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PHYSICS & SOCIETY

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Message from the Editor

In our last newsletter, we published three articles from scientists that have played important roles as scientific advisers at the national level. As pointed out in a letter published in this edition below, it is equally important to be involved at the local level, perhaps even more so given the crisis within our political system.

Also in this issue, the FPS representative to POPA, Phil Taylor, updates us on some of their recent activities and asks for our input on the ongoing review of the APS statement on climate change. Please email him directly at the address he provides at the end of his report.

For those interested in learning about technical issues of importance to the intersection of physics and society, we have announcements of upcoming workshops on nuclear weapons issues (November 2-3, 2013 in Washington, DC) and sustainable energy (March 8-9, 2014 in Berkeley, CA).

I am extremely pleased to include an outstanding article by Murray Hitzman and colleagues on "Energy Technologies and Induced Seismicity." This article provides a summary of many of the key points of the recent NRC report and is well worth your time to read. Also, we have two excellent reviews of books recently published that should be of great interest.

I am happy to announce that Professor Jeremiah Williams from Wittenberg University has agreed to join our Editorial Board and Drexel University undergraduate student Matthew Parsons has agreed to help identify new ways to get our newsletter into the hands of students that are interested in the activities of the Forum.

We are always looking for interesting topics and authors willing to write about the latest advances. Please contact me with your ideas and consider submitting an article for publication in a future edition of the newsletter.

Andrew Zwicker, azwicker@princeton.edu

IN THIS ISSUE

LETTERS

(Ed. Note: The July 2013 edition included a series of articles on "Science Advising" referenced by the author.)

Dear Dr. Thomas:

The articles in this issue, including yours, are quite interesting. However, when it comes to policy advice and public service, it never ceases to amaze me that the FPS (and most physicists) always appear to concentrate on physics and policy at the national level (and at APS meeting levels as you write below regarding conferences and committees). Physics at this national level is, of course, important for our nation. In fact, however, there are numerous opportunities and instances where physicists make important contributions to society at state and local levels, bringing insights to problems close to their communities, universities, and industries. It is certainly important to have physicists serve nationally, including in the highest level positions in the federal government. But there are numerous physicists (and members of the APS) throughout our country who contribute quietly and effectively to society everyday, from service on their local zoning and planning boards, on their environmental commissions, in elected offices from school boards to town council members to mayors, and in state advisory committees. These positions may not be as glamorous (and as visible to FPS and APS) as those in Washington, but they are important for society. And the positions demonstrate to local voters what a physicist does and knows, and why physics is important. As the late House Speaker Tip O'Neal titled his little book, "All Politics is Local".

The FPS might eventually enlarge its scope of interest to encompass the opportunities for physicists in public service beyond the continued concentration of FPS inside the Washington beltway.

Louis J. Lanzerotti, APS Fellow

Dear Dr. Lanzerotti,

Thank you for highlighting this important point; I agree that state and local science advice should receive more attention.

In my talk at the April APS meeting I did speak about Art Rosenfeld, who has served with distinction on the California Energy Commission. And John Morgan's piece in the latest issue of Physics and Society mentions that he was an elected Maryland State Delegate for eight years. Nevertheless, the set of three articles did focus mostly on national level science advice. In future FPS sessions or newsletter articles, we'll look for opportunities to bring more attention to state and local service, and, in parallel, to scientists active in international advisory roles.

Sincerely, Valerie Thomas

Announcement

Last issue, we reported on work leading to a biography of Richard Garwin and we are making significant progress. He is, as most of you know, a major figure of the early atomic age, who is quite amazingly (given the number of intervening years) still very active in providing the government with technical advice and analysis related to defense and defense policy. Dr. Garwin has had an incredibly eclectic career, contributing advances in many areas of physics and applied mathematics, over the course of well over half a century. Many, but not all, of these contributions had important defense and intelligence applications. Beyond a mere list of diverse and major contributions, his career could alternatively and interestingly be interpreted as a paradigm and metaphor for the efforts of leading scientists — indeed of the scientific community — since World War II to influence government policy in their areas of expertise. For example, Dr. Garwin is famous for, among many other contributions, leading the design of the world's first thermonuclear device, and later becoming a leading advocate for test ban treaties and stockpile reductions. A prospective author has been identified, and the project is proceeding.

For further information, go to indiegogo.com after Nov. 1 and search for "Richard Garwin Biography" or please contact Tony Fainberg, fainberg666@comcast.net or tfainber@ida.org.

FORUM NEWS

Report from the FPS representative on the Panel on Public Affairs of the APS

September 16, 2013

The Panel on Public Affairs has about twenty members, all but one of whom are elected by the thirty-member APS Council. The exception is the representative to POPA from the Forum on Physics and Society, who is elected by whatever fraction of our roughly six thousand members choose to vote. As your current representative, I have pondered the significance of this difference ever since I was elected. Does this give me some special role as the voice of the sweaty masses working in the trenches? Or should I defer to those who were nominated and chosen by the select group of the great and the good?

While contemplating this question I have kept a fairly low profile, only raising questions about one issue. This involved a study of the technical challenges associated with extending nuclear reactor lifetimes from the current 60 years to 80 years. This struck me as somewhat akin to a study of the technical challenges associated with extending the lifetime of a 1933 Pontiac so that it could continue to be driven down the public highways at high speeds. I actually did own a 1933 automobile once, and vividly remember the difficulty I had in stopping it without veering off to left or right as I applied pressure to the cable-operated brakes. This analogy led me to question the advisability of keeping running some of our more primitive reactors, such as the early ones identical in type to those that experienced problems at Fukushima. However, the issue may soon be moot, as the economics of maintaining these creaky old machines may cause their owners to shut them down sooner rather than later. The Entergy Corporation announced in August that they plan to close their Fukushima-style 620 MW Vermont Yankee plant next year, although the SAFSTOR decommissioning process they would like to use would take 60 years to complete!

Returning to the issue of whether my role in POPA is special, I do have to concede that any claim I would make to represent the voice of a wider spectrum of APS membership than any other member is hardly valid if all I do is just sit there and offer my own opinions. To be the voice of the FPS membership I should actually consult that membership occasionally to sound out their (that is, your) views. As it happens, there can surely be no better time than the present to do that, for we are about to take up consideration of one of the most important statements that the APS has ever made, namely the statement on climate change. It was adopted by the APS Council in 2007, and can be found at http://www.aps.org/policy/statements/07_1.cfm along with a clarifying commentary added by the APS Council in 2010.

POPA is not leaping into this particular maelstrom of its own volition: the bylaws of the APS require that every statement be re-examined every five years. A subcommittee has been formed, and it is hoped that its recommendations can be considered very early in 2014. Performing this task will require an extraordinarily intricate combination of insight, wisdom, delicacy, and, above all, transparency. It will be informed by such parts of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) as are available at the time. The most relevant part for POPA purposes is the report of Working Group I, which is concerned with the physical science basis of the assessment, and is due to be released in Stockholm in late September. The existence of news leaks alleged to come from the report suggests that it will be ready on time.

Thus I end this report with the suggestion that, if you have any thoughts regarding revision (or non-revision) of the Climate Change Statement, or, indeed, any more general suggestions for topics that POPA might usefully address, you communicate them to me. I am not on the subcommittee considering the Climate Change Statement, but I will have the opportunity to pass on your comments to its members. General suggestions rather than wordsmithing are probably most useful at this stage. An e-mail sent to taylor@case.edu with a subject line starting with the letters FPS should escape my spam filter.

Philip Taylor
Case Western Reserve University

Physics and Society is the non-peer-reviewed quarterly newsletter of the Forum on Physics and Society, a division of the American Physical Society. It presents letters, commentary, book reviews and articles on the relations of physics and the physics community to government and society. It also carries news of the Forum and provides a medium for Forum members to exchange ideas. ***Opinions expressed are those of the authors alone and do not necessarily reflect the views of the APS or of the Forum.*** Contributed articles (up to 2500 words), letters (500 words), commentary (1000 words), reviews (1000 words) and brief news articles are welcome. Send them to the relevant editor by e-mail (preferred) or regular mail.

***Physics and Society* can be found on the web at www.aps.org/units/fps.**

Short Course on Nuclear Weapon Issues in the 21st Century

Sponsored by the American Physical Society's Forum on Physics & Society & GWU Elliot School

Saturday/Sunday, November 2–3, 2013

The George Washington University, Elliott School of International Affairs, Washington, DC

A popular technical workshop is making a repeat performance. The first two conferences on physics and nuclear weapon issues were published in American Institute of Physics Conference Proceedings #104 and #178. International experts will give the technical background to understand the issues. We recommend signing up early, as it probably will sell out. The cost is $100 for 24 talks, a 400-page book, 2 lunches, plus $30 for the banquet (first 70).

The event is organized by Pierce Corden (AAAS), David Hafemeister (CalPoly) and Peter Zimmerman (Kings College, emeritus). Information/registration at www.aps.org/units/fps/meetings/nucwpissues/ or by check, APS Meetings Dept., American Physical Society, 1 Physics Ellipse, College Park, MD, 20740-3844. Contact dhafemei@calpoly.edu (805-544-5096) for more details.

Saturday, November 2, 8:30 am

Keynote Address: Nuclear Arms Control Issues

Rose Gottemoeller, Under Secretary of State

I. Nuclear Weapons and Arms Control

Monitoring the START Treaties – Edward Ifft, Georgetown U.

Monitoring Nuclear Weapons – Dick Garwin, IBM Fellow, Sunday PM

Modernizing the U.S. Nuclear Arsenal – Hans Kristensen, Federation of American Scientists

Future Nuclear Weapons Policies – James Acton, Carnegie Endowment for International Peace

II. Comprehensive Nuclear–Test Ban Treaty

Radioxenon Monitoring and the CTBT – Ted Bowyer, PNNL

Seismic Monitoring: 2012 NAS Report and Recent Explosions, Earthquakes, Meteorites – Paul Richards, Columbia

CTBT On-site Inspections – Jay Zucca, LLNL

Stockpile Stewardship and the NAS Report – Marvin Adams, Texas A&M

III. Ballistic Missile Defense

NAS Study on Ballistic Missile Defense – Dean Wilkening, LLNL

Science, Technology and Politics of BMD – Philip Coyle, CACNP

Saturday Evening Banquet: Intersection of CTBT with NPT and FMCT

Tom Graham, former ACDA General Counsel

Sunday November 3, 8:30 am

IV. Nuclear Proliferation

Evolution of the Non-Proliferation Regime – Arian Pregenzer, Sandia, Saturday PM

North Korean Nuclear Program, Negotiations and the Role of Science – Robert Gallucci, MacArthur Foundation

India and Pakistan's Nuclear Programs – Zia Mian, Princeton

Monitoring Centrifuges and Blend-Down – Larry Satkowiak, ORNL

Laser and Centrifuge Enrichment – Francis Slakey, APS/Georgetown U.

Monitoring the FMCT – Frank Von Hippel, Princeton

Nuclear Forensics – Jay Davis, Hertz Foundation

Iran's Nuclear Program and Negotiations – David Albright, ISIS

V. Mass Casualty Terrorism

Science and Technology for Homeland Security – Daniel Gerstein, Deputy Under Secretary Homeland Security

Risks and Responses to Mass Terrorism – Peter Zimmerman, Kings College, emeritus

Terrorism and Nuclear Detection – Warren Stern, BNL

Scanning of Vehicles for Nuclear Materials – Jonathan Katz, Washington U.

Conference Review and the Future

Pierce Corden, AAAS

Physics of Sustainable Energy III: Using Energy Efficiently and Producing It Renewably

Sponsored by: The American Physical Society's Forum on Physics and Society, Topical Group on Energy Research and Applications & the American Association of Physics Teachers

Saturday/Sunday, March 8-9, 2014

University of California at Berkeley

This third workshop on Physics of Renewable Energy continues the tradition begun by two successful predecessors, held in 2008 and 2011. Once again, experts will give the technical background to understand current energy issues. The talks will be aimed at college professors and students wanting to teach or do research in this field.

Organizers: Rob Knapp, Evergreen State College; Dan Kammen, University of California at Berkeley; Barbara Levi, Physics Today. For information, see http://rael.berkeley.edu/apsenergy2014

Saturday, March 8

Welcome and Overview:

Daniel Kammen (UC Berkeley) and Rob Knapp (Evergreen State College)

Session A: Global and Regional Issues

Global Carbon Balance – Ken Caldeira, Carnegie Institution

Energy and the Global Poor – Daniel Kammen, UC Berkeley

Black Carbon – Sarah Doherty, University of Washington

Session B: Renewable Energy Sources

Progress in Photovoltaics – Jennifer Dionne, Stanford U.

Solar Power Life Cycle - TBA

Biofuels: status and prospects – Chris Somerville, Energy Biosciences Institute, UC Berkeley

Wind – John O. Dabiri, Caltech

Synergies of Energy and Information Technologies - TBA

Session C: Efficient and Transformed Uses Part I

Buildings - TBA

Energy Use in the Information Economy – Jonathan Koomey, Stanford

Industrial Ecology – Valerie Thomas, Georgia Tech

The Rebound Effect - TBA

Banquet Keynote Speaker

Amory Lovins, Rocky Mountain Institute

Sunday March 9

Session D: Sustainability and Nonrenewable Energy

ARPA-E – searching for breakthroughs – Arun Majumdar, Google, Inc.

Natural Gas: costs and benefits - TBA

Nuclear Power after Fukushima – Robert Budnitz, LBNL

Session E: Efficient and Transformed Uses Part II

The Science of Smart Grids - TBA

Micro-grid and Off-grid - TBA

Monitoring and Regulating Buildings in Japan - TBA

Batteries – George Crabtree, Argonne National Laboratory

Session F: From Lab to Market

Government Initiatives - TBA

Private Sector Initiatives - TBA

Session G: Non-Energy Climate Initiatives

Adapting to Climate Change – Ann Kinzig, Arizona State U.

Geoengineering – Alan Robock, Rutgers University

Final Comments

Monday-Tuesday, March 10 & 11

Optional field trip visits available: LBNL FlexLab, The Biosciences Institute, and local cleantech companies, including Enphase, Natel Energy, Sunpower, and more.

ARTICLE

Energy Technologies and Induced Seismicity

Murray W. Hitzman, Colorado School of Mines; Donald D. Clarke, Geological Consultant; Emmanuel Detournay, University of Minnesota, CSIRO (Earth Science and Resource Engineering), Australia; James H. Dieterich, University of California; David K. Dillon, David K. Dillon PE, LLC; Elizabeth A. Eide, National Research Council; Sidney J. Green, University of Utah; Robert M. Habiger, Spectraseis; Robin K. McGuire, Lettis Consultants International, Inc.; James K. Mitchell, Virginia Polytechnic Institute and State University; Julie E. Shemeta, MEQ Geo, Inc.; John L. (Bill) Smith, Geothermal Consultant

In recent years, small seismic events in a few locations in the United States have been attributed to injection of fluids related to energy development projects. Although only a small number of the many thousands of earthquakes occurring throughout the world each year are related to any kind of human activity (Figure 1), these "induced seismic events" or "induced earthquakes" can occur at levels noticeable to the public and have caused concern about the potential for further induced events as energy development proceeds (NRC, 2013).

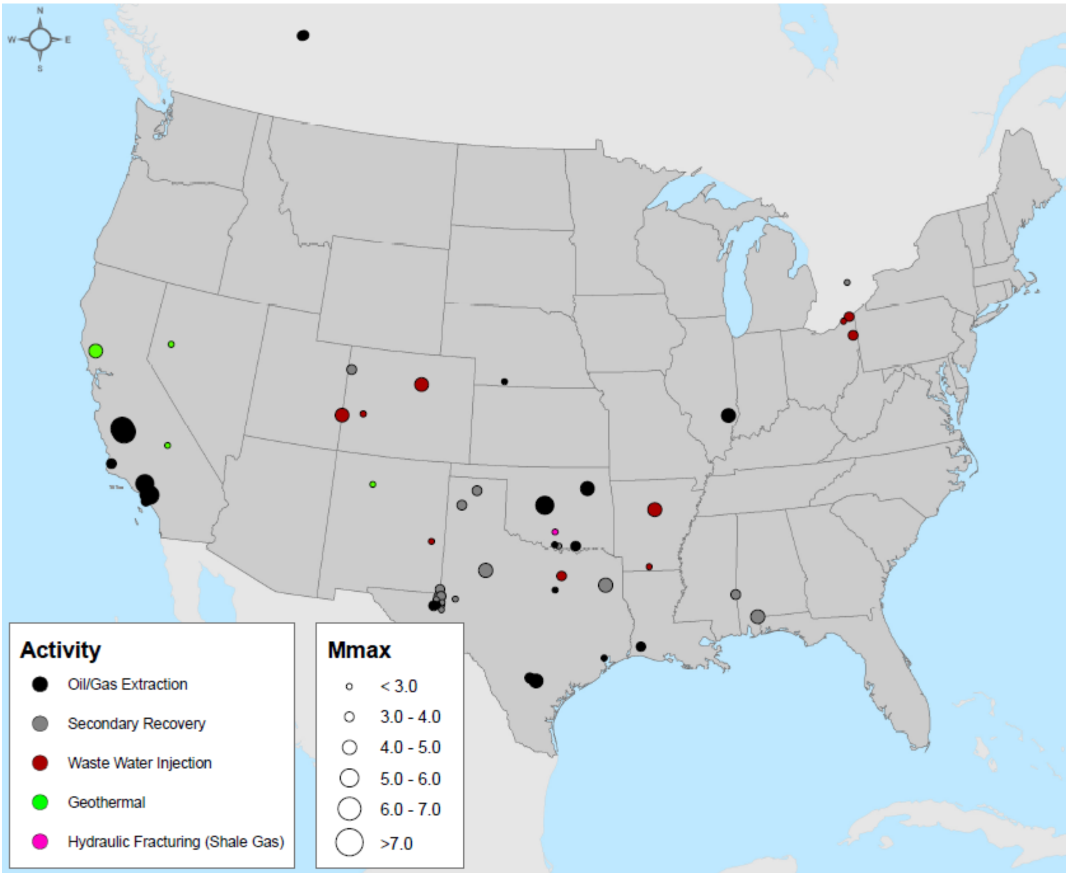

Figure 1 Sites in the United States and Canada with documented reports of seismicity caused by or potentially related to human activities, including injection or withdrawal of fluids related to energy development. Other human activities that have caused induced seismic events include the impoundment of water behind dams, planned explosions at mining and construction sites, and underground nuclear tests. These kinds of induced seismic events have been described since at least the 1920s. SOURCE: NRC (2013)

The occurrence of these recent induced earthquakes related to fluid injection and withdrawal for energy development encouraged the U.S. Department of Energy in 2010 to ask the National Research Council (NRC) to examine induced seismicity that might occur during geothermal energy production, oil and gas production, carbon capture and storage (CCS), and wastewater injection. The work of the NRC committee resulted in a consensus report that was released in June 2012 (see http://www.nap.edu/catalog.php?record_id=13355; NRC, 2013).[1] The significant points of that report including the physical causes, scale and scope, hazards and risks, steps toward developing protocols and best practices, and gaps in current research are outlined briefly in this contribution. A YouTube video, which describes key elements of the report was also developed by the NRC and is available on the National Academies YouTube channel (http://www.youtube.com/watch?v=Uuh9lHavdvc).

What Causes Induced Seismicity?

Earthquakes are generated when a fault moves or slips. The key elements controlling the initiation of slip on a fault are the normal and shear stresses acting on the fault, which are affected by the pore fluid pressure (or pore pressure). The pore

1 *Since the June 2012 release of the National Research Council report, additional work related to induced seismicity, including examination of new seismic events caused or potentially related to energy development, has been undertaken by many researchers. The present contribution is confined to the information that was contained in the NRC report. For information about more recent work related to new and recently documented events in Oklahoma, Colorado, and British Columbia, the reader is referred to some recent work by various authors: Holland (2013), BC Oil and Gas Commission (2013), Kim (2013), and Rubinstein et al. (2013).*

pressure in a rock at depth represents the pressure exerted by the naturally occurring fluids that occupy the voids, faults, and fractures in the rock mass. In principle, faults can be activated if the shear stress (τ) on a fault surpasses its shear resistance. The shear resistance is generally due to friction and is proportional to the difference between the normal stress (σ) acting on the fault, and the pressure (ϱ) of the fluid in the fault and the surrounding rock.

The fault remains stable as long as the magnitude of the shear stress is smaller than the frictional strength, represented by this expression, $\mu(\sigma - \varrho)$, where the term $(\sigma - \varrho)$ is the effective stress and μ is the friction coefficient. This condition for triggering slip is called the Coulomb criterion. If the pore pressure on a fault is perturbed either by pumping fluids into or withdrawing fluids from the surrounding rock, slip on the fault could occur (Figure 2). The magnitude of the pore pressure change ($\Delta\varrho$) is proportional to the volume of fluid injected (see also Nicholson and Wesson, 1990).

Although the conditions for initiating slip on a pre-existing fault are well understood and the state of stress and pore pressure throughout much of the Earth's crust are often not far from the critical conditions for fault slip (Zoback and Zoback, 1980, 1989), reliable estimates of the various quantities in the Coulomb criterion are difficult to make. Similarly, the magnitude of the change in pore pressure that will cause a fault to slip cannot readily be calculated which leads to difficulty in predicting the stability of a fault system.

Scale and Scope of Induced Seismicity for Energy Technologies

Inducing a significant, felt seismic event in association with energy technology development requires (1) an increase or decrease of the pore pressure relative to the pore pressure that existed prior to fluid injection or withdrawal, and (2) a condition such that the change in pore pressure occurs over a region large enough to intersect a fault in a critical state of stress and capable of undergoing slip. The technologies associated with injection and withdrawal of fluids to generate geothermal energy, to produce oil or gas, to dispose of wastewater, and to store carbon dioxide are described briefly in terms of their potential to produce felt seismic events (see also Table 1; NRC, 2013).

Geothermal energy

Three forms of geothermal energy include vapor-dominated, liquid-dominated, and engineered geothermal systems (EGS). The majority of hydrothermal resources are liquid dominated, where primarily hot water is contained in the rock. The Geysers geothermal steam field in northern California is the only vapor-dominated field in the United States and is the most productive geothermal field in the world. EGS, which uses hot, dry rock as the resource, is developed by mechanically

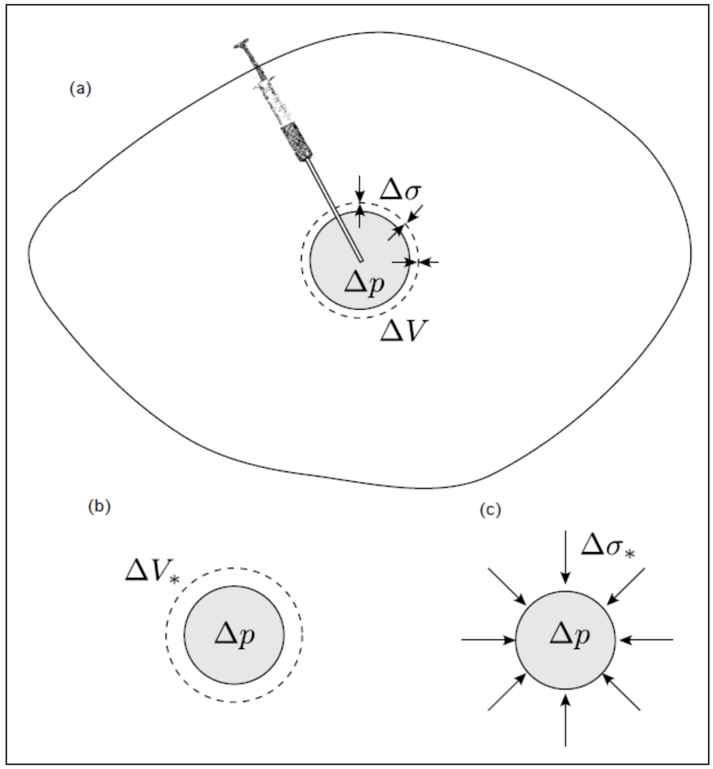

Figure 2 (a) Injection of a finite volume of fluid inside a porous elastic sphere (gray shaded circle) embedded in a large impermeable elastic body (white shape) generates a pore pressure increase ($\Delta\varrho$) inside the sphere and a stress perturbation inside and outside the sphere, caused by the change in volume (ΔV) of the gray sphere (represented by the dashed line around the original sphere and the arrowheads). (b) If the sphere is removed from its elastic surrounding, it will expand by the amount ΔV^* (dashed line around the gray sphere) due to the pore pressure increase, $\Delta\varrho$. (c) When outside of the elastic body, a confining stress $\Delta\sigma^*$ needs to be applied to the gray sphere to prevent the volume change caused by the change in pore pressure.

fracturing the hot rock and circulating fluids through the new fracture system. The fluid becomes heated and is then pumped to the surface where it can be used to generate electricity. EGS is a relatively new technology and commercial projects do not yet exist in the United States, although some are in development.

In terms of overall fluid balance, geothermal projects generally try to maintain a balance between fluid volumes extracted from the reservoir and fluids injected in order to maintain the energy production from the field. This fluid balance helps to maintain fairly constant reservoir pressure and thus reduce the potential for induced seismicity.

Seismic monitoring at liquid-dominated geothermal fields in the western United States has demonstrated relatively few occurrences of felt induced seismicity (Table 1). In The Geysers, the large temperature difference between the injected fluid and the subsurface reservoir causes significant cooling of the hot reservoir rocks; cooling causes the rocks to contract and allows the release of local stresses resulting in some felt induced seismicity each year. Because EGS involves fracturing naturally hot dry rock, small earthquakes, generally below the level that can be felt by humans, would be expected to oc-

Table 1: Summary Information about Historical Felt Seismic Events Caused by or Likely Related to Energy Technology Development in the United States.

Energy technology	Number of Projects	Number of Felt Induced Events	Maximum Magnitude of Felt Events	Number of Events M ≥ 4.0b	Net Reservoir Pressure Change	Mechanism for Induced Seismicity	Location of M ≥ 2.0 Events
Vapor-dominated geothermal	1	300–400 per year since 2005	4.6	1-3 per year	Attempt to maintain balance	Temperature change between injectate and reservoir	CA (The Geysers)
Liquid-dominated geothermal	23	10–40 per year	4.1c	Possibly one	Attempt to maintain balance	Pore pressure increase	CA
Enhanced geothermal systems	~8 pilot projects	2–5 per year d	2.6	0	Attempt to maintain balance	Pore pressure increase and cooling	CA, NV
Secondary oil and gas recovery (waterflooding)	~108,000 (wells)	One or more events at 18 sites across the country	4.9	3	Attempt to maintain balance	Pore pressure increase	AL, CA, CO, MS, OK, TX
Tertiary oil and gas recovery (EOR)	~13,000 (wells)	None known	None known	0	Attempt to maintain balance	Pore pressure increase (likely mechanism)	None known
Hydraulic fracturing for shale gas production	35,000 (wells)	1	2.8	0	Initial positive; then withdraw	Pore pressure increase	OK
Hydrocarbon withdrawal	~6,000 fields	20 sites	6.5	5	Withdrawal	Pore pressure decrease	CA, IL, NB, OK, TX
Waste water disposal wells	~30,000	9 sites	4.8e	7	Addition	Pore pressure increase	AR, CO, OH
Carbon capture and storage, small scale	2f	None known	None known	0	Addition	Pore pressure increase	IL, MS
Carbon capture and storage, large scale	0	None	None	0	Addition	Pore pressure increase	None yet in operation

a Note that that in several cases the causal relationship between the technology and the event was suspected but not confirmed. Determining whethe r a particular earthquake was caused by human activity is often very difficult. The references for the events in this table and the way in which causality may be determined are discussed in the report. Also important is the fact that the well numbers are those wells in operation today, while the numbers of seismic events that are listed refer to events that have taken place over a total period of decades. bAlthough seismic events M > 2.0 can be felt by some people in the vicinity of the event, events M ≥ 4.0 can be felt by most people and may be accompanied by more significant ground shaking, potentially causing greater public concern.

cur during development of EGS fields. The commercial EGS projects in existence around the world monitor this low-level seismicity and have recorded some small events that were felt by local residents.

Oil and gas production

Oil and gas withdrawal. Withdrawal of oil and gas has been linked to felt seismic events at approximately 20 sites in the United States (Table 1; NRC, 2013). These extraction-related events have generally been of M < 4.0 and are rare relative to the very large number of oil and gas fields. The cause of these induced events is generally interpreted to be a net decrease in pore pressure in the reservoir over time if fluids are not re-injected to maintain original pore pressure conditions.

Waterflooding for enhanced recovery. As of early 2012, approximately 108,000 waterflooding wells were permitted in the United States. Few historical or current wells using waterflooding for enhanced oil or gas recovery in the United States have been associated with felt induced seismic events (Table 1). The relatively low number of felt events associated with these projects is attributed to the fact that operators generally do not exceed pre-production pore pressures, and attempt instead to maintain relative balance between the volumes of fluid injected and extracted from the field.

Hydraulic fracturing for unconventional hydrocarbon development. Gas and oil from shale reservoirs is often extracted through the combination of horizontal drilling and hydraulic fracturing (Figure 3). Estimates suggest that well over ~35,000 wells drilled for unconventional oil and gas development existed in the United States in 2011 (EPA, 2011).[2] As with EGS, low-level seismicity (M<2) is often monitored during hydraulic fracturing as a means to observe the developing fracture geometry. Felt seismicity associated with hydraulic fracturing has been rare with one established case worldwide in Blackpool, England (De Pater and Baisch, 2011) at the time of the publication of the NRC report in 2012. Other possible earthquake sequences in Oklahoma that may be associated with hydraulic fracturing have been discussed in the literature (Nicholson and Wesson, 1990, Holland, 2011, 2013; Kim, 2013). Although hydraulic fracturing does increase pore pressure above the minimum in situ stress, the volumes of fluid injected are generally low and are injected over a short time, and the area affected by the increase in pore pressure is localized, remaining in the near vicinity of the created fracture.

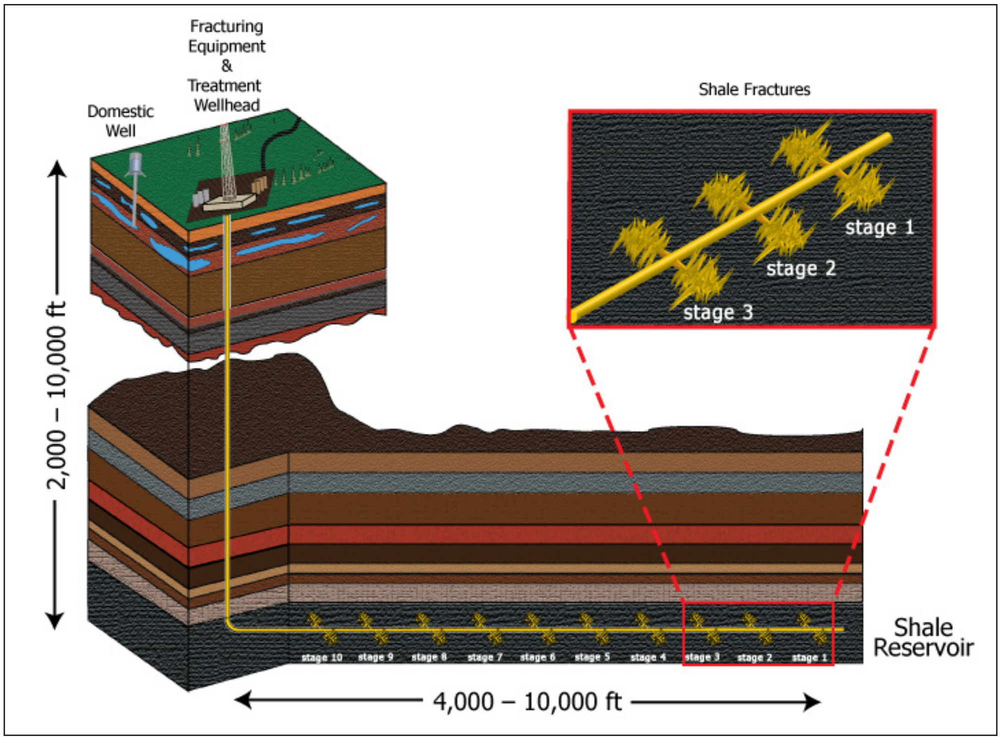

Figure 3. Schematic diagram of a horizontal well with a 10-stage hydraulic fracture treatment. Upper right inset shows the induced fractures (yellow) created during the hydraulic fracture treatment. The well is fractured in stages from the end of the well (stage 1) to the start of the well (stage 10). The depth to the shale reservoir and the length of the horizontal well vary from area to area; approximate averages for North America are shown. The relative depths of local water wells are shown near the surface. SOURCE: Adapted after Southwestern Energy, used with permission.

Wastewater Disposal Wells

To manage wastewater generated by geothermal and oil and gas production, injection wells can be drilled to dispose of the water. Tens of thousands of such wastewater disposal wells are currently active in the United States. This total does not include the many thousands of permitted wastewater disposal wells that are no longer in use. Among both currently active and legacy wells, induced seismicity has been documented at approximately 9 sites over the past several decades (Table 1; NRC, 2013). Nonetheless, a few felt events have occurred recently that generated considerable public attention. Examination of seismic activity in both the Dallas-Ft. Worth area of Texas (Frohlich et al., 2010; Frohlich, 2012) and Guy-Greenbrier area of Arkansas (Horton, 2012) has suggested causal links between the injection zones and subsurface faults.

Because most wastewater disposal wells inject fluid at relatively low pressures into large porous and permeable aquifers designed to accommodate large volumes of fluid, the pore pressure in the subsurface for most wastewater wells would not be anticipated to change significantly. However, high volumes of fluid injected over time or fluid volumes injected into an area in proximity of a pre-existing fault can lead to induced seismic events.

Carbon Capture and Storage

Capturing carbon dioxide as a gas, compressing it, and storing it deep underground as a liquid is a technology being developed to reduce carbon dioxide emissions to the atmosphere. At present, only a few small commercial projects globally have attempted to inject and store carbon dioxide for this purpose. In the United States, several pilot projects are in development. Thus, although data to evaluate the induced seismicity potential of this technology are few, carbon capture and storage differs from other energy technologies because the purpose is to inject large volumes of carbon dioxide under high pressure over a long time for permanent storage with no associated fluid withdrawal. The objective is to store the carbon dioxide forever. The large net volumes of carbon dioxide proposed to be stored with this technology may have potential for inducing felt seismic events due to increases in pore pressure over time and the potential that the total volume of the stored carbon dioxide could at some point intersect a fault in a critical state of stress. The possible effects of large-scale carbon capture storage projects require further research (Zoback and Gorelick, 2012).

2 Note that since the publication of the NRC report in June 2012, the count for hydraulically fractured wells in shale formations has increased substantially.

Hazards and Risk Assessment

Understanding what is meant by hazard and risk related to induced seismicity is critical to any discussion of the options to mitigate the occurrence of felt events and their potential effects. The hazard of induced seismicity takes into account the earthquakes and other physical effects that could be generated by human activities associated with energy technologies involving fluid injection or withdrawal. The risk of induced seismicity considers how induced earthquakes might damage structures. If seismic events occur in areas where no structures exist, there is no risk.

The types of information and data required to provide robust risk assessments for induced seismicity related to energy development projects include net pore pressures and stresses; information on the presence, orientation, and stresses on faults; data on background seismicity; and statistics about previous induced seismicity and volumes and pressures of fluids injected or extracted. No standard methods currently exist to implement risk assessments for induced seismicity.

Best Practices and Protocols

Quantifying hazard and risk can help establish specific "best practice" protocols for energy project development, which aim to reduce the possibility of a felt seismic event and to mitigate the effects of an event if one should occur. Induced seismicity does not fall squarely in the sole purview of any single government agency and requires cooperation among various local, state, and federal government agencies, as well as operators, researchers, and the general public. In areas that are known to have had felt induced seismicity related to fluid injection or withdrawal, a best practices protocol could be part of the approval process for any new injection permit. In areas where unanticipated felt induced seismicity occurs, existing injection permits in that area could be revised to include a best practices protocol.

Using the Department of Energy protocol for induced seismicity related to EGS (Majer et al., 2012), the report developed a set of parallel and concurrent activities to help manage and mitigate induced seismicity from injection associated with EGS. Viewing a protocol as a set of parallel activities can provide the means to reassess the protocol through time as circumstances of an energy project change and more data become available. Such a protocol might include a "traffic light" control system to respond to the occurrence of induced seismicity and could allow for low levels of seismicity but may add monitoring and mitigation requirements if seismic events increase in magnitude or frequency. A critical part of the implementation of any protocol is the clear, regular, and prompt communication with the public and the appropriate regulatory agencies regarding the purpose of the energy project, the intended operations, and the expected impacts on the local communities and facilities (NRC, 2013). The report also suggested that best practice protocols for induced seismicity be developed for each of the energy technologies analyzed in the report.

Proposed Research Needs

Research in five areas was suggested to address gaps in the present understanding of induced seismicity (NRC, 2013).

(1) Collecting field and laboratory data on active seismic events possibly caused by energy development and on specific aspects of the rock system at energy development sites (for example, on fault and fracture properties and orientations, injection rates, fluid volumes).

(2) Developing instrumentation to measure rock and fluid properties before and during energy development projects.

(3) Hazard and risk assessment for individual energy projects.

(4) Developing models, including codes that link geomechanical models with models for reservoir fluid flow and earthquake simulation.

(5) Conducting research on carbon capture and storage, incorporating data from existing sites where carbon dioxide is injected for enhanced oil recovery, and developing models to estimate the potential magnitude of seismic events induced by the large-scale injection of carbon dioxide for storage.

Summary and Major Findings

Many thousands of wells are currently permitted in the United States for developing geothermal resources, oil and gas production, and wastewater disposal; wells for pilot projects for carbon capture and storage are also being permitted. To date, a few documented incidents have occurred in which a few felt earthquakes occurred and were caused by or likely related to fluid injection or withdrawal for these technologies.

Three major findings emerged from the NRC study:

the process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events;

injection for disposal of waste water derived from energy technologies into the subsurface does pose some risk for induced seismicity, but very few events have been documented over the past several decades relative to the large number of disposal wells in operation; and

CCS, due to the large net volumes of injected fluids, may have potential for inducing larger seismic events.

Induced seismicity associated with fluid injection or withdrawal in energy projects seems to be caused in most cases by a change in pore pressure that contributes to change in stress in the subsurface in the presence of faults with specific properties and orientations and a critical state of stress. Although various factors may influence the way fluids behave in the subsurface, the factor that appears to have the most bearing with regard to inducing seismic events along pre-existing faults is the net fluid balance (total balance of fluid introduced into or removed from the subsurface). A change in the fluid balance may change the pore pressure in the vicinity of an existing fault, potentially causing that fault to slip. Energy technology projects that maintain a balance between the amount of fluid being injected and withdrawn, such as most oil and gas development projects, appear to produce fewer seismic events than projects that do not maintain fluid balance. Steps for assessing the potential for and mitigation of induced seismicity related to energy projects that include fluid injection or withdrawal will involve development of methods for quantitative hazard and risk assessment as well as best practice protocols.

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REVIEWS

Atmosphere, Clouds, and Climate

David Randall (Princeton University Press, 2012), 277 pp, $27.95, ISBN 978-0-691-14375-0 (paper); ISBN 978-0-691-14374-3 (hardcover)

This book is a volume in the series "Princeton Primers in Climate." Author David Randall, a professor of atmospheric science at Colorado State University, describes his goals in the preface: "to teach you something about the role of atmospheric processes in climate and to entice you to want to know more." The book is aimed at "college undergraduates who have an interest in climate and some familiarity with basic physics." Randall assumes familiarity with basic calculus and there are a few equations in almost every chapter, "but there are no complicated derivations. The penalty paid for this simplicity is that the explanations given are much less complete and rigorous than they could be in a more technical book."

The book's nine chapters are: (1) Basics; (2) Radiative Energy Flows; (3) How Turbulence and Cumulus Clouds Carry Energy Upward; (4) How Energy Travels from the Tropics to the Poles; (5) Feedbacks; (6) The Water Planet; (7) Predictability of Weather and Climate; (8) Air, Sea, Land; (9) Frontiers.

The author uses a section heading every few pages to divide each chapter into recognizable and easily searchable sections. For example, the nine sections of Chapter 3 are titled Energy Flows Back to the Atmosphere; Turbulent Mixing; Stratification; Static Stability and Instability in Dry Air; Cumulus Instability; Widely Spaced Towers; What Determines the Intensity of the Convection?; Cumulus Fluxes of Energy and Other Things; and Appendix to Chapter 3: More About Energy Fluxes. Randall also usually closes the narrative of each chapter with a look ahead at what is coming next.

The reading aids are needed, because the author's treatment is faithful to the complexity and subtleties of his topic: calculus (including partial derivatives) and vector algebra (specifically vector cross products in treating the geostrophic wind) are used when necessary. The text includes nearly 70 equations, but it also includes more than 40 tables and figures, most of which are discussed well in captions and the narrative, and there is also a good glossary of nearly 60 terms.

Although the subject requires serious attention to technical detail, the author is willing to be informal to be clear. For example, on pp. 90-91, Randall concludes his treatment of "convective available potential energy" (CAPE) with these two paragraphs:

"To gain an intuitive understanding of why this is true, consider an earthy analogy. In this analogy, the convection is represented by a large, very hungry dog. The CAPE is the food in the dog's bowl. CAPE is generated when you, the dog's human companion, add food to the bowl. The ravenous dog wolfs the food down as fast as it appears, so the rate at which the dog consumes the food (the intensity of the convection) is equal to the rate at which you supply the food (the rate of CAPE production).

"Because the dog is such an efficient eater, the bowl is always nearly empty. The analogy here is that the convection consumes CAPE so efficiently that the measured CAPE is always close to zero, despite the fact that CAPE is continually generated by various processes. Because of this, the actual lapse rate is observed to be close to the moist adiabatic lapse rate (Xu and Emanuel, 1989) throughout the tropical troposphere (except in the boundary layer). For reasons explained in Chapter 4, this is true even in portions of the tropics that are far away from regions of active convection."

This excerpt also shows the author's commendable readiness to vary his degree of formality to suit the pedagogical purpose. Notice also the citation of an article in the professional literature. There are more than 70 such works in the bibliography, as well chapter-by-chapter suggestions for further reading. These cover a very wide range, from Arrhenius' 1896 article on the influence of atmospheric carbon dioxide on Earth's surface temperature through recent articles and monographs on climate science.

This reviewer detected a few flaws in the presentation. On page 34, Randall points out that the several important greenhouse molecules all have three or more atoms, and states that "molecules with only two atoms, such as molecular nitrogen and oxygen, do not absorb or emit infrared radiation." This is true in practical terms, but not literally – diatomic oxygen does absorb in several narrow bands in the infrared. In Chapter 2, the text might have been clearer about the fact that different sign conventions are used in Table 2.1 and Figure 2.5. In Chapter 3, Randall uses two different terms ("water vapor mixing ratio" and "specific humidity") for the same quantity without being explicit about it.

Such minor matters do not significantly detract from what is an excellent presentation of a complex subject. Each chapter explains well what it claims to tackle. One of the strongest chapters is Chapter 7: Predictablity of Weather and Climate. Here are two paragraphs from pp. 202-203:

"If weather prediction is impossible beyond two weeks, how can climate prediction be contemplated at all? Two factors have the potential to make climate change prediction possible. First, the climate system has components with very long memories, including especially the ocean. Second, the climate system responds in systematic and predictable ways to changes in the external forcing."

"Weather prediction is very different from climate prediction because changes in the day-to-day weather are not due to changes in the external forcing, while changes in climate are. Weather prediction is limited by sensitive dependence on past history. Climate prediction is not."

The admonition that "There is no royal road to Geometry" is attributed to Euclid, and the same can certainly be said about atmospheric science. The path to expert knowledge is arduous. But for the reader who is prepared to think carefully and sometimes mathematically, David Randall's primer is a wonderful companion for starting along that path. I recommend it highly.

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Straphanger: Saving our cities and ourselves from the automobile

by Taras Grescoe (Henry Holt and Company, New York, 2012), ISBN 978-9-8050-9173-1, hardback $25

(Author note: This article will also appear in "Teachers Clearinghouse Newsletter for Science and Society", and in Northwest Arkansas newspapers.

After a century of car-oriented planning and of rising oil prices that portend the end of cheap energy, Taras Grescoe chronicles a global revolution in transportation. Journeying to many cities, Grescoe gets the story on the world's transit systems and presents an extended argument for expanding such systems.

He focuses on rail, whether subways, light rail, or streetcars, devoting occasional attention to bicycles, sidewalks, and buses, and mindful of the omnipresent automobile. His twelve chapters, one city per chapter, provide a panorama of worldwide transit and its human impacts.

The lessons are many. At an auto show in Shanghai, China, consumers' lust for cars is palpable. The country has overtaken the United States as the world's largest automobile market. Yet on Shanghai's double-decked Inner Ring Road, congestion turns the highway into a six-lane parking lot. Drivers in Beijing were stuck for ten days in a jam that stretched 60 miles. China's air pollution, fed by gasoline engines and coal-burning power plants, is the worst in the world and kills 656,000 citizens prematurely every year. But Shanghai citizens now have a choice: brave the traffic, or ride the Metro. China is investing in new subway systems with thousands of miles of track, and in fast rail that already connects cities with 5,000 miles of track. Only 15 years after opening, Shanghai's Metro counts eleven lines and 261 miles of track, making it the world's largest subway system. It's the fastest way to get around town.

Grescoe, in his mid-forties, has never owned a car. His preface notes, "This book is, in part, the story of a bad idea: the notion that our metropolises should be shaped by the needs of cars, rather than people. ...By diminishing public space, the automobile has made once great cities terrible places to live." However, "This book also tells the story of some very good ideas. ...The movement goes under a variety of names: transit-oriented development, smart growth, new urbanism. ...By investing in development that includes well-conceived transit, we can create more sustainable and, crucially, more civil communities."

He asks whether New York City really needs so much subway. His answer: Definitely. The lines are always full, and standing-room-only at rush hour. Thanks to transit, the city was on its way a century ago to becoming a remarkably good place to live. But then, "like a slow-motion tsunami," the coming of masses of automobiles reshaped the city. By 1932, New York was choking on traffic. But the worst was yet to come: It was architect and "master builder" Robert Moses who made the metropolis safe for the car and, in the process, nearly destroyed the city's quality of life. Today, the promise of North American cities as good places to live is finally being revived, because many people have the courage to oppose what Robert Moses and others tried to impose: Cities built for cars, rather than people. Today in New York even Mayor Bloomberg, to his immense credit, takes the subway to work daily.

Los Angeles is "one city that even the most visionary planners and politicians might not be able to redeem." The trouble is, Angelenos have never really wanted it to be a city. Today it's a random distribution of car-oriented suburbs. Los Angeles was a battlefront during the 1920-1950 destruction of America's streetcars by the automobile industry. Because General Motors, Firestone Tires, Standard Oil, and Mack Truck bought up and eventually scrapped streetcar systems in 45 cities in order to make way for buses built by GM and Mack Truck--buses that were later sold to make way for the automobile--America's cities have for decades been car-dominated. In L.A., the outcome is that the city is built along a thousand miles of urban freeways that function as ersatz city streets.

The Phoenix chapter is sub-titled "The Highway to Hell." Phoenix is "a nightmare, the antithesis of any city I could imagine living in. ...A centerless city." In every city, Grescoe dialogues with leaders and planners. His dialogue with Phoenix planner Joel Kotkin, "probably America's best-known apologist for sprawl," points up the differences between conventional fossil-fueled optimism regarding the future of freeways and far-flung suburbs, versus the new urbanism that thrives on higher densities, walking communities, and transit. Grescoe notes Phoenix's new light-rail system, running on 20 miles of track to the suburb of Mesa. But the city is so sprawled that 20 miles of rail cannot begin to reach the people, so the system is little used. Away from the freeways, one discovers how the subprime crisis has wracked Phoenix. The Metrocenter, for example, was once Arizona's biggest mall but is now a crime-ridden shell of vacant big-box stores. Entire outer subdivisions seem empty. Everything is for sale. Phoenix "could well be the West's next ghost town."

Moving to foreign shores, Grescoe glowingly describes the Paris Metro that, by preserving the city's historic integrity, saved the city. The hero of Copenhagen is the bicycle, "the most decentralized, affordable, and efficient mode of mass transit ever invented." 55 percent of the central city's residents get to work or school by bicycle, and the number is rising. In greater Copenhagen, population 1.8 million, there are more bike-to-work commuters than there are in the entire United States. Copenhagen has waged "a quiet war on cars." As a result, "When sociologists undertake international surveys of life satisfaction, the Danes consistently come out on top."

Moscow is crushed by its congested highways, but partly redeemed by fast, cheap, comfortable subways. Tokyo's trains, whose organizational efficiency is a wonder to behold, keep the city working smoothly. Bogota, Colombia, was declining and headed for tough crime-ridden city streets until a succession of two forward-looking mayors tamed the violence and introduced regulated, modern, "bus rapid transit." BRT, with passenger loading that's similar to subway stations, originated in Curitiba, Brazil, in 1972, and is copied worldwide.

Back in North America, Grescoe studies Portland, Vancouver, Philadelphia, and Montreal--cities that offer hopeful examples for this urbanizing world. The Philadelphia story is the most surprising and most hopeful of the four. Philadelphia is "one city whose center has held," thanks to its well-frequented transit and its rail connections to the east coast Amtrak system. Philly was slowly declining for decades but has been on the upswing, partly due to its long history of rail-centered growth. Transit-proximate households in the United States devote only 9 percent of their income to transportation, compared to 25 percent for car-dependent households. This translates to an enormous economic advantage for people living near transit, an advantage that is maximized in Philadelphia's extensive and dense low-rise residential areas close to the central city. It's worth noting that 35 percent of Americans don't have automobile access, because they are too young, old, infirm, or poor to drive. Thus, Philly is in an excellent position to profit from the urban renaissance that Grescoe foresees. "It bodes well for the future that the public in Philadelphia never lost the habit of using public transport."

Grescoe waxes philosophical about transportation's future. "As the era of cheap fossil fuels that kicked the North American metropolis into a manic state of overdrive comes to an end, the ideology of growth for growth's sake has also reached its limits. When it comes to houses and cities, bigger is not better. Bigger is more McMansions; bigger is subdivisions so sprawled people never get to know their neighbors; bigger is ever longer, ever more soul-sucking commutes. Bigger is stupider."

It's a reasoned, beautifully written, entertaining, and instructive read.

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