



## ON LIMIT-LINE CURVES IN RISK EVALUATION

Farmer<sup>1,2</sup> proposed the use of a limit line relating acceptable release and probability per year for a single accident sequence, and he estimated overall risk (i.e., curies released per year) on the assumption that only a few accidents would be near the limit line. Others<sup>3-5</sup> have chosen to integrate such a limit line to assess the overall risk to the public, with the specification that each and every detailed accident chain should lead to a combination of release magnitude and recurrence interval such that the point falls below the limit line. However, in Ref. 5 the authors also state that "a single nuclear accident is represented by a point on the Farmer limit line." Farmer<sup>6</sup> questioned aspects of Ref. 5, but does not take issue specifically with the above quote.

It appears that the approach of integrating a limit line per Ref. 5 affords potential difficulties in that, at least in principle, it can underestimate the overall risk from the totality of accident chains. More directly, an individual accident sequence, having some frequency of occurrence and some associated consequence (release) does not correspond to a point on the limit line. If integration of the limit line is to be limiting, an additional condition must be met, namely,

$$\sum_{\text{all } i} C_i P_i \leq \int_0^{C_{\text{max}}} L(c) dc = \int_{f_{\text{min}}}^{f_{\text{max}}} \mathcal{L}(f) df ,$$

where

$C_i$  = curies released in each specific  $i$

$P_i$  = frequency of specific event  $i$ , yr<sup>-1</sup>

$L(c)$  = "limit line" drawn on a plot of frequency ( $f$ ) versus release ( $c$ ) that envelopes points corresponding to events  $i$ . [Reference 5 sets the release =  $\int \mathcal{L}(f) df$ ].

In other words, there may be so great a density of points (i.e., events) lying near the limit line that the above condition is not met.

This problem should not arise (in principle) if one defines<sup>3</sup>

$$dP(c) = g(c)dc ,$$

where  $dP(c)$  is the number of events per unit time that give a release between  $c$  and  $c + dc$ , and where  $g(c)$  is a "probability distribution" that has been determined from a detailed analysis of reactor system faults, and presumably reflects the actual situation.

Then

$$P(C_2) - P(C_1) = \int_{C_1}^{C_2} g(c)dc$$

is the probability per unit time that a release between  $C_1$  and  $C_2$  will occur. The total release per unit time is given by

$$R = \int_0^{C_{\text{max}}} cg(c)dc = \sum_{\text{all } i} C_i P_i .$$

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## COMMENTS ON "TOTAL ENERGY INVESTMENT IN NUCLEAR POWER PLANTS"

In their recent paper,<sup>1</sup> Rombough and Koen purport to calculate the total amount of energy required to construct and operate a 1000-MW(e) light water reactor (LWR) for 30 yr. We agree with the authors that an energy accounting system is superior to an economic one and, therefore, applaud the effort their paper

represents. However, a number of energy subsidies to the LWR were not included in the evaluation, and there are several misleading, if not erroneous, calculations given. The implication that these calculations represent total energy investment is inaccurate.

The energy investments calculated by Rombough and Koen include only the construction energy for the LWR and the fossil fuel energy used for mining, milling, enrichment, fuel fabrication, and reprocessing. Conspicuous omissions include construction energy for the milling, enrichment, fabrication, and reprocessing facilities prorated for one 1000-MW(e) reactor over 30 yr; the energy value of the chemicals and other materials used in operating these same facilities; energy utilization in transporting the various forms of uranium from facility to facility; and the energy requirements of radioactive waste disposal which include the required system infrastructure and security. These are no more difficult to calculate than the energy costs included by Rombough and Koen and, in fact, some of them have already been calculated. More difficult to evaluate but important in a total energy investment analysis are the environmental costs (in energy units) resulting from each step in the fuel cycle, the energy value of the federal research and development support of the nuclear industry, and the energy cost of a nuclear accident.

In addition, Rombough and Koen add and compare Btu's of electricity and Btu's of petroleum. A Btu of electricity can do more work than a Btu of petroleum and thus electricity represents a higher quality energy than petroleum. The dollar-to-Btu conversion calculated by Rombough and Koen (69 000 Btu/\$) is for the petroleum based economy of the U.S. and represents Btu's of petroleum per dollar. Thus, it should not be compared with Btu's of electricity. Converting all energies to the same quality is a fundamental step in the energy accounting procedures. To compare the energy investment to the reactor electrical output, all investment quantities must be in Btu's electric. The  $1.5 \times 10^{13}$  Btu of LWR construction energy calculated by Rombough and Koen is equivalent to petroleum Btu's in potential work done and represents only  $0.5 \times 10^{13}$  Btu of electricity or 0.7% of the reactor output.

Note also that Rombough and Koen have misquoted the "Environmental Survey of the Nuclear Fuel Cycle," (WASH 1248) when they state that enrichment accounts for 98% of the total energy required by the fuel cycle. WASH 1248, their source document, clearly states (p. S-17) that it accounts for 98% of total *electrical* energy.

While we find some of the data in this paper quite useful, the investment energy calculated for construction of an LWR is inaccurate, and the energy value presented as a total represents only a part (probably a small part) of the actual energy investment in an LWR.

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## REFERENCE

1. CHARLES T. ROMBOUGH and BILLY V. KOEN, "Total Energy Investment in Nuclear Power Plants," *Nucl. Technol.*, **26**, 5 (1975).

## RESPONSE TO "COMMENTS ON 'TOTAL ENERGY INVESTMENT IN NUCLEAR POWER PLANTS'"

We thank Gilliland and Freim for their interest and comments<sup>1</sup> concerning our paper. We agree that it is important to consider the indirect energy costs associated with the nuclear system. A more complete accounting of the energy investment in nuclear power plants can be found in Ref. 2. This work evaluates the indirect energy costs associated with the fuel cycle facilities, transportation, waste disposal, government subsidy, nuclear accidents, and environmental aspects. Since such an exhaustive analysis of a coal plant has not been performed, these secondary costs were not included so that the comparison could be made on the same basis. In addition, the above work demonstrates that all of these indirect costs account for only ~20% of the total energy investment, and therefore the implication that the value reported is only a "small part" of the total is incorrect.

Generally, there are three ways to interpret the energy investment when dealing with different forms of energy. Consider for example, that an energy investment were 50 Btu's of electricity and 50 Btu's of thermal energy for an output of 1000 Btu's of electricity. The first method assumes that we are interested in how much energy in the electrical form is required. This method assumes that the 50 Btu's of thermal energy *could have been* used to generate  $50/3 = 17$  Btu's of electricity so that the total input is 67 Btu's of electricity. The ratio is then  $67/1000 = 6.7\%$ . This is the method favored by Gilliland and Freim. The second method assumes that we are interested in how much thermal energy is required. In this case, the input electricity is converted to  $50 \times 3 = 150$  Btu's of thermal energy for a total input of 200 Btu's of thermal energy. The ratio is then  $200/1000 = 20\%$ . Note that there is a factor of 3 difference between these two methods. The third alternative assumes that any input energy would eventually be made up from the plant itself. That is, electricity is substituted directly for input energy regardless of form. In this case, the investment is  $100/1000 = 10\%$ . Since the third alternative lies between the other two alternatives and appears to be more fundamental, this is the one that we chose in performing the analysis. The final alternative is conservative in that electricity is used more efficiently than fossil fuels, though not with a ratio of 3 to 1. For example, a natural gas water heater may be 62% efficient compared to a 95% efficient electric water heater (a ratio of 1.5). The error then introduced by assuming that electricity is substituted directly for thermal energy would be a factor of 1.25 for the above example (since 50% of the input is thermal).

We regret that the word "electrical" was inadver-