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## **Sustainable nuclear energy: some reasons for optimism**

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**Abstract:** This paper traces various aspects of nuclear electrical power from about 1970 when it burst on the world scene, starting in the USA and spreading rapidly to the rest of the world. Taking the US situation as typical, and perhaps dominant, I show that the cost of nuclear electricity was cheap in 1973, and the developments since then mostly related to public perception, that made it more expensive. I then describe changes since 1995 that lead me to a cautiously optimistic view that public opinion is changing again and that the cost of nuclear energy will drop as public opinion becomes more favourable.

**Keywords:** nuclear; renewable; fission; reactor; uranium; plutonium; coolant; radiation; sustainability.

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**Biographical notes:** Richard Wilson, MA, DPhil, Oxon, 1949, has taught at Harvard University since 1955 where he is now Mallinckrodt Professor of Physics (emeritus). He is the author or co-author of 890 published papers. Richard and Andrée Desirée Wilson live in Newton Centre. He has engaged in various nuclear studies; measuring the spin of the pi zero meson; nucleon-nucleon scattering, and a study of nucleon structure by electron-proton scattering and muon proton scattering. He became involved with risk analysis of energy and environmental systems starting in 1970 for which he has been recognised by the 'Erice 2005' award for Science and Peace, and the 2007 Dixy Lee Ray award of ASME for risk analysis. His recent books include a *Short History of the Harvard cyclotrons* and *Risk Benefit Analysis*.

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### **1 Introduction: the need for nuclear energy**

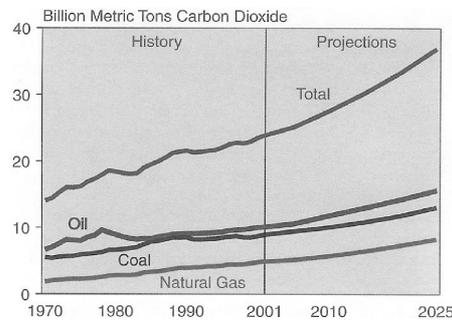
If we accept that it is necessary to reduce the CO<sub>2</sub> concentrations in the air to prevent or cope with global warming, and assume, as seems reasonable, that these concentrations are related to carbon burning as a result of fossil fuel consumption, we must either reduce this fossil fuel consumption or sequester the carbon dioxide for a long period. In the first approach we may either reduce drastically any use of fuels and otherwise use of energy in man's activities (which may be done either by restraint or more efficient use), or switch from fossil fuels to other fuels. There are no reasonable projections that efficient use and renewables can make any appreciable dent in the near future. Numerous experts, of which I quote only two, agree that CO<sub>2</sub> production will increase in the next 25 years.

The Energy Information Agency (2004) projects (Figure 1) a 30% or so increase in CO<sub>2</sub> production, even though a further reduction in energy intensity of 1/3 (to a value 2/3 of the present value) is anticipated in developed countries as shown in Table 1 from the International Energy Office. OPEC is also projecting a similar increase in oil consumption (Shihab-Eldin et al., 2004). This, of course, depends upon cost. In 2005 prices rose to over \$60 a barrel, because of three effects: Failure of the government in Iraq to expand or even maintain, oil production because of instability; fear that international action might stop the flow of Iranian oil; and the adverse effects of the September 2005 hurricanes in the Gulf of Mexico. But even these prices seem not to affect demand appreciably. The options for other fuels include nuclear fusion, nuclear fission, and various 'renewable' resources: hydro, wind, direct solar conversion.

Thus the options are:

- i restraint in any energy use
- ii efficiency in energy use
- iii sequestering carbon
- iv switch to nuclear fission
- v switch to nuclear fusion
- vi switch to hydropower
- vii switch to windpower
- viii switch to other 'renewable' resources.

**Figure 1** CO<sub>2</sub> production in the next 20 years as projected by the Energy Information Administration (EIA)



Source: International Energy Outlook 2004 (IEO 2004)

**Table 1** Energy intensity showing past efficiency improvements and future expectations

	<i>Energy intensity 1000 BTU/\$GDP (1997)</i>		
	<i>1977</i>	<i>2001</i>	<i>2025 (e)</i>
Industrialised Countries (ICs)	13	8	5
Developing Countries (DCs)	23	22	14
East Europe/FSU	45	50	30

Source: IEO (2004)

## 2 Nuclear power: a brief history of the dream and the nightmare

One of the dreams of nuclear physicists ever since the discovery of nuclear fission and the possibility of chain reaction in spring 1939 has been that it can be the basis for a sustainable long-term energy future. When included with Fermi's idea of a breeder reactor to get the most out of the fuel it can easily be shown to produce enough for thousands of years at moderate cost. Glenn Seaborg, when Chairman of the Atomic Energy Commission, had emphasised to the Joint Committee on Atomic Energy of the US Congress in 1968 that nuclear fission can help to avoid global warming.<sup>1</sup> Even before 1975 each step in that process had been tested: mining, fuel fabrication, reactor, waste processing, sequestration. The US people were enthusiastic. But in the early 1970s public perception changed with disastrous effects on the burgeoning nuclear power industry.

Since 1975 environmentalists have urged that the USA and the world return to various 'renewable' resources (vi–viii) and some claim that this can solve the problem. However, the rate of introduction has been slow and it is widely believed that they cannot cope with the problem. Nuclear fusion (v) has not yet been shown to be feasible on any scale. Sequestering carbon, (ii), will certainly be effective on a small scale (capturing CO<sub>2</sub> and selling it to oil companies for secondary and tertiary recovery of oil will certainly be cost effective), but the cost is certain to increase with increasing amounts of carbon sequestered and may soon be excessive. I assume here that no one technology can do the whole job, and a bit of them all may be necessary. In this sense I urge that nuclear fission once again be considered as an important component of any future energy mix *on a par with all other non-fossil technologies*. Although there are reasons for the world's rejection of nuclear fission from 1980 on, I contend, as have other commentators (Cottrell, 1982), that only one objection has any validity, the contribution of nuclear energy to potential proliferation of nuclear weapons, and that is debatable and should be controllable.

I illustrate the differences between those who rejected nuclear power and those who accepted it by two quotations:

In Daniel Ford's view the US nuclear power program is

“the most ambitious, expensive and risky industrial venture ever undertaken,”  
(Ford, 1982)

On the other hand, Samuel McCracken concluded that

“nuclear energy is environmentally the most benign of major energy sources except natural gas. The most benign in terms of public health [and] major accidents and the only major source able, over a long period of time to give us large amounts of flexible energy.” (McCracken, 1982)

I find it hard to believe that these two men were discussing the same subject! In a talk I gave at a meeting on global warming in 1991, I noted the very unfavourable public opinion and some of its bad consequences. I predicted that all the nuclear power plants in the USA would be abandoned as their licenses expired and there would be no nuclear power plants left by 2025. I even commented, not entirely in jest, that the Nuclear Regulatory Commission might still be expanding at the rate of 4.8% per year as suggested by Parkinson's first law (Parkinson, 1955, 1957, 1958). Matters got worse until about 1995 and since then a number of reasons have changed my pessimism into cautious optimism. What had gone wrong and what has now gone right? Will it stay that way?

### 3 Public visibility

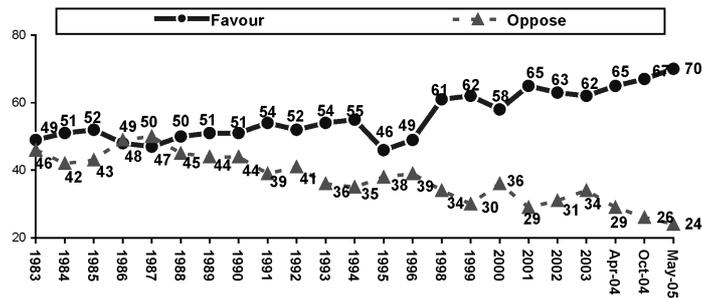
The nuclear enterprise has been much more open than many comparable enterprises. In the USA, for example, most technically minded people have been able to obtain information and data from AEC, ERDA, NRC and DOE and nuclear engineers when they ask.<sup>2</sup> But utility management often failed to interact positively with the public, and many executives failed to understand the technical issues, and hid this failure from the public. This inevitably led to mistrust among the non-technical public. Public opposition affects almost every aspect of the nuclear enterprise. Before 1970, there was general support among the US public. Public hearings took less than a day and were usually unopposed. After 1970 opposition increased rapidly. The US licensing system had deliberately been set up to allow many places for the public to express their views. Express them they did in formal public hearings – making these hearings last from the hours in the 1960s to years in the 1980s. It is evident that regulators of the industry, both safety regulators and economic regulators are strongly influenced by the public. Other effects of public concern and opposition are more subtle but nonetheless real.

Opposition increased dramatically after the Three Mile Island accident in 1979, although, unlike most serious industrial accidents, this accident killed nobody and gave nobody an excessive radiation dose. It increased still further after the Chernobyl accident in the Ukraine in 1986, even though that accident occurred at a power plant of a design that would not have been acceptable in any western country, and which was operated in a manner without the regard given in the west of learning from industrial experience. One leading Russian scientist commented that the accident proved that their political system could not handle modern technology.<sup>3</sup> The Chernobyl accident resulted in 31 reported direct fatalities, and estimates for *calculated* long term cancer fatalities range from 5,000 to 300,000. The larger figure was from physicians and others who took a pessimistic approach, and the smaller one represents the considered opinion of experts, particularly in 2005 (International Atomic Energy Agency, 2005) which opinion is now being given more weight. I have described elsewhere how the secrecy inherent in their society made such an accident inevitable (Shlyakhter and Wilson, 1992a, 1992b). In contrast, coal mining worker fatalities in the USA average 100 *per year*, and estimates for premature deaths due to particulate air pollution in the US range from 5,000 to 70,000 *per year* (Wilson, 1972a).<sup>4</sup> Estimates of the death toll from the arsenic catastrophe in Bangladesh range up to a million. Arsenic pollution in Bangladesh water is also a man made disaster because UNICEF, the World Bank and the British Geological Survey encouraged drilling of tube wells to tap ground water instead of using surface water. The aquifer had not previously been used and no one checked for arsenic. There were no public opinion polls in the 1970s. The above statements about public opinion are based, therefore on less quantitative justifications. My personal experience is that students at Harvard University from 1975 to 1995 considered that “safe and environmentally friendly” nuclear power is an oxymoron. But by the year 2000 students are critical but positive and are now saying: ‘why not?’.

The change since the early 1990s is shown in public opinion polls. The answers to polls depend on the exact wording of the question. I noted many years ago that polls seemed to find a hard core of 20% opposition, and a hard core, mostly of scientists, who were strongly in favour – with 60% in the middle whose answer depended critically on the question. To avoid the problem that the answer depends upon the detailed question, I take the polls from one organisation – Ann Bisconti Research in the USA and only

examine the trend. Figure 2 shows the trend in the answer to the question “Do you strongly agree, or do you somewhat agree that we should build more nuclear power plants?” In addition to the increasing fraction of people who agree, there is a greater perception of the support of other members of the public – one’s friends and neighbours. Figure 3 shows the (2003) response to the question: “US DOE and electricity companies should work together to build state-of-the-art nuclear power plants that can be built to meet public demand”. European support is similar. Table 2 shows the response in several European countries to the question: “If the waste is managed safely, nuclear power should remain an option for electricity production in the European Union”. The *public* responses from France and Italy are very similar although France has developed nuclear power and Italy, after a public referendum 20 years ago decided not to do so. Public support in Germany likewise is similar to that in France in spite of their official governmental opposition. The French *government* support is usually attributed to their centralised governmental structure as contrasted to a federal system in Germany. The surprising result for me is the large public support in Sweden – a country whose government officially decided 20 years ago to close down all plants and whose prime minister stated in 1986: “Nuclear power is one of the greatest threats to our environment ... Nuclear power must be gotten rid of!”<sup>5</sup>

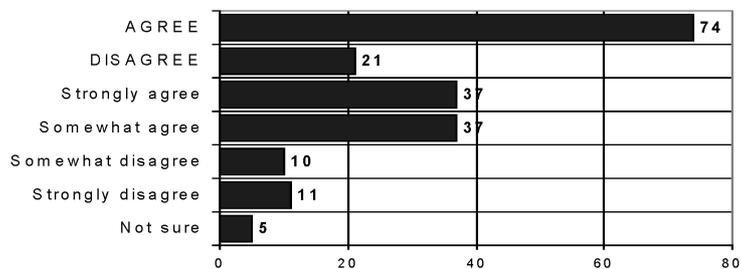
**Figure 2** The percentage of people who wholly or somewhat favour building new nuclear power plants in the USA (black) and those who oppose (grey)



Source: From Bisconti (2005)

**Figure 3** Public opinion about how to construct new nuclear power in the USA

US Department of Energy and electric companies should work together to develop state-of-the-art nuclear power plants that can be built to meet new electricity demand.”



Source: Bisconti (2005)

**Table 2** A 2003 public opinion poll in Europe in response to the question: “If the waste is managed safely, nuclear power should remain an option for electricity production in the European Union”

Country	Strongly agree	Tend to agree	Tend to disagree	Strongly disagree	Average	Do not know
Belgium	13.1	46.9	11.0	5.9	2.87	23.1
Denmark	29.5	24.7	13.4	25.3	2.63	7.1
Deutschland-W	12.7	33.3	21.7	14.0	2.55	18.3
D-Total	12.5	35.1	20.7	13.1	2.58	18.6
Deutschland-E	11.9	42.1	16.7	9.6	2.70	19.7
Greece	19.0	29.4	13.9	8.1	2.84	29.6
Estonia	9.0	22.6	17.9	10.0	2.52	40.6
France	15.8	43.4	13.6	8.7	2.81	18.6
Ireland	7.2	30.3	14.8	10.7	2.54	37.0
Italy	13.7	40.8	11.4	6.6	2.85	27.5
Lithuania	14.9	40.5	18.8	12.9	2.66	12.9
Netherlands	30.8	29.4	10.0	14.6	2.90	15.2
Austria	8.0	16.6	23.2	38.6	1.93	13.6
Poland	5.7	32.5	12.4	7.6	2.62	41.8
Finland	26.5	38.5	14.7	9.5	2.92	10.8
Sweden	47.3	26.3	9.9	8.0	3.23	8.5
UK	14.0	38.6	13.0	7.9	2.80	26.5
EU 15	14.9	35.6	15.1	10.4	2.72	24.0

Source: Bisconti (2005)

There is another indication of the change which, in my view, should not be ignored. Patrick Moore, chairman and chief scientist of Green Spirit Strategies Ltd. and a founder of Greenpeace, testified in a Congressional hearing that, in his view, the development of nuclear energy is very important for environmental reasons.<sup>6</sup> The rise in gasoline prices in September 1955 also has an effect on public opinion. This is probably the case even though, in the USA at least, alternates to conventional oil are likely to become available at reasonable cost – oil from tar sands and methanol from coal. In this way fossil fuels are likely to be available for the next 100 years at least.

One must not exaggerate the change in public opinion. The question posed in Figure 2 was a general one for the future. When it comes to a specific plant at a specific site, the answers are different (Carlson, 2004). In general those in the specific locality tend to be in favour, because the facility pays real estate taxes on an expensive facility,<sup>7</sup> but those further removed (for example at the state level) tend to object. NIMBY (not in my back yard) does not therefore seem to apply but NIMNBY (not in my neighbours back yard) does (Shlyakhter et al., 1995). Perhaps because of this, tentative locations for new nuclear plants in the USA are locations where there is already an existing power plant. This may avoid this particular problem for a while. Also the rising cost of natural gas and of oil may sway the 60% of those polled, who as noted above, vote in different ways depending upon the exact question.

In 1991 it was felt that the operating licenses for nuclear reactors, which would be coming up for review in the 2000–2020 period would meet with the intense public opposition that the initial operating licenses met in the 1980s. But this has not turned out to be the case. Operating licenses which were typically for 40 years are now being extended to 60 years without appreciable public opposition. The recent announcement (August 2004) that the State of New Jersey will oppose the license extension for the Oyster Creek plant is unusual, and may be only because it is one of the oldest plants and the first of a series). Many scientists and engineers think that the extension can be for an even longer period.

Public perception and public opposition would not matter if it did not impact cost.

#### 4 Cost

Eugene Wigner reminded us in 1975 that if nuclear power is more expensive than other fuels it will not be used. But that was before opposition arose. Moreover costs depend upon the boundary conditions and upon the way they are calculated. These have changed. In this I urge a look at history. Indeed, I urge the proponents of any resurgence in a technology to look at history and explain why matters are now different. It is a historical fact that in 1973 nuclear powered electricity was cheaper than other sources of electricity in the USA. Connecticut Yankee was producing electricity at 0.55 cents/kWh including paying off the mortgage on the capital investment.<sup>8</sup> Capital costs were less than \$200 per kilowatt electric (kWe).<sup>9</sup> The cost calculations of Virginia Power and Light, made when they decided to build a nuclear rather than a coal plant (at Surry), are shown in the last column of Table 3. (Benedict, 1971) Note that they used a charge on capital of 13% which is higher than used for many governmental projects. For example France has often used 5%.

**Table 3** Projected Busbar costs of nuclear energy at various times (uncorrected for inflation) 1971 costs from Benedict (1971) as calculated by Virginia power and light

<i>Description</i>	<i>2005</i>	<i>2002</i>	<i>1971</i>
Unit investment cost of plant, dollars/kw	\$1,400	\$1,700	\$255
Annual capital charge rate per year	0.13	0.13	0.13
Kilowatt-hours generated per year per kw capacity	8,200	7,446	5,256
<i>Cost of electricity (cents/kwh)</i>			
Plant investment	2.22	2.97	0.63
Operation and maintenance	1.3	1.50	0.04
Fuel	0.18	0.21	0.19
<i>Total</i>	<i>3.7</i>	<i>4.68</i>	<i>0.86</i>

##### 4.1 Capital costs

Since 1973 there have been many improvements in the existing technology that should have made nuclear power safer and cheaper. Although the consumer price index only went up a factor of 4.5, capital costs went up after 1973 over 10 fold from \$200 per kWe to \$2,000 per kWe (and for badly managed plants to \$5,000 per kWe and operating costs

a factor of 50 from 0.04 cents per kwh to 2 cents per kwh – both much more than inflation. Why has there been this dramatic increase in cost? For most technologies there has been a modest improvement (reduction) in cost with time as engineers and others learn to cut costs. This is known as a *Learning Curve*. For nuclear power we seem to have had a *Forgetting Curve*! Several reasons have been suggested.

- In 1970 manufacturers built ‘turn key’ plants or otherwise sold cheap reactors as loss leaders. But this can only account for a small proportion of the capital cost.
- Construction costs generally have risen since 1970 even when corrected for inflation.
- It may be that in 1972 we had good management and good technical people. But why has management got worse when that has not been true for other technologies?
- Operating costs rose rapidly in the 1970s because the rate of expansion of nuclear energy exceeded the rate of training of good personnel.
- A sudden rise in costs came in the late 1970s after the accident at Three Mile Island unit II. This aggravated the next item.
- Mandated retrofits have been blamed for some cost increases, this applies to mostly existing plants and to a lesser extent to new construction.

Although it is abundantly clear that poor management has been the reason for much of the problem, I contend that a large part has been a reaction to the unfavourable public opinion including some excessive regulatory requirements that were imposed in response to the public concern. In the following sections I will detail some of these and how they have changed in the last nine years. (Reasonable) projections are that the capital costs for new nuclear plants (with the newer designs) will be \$1,400 per kWe for the first plant in a series and \$1,000 per kWe after the first of a type. Operating costs have also been declining slightly, and plant availability has increased markedly. I put these numbers in the first column of Table 3 and suggest that nuclear power will be cost competitive against all other sources *provided that the present favourable climate continues*.

#### 4.2 *Operating costs*

Management and operation costs have had an even more dramatic increase than capital costs that will be hard to reverse. The cost is even higher than the 2004 number of 1.4 cents/kwh and 0.04 kWh, because the present 1.4 cents/kWh cost is inversely proportional to availability and the availability has improved.

Various plant operators have described factors that caused the increase. The number of security guards at Point Beach, Wisconsin went from 3 to over 100 in 10 years. Dresden power plant went from 250 employees in 1975 to over 1,300 in 15 years.<sup>10</sup> The increasing attention to sabotage and terrorism since 2001 ensures that the increase in security personnel will stay. Much of the other increases in staff will also stay because they are needed to carry out maintenance during operation. However the average number of staff at two unit plants has fallen again to 1,100 persons (FTE) and at single unit plants has fallen to about 700 (Navigant Consulting, 2004). Although the operating cost remains higher than originally anticipated in 1970, they are manageable.

## **5 Construction delays**

In 1980 the time between approval (issuance by the Nuclear Regulatory Commission of a construction permit) and completion (issuance of an operating license and connection to the electricity grid) had increased from the 3 years to construct of Connecticut Yankee first to 6 years and then to more than 12 years. (A simple average of construction times is infinite and means nothing because some plants were never completed!) This increase in time was due almost entirely to public opposition in the licensing process. This added considerably to cost. The original intention was that major aspects of nuclear power and of the plant design would be decided (and litigated if necessary) before the construction permit was issued, leaving only a discussion of whether the construction proceeded according to design, and whether any variations from that design made a difference in safety. But public opposition in the operating license phase prevented this. It is well known that to build a project cheaply it should be built fast. This keeps labour costs down. Moreover a major cost item is always interest on capital expended during construction. The 'capital charge rate' (related to but not identical with the interest rate) had increased from the 13% assumed in 1973 to 17%. Many power plant operators had ordered the expensive item, the reactor vessel, too early, and for these the interest cost loomed large. For some plants interest during construction was more than half the total capital cost.

By careful planning (scheduling) and improvements in public acceptance and other improvements suggest that these costs can be brought down. But most importantly, the licensing process has been changed with a 'one stop' licensing with most details accepted early in the process. It remains to be seen whether this will be opposed and if so whether the procedure will survive the opposition. For example the NRC has been asked for preliminary approval for a new Advanced Boiling Reactor at the site of the existing Grand Gulf reactor in Port Gibson, Mississippi, and a 1000 We Advanced Pressured Water Reactor at the site of the Bellefonte reactor near Scottsboro, Tennessee.

## **6 Raw materials requirements**

The evolutionary plants ordered and built (overseas) in the 1990s, like the General Electric Advanced Boiling Water Reactor, actually used more steel and concrete for construction, per unit of power output, than their 1970s predecessors, due to design changes to address safety issues. However, this has changed greatly with the new plants with 'passive' safety features that depend upon fundamental physical principles for safety rather than an engineered safety device. These are the ESBWR and AP-1000 – now being certified by the NRC and being considered by US utilities for new construction. These new power plant designs have been made which use fewer components – especially fewer components of 'safety grade' and less materials generally. This will reduce costs.

The cost of processing raw materials and constructing buildings out of them has increased generally faster than inflation. Early critics of nuclear energy pointed out that energy is needed to prepare the fuel, separate the isotopes adequately for a fission process to proceed, and for the materials for the reactor and all parts of the fuel chain. Many of the critics exaggerated the numbers by attributing to the early nuclear reactors all the costs of the nuclear weapons program. Others implied, incorrectly, that these costs were higher for nuclear power than for other sources of energy. A lot depends on the specific

technology, but recent studies confirm the relatively small use of these resources by nuclear power generation.

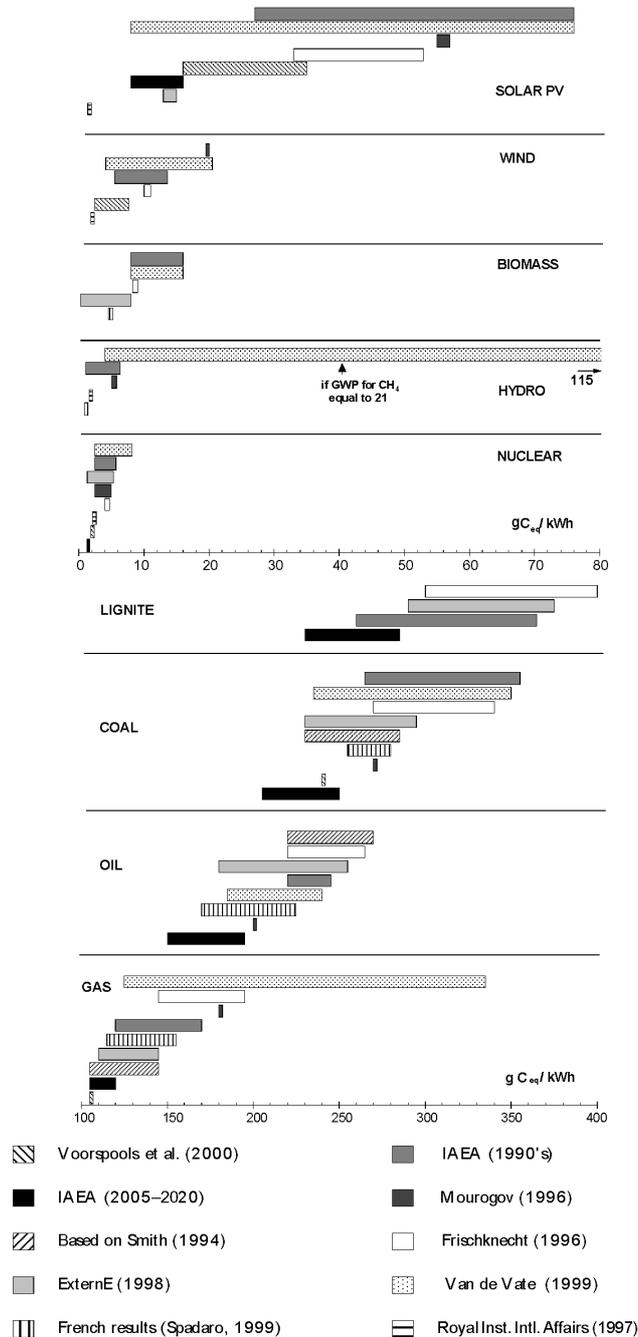
New 'passive' nuclear power plant designs will need 20–40% less construction materials than previously. Existing 1970-vintage US nuclear power plants use 40 Mt of steel and 190 m<sup>3</sup> of concrete per average megawatt of electricity generation capacity (Bryan and Dudley, 1974).<sup>11</sup> A large part of this reduction is a reduction in the size of the nuclear 'island'. In addition the incorporation of many passive safety features should reduce the number of 'safety qualified' components needed in this nuclear island.

Although the material required in construction is rarely an explicit part of a construction decision, it has often been discussed by opponents of nuclear power who remind us that in providing the raw materials for nuclear reactors, as well as other power plants, carbon dioxide is produced. For comparison, a typical wind-energy system operating with 6.5 m/s average wind speed requires construction inputs of 460 Mt of steel and 870 m<sup>3</sup> of concrete per average MW(e) (Pacca and Horvath, 2002)<sup>12</sup> although this also is being reduced. Coal uses 98 Mt of steel and 160 m<sup>3</sup> of concrete per average MW(e), and natural-gas combined cycle plants use 3.3 MT steel and 27 m<sup>3</sup> concrete (Meier, 2002). A systematic study prepared for IAEA by Spadaro (2001) notes that various construction materials, such as making concrete, generates CO<sub>2</sub>, and puts this into the entire fuel chain and calculated the CO<sub>2</sub> from the entire chain (Figure 4).

## **7 Nuclear fuel integrity**

The problem with nuclear fuel is that during operation it undergoes a dramatic change as the uranium changes to plutonium and fission products fill any gaps in the structure. In 1973, the nuclear fuel in the fuel rods was not always able to maintain integrity, and in common parlance 'fell apart' after a certain 'burn up' (in the peculiar units engineers use, after 20,000 Mw-day per ton). Now nuclear utilities regularly attain a 'burn up' of 42,000 Mw-day per ton and future designs anticipate 100,000 MW-day per ton. Not only does that improvement cut fuel fabrication costs, and waste disposal costs in half, it enables a longer period between shut downs for fuel changes. Although it increases the utilisation of the fuel, with plutonium being burnt in the later times, this improvement is not proportional to the burn up since the fuel has to start with higher enrichment. Associated with the improvements in fuel integrity are improvements in radioactivity containment. The original power plants were designed to allow 1% of fuel rods to leak. Now 70% of power plants operate without any leaking fuel. This improves employee radiation safety. By the above and other methods, radiation doses to employees have steadily been reduced. This improvement in fuel rod integrity is a major factor in my cautious optimism.

**Figure 4** Total GHG emission factors in grams of carbon emitted per kWh) from electricity generation using fossil fuels (a), nuclear power and renewable forms of energy (b). Details are provided in the legend below. Since van de Vate's upper limit for hydropower was based on a Global Warming Potential of 60 for methane, we show an updated estimate using the IPCC 1996 recommended value of 21



Source: From Spadaro (2001)

## 8 Cooling channel failures

A major problem with US reactors in the 1970s was a corrosion-related failure, in many reactors, of the cooling water tubes in the heat exchangers (steam generators) of Pressurised Water Reactors. Individual tubes could be plugged but there was a limit after which complete replacement of the steam generator was necessary. Since the steam generator is physically large this often entailed considerable cost. While this contributed extensively to nuclear power costs in the 1980s, better materials science has enabled the problems to be effectively solved for all future reactors.

The coolant in the Canadian CANDU reactors proved even more troublesome, since each coolant channel is a fuel channel in the reactor itself. Starting in the 1980s and continuing through the 1990s, the Canadian CANDUs were shut down. Many experts predicted that they would never restart. But one after another is being returned to the grid (Blake, 2005). (see also Table 4). There is good reason to hope and expect that the newer tubes will be free of the materials defect.

**Table 4** Nuclear power additions and subtractions January 1st 2004 to August 31st 2005

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*442 total operating nuclear power plants with total generating capacity 369 Gwe  
24 nuclear power plants under construction*

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*Changes of NPP status during 2004 (as of 31 December 2004)*

- New connection to the grid
  - Qinshan 2-2, 610 MW(e), PWR, China, (March)
  - Hamaoka 5, 1325 MW(e), ABWR, Japan, (April – commercial operation January 2005)
  - Khmel'nitski 2, 950 MW(e), PWR (WWER), Ukraine, (August-commercial operation September 2005)
  - Rovno 4, 950 MW(e), PWR (WWER), Ukraine, (October)
  - Kalinin 3, 950 MW(e) PWR (WWER), Russia, (December)
- Reconnection to the grid following a long term shutdown
  - Bruce 3, 790 MW(e), PHWR, Canada, (January)
- Final shutdown
  - Chapelcross A, B, C, D units, 50 MW(e)/each, GCR, UK, (June)
  - Ignalina 1, 1185 MW(e), RBMK, Lithuania, (December)
- Construction initiation
  - Tomari 3, 866 MW(e), PWR, Japan (October)
  - PFBR Kalpakkam, 470 MW(e), FBR, India (October) \

*Changes in 2005*

- New units
    - Shika 2 (1304 MW(e), ABWR, Japan) was connected to the grid on 4 July
    - Tarapur 4 (490 MW(e), PHWR, India) was connected to the grid on 4 June
    - Ulchin 6 (960 MW(e), PWR, South Korea) was connected to the grid on 7 January
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**Table 4** Nuclear power additions and subtractions January 1st 2004 to August 31st 2005 (continued)

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*442 total operating nuclear power plants with total generating capacity 369 Gwe*

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*24 nuclear power plants under construction*

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*Changes in 2005*

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- Restarts after a long term shutdown
  - Pickering 1 (515 MW(e), PHWR, Canada) was reconnected to the grid on 26 September
- Final shutdowns
  - Barsebäck 2 (600 MW(e), BWR, Sweden) was shut-down on 31 May
  - Obrigheim (340 MW(e), PWR, Germany) was shut-down on 11 May
- Construction initiation
  - Olkiluoto 3 (1600 MW(e), PWR, Finland) – construction officially started on 12 August
  - Chasnupp 2 (300 MW(e), PWR, Pakistan) – the first groundbreaking was done on 8 April
  - Qinshan 3-2, a 665 MW(e) PHWR in China
  - Ulchin 5, a 960 MW(e) PWR on S. Korea

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*Source:* Data from IAEA website in October 2005

## 9 Safety regulation

It has been said that the power to regulate is the power to destroy. This has certainly been the experience of the nuclear industry. Regulation of many industries increased rapidly during the 1970s. In 1970 when Maine Yankee was being licensed, there were 91 permits to be obtained including, for example, a permit to discharge sewage. By 1975 this had risen to over 400 permits per plant! But there are only two regulatory authorities of importance: the Federal Nuclear Regulatory Commission (NRC) and the various state Public Utility Commissions (PUCs).

The NRC regulates safety, including radiation safety, although radiation safety for small amounts of radiation is often delegated to the states when the states show adequate competence. Regulatory authorities, especially state authorities, are sensitive to public opinion and have often been very assertive of their power and their duty. A power plant can earn \$1,000,000 in electricity sales each day and the incentive to keep the plant operating is great. Correspondingly the power of the regulator is great. This has often been used in undesirable ways. For example in spring 1978 concern was raised about ability of piping to withstand an earthquake. The NRC insisted on a shut down of the affected plants while this was being investigated. For most plants no change was needed and it was clear that the calculated effect on safety was small. A better NRC action would have been to order an immediate staged study of the situation; firstly to see whether an immediate shut down was necessary and secondly to suggest, or order, changes in a calm and orderly manner.

In 1996 Northeast Utilities, operator of four nuclear power reactors, including Connecticut Yankee which as noted above had generated cheap electricity, was in trouble. The original specific problem appears to have been the movement of a larger number of fuel bundles from the reactor to the spent fuel pit during shut down than envisaged (allowed) in the technical specifications. Moreover Northeast Utilities supplied inadequate information about it to NRC regulators rather than investing the modest effort required to modify the plant or modify the technical specifications. Although the calculated effect on accident probability was small and well within the NRC's safety goals, they were clearly in violation of the specific specifications. Other similar problems were found and the Chairman of the Nuclear Regulatory Commission insisted on a shut down<sup>13</sup> – which ended up in a shut down of two plants (Millstone 2 and 3) and a permanent shut down of Millstone 1 and Connecticut Yankee. In one sense this was a reasonable decision. Nuclear operators should operate their plants according to the rules, and society should make sure that the rules are reasonable and can be modified based on reasoned analysis. Providing inadequate reports is sloppy, and shows business incompetence. It is also unnecessary because the regulatory system permits utilities to change the rules if they can show that indeed there are no safety impacts.

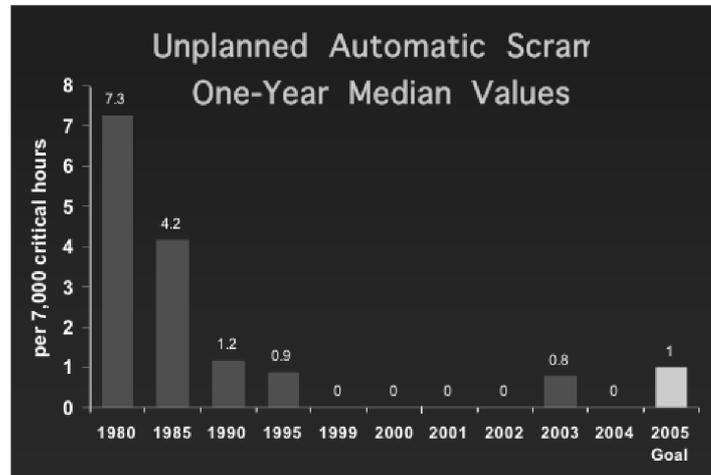
Nonetheless the response was stronger than necessary – some would call it draconian. It was very costly in money and in air pollution from substitute power. It gave a very negative signal to the industry. While the executives of Northeast Utilities deserved this slap in the face, the people of Connecticut (who pay higher rates in consequence) did not. In a Senate hearing (Wilson, 1998) I likened this to the problems that would be created by a bus driver who regularly drove down 5th Avenue at 5 mph more than the speed limit and the policeman on beat waved at him. A whistle blower insisted on action so that the whole bus system was shut down for two years. Unfortunately in the 1990s utility companies got the message and several reactors were shut down rather than face a future which seemed, at the time, to be bleak. The response of NRC to public enquiry was slow. When I politely asked the Chairman, by mail and fax, whether my estimate was correct that the effect on safety of the specific action was less than the NRC guidelines, I received no reply for two months. Then I received a two page letter from the Director of Regulation, not the Chairman, describing the regulatory authority but not answering my question. He was not as forthcoming as the chairman of the excessively maligned AEC, was some 20 years earlier.

But in 2004 the regulatory procedure had changed. The commission has now endorsed “risk informed regulation” (Jackson, 1998).<sup>14</sup> Rigorous regulation is only used for those aspects of the system that have a large impact on safety as measured by the calculated accident probability. The situations just described would probably not have led to plant shut down but regulatory action short of shut down. Part of the reason for the change is in the thinking of the regulatory body and a part due to the changed thinking of engineers generally. Many older engineers had preferred the definiteness of a strict regulation to the calculation procedure of the Probabilistic Risk Assessment (PRA).

Associated with this Risk Informed Regulation is a realisation by industry and regulators alike that a well operating plant is a safe plant. World Association of Nuclear Operators (WANO) has developed a number of indicators of plant performance. There are many of these and I show just one, unplanned shut downs or ‘scrams’. These have been reduced over the last decade as shown in Figure 5, with a consequent reduction in stress on the plant, and according to the PRA, an improvement in safety.

But the situation could change back.

**Figure 5** The reduction in the number of unplanned automatic shut downs (scrams) per year (data from the World Association of Nuclear Operators (WANO))



## 10 Economic regulation

For most of the 20th century public utilities in the USA were monopolies. In exchange for this monopoly they were subject to state economic regulation by PUCs. Utilities were only allowed to collect a fixed percentage of their capital assets – usually about 6%. Although the state PUCs were only supposed to regulate the economics, this was interpreted ‘liberally’ and in many cases the PUCs used their considerable power to prevent nuclear power plants coming online. This power was exercised in subtle ways.

The most evident example was the refusal of the PUC of New York State to allow a rate increase to Long Island Lighting Company until they abandoned the Shoreham Nuclear Power plant which had just (April 1989) obtained a full power license from NRC after a long battle with public opposition.

But in the late 1990s all has changed. In most states the electricity system has been deregulated to some degree and the utility companies have sold their power plants to an independent generator. The power plant operator is now subject, of course, to ordinary economic competition, and to federal regulation by the NRC, but no longer subject to the unpredictable behaviour of the PUCs.

## 11 Miscellaneous improvements

Although there appears to have been no learning curve when cost is concerned, there is a learning curve in safety – as measured by a number of indicators by the Institute of Nuclear Power Operators (INPO) and its world equivalent, the World Association of Nuclear Operators (WANO) and by the calculated accident probability. The criticisms of the PRA approach of Rasmussen in the 1970s have either been taken into account or demonstrated to be invalid. This, and the absence of severe accidents for 15 years, have in themselves had an effect on public perception world wide.

Small improvements in individual designs have been made that enable small (10–20%) power increases of existing plants. These are being made with little or no public opposition. This shows up in improved operating efficiency.

## 12 Plant availability

Many of the improvements above, in management competence, in fuel integrity, in safety and in regulatory behaviour have showed up in improvement in the availability of a nuclear power plant and hence on the cost. As shown in Table 3, Virginia Power and Light assumed that the power plant would operate 65% of the time (65% availability) – a figure achieved by the first plants. This was increasing with time but fell again to 60%. And stayed this way till 1990. Since the cost of the fuel consumed is relatively small, it is evident that the costs, both capital and operating, of nuclear electricity are (approximately) inversely proportional to this availability. Even in the much vaunted French nuclear program, the availability at this time was only just over 57% (Baumier and Bertel, 1987). A part of this decrease in availability before 1990 was certainly bad operating practice, but another part can reasonably be attributed to a regulatory environment that demanded unnecessary shutdowns for small infractions.

Figure 6 shows how plant capacity factor has increased in the USA from records over the last 15 years. This in itself leads to increased safety because it is safer to run at full power than to continually go up and down. Similar improvements have been found elsewhere in the world.

**Figure 6** The increasing capacity factor of US nuclear power plants from records of World Association of Nuclear Operators (WANO)



## 13 Sustainability of nuclear fuel supply

I now return to the claim in this paper that I address *sustainability*. I maintain that nuclear energy is a source that is sustainable over a long period. For how long can the nuclear fuel supply be maintained? As with all minerals the supply depends upon the price. A summary of the amount of uranium reserves, at different prices is shown in Figure 7 (OECD, 1996). This chart separates the reserves into several categories such as proven reserves and estimated reserves. I take the total. In 1971 it was felt that an increase in fuel cost of 0.5 cents/kwh was excessive, and it was imperative to start a rapid program to



A more complete summary of the situation in other countries was published as a book chapter by Krakowski and Wilson (2002).

#### **14 A cautious summary**

I have outlined some reasons for optimism about the future of nuclear power and its ability to supply electricity for the foreseeable future. This change in my thinking since 1991 has been due to a number of factors:

- improvement in public perception and reduction of public opposition
- improvement in fuel behaviour
- risk informed regulation
- steady safety improvements
- improved plant availability
- improved designs.

But no new plant has been ordered in the USA for nearly 30 years and in most of Europe for 20 years. The optimistic exceptions seem to be Finland where construction of a new PWR was begun during 2005, and Ukraine and Russia where nuclear reactors planned many years ago are now being completed. The large construction plans of China and India are proceeding slowly but steadily (Table 4). Although two consortia are discussing new plants with NRC, construction of these have not yet begun. According to IAEA figures shown in Table 4 the number of new plants under construction throughout the world is only 6% of those operating, leading to an increase of only 1½% a year even if no existing plants are shut down – not enough to make a dent in the global warming problem. Will the optimism lead to new construction? That remains to be seen.

There remains one critical facet of public perception – it is often perceived that there is no way to dispose of the waste. Indeed the question in the European public opinion poll of Table 2 presupposed a solution to this problem. While technically minded people keep asserting that nuclear waste is the easiest waste problem in society to solve and scientific committees have insisted that there is no scientific obstacle to a good solution (Hebel et al., 1978), politicians in the USA in particular, following uninformed public opinion, have delayed a ‘solution’ while insisting that nothing proceed till a ‘solution’ has been found.

Several aspects give me some optimism that this log jam will be removed. The Swedish plans, encapsulating in copper containers and placing them 500 metres down in bedrock, seems to be on track (Thegerstrom, 2004). Secondly, ‘contact’ nuclear waste from the US military (mostly contaminated by plutonium and other alpha emitters) is being safely disposed of at the Carlsbad salt mine. Application has been made for remotely handled waste at that mine (which includes gamma emitters) and it is likely that remote handled waste from the military program will soon be so buried also.

Thirdly, a committee of the National Academy of Sciences has outlined reasonable steps to be taken for waste disposal in rock formations on a risk based criterion (Fri, 1995). This report seems to have been accepted and overcomes a criticism I made in 1995:

“We suggest that the problem in all of these cases is the absence of a realistic criterion, based upon public health or at least some other criterion of clear and demonstrated importance, for disposing of waste; without this criterion, political discussions on who should decide and so on are empty.” (Shlyakhter et al., 1995)

Fourthly, the Yucca Mountain disposal site has been accepted by Congress subject to Nuclear Regulatory Commission approval. Legal objections to the right of the US Congress to decide on a waste site in a specific state have been declared invalid by the courts (US Court of Appeals for the District of Columbia Circuit, 2004). The Nuclear Waste Technical Review Board raised a major concern that the fuel canisters were likely to corrode but reversed itself (in a July 28th 2004 letter) after the Department of Energy scientists produced evidence on that topic.<sup>16</sup> In the 2004 court decision, the court held that a calculation limited to 10,000 years is inadequate, and an appeal to that decision was rejected. But, in unusual harmony, both the Environmental Protection Agency and the Nuclear Regulatory Commission have acted to address this. They recognise that calculations become increasingly uncertain after 10,000 years. Leaving the regulatory limit of exposure of 15 mrems up to 10,000 years in place, they have added a higher level of 350 mrems for exposures in the longer term.<sup>17</sup>

In another sign of forward progress, a ‘temporary’ high level waste site on the reservation of the Skull Valley Band of Goshute Indians was approved by the Nuclear Regulatory Commission after a seven year public hearing,<sup>18</sup> and NRC was prepared to issue a license. But the state of Utah was not only prepared to oppose it in the courts (Hatch, 2005),<sup>19</sup> but in late December 2005 persuaded two US government agencies, Bureau of Indian Affairs and Bureau of Land Management to oppose it also. As of the time of this last proof correction, 18 months later, the whole proposal is in limbo. Other countries have made comparable progress and it is to be hoped that they will not have the same set backs for short sighted political reasons that delays matters in the USA and are so extraordinarily expensive. Germany contemplates storage in salt deposits, Finland and Sweden in rock, and UK plans temporary storage on site for many years till the technical situation clarifies further.

Much of the world is concerned about the potential for climate change by large CO<sub>2</sub> emissions. Of the three major attempts to cope with climate change, renewables, carbon sequestration, and nuclear energy, only the first is now receiving subsidies and tax breaks. For example, neither sequestration nor nuclear power are included in the “clean development mechanism” favoured by economists and adopted in part by the European Union. If all three carbon dioxide reduction technologies are treated equally, then nuclear energy would have the “shot in the arm” that many advocates believe is necessary. I have always preferred a carbon tax, charge or permit scheme (Wilson, 1972b; Lackner et al., 2000), but a subsidy for development might achieve much of the desired end. In the USA a carbon charge, or any new energy tax, seems unpopular in 2005 and the present policy of the US Department of Energy, enshrined in the energy bill of 2005, is to subsidise the first plant of a series to help test the new licensing process, and test the response to any opposition.

Three independent groups have come out with statements along these lines. A report on the future of nuclear power from MIT, chaired by two professors who had worked in Washington, Deutsch and Moniz, stated: “We recommend that incremental nuclear power be eligible for all ‘carbon free’ federal portfolio standard programs” (Deutsch and Moniz, 2003).

The Atlantic Council of the USA stated inter alia:

“In implementing international emission trading programs, credit should be given to nuclear power facilities for their contribution to reduction of greenhouse gas emissions.” (Atlantic Council of the United States, 1999)

The Permanent Energy Monitoring Panel of the World Federation Scientists stated, after careful deliberation:

“Therefore we recommend that governments and international agencies treat all non carbon energy technologies on a par with each other with access to similar subsidies and benefits of removal of financial market barriers so that improved versions of all these technologies can rapidly be utilised for achieving stabilisation of greenhouse gas emissions while meeting energy demand.” (Wilson, 2004)

Although politicians world wide have made statements during 2004–2005 in favour of nuclear energy, only in the US policy act of 2005 (H.R. 6) has this yet been translated into the needed “shot in the arm”. Moreover, as of the last proof reading, June 2007, this shot in the arm has not yet resulted in a shovel in the ground.

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## Notes

- <sup>1</sup>The exact quotation is unavailable. That it was said was confirmed to me personally by Professor Seaborg.
- <sup>2</sup>In 1972 when I first criticised nuclear energy I wrote to the Chairman of the Atomic Energy Commission, Dr. Glenn Seaborg. He replied with a personal telephone call within two days and invited me to spend 2 days at the AEC. He introduced me to each relevant Assistant Secretary with the comment "Now you know him and his telephone number he will answer any question you wish". Which they did. This AEC during this period was often called secretive. But compare that secrecy with the lack of response I received from the Chairman of NRC 25 years later.
- <sup>3</sup>Communication to the author by Dr. Sergei Kapitsa in 1987. Andre Sakharov also said something similar but his words were lost in translation.
- <sup>4</sup>Calculations such as these have been made with increasing sophistication by many authors for the last 33 years from the simplistic: Wilson (1972a) to 'EXTERNe Externalities of Energy' in many country reports with eight common 'Annexes', project of the European Commission, available at: <http://externe.jrc.es/>.
- <sup>5</sup>Prime Minister Carlsson quoted in NY Times, Summer 1986.
- <sup>6</sup>April 28, 2005, hearing before the Subcommittee on Energy and Resources of the US House of Representatives' Committee on Government Reform. The topic of the hearing was "Nuclear Power Generation as an Approach to Meeting America's Energy Needs".
- <sup>7</sup>In France there is a reduction of electricity rates for those in the neighborhood of a power plant.
- <sup>8</sup>Cost figures given to the author in 1973 by William Webster, Chairman of New England Electricity System, which operated Connecticut Yankee.
- <sup>9</sup>The cost of Maine Yankee Nuclear Power Plant (900 Mwe) was slightly higher. It went to \$220 per kilowatt when a causeway was replaced by a bridge to make a smaller cooling water impact on the estuary. This was not required of any coal fired plant at the time.
- <sup>10</sup>Benhke, W. former C.E.O. of Commonwealth Edison Co., owner and operator of Dresden II and Dresden III, communication to the author in 1997.

<sup>11</sup>Based on the current US average capacity factor of 90%, with data from Bryan and Dudley (1974).

<sup>12</sup>For wind and coal, see Pacca and Horvath (2002).

<sup>13</sup>US Nuclear Regulatory Commission Enforcement Actions EA 96-034 and EA 96-151.

<sup>14</sup>Interestingly, the new approach was announced by the same person responsible for the extreme of the old approach. Chairman Jackson (1998).

<sup>15</sup>Nuclear Power and Proliferation Resistance: Securing Benefits, Limiting Risks Nuclear Energy Study Group of the Panel on Public Affairs, American Physical Society, NY, Available on: [http://www.aps.org/public\\_affairs/proliferation-resistance/](http://www.aps.org/public_affairs/proliferation-resistance/).

<sup>16</sup>Letter of November 25, 2003 from Dr. M.S.Y. Chu to US DOE and subsequent letter of July 28th 2004.

<sup>17</sup>EPA rules published August 22nd 2005; NRC proposed concurrence September 7th 2005.

<sup>18</sup>NRC announcement, September 9th 2005.

<sup>19</sup>Letter by Hatch in December (2005).