Rohsenow Symposium, MIT, 16 May 2003
Comments on papers – Session on Advanced Energy Systems
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I am very pleased to participate in this symposium honoring a great MIT faculty member – Warren Rohsenow.   My task is to comment on the three excellent presentations offered at this morning's session on advanced energy systems. I have been asked to be brief in order to permit time for discussion.

Professor Michael Coradini present an admirably informative technical review of advanced nuclear reactor concepts with attention to heat transfer. I commend it to you.

It is unfair to offer comments that go beyond the subjects Professor Coradini addresses, but I nevertheless choose to do so.

I have long believed it unfortunate that analysis of advanced nuclear systems frequently separate, quite completely, the reactor from the overall fuel cycle. Certainly the cost, safety, waste, and proliferation criteria that will determine the system selected for deployment will depend as much, if not more, on reprocessing, fuel fabrication, and waste form as on reactor type. This calls for an overall system assessment.

You will shortly learn that the MIT study on nuclear energy will recommend that DOE mount a $100 million per year Nuclear System Modeling Project to perform the analysis, modeling, simulation, and collection of engineering data required for quantitative comparison and trade-off between different fuel cycle configurations.

Professor Coradini mentions the importance of competitive economics for consumers. This has implication for the balance of R&D effort between open and closed fuel cycles. In my view, even assuming an ambitious mid-century world wide nuclear deployment of 1000 GWe or 2.5 times today, there will ample uranium resources available to fuel an open cycle at competitive cost to the end of the century, if not beyond. There is no chance that a closed fuel cycle will be economically competitive with an open fuel cycle for well over fifty years. Some argue the closed cycle has significant waste management advantage but this remains to be demonstrated and I do not believe it so.
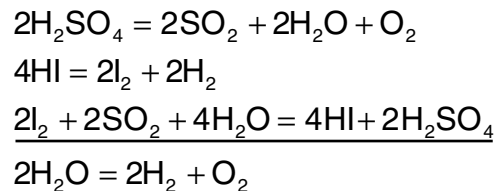
Even acknowledging very long lead times for development of advanced nuclear systems there is no justification for carrying advanced nuclear system development beyond conceptual design studies to a more expensive development effort. R&D priority should be placed on the once through open cycle with attention, for example, on advanced light water reactors, high

temperature gas cooled reactors, and, in the long run, fast reactors that can achieve sufficient internal conversion and burn, that a single fueling will last for almost an entire reactor lifetime.

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Dr. Forsberg addresses the exciting subject of a carbon-free hydrogen economy. In particular, Dr. Forsberg explores the use of high temperature heat from nuclear reactors to produce hydrogen.   We know that H_2 can be produced by electrolysis with an efficiency of about 25%, (33% efficiency for electricity production x 80% efficiency for electrolysis). The question is whether high temperature heat can be used to crack water at advantageous efficiency.

Forsberg reports that the leading candidate is the sulfur-iodine, (S-I) process:

$$2H_2SO_4 = 2SO_2 + 2H_2O + O_2$$
$$4HI = 2I_2 + 2H_2$$
$$\underline{2I_2 + 2SO_2 + 4H_2O = 4HI + 2H_2SO_4}$$
$$2H_2O = 2H_2 + O_2$$

At this point, your attention should immediately shift from the nuclear heat supply subsystem to chemistry and chemical engineering because this is where the technical challenge lies.

In general, the problem presented by water dissociation is to find a photolytic or thermolytic catalytic system that lowers the energy transition state barrier between water and the dissociation products of hydrogen and oxygen. The S-I system may not be the best catalytic pathway and, in any event, the overall energy efficiency will be determined both by the energy cost of the decomposition reaction and by useful heat recovery which, in turn, depends, on process configuration.

I want to stress how little we know about the S-I system or any other thermochemical cracking scheme and whether any thermochemical approach will be practical or economical compared to electrolysis. Not much is known, even at laboratory scale, about the performance of the S-I system under different conditions of temperature, pressure, and composition.

Small impurities may well interrupt the designated reactions; the composition of the reacting system is not defined, and different configurations will present different process challenge, e.g. separation of the O_2 and H_2. To my knowledge there is no experience with engineering process development units and hence no data on which to base a realistic analysis of this thermochemical cycle relative to electrolysis.

I think thermal or photolytic cracking of water will prove to be difficult. But there are other clever ideas, for example the Texas Instrument proposal of the late 1970s of a closed system of HBr in water. In sunlight HBr is photolyzed on the roof to H_2 and Br_2 that is stored in the basement for use in a fuel cell to produce electricity.

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Commissioner Rosenfeld quite properly reminds us that improved energy efficiency acts as an effective energy source. He reports on welcome progress in California. My attention is drawn to his slide No. 16 that projects the benefits of improved energy efficiency over a century period for the entire world.
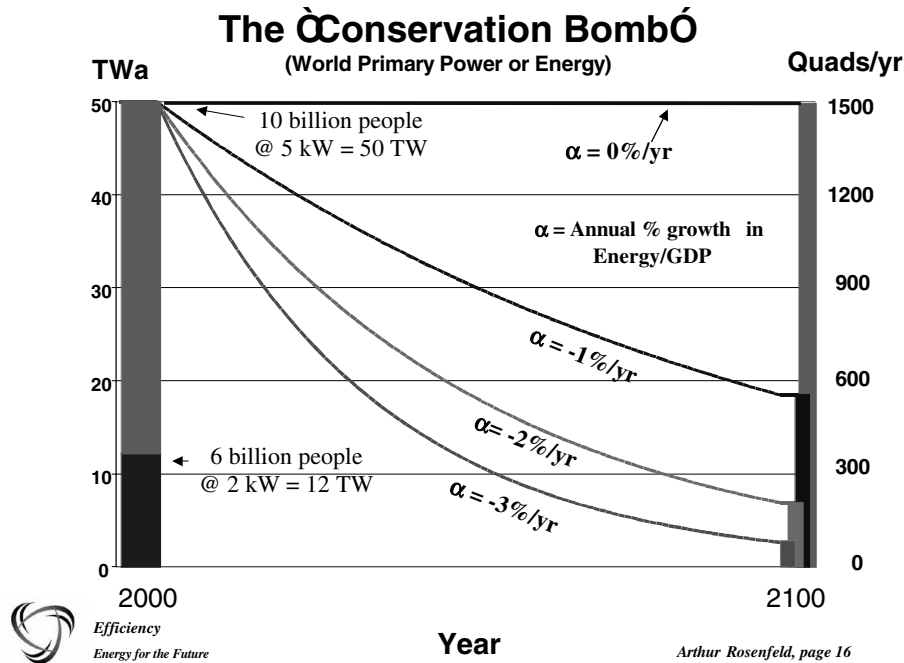
Dr Rosenfeld draws the correct conclusion from this dramatic slide: energy efficiency makes a difference and the more energy efficiency the better.

I want to emphasize two points in this projection. Consider the "Kaya" identity that relates different growth rates of energy E, gross national product Y, and population P. The following relation must hold between the different rates of change per year:

$$\frac{\delta E}{E} = \frac{\delta(E/Y)}{(E/Y)} + \frac{\delta(Y/P)}{(Y/P)} + \frac{\delta P}{P} \quad .$$

If we assume that over this century we would like for GDP per capita to grow <u>at least</u> 2% per year and the conservative population growth from Dr. Rosenfeld's chart of 1/2 % per year, then

$$\frac{\delta E}{E} = \frac{\delta(E/Y)}{(E/Y)} + 2.5\%.$$

If $\alpha = \dfrac{\delta(E/Y)}{(E/Y)}$ is – 1 to - 1.5 % per year, then energy growth per year over the <u>entire century</u> will be between 1 and 1.5% per year.

My first observation is that an average rate of energy improvement over the next century better than α = -1.0% is highly unlikely. High levels of energy efficiency in a market economy will only be achieved if real energy prices increase to compensate for the higher initial capital cost that often accompany more energy productive technologies, e.g. low heat rate thermal power plants. This makes adoption of energy efficient technologies in developing countries where energy growth is expected to high, problematic without equally burdensome energy taxes or government regulation. Moreover, the progress that the United States and other OECD countries make on energy efficiency depends on exporting energy intensive industries, such as steel making, to other countries thus constraining the pace of improvement in this parameter.

Second, even rates of energy growth as low as 1 to 1.5% per year may not be acceptable because of the implied growth rate of carbon emissions. Rosenfeld's chart # 15 suggest rate of improvement of carbon intensity $\dfrac{\delta(C/Y)}{(C/Y)}$ could be in the range of –2 to –3% per year. I hope so, because the Kaya identity

$$\frac{\delta C}{C} = \frac{\delta(C/Y)}{(C/Y)} + \frac{\delta Y}{Y}$$

$$\text{then} \quad \frac{\delta C}{C} \quad \text{is} \quad \text{between} \quad -1/2\% \quad \text{and} \quad +1/2\%$$

implies that we should expect zero net carbon growth over the period. But, this is not good enough. Global warming experts say that we need to <u>decrease </u>carbon emissions over the next century to keep atmospheric greenhouse gas concentrations below twice the pre-industrial level that many regard as a "safe" level from the point of climate change.

I conclude that relying on energy efficiency trends is not sufficient. We must pursue options for reducing carbon emission – renewable energy sources, carbon capture and sequestration, and nuclear power – in a way that will put us on a new trend line.

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