries –including research and development (R&D) groups[3] - adds a sense of urgency to this discussion.

The ultimate responsibility of private sector industry must be to its shareholders, but there has been, usually, some acknowledgment that R&D is not an activity that can be switched on and off from year to year.

Petroleum and Mining companies have always been subject to 'boom and bust' economic cycles and learn to survive via cost-cutting, but the fact that R&D has suffered significantly in the current downturn may indicate a more serious problem. It takes many years to establish a high quality R&D group. Composed of research scientists and engineers from a variety of disciplines, they are mobile and, once laid off, may be loath to return when the economy rebounds. R&D groups in the petroleum industry are responsible for some of the most important advances in subsurface engineering. Long-reach directional drilling, for example, is providing considerable stimulation to other branches of 'Earth Resource Engineering.' There are other important advances in petroleum-related R&D that have potentially major benefit in these other branches.

Earth Resources Engineering

The term *Earth Resources Engineering*[4] was introduced by the US National Academy of Engineering (NAE) in 2006 to replace the name *Petroleum, Mining and Geological Engineering*[5] when NAE was established in 1966. The change was made because of the growing recognition that, in addition to being the location of fossil fuels and minerals, the Earth's subsurface had a unique capability to protect the global population and the biosphere from danger and harm. Also, the technological know-how used for extraction was needed for these new activities. Isolation of high-level radioactive wastes in geological repositories, recommended by the US National Academy of Sciences in 1957,[6] was an early example, but an increasing variety of other uses are being identified. Engineered Geothermal Systems (EGS), CO_2 sequestration, Compressed Air Energy Storage (CAES), 3D Cities, are examples of many [See e.g. Anderson and Fairhurst (2014)] Bergman (1978); Winqvist and Mellegren (1988).

It is of vital importance that the United States develop and maintain a position of international leadership in Subsurface Earth Resources Engineering.

Availability of adequate and assured supplies of resources, both fossil fuels and mineral, is crucial to the welfare of the nation. The US Strategic Petroleum Reserve,[7] plus US technological leadership in development of domestic unconventional oil and gas resources, provides reasonable assurance against interruption of supply of these fuels to the nation.

There is no comparable program to protect against interruption of the supply of minerals. These are also essential to the effective functioning of US industry and Society.

As noted in the USGS Mineral Commodity Summaries 2016 (p.5)[8] *"the value added to gross domestic product [GDP] by major industries that consume processed mineral materials (2016) is $ 2,490 billion"*. The US GDP in 2016 is $18,000 billion, - so these activities represent 14% of the GDP.

Without this core activity, much of the remainder of the GDP would not develop. The US manufacturing industry is absolutely dependent on minerals. The entire US space exploration program could not have developed without a supply of the raw materials from which the rockets, computers, control systems etc. were derived. The much-needed refurbishment of the US infrastructure will place heavy demands on minerals.[9]

The Mineral Commodity Summaries also notes:

> *In 2015, imports made up more than one-half of the U.S. apparent consumption of 47 nonfuel mineral commodities …..[10] The United States was 100% import reliant for 19 of those. China, followed by Canada, supplied the largest number of nonfuel mineral commodities.*

Concern that the US supply of minerals was vulnerable to international politics has been voiced continuously for a number of years. The following comments are extracts from a 2008 report of the US National Academies[11]

> *"The unique properties of nonfuel minerals, mineral products, metals, and alloys contribute to the provision of food, shelter, infrastructure, transportation, communications, health care, and defense. Every year more than 25,000 pounds (11.3 metric tons) of new nonfuel minerals must be provided for each person in the United States to make the items that we use every day." [p.1]*

> *"Without renewed federal commitment to innovative research and education on minerals, it is doubtful whether the activities recommended in this report regarding information about minerals will be sufficient for the nation to successfully anticipate and respond to possible short- to long-term restrictions in mineral markets." [p.221]*

Two years after the 2008 National Academies Report, the US became alarmed that China, then the main international supplier of Rare Earth minerals, was about to reduce its exports.[12]

The importance of Rare Earths is described in the following quote from an article in the US News and World Report of Nov. 20, 2012

> *"Everything from smartphones to iPods to missile systems requires rare earths. Almost every piece of high tech gadgetry contains some combination of rare earths to make volumes louder, E-mails vibrate, and bombs able to hit their targets. Nations that control rare earth production own one of the most capable economic and national security levers in the modern world. Over the last quarter century, that lever has been controlled overwhelmingly by China."[13]*

In March 2016, the US Office of Science and Technology Policy issued a report to Congress on *"Assessment of Critical Minerals: Screening Methodology and Initial Applications."* In his March 11, 2016 letter of transmittal of this report to Congress, Dr. John P. Holdren, Assistant to the President for Science and Technology, and Director, Office of Science and Technology Policy, notes

> *"A consistent approach for making assessments across a broad range of minerals and providing early warning of potential supply vulnerabilities is important to U.S. economic and national security. Critical minerals are essential to a wide range of leading technologies, ranging from aircraft and automotive components to electronics and telecommunications devices, and from displays to photovoltaics."*

The report contains a world map (Figure 6, p.9). This depicts the '**Composite Governance Index**' which is, in effect, a measure of the perceived stability of governments around the world.[14] It is seen that there are sizable regions of the world where a reliable supply of minerals may not be assured. This is the reality of today's world. An added factor to be considered is that substantial portions of the low governance (high risk) areas are regions of low 'standard of living' and high population growth – areas that will have a significantly increased demand for minerals in the years ahead.[15]

This demand tends to increase at a rate of the order of five or more times the increase in population, Freeman and Highsmith (2014).

How then can the US best ensure that its needs for fossil fuels and minerals receive favorable consideration in such a world?

The most important and effective strategy is to be in the forefront of fossil fuel and mineral resources technology.

In the phrase attributed to Sir Francis Bacon (1597)

scientia est potentia "Knowledge itself is power."

Everyone is interested to have access to the most environmentally acceptable, cost-effective technology in any commercial endeavor.

Earth Resources Engineering in the US

Of the three original disciplines embraced by the term 'Earth Resources Engineering' as defined by NAE, Petroleum Engineering is the field with a long-standing commitment to R&D. Interest in extending the impressive advances resulting from this research e.g. directional drilling, to other applications e.g. geothermal energy, is strong.

Geological Engineering has tended to emphasize groundwater issues, with research most often pursued by the US Geological Survey.

Mining Engineering has relied for much of its innovation on equipment suppliers. Research on topics such as mine safety and rock mechanics was spearheaded by the US Bureau of Mines until this Federal agency was closed by the US Congress in 1995. Australia and Canada have maintained a commitment to mining R&D. In both countries, industry support of university research is encouraged by government matching, usually on a 50:50 basis with industry funds.

Although mining research includes a variety of topics, rock mechanics is a central element that continues to grow in importance. The writer recalls, for example, a discussion (ca 1964) with Dr. Neville Cook, then Director of Research for deep hard rock mining in South Africa, re the possible limits on depths to which mines could be developed. Dr. Cook was of the opinion that heat and humidity limits would be reached before issues of high rock stress became limiting. Special acclimatization programs for miners were required[16] even at the 2 km or so depths of that period. Today, these mines have reached, recently, a depth of 4km, but impressive and ongoing developments in autonomous mining are reducing human exposure to the underground environment and, correspondingly, the need for worker acclimatization. High rock stress seems likely to become the primary issue.

Earthquakes indicate that the subsurface is a *'restless'* environment. Rockbursts in deep mines, and seismicity induced by hydraulic fracturing, are smaller scale 'man –made' reminders of this fact. Subject to successive epochs of tectonic and gravitational forces over hundreds of millions and as much as a few billions of years, these heterogeneous assemblies of rock have been deformed and fractured, introducing a variety of planar discontinuities at various times and orientations in space, over a huge range of scales from microscopic grains to tectonic plates. The forces imposed on the rock are transmitted in part through the solid structure and in part also by the fluid in the pore spaces within the rock. Some rocks will continue to deform and readjust slowly over millions of years, while other rock types in close proximity will remain elastic and unchanging. A rock mass is a far more complex and uncertain material than any fabricated material used in other branches of engineering. In some respects, engineering in a rock mass is comparable to the practice of Medicine –one is dealing with an animate, living system. Understanding the mechanical response of such material to sub-surface engineering activities –and developing practical insights on how to conduct those activities safely, and develop resources economically, is a "Grand Challenge" – comparable to any of those already defined by the NAE[17]

Newtonian mechanics applies to both sub-surface and outer-space engineering situations but, in some respects, *Subsurface Engineering is more than Rocket Science!"*.

This in no way diminishes the remarkable accomplishments of the original Apollo Program. The cost to the US taxpayer of approximately $140 billion (in 2017 dollars)[18] has been returned many times over –and to the entire world. And there are certainly benefits yet to come. Some of these benefits could accrue to Earth Resources Engineering.

In a discussion of 'Grand Challenges in Earth Resources Engineering' some years ago, Dr. J.R.A. Pearson F.R.S. (Schlumberger - Cambridge, UK) suggested *"We should attempt to map the upper 10 km (with particular emphasis on the upper 500m) of the earth's crust in more than just descriptive geological terms."* Although perhaps not yet as comprehensive as proposed by Dr. Pearson, satellite exploration of the shallow subsurface is already revealing valuable insights, including identification of mineral deposits, potential water resources around the globe[19] and other subsurface features of possible engineering significance. Others are yet more ambitious. The following quotation is from the January 2017 issue of Mining Engineering; Peacock (2017)

> *In the future, mining and metallurgical engineers and geologists will work on project teams with aeronautical, aerospace, astrophysics, agricultural and planetary civil engineers to design, test, develop and deploy robotic and human habitats, colonies, orbital and planetary surface processing units, mining operations, and power, transportation and distribution facilities.*
>
> *A transitional change in training and education for future space ventures will be required to provide specific space engineering skills sets for the following outer space environments, including: non gravity, high –radiation exposure, non atmosphere vacuum, planetary material handling and use, temperature fluctuations and periods of hibernation. For mining on the moon and asteroids, new technologies and methods are needed to provide: planetary surface and orbital bases, special mining and metallurgical methods for extraction and processing, planetary materials characterization, materials handling and transportation, drilling, blasting, construction, power and life and safety systems.*[20]

This seems to presume the existence of strong graduate programs in 'Earth Resources Engineering' (at US universities?) in the future.

The SubTER and FORGE initiatives of the US Dept of Energy, together with the outstanding research teams at DOE's National Laboratories, are an excellent first step towards strengtheni1ng US capabilities in Earth Resources Engineering.

Development of interdisciplinary Earth Resource Engineering Research Centers at leading US universities would provide a much-needed complement to the DOE program, and could address other issues re stimulating interest of students in these university programs.

US research universities attract a large number of the world's brightest students to its science and engineering graduate programs. Currently over 50% of graduate students in these US programs are from other countries. Many of these students opt to stay in the US on graduation, and enter the US workforce, some becoming leaders in industry, university science and engineering faculty, and in US science and engineering government agencies.

The disciplines traditionally embraced by the term 'Earth Resources Engineering' have not fared so well at US universities.

Often referred to as 'mature' branches of engineering with well-established technologies, and the related industries subject to 'boom and bust' cycles, university programs in these disciplines have tended to attract fewer students than the newer 'emerging' disciplines. This has been the case particularly in mining engineering at US universities. The decision by the US Congress, in 1995, to close the US Bureau of Mines, has not helped. A position paper published by the Society of Mining Engineers (SME) in March 2013[21] states,

> *"As of 2012, in the United States, there are 12 degree programs in Mining Engineering. Over 50% of the faculty are likely to retire within the next five years. With low student enrollments and few Ph.D. faculty replacements available, several universities may decide to eliminate the degree program."*

When the Bureau of Mines closed in 1995, *"almost $100 million, or 66%, of its 1995 programs ceased"*.[22] Adjusted for inflation, $100 million/yr in 1995 is equivalent to $157 million/yr in 2016.

The following comments are just two examples over the past decade relating to this lack of Federal research support of subsurface engineering

In 2006, *"...in geo-engineering the funds available for unsolicited investigator-driven research appear to have diminished almost to the point of disappearance"*[23]

In 2009 *"Chronic underinvestment in federal R&D in these subsurface [engineering and geosciences] disciplines has eroded the nation's capacity to educate and train the next generation workforce necessary for industry, academia, and government. As a result, the U.S. faces the prospect of ceding its historic leadership role in these disciplines, and thereby undermining its resource security."*[24]

The 2014 report by the JASON group[25] to DOE that helped stimulate the current SubTER and FORGE initiatives, concluded

> *"We recommend that DOE take a leadership role in the science and engineering needed for developing engineered subsurface systems, addressing major energy and security challenges of the nation. Our overarching finding is that in addition to the engineered subsurface being important in several of DOE's mission areas, the science appears ripe for breakthroughs. Disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can effect these advances."*[26]

The US Bureau of Mines was the main sponsor of research in mining at US universities - and had a distinguished record in rock mechanics. Dr Leonard Obert, supported by a team of scientists and engineers at several USBM laboratories across the US, led a vigorous research program. Together with his colleague, Wilbur Duvall, in 1939, he pioneered the use of 'microseismims' to assess danger in rockburst- prone mines. The Introduction to their 1956 report (Obert and Duvall, 1956) reads

> *"The cracking and popping of rock, often heard by men working underground, for years has been interpreted as a warning of danger and unstable ground. However, not until 1939 was it discovered that rock under stress generates sub-audible and sometimes audible seismic disturbances (referred to as "micro-seismims"), which can be detected with the use of a suitable seismic apparatus"* [27]

These 'micro-seismins'are widely used today to monitor the development of fractures in stimulation of non-conventional petroleum resources, and in rockburst monitoring in mines.

Dr. Obert was elected as the Third President of the ISRM (International Society for Rock Mechanics) serving from 1970-74. He was the main driver in securing funds, primarily from the USBM, to support the Congress – which was a marked success. It is the only ISRM Congress ever held in the United States.

Today, the primary source of financial support for US university research related to rock mechanics is the National Science Foundation. It is difficult to provide a precise amount for this support, because there is no specific rock mechanics program, although NSF has several programs to which rock mechanics-related proposals can be directed.[28] Currently, the NSF funding for university research in rock mechanics is of the order of $1-$2 million per year in total![29]

Although this level is very low, it does not necessarily indicate any bias by NSF against subsurface engineering or rock mechanics research. Research awards are a function of research proposals submitted to the agency, so the low level of funding is an indication that the university research community in these disciplines is small.

Clearly, if the US is to develop world-class competence in Earth Resource Engineering, and a sufficient workforce of engineers to provide the nation with global leadership in these technologies, the level of university funding to develop the needed interdisciplinary research must be ***substantially*** greater than $2 million per year.

The current situation reminds the writer of his grandfather's admonition when, during WWII, he sensed my reluctance to eat the odd-looking concoction facing me at dinner.

"I had a donkey once, and had just trained it to go without food, when it died!

Earth Resources Engineering R&D at US universities has been on a starvation diet for too long.

Establishment of several ***interdisciplinary*** Engineering Research Centers, in which current research groups in Subsurface Engineering and Rock Mechanics partner with colleagues in the variety of disciplines that could contribute to advancing the 'State of the Art', seems to be an obvious opportunity.

The four *Grand Challenges in Earth Resources Engineering* described in this issue of *Hydraulic Fracturing Journal* provides examples of such possible collaborations. And, obviously, there are others.

If there are to be "mining and metallurgical engineers and geologists" at US research universities with the abilities and skills relevant to extraction of resources from the Moon, then it would seem prudent to ensure that, in the meantime, the expertise for development of subsurface engineering on Earth is alive and healthy.

Recommendation

As will be evident from the preceding comments, the writer is convinced that it is in the National interest to energize graduate programs in Earth Resources Engineering disciplines at US research universities.

Establishment of interdisciplinary Engineering Research Centers seems to be the most realistic option to accomplish this goal.

The cost of university-based Engineering Research Centers is typically of the order of $5 million/yr with an initial commitment of five years, and a possible extension for a further five years if progress is satisfactory i.e. a commitment of $50 million over 10 years per Center.

Each Center typically involves several universities. Ten such Centers would represent a commitment of $500 million over a 10-year period. Given that Rock Mechanics/Engineering is such a central part of Earth Resources Engineering it would seem reasonable to suggest that four or five of the ten should emphasize Rock Mechanics/Engineering. Close interaction with industry should be a mandatory element of such centers, especially since field scale phenomena that cannot be observed or tested in a classical laboratory are an important element of rock engineering.

Some preference could be given to proposals that involve a 50:50 matching of Federal funds with Industry funds. Both Australian and Canadian governments have used this incentive for many years. Also, since most mining companies operate globally, they have the freedom to support research in several countries –and are likely to choose those that have the matching funds incentive –assuming that there is also a good research university in that country. It is noteworthy that Rio Tinto supported Research Centers in Australia, Canada, and the UK - but not in the US.

Another option would be to allow matching of Federal funds to be provided by a State. In some cases, there may be an Earth Resources Engineering issue that is of major relevance to that State, e.g.in Oklahoma - the effect of waste water injection on induced 'earthquake' activity ¯and development of sound mechanics-based strategies to predict, monitor, and minimize the earthquake magnitudes.[30]

A major concern often voiced in such disputes is that companies are not forthcoming or trustworthy, and citizen groups do not have the resources to develop a comparable level of understanding of the underlying scientific and engineering issues.

All information gathered in Engineering Research Centers is usually publically available –so the State and its citizens would have reliable information and experienced scientists and engineers to make an objective, informed analysis of the situation. As expressed by a 2016 editorial in the Minneapolis Star –Tribune

Let Regulatory Science[31] decide, not Politics and Passion.

For such situations, matching of Federal funds with State funds would seem to be a logical option –and would allow States to establish appropriate regulatory requirements for such operations.

As noted in the earlier discussion, it is important that the US become as self-sufficient as possible in mineral resources. Subsurface Earth Resource Engineering Centers would help develop the technology to facilitate this; shared Federal/State funding would allow the number of Centers to be increased without increase in Federal funding.

Earth Resource Engineering Centers would also provide an excellent opportunity for groups with expertise in Satellite and Outer Space Research to explore how their expertise e.g. in communications, adaptive control logic, etc. can be used to advantage in Subsurface Earth Resource Engineering; to the benefit of the Inner Space of Planet Earth as well as to exploration of other planets.

Challenges in science and technology can be classified in two general categories; those that are hard and those that may not be so difficult but have not been given adequate attention. Earth Resources Engineering includes both.

Persuading Congress and government agencies of the critical need to 'energize' US university–based research in Subsurface Earth Resources Engineering may not be easy – but it has the advantage that the needed public investment is relatively small compared to others considered to be worthwhile and in the national interest.[32] It is also clear that the loss of 'well-paying middle class jobs' has been a major and growing concern of US citizens and of Congress over the past decade.

Two reports of the US National Academies deserve special attention in addressing this concern.

In 2005, bipartisan requests from the United States House of Representatives and the United States Senate prompted the National Academies to conduct a study of America's competitiveness in the newly evolved global marketplace. A report, popularly referred to as the "*Gathering Storm*" report after the first line in its title, was issued in January 2007. The report made several recommendations, one of which was that Congress double the Federal research budget. Concerned that its recommendations were not being given sufficient attention, the Academy issued a follow-up Report in 2010. *Rising Above the Gathering Storm Revisited -Rapidly Approaching Category 5*.[33] The Executive Summary[34] to this report includes the following observations.

> *It would be impossible not to recognize the great difficulty of carrying out the Gathering Storm recommendations, such as doubling the research budget, in today's fiscal environment…with worthy demand after worthy demand confronting budgetary realities. However, it is emphasized that actions such as doubling the research budget are **investments** that will need to be made if the nation is to maintain the economic strength to provide for its citizens healthcare, social security, national security, and more. **One seemingly relevant analogy is that a non-solution to making an over-weight aircraft flight-worthy is to remove an engine.***
>
> *While … progress by other nations is to be both encouraged and welcomed, so too is the notion that Americans wish to continue to be among those peoples who do prosper.*
>
> *Finally, many other nations have been markedly progressing, thereby affecting America's relative ability to compete effectively for new factories, research laboratories, administrative centers—and **jobs**.*
>
> *The only promising avenue for achieving this latter outcome, in the view of the Gathering Storm committee and many others, is through **innovation**.*
>
> *The 2010 Report noted also that*
> - *Over two-thirds of the engineers who receive PhD's from United States universities are not United States citizens.*[35]
> - *While only four percent of the nation's work force is composed of scientists and engineers, this group disproportionately creates jobs for the other 96 percent.*

Petroleum and Mining Engineering companies have a strong global orientation. Of the world' ten largest petroleum companies, one – Exxon-Mobil (No.5), Irving, Texas –is based in the US.[36] Similarly, Freeport McMoRan (No.7), in Phoenix, Arizona, is the only US-based top-ten mining company.[37] Many of the companies have operations in the US.

In one sense, these companies are less reliant on US engineering graduates than is the case for other engineering enterprises based predominantly in the US. This situation simply provides an extra incentive for the US to be at the international forefront of these disciplines. Further, if the US provides incentives similar to those that already exist in other countries e.g. Australia and Canada, these companies will probably also invest in US university research.

Availability of multi-year research funding, as is provided by Engineering Research Centers, would bring a much –needed element of stability to research activities that is now missing from Earth Resources Engineering.

Closing Comment

The articles in this issue of HF Journal are offered with the hope that they will stimulate discussion and action by the US professional community to begin to correct a significant weakening in US rock mechanics and subsurface engineering research over the past several decades. It is hoped also that the comments have convinced the reader that it is very much in the interest of the United States to begin to reverse this decline.

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Endnotes

[1] The Symposium was co-sponsored by the Mining Engineering departments of Colorado School of Mines, the University of Minnesota and The Pennsylvania State University.

[2] The symposium was not held in some years to avoid conflicts with other international symposia (e.g. the Third ISRM Congress, Denver 1974), North American Rock Mechanics Symposia, etc.

[3] Petroleum company R&D groups, usually fairly immune during past economic downturns, have suffered major lay-offs. Rio Tinto Mining Company, which had established eight or so university mining research centers in Australia, Canada and the United Kingdom over the past several years, has closed all of these Centers over the past three years.

[4] Defined by NAE as *Engineering applied to the discovery, development and* ***environmentally*** *responsible production of* ***subsurface earth resources****.*

[5] Defined by NAE as Engineering applied to the discovery, development and responsible production of **nonrenewable earth resources**.

[6] https://www.nap.edu/catalog/10294/the-disposal-of-radioactive-waste-on-land Geological Isolation has since been adopted by all of the 'thirty plus' countries with a need to isolate high level radioactive waste. The US program of high level radioactive waste isolation is currently mired in political controversy. See Voegele and Vieth. (2016)

[7] https://en.wikipedia.org/wiki/Strategic_Petroleum_Reserve_(United_States)

[8] https://minerals.usgs.gov/minerals/pubs/mcs/2016/mcs2016.pdf

[9] *Is Mining Important?* [K.J.Reid (April 2016). 2 minute video.] https://www.youtube.com/watch?v=JXoQQB0_3SM

[10] *"The figure on page 8 shows the countries from which the majority of these mineral commodities were imported and the number of mineral commodities for which each highlighted country was a leading supplier."*

[11] Minerals, Critical Minerals and the US Economy (2008). Nat'l Acad. Press. https://www.nap.edu/catalog/12034/minerals-critical-minerals-and-the-us-economy [Chapter 8. p.221]

[12] https://en.wikipedia.org/wiki/Rare_Earths_Trade_Dispute

[13] http://www.usnews.com/opinion/blogs/world-report/2012/11/20/the-us-needs-rare-earth-independence-from-china

[14] The governance values are based on an aggregation of six WGI (Worldwide Governance Indicators): 1) Voice and Accountability, 2) Political Stability and Absence of Violence, 3) Government Effectiveness, 4) Regulatory Quality, 5) Rule of Law and 6) Control of Corruption.]

[15] The current GPD/capita of the Central African Republic, for example, is $600 -i.e. approximately 1% of that of the US and other 'developed' countries.

[16] Wyndham, C.N. and N.B.Strydom (1969) *Acclimatizing Men to Heat in Climatic Rooms on Mines*. Journal So. Afr. Inst. Min. Met. Oct 1969 pp 60-64 https://www.saimm.co.za/Journal/v070n03p060.pdf

[17] http://engineeringchallenges.org/challenges.aspx Former NAE President Charles Vest defined a 'Grand Challenge' as *one that is "visionary, but do-able with the right influx of work and resources over the next few decades"— a challenge that, if met, would be 'game-changing' and have a "transformative" effect on technology.*" Hear 'Introductory Comments' by Dr. Vest http://www.engineeringchallenges.org/challenges/15583/newsconf.aspx

[18] https://en.wikipedia.org/wiki/Apollo_program#Costs (Section 9. Costs. Last Para; "In 2009 NASA held a Symposium…")

[19] http://www.aapsinc.com/technologies/detector-and-imaging-technology/geophysical-exploration/ See also https://www.theguardian.com/science/2015/nov/10/ancient-river-network-discoverd-buried-under-saharan-sand

[20] The writer had a 'brief encounter' with the challenges of rock mechanics in the lunar environment when he participated in discussions re design of a coring drill to take samples of the solid rock on the surface of the moon. Since gravity on the Moon is one –sixth of gravity on Earth, the weight of the astronaut plus space suit etc. would be one-sixth of his weight on Earth. The strength of the moon rock would be the same as similar rock on Earth. How then could we develop a sufficient force reaction to counter the drill impact force needed to break the rock; and how could the astronaut develop sufficient reaction to the drill torque to prevent being spun around by the drill. A drill was designed and intended to be part of the Apollo 13 mission. An explosion on board the spacecraft forced it to return to Earth without landing on the Moon, and so we did not learn whether or not the drill would have cored the rock successfully.

[21] https://www.smenet.org/docs/public/USMiningSchools-SME.pdf

[22] http://en.wikipedia.org/wiki/United_States_Bureau_of_Mines.

[23] US National Resources Council NRC 2006. *Geological and Geotechnical Engineering in the New Millennium*. (p.150)

[24] U.S. Dep't of Energy, 2009. *Energy Research and Development (Document END09278) Strengthening Education and Training in the Subsurface Geosciences and Engineering for Energy Development*; Section 33, Subtitle C p.3

[25] https://en.wikipedia.org/wiki/JASON_(advisory_group)

[26] https://www.energy.gov/sites/prod/files/2014/09/f18/2014%20SubTER%20JASON%20Report_1.pdf See p.14

[27] Dr. Obert mentioned to the writer that, during these early studies, he and Duvall had persuaded a mine manager in Canada to stop mining operations for one day. They felt confident, from their observations, that a serious rockburst would occur on that day. The day came, but no burst! Operations were resumed –and two days later, there was a serious burst. *"That day,"* he observed, *"we learned an important lesson about uncertainties in practical rock mechanics!"*

[28] Some examples are: Major Research Instrumentation (MRI) for equipment (several awards in recent years for rock testing equipment); Partnerships in International Research and Education (PIRE); The Engineering for Natural Hazards (ENH) program (e.g. for landslide or seismic hazards) https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505177; and Integrated NSF Support Promoting Interdisciplinary Research and Education (INSPIRE). The EAR [Earth Sciences Program] in GEO [Directorate for Geosciences] also funds some rock mechanics awards but, of course, these are more related to geosciences than engineering.

Dr Richard Fragaszy, whose responsibilities include directing the Geotechnical Engineering and Materials (GEM) program kindly supplied this information (Dec 15,2014). He stated, *"Last year, my combined programs funded approximately $7.5 million of awards, of which about $1.1 million went to rock - related research. This is approximately in proportion to the number of proposals in rock vs. soil."* The situation has not changed significantly in the past two years.

[39] The total FY2016 NSF appropriation for *"Research and related activities"* is approximately $6 billion/yr. See https://www.nsf.gov/about/congress/114/highlights/cu16_0104.jsp

[30] The State of Minnesota is involved in a very contentious issue as to whether or not to allow Copper/Nickel and Platinum group metals to be mined in the vicinity of the pristine Boundary Waters Canoe Area. The principal issue is whether surface wastewater from the mine will enter the BWCA watershed and contaminate the lakes. This could be an opportunity to solve a specific issue through research and perhaps develop general procedures of value to agencies such as the EPA

[31] Meaning that research would establish the scientific facts of the situation –and the State could either a) not allow the proposed activity, or b) establish Regulations to ensure that no significant environmental damage or other adverse societal impact occurs.

[32] A probe to collect asteroid dust in search for origins of life on Earth, launched in September 2016, is indicated to cost $800 million. http://www.abc.net.au/news/2016-09-09/nasa-launches-spacecraft-to-collect-asteroid-dust/7829816

[33] https://www.nap.edu/catalog/12999/rising-above-the-gathering-storm-revisited-rapidly-approaching-category-5

[34] https://www.nap.edu/read/12999/chapter/2

[35] More recent statistics suggest that this situation has not changed significantly. https://www.nsf.gov/statistics/srvydoctorates/

[36] https://en.wikipedia.org/wiki/List_of_largest_oil_and_gas_companies_by_revenue

[37] http://www.miningglobal.com/top10/1060/Top-10-Mining-Companies-Based-on-Revenue

Biography

Charles Fairhurst, Professor Emeritus, University of Minnesota, Minneapolis, USA; Senior Consultant, Itasca International Inc. Minneapolis, obtained his Ph.D. in Mining Engineering from the University of Sheffield, UK in 1955. He joined the University of Minnesota faculty, School of Mines and Metallurgy in 1956, serving as Head for several years to 1970, when the Mining program was joined with Civil Engineering to form the Department of Civil and Mineral Engineering. He served as Head of the joint Department from 1973-87, and retired in 1997.

He has consulted on rock stability problems for tunnels, dams, mines and excavations throughout the world. He remains active in consulting, with a current emphasis on the mechanics of fracture propagation in naturally fractured rock and the effective stimulation of geothermal reservoirs. He served as President of the International Society for Rock Mechanics from 1991-1995, and has been elected to the U.S. National Academy of Engineering (1991) and the Royal Swedish Academy of Engineering Sciences (1979). He is a Fellow of the American Rock Mechanics Association.

Dr. Fairhurst holds honorary doctorate degrees from the University of Nancy, France; St. Petersburg Mining Academy, Russia; University of Sheffield, England; and University of Minnesota, USA; and is Advisory Professor to Tongji University, Shanghai, China.

In December, 2013, he was inducted as Officier, Légion d'Honneur, France.