Uranium and Nuclear Power: The Role of Exploration Information in Framing Public Policy

Charles F. Mason

H.A. True Chair in Petroleum and Natural Gas Economics
Department of Economics & Finance
University of Wyoming
Laramie, Wyoming

4 April 2013
The Beginning of the End?

➤ on 11 March 2011 Fukushima Daiichi in Japan suffers reactor meltdown
➤ shortly thereafter:
  ▶ Japanese government orders shutdown of all nuclear reactors
  ▶ similar decisions by German and Swiss governments
➤ “beginning of the end” for Nuclear power?
➤ and yet, ...
The Beginning of the End?

- on 11 March 2011 Fukushima Daiichi in Japan suffers reactor meltdown
- shortly thereafter:
  - Japanese government orders shutdown of all nuclear reactors
  - similar decisions by German and Swiss governments
- “beginning of the end” for Nuclear power?
- and yet, ... shortly before the Fukushima event pundits were speaking of a “nuclear renaissance”
Déjà vu All Over Again

► rewind 65 years...
Déjà vu All Over Again

- rewind 65 years...
- At end of WWII, US government wanted to encourage new uranium industry
Déjà vu All Over Again

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► At end of WWII, US government wanted to encourage new uranium industry
  ▶ strong price incentives
Déjà vu All Over Again

► rewind 65 years...
► At end of WWII, US government wanted to encourage new uranium industry
  ▶ strong price incentives
  ▶ extensive road building by AEC
Déjà vu All Over Again

- rewind 65 years...
- At end of WWII, US government wanted to encourage new uranium industry
  - strong price incentives
  - extensive road building by AEC
- solid expansion of uranium industry
- transition in mid-1960s, when nuclear power industry took root
- strong growth in uranium market followed
- until March 1979
Two incidents in March 1979

16 March: release of *China Syndrome*
Two incidents in March 1979

16 March: release of *China Syndrome*

28 March: partial meltdown of Three Mile Island reactor
Two incidents in March 1979

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▶ conventional wisdom: TMI sealed Nuclear power’s fate
Two incidents in March 1979

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- conventional wisdom: TMI sealed Nuclear power’s fate
  - no new Nuclear plant built in US from that date forward*

*FEEM, Venice, 4 April 2013*
Two incidents in March 1979

16 March: release of *China Syndrome*

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- conventional wisdom: TMI sealed Nuclear power’s fate
  - no new Nuclear plant built in US from that date forward*
- “beginning of the end” for Nuclear power?
Time path: price of uranium

U.S. Dollars


Real Value

Nominal Value $U_3O_8$  Real Value $U_3O_8$, 1979 USD
Time path: Nuclear Power

FEEM, Venice, 4 April 2013

Uranium and Nuclear Power

FEEM, Venice, 4 April 2013

Uranium and Nuclear Power
Time path: Nuclear Power, Capacity Utilization

![Graph showing the time path of nuclear power and capacity utilization from 1960 to 2010. The x-axis represents the years, and the y-axis represents the annual nuclear power and nuclear capacity factor. The graph illustrates the increase in nuclear power and capacity utilization over time.]
Time path: Nuclear Power, Summer Capacity
Time path: Electricity Production, Various Fuels

- Electricity from Nuclear
- Electricity from Natural Gas
- Electricity from Coal

FEEM, Venice, 4 April 2013

Uranium and Nuclear Power
Time path: Various Fuels, Summer Power Capacity

- Coal capacity, MW
- Natural gas capacity, MW
- Nuclear capacity, MW
Nuclear Power: Global Role

World nuclear electricity generating capacity by region, 1955-2011

gigawatts

North America 115.4
Europe 125.8
Former Soviet Union 37.1
Asia 63.0
Middle East 0.9
Africa 1.8
Central & South America 2.8

2011
Time Path: Global Nuclear Capacity

![Graph showing the time path of global nuclear capacity and plants.](chart.png)
Nuclear Power: Historical Global Expansion

The graph illustrates the change in world nuclear capacity and planned additions to world capacity from 1950 to 2010.
Why Nuclear Expansion?

![Graph showing planned additions to World capacity and real crude oil price](image-url)
Assumptions

- several identical resource-extracting firms
- initial stock $R_0$, which can be added to via exploration
  - $R_{t+1} = R_t - y_t + x_t \theta_t$
  - new finds are $x \theta$
    - $x$ is rate of exploration
    - $\theta$ is ‘find rate’: amount found per unit drilled
- assume $\theta$ is a log-normally distributed, subject to deterministic effect linked to cumulative exploration, $X$
  - $\theta = f(X) e^{\eta}$
  - $\eta$ is Normal with unknown mean $\mu$, precision $\rho$
  - beliefs over $(\mu, \rho)$ summarized by so-called Normal-Gamma distribution
  - beliefs updated based on exploratory results, posterior distribution also Normal-Gamma
- integrate out uncertainty over $(\mu, \rho)$ to get $g(\eta; I)$
  - generalized student’s t-distribution
  - agent effectively uses this distribution over $\eta$
Learning and value of information

- increasing level of exploration changes $I$ ...
Learning and value of information

- increasing level of exploration changes $I$ ...
- manifested by change in posterior parameters of distribution over $\eta$ ...
Learning and value of information

- increasing level of exploration changes $I$ ...
- manifested by change in posterior parameters of distribution over $\eta$ ...
- which induces a change in parameters of $g(\eta; I)$ ...
Learning and value of information

- Increasing level of exploration changes $l$...
- Manifested by change in posterior parameters of distribution over $\eta$...
- Which induces a change in parameters of $g(\eta; l)$...
- Which yields a value that depends on the agent’s objective function, $\Omega$, $F(\Omega)$:

$$F(\Omega_t) = \int \int \Omega_t g(\eta_t; l_t) \frac{\partial g(\eta_{t+1}; l_{t+1})}{\partial x_t} d\eta_t d\eta_{t+1}$$
Optimal behavior

- privately optimal rate of extraction sets current rents equal to discounted future expected rents
- expectation depends on current beliefs
- but also manifest anticipated extraction next period
  - if current exploration rises, this increases expected finds, which in turn motivates larger production today
  - so current explor’n influences current prod’n (indirectly)
- privately optimal exploration balances current marginal exploration cost against future expected benefits
  - value of expected finds
  - (negative?) impact of current exploration on future find rate, which will adversely impact payoffs two periods hence
  - expected value of information
    - current exploration yields inform’n, changes future beliefs
    - this is true for other firms as well
    - possibility of public good aspect to information
    - also possibility of using information for speculative purposes
Optimality conditions

private optimality conditions:

\[ P_t - C'(y_t^*) = \delta \left\{ P_{t+1} - E_1[C'(y_{t+1}^*)] \right\}; \]
\[ C^e'(x_t^*) = \delta \left\{ E_1[\theta_t(P_{t+1} - C'(y_{t+1}^*))] \right\} + \]
\[ \delta^2 \left\{ E_2\left[ (P_{t+2} - C'(y_{t+2}^*))x_{t+1}^* f'(X_t)e^{\eta t+1} \right] + F(\Pi_{t+2}) \right\} \]
Optimality conditions

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\[ C^e'(x_t^*) = \delta \{ E_1[\theta_t(P_{t+1} - C'(y_{t+1}^*))] \} + \]
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social optimality conditions:

\[ P(y_t^{**}) - C'(y_t^{**}) = \delta [P(y_{t+1}^{**}) - E_1[C'(y_{t+1}^{**})]]; \]
Optimality conditions

private optimality conditions:

\[ P_t - C'(y^*_t) = \delta \{ P_{t+1} - E_1[C'(y^*_{t+1})] \}; \]

\[ C^e'(x^*_t) = \delta \{ E_1[\theta_t(P_{t+1} - C'(y^*_{t+1}))] \} + \]

\[ \delta^2 \left\{ E_2 \left[ \left( P_{t+2} - C'(y^*_{t+2}) \right)x^*_{t+1} f'(X_t)e^{\eta_{t+1}} \right] + F(\Pi_{t+2}) \right\} \]

social optimality conditions:

\[ P(y^**_t) - C'(y^**_t) = \delta \{ P(y^**_{t+1}) - E_1[C'(y^**_{t+1})] \}; \]

\[ C^e'(x^*_t) = \delta \{ E_1[\theta_t(P(y^**_{t+1}) - C'(y^**_{t+1}))] \} + \]

\[ \delta^2 \left\{ E_2 \left[ \left( P(y^**_{t+2}) - C'(y^**_{t+2}) \right)x^*_{t+1} f'(X_t)e^{\eta_{t+1}} \right] + F(W_{t+2}) \right\} \]
Inefficiencies?

- structure of FOC similar for private, social concerns
- in particular, if industry chooses socially optimal exploration then socially optimal production follows
Inefficiencies?

► structure of FOC similar for private, social concerns
► in particular, if industry chooses socially optimal exploration then socially optimal production follows
► but there are reasons exploration is not socially optimal
  ▶ public good vs. speculation
  ▶ fundamental issue: can the firm conceal its exploratory results?
  ▶ nature of mining operations suggests difficulty in spying on other firms
    ▶ contrast to oil exploration
      ▶ $x_t^* \neq x_t^{**}$ if $F(\Pi_{t+2}) \neq F(W_{t+2})$
      ▶ if $W = CS + \Pi$ then inefficient exploration if $F(CS_{t+2}) \neq 0$
      ▶ to evaluate need estimates of production, exploration costs; learning model; demand
Impact of cumulative exploration

\[ f(X) = X^{2.651} e^{-0.5425 - 0.0000295X} \]
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<thead>
<tr>
<th>year</th>
<th>No. Holes</th>
<th>ave. depth</th>
<th>mean</th>
<th>variance</th>
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<td>—</td>
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<td>1968</td>
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<td>482</td>
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Table 2.2: AEC Involvement in the U.S. Uranium Industry

<table>
<thead>
<tr>
<th>Year</th>
<th>Price per lb. U₃O₈</th>
<th>AEC Purchases, % of Output</th>
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<tr>
<td>1948</td>
<td>7.14</td>
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<tr>
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<td>8.53</td>
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</tr>
<tr>
<td>1953</td>
<td>12.35</td>
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<td>1954</td>
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<td>1961</td>
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<td>1963</td>
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<tr>
<td>1964</td>
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<td>1970</td>
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<td>32</td>
</tr>
<tr>
<td>1971</td>
<td>5.54</td>
<td>20</td>
</tr>
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</table>

The result of the AEC policy was the rapid expansion of the mining and milling industry. By 1957, 24 mills had either been built or were under construction with a combined capacity of over 21,000 tons of ore per day (about 18,000 tons of U₃O₈ per year at then prevailing levels of U₃O₈ content in ore).
Uranium demand during AEC epoch

- prior to 1967 AEC only (legal) purchaser of $\text{U}_3\text{O}_8$
- primary motive for purchase: defense
- goal: maximize PDV of $W$ (s.t. industry FOC)
- implies maximization of PDV of $CS$ (s.t. industry FOC)
- if so, then observed pattern of prices, production and exploration would be consistent with
  - Industry FOC on exploration
  - industry FOC on production
  - $F(CS) = 0$
- previous results indicate $F(CS) < 0$ during AEC epoch
Uranium demand after AEC

- private market emerges; prices determined by S & D
- different demand function from first epoch?
- primary purchase motive is electricity production
  - important role for competing input resources
  - proxy: crude oil price
- important and growing role for international supplies
  - likely limited market power for domestic producers
  - reserves key in determining production costs

<table>
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<tr>
<th>regressor</th>
<th>Demand OLS</th>
<th>Demand IV</th>
<th>Supply OLS</th>
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<td>$P_{dom}$</td>
<td>.0837</td>
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<td></td>
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<td>(.4022)</td>
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<td>(.0834)</td>
<td>(.1047)</td>
<td>(.0251)</td>
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<td></td>
<td>(6.469)</td>
<td>(10.848)</td>
<td></td>
<td>(278.27)</td>
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</table>
Uranium demand after AEC, cont.
Peering Into the Future

- Coal is faltering
- Natural Gas is rising rapidly
- huge new deposits of Natural Gas apparently at hand
- what about Uranium?
  - Nuclear continues steady growth, particularly if
    - oil prices continue to rise
    - meaningful carbon policy is enacted
  - likely push towards new exploration, new development
crude prices start to escalate rapidly after 2003
Oil Prices

- Crude prices start to escalate rapidly after 2003

- Single best predictor:
Oil Prices

- Crude prices start to escalate rapidly after 2003

- Single best predictor: size of Chinese economy
Climate Change

[Graph showing global mean temperature from 1960 to 2010]
Carbon Policy and Nuclear Power

- 1.020 kg CO$_2$ per kWh for coal
- 0.515 kg CO$_2$ per kWh for natural gas
- Plausible impact of carbon policy: pressure towards reduced use of both fuels as inputs into electricity
- Then increased pressure for usage of Nuclear energy
  - In North America and Europe
  - Also in FSU, BRIC countries
- Induces increased demand for Uranium
What can we learn from the past experience?

- **AEC epoch**
  - strong price signals lead to over-exuberant exploration
  - excess exploration spills over into extraction levels, yielding social over-production
  - attendant welfare losses from over-exploration, over-production

- **electricity input demand epoch**
  - apparently less persuasive motive for exploration
  - now, socially insufficient exploration levels
  - attendant welfare losses from under-exploration into under-production
    - result: inefficiently large demand for substitute fuels, particularly coal

- **is there a role for (international) governmental intervention?**
  - will a carbon tax motivate exploration?
  - would a separate incentive do better?
    - analogy to R&D
Rift Widens Over Mining of Uranium in Virginia