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COMPARING ADVANCED ENERGY CYCLES AND DEVELOPING PRIORITIES FOR FUTURE R&D

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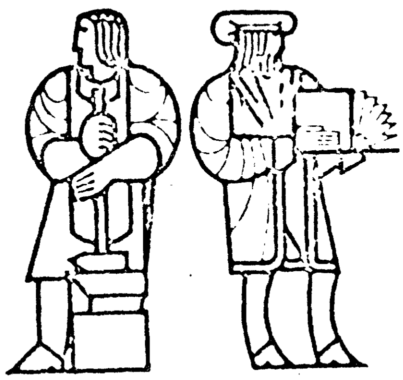

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ABSTRACT

This report lists and discusses the types of information that are necessary for making decisions about the allocation of R&D funds among various electric power related energy technologies. The discussion is divided into two parts: (1) the task of choosing among different technologies and (2) the task of guiding toward the most important specific projects within an individual technology. To choose among alternative energy technologies requires assumptive information, assessment information, probabilistic information, and techniques for quantifying the overall desirability of each alternative. Guidance toward the most important projects requires information about levels and uncertainties of certain performance measures and their importance relative to external thresholds or relative to the performance of competing technologies. Some simple examples are presented to illustrate the discussion. A bibliography of more than 200 important references in this field was compiled and is appended to this report.

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I. INTRODUCTION

Only a small part of research and development planning, especially in the field of energy technologies, is concerned with actual decision making. The majority of R&D planning efforts are primarily concerned with the collection of appropriate pieces of information. This discussion focuses on identifying the relevant categories of data that must be collected. The actual data collection and choice of decision methodologies are only briefly addressed here. The reasons for brevity are that (1) data collection is very much task-specific and cannot be handled here in a generally useful manner and, (2) there is an abundance of literature on the various decision methodologies for "project selection" or "expenditure allocation".

Taken as a whole, allocating all of the energy R&D funds to the individual projects is a formidable task. For purposes of discussion a simple hierarchy of decision tasks of the type shown in Figure 1 is used for identifying the groups of necessary information. The first two levels, allocation among technologies and among designs, are very similar and are discussed next in Section II. The more specific problems involved in aiming at the next best experiments, facilities, or analytic tasks are treated in Section III.

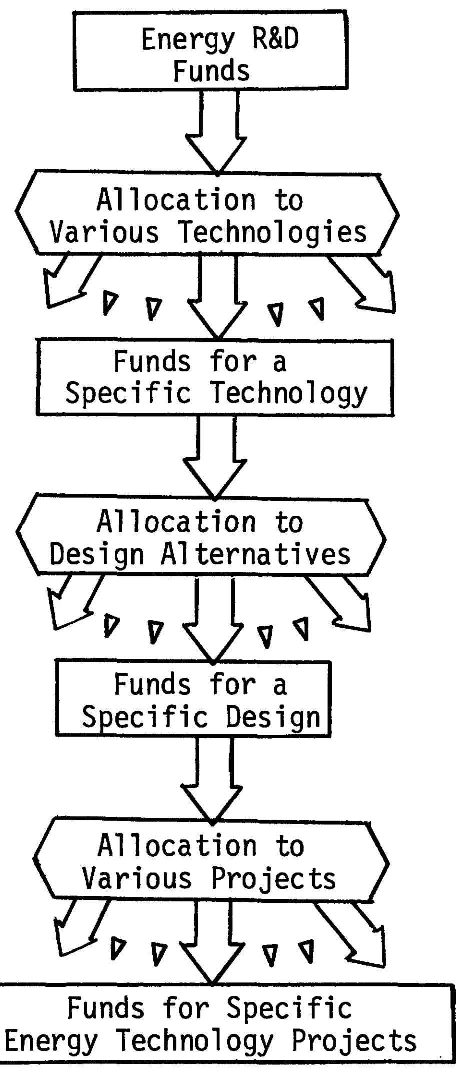

Figure 1 Hierarchy of decisions in the allocation of energy R&D expenditures

II. COMPARATIVE TECHNOLOGY ASSESSMENT

What data are necessary for a decision maker to properly choose or spread his research funds among several similar advanced energy technologies? To answer this question it is necessary to first gain perspective of the overall national and regional energy situations. The potential performance of any new energy technology must be measured in this overall context. On the national level, Tables 1 and 2 show the objectives, constraints, and controls that define this overall problem area. The performances of electric power related energy technologies within this broad context must also be weighed against their performance in the related but slightly different problem area defined by their regional power pool or individual utility perspectives. The constraints, objectives and controls of concern at this region level are outlined in Table 3.

A brief scan of these two problem formulations shows that an overall evaluation of the potential performance of any upcoming energy technology requires information about:

1) economics, in terms of cost of unit energy output, investment and operating costs;
2) timeliness, availability for commercial use and fit into energy-economic context;
3) resource consumption, including use of unpolluted air and water, materials, fuels, manpower, and capital;
4) environmental, safety, and health characteristics;
5) basic research, meaning those contributions that will also apply to other processes;
6) institutional factors such as public image and government-industry interference and cooperation; and
7) national security enhancement, primarily in aiming at replacing or avoiding cartel-vulnerable products, such as foreign oil or imported rare metals, and avoiding disruptions that could affect the survival of the establishment.

The effort required to develop these kinds of information can be broken into two separate tasks:

1) The assessment work that can be done by scientists and engineers, which should result in objective, unambiguous technical information; and

Table 1 Constraints and Performance Measures or Objectives of the National Electric Energy Situation

Constraints:

- Energy Resources
  - Fuel
  - Non-Fuel
  - Conservation Potential
- Materials
- Capital
- Manpower
- Time

Objectives: (all are essentially public perception of quality of life)

- Survival of System
  - Vulnerability to Foreign Disruption
  - Infrastructure Problems
- Satisfying Energy Demands with Minimum Cost
- Environmental Protection
  - Materials
  - Vegetation
  - Animal Life (Non-Human)
  - Human Well-Being

Controls: (related to electric power)

- Policy Actions (see next page)

Table 2 Actions That Can Be Used to Control the National Energy Situation, Showing R&D Funding in the Context of the Other Possible Controls

Policy Actions

Information
- Public Awareness of Technologies Risks/Benefits
- Public Awareness of Conservation Measure Cost/Benefits

Fiscal Changes, Incentives, Uses
- R&D Funding
  - Advanced Generation
    - Centralized and Distributed
    - Conventional and Unconventional
    - Co-Generation
    - Fuel Conversion
    - Nuclear
    - Storage
  - Advanced Transmission
  - Abatement Alternatives
  - System Studies
    - Operating Strategies
    - Planning Strategies
    - Potential Uncertainties
    - Research Payoffs
  - Health and Environmental Effects Information
- Cost of Financing
- State Financing
- Incentives for Market Penetration
- Tariffs, Regulation of Fuel, Plant, Wage Costs
- Btu Taxes

Regulatory Changes
- Change Rate of Return
- Accelerate Licensing of Attractive Alternatives
- Include Work-In-Progress in Rate Base
- Forced Retirement of Plants and Retrofitting
- Regulate Reserve Margin

Load Management
- Peak Load Pricing
- Seasonal Pricing
- Rationing and Source Regulations
- Influence Economic/Demographic Trends
- Conservation Policies

Environmentally Motivated Actions
- Change Environmental Standards
- Change Siting Restrictions
- Capital Equipment Requirements
- Operating and Planning Strategy Requirements

Table 3 The Formulation of the Information and Components of the Electric Utility Energy Alternatives Problem

Constraints:
- Energy Resources
  - Fuel
  - Non-Fuel
  - Conservation Potential
- Energy Technologies
- Capital and Cash Flow
- Sites
- Manpower
- Materials
- Time Frame
- Environmental Standards

Objectives:
- Survival of Private Power Sector
  - Satisfactory Reliability (meeting demand)
  - Satisfactory Cost of Electricity
- Profit to Investors
  - Cost Effectiveness
  - High Efficiency
  - Awareness of National Research and Trends
    - Avoid Retrofits
    - Avoid Costly Interventions and Moratoriums

Controls: (all depend on time frame constraint)
- R&D Funding (mostly through EPRI)
- Influence Policy Actions
- Generation Expansion
  - Technology and Fuel Choices
  - Site Selection
- Transmission Expansion
- Production Scheduling
  - Nuclear Refueling
  - Hydro Scheduling
  - Maintenance Scheduling
  - Unit Commitment
  - Economic Dispatch and Faster Controls
- Demand Modification
  - Pricing Policies
  - Conservation and Growth Incentives
  - Public Awareness of Conservation

2) The evaluation work that is performed by a decision maker, which will incorporate subjective judgments and which will vary according to the perspective of each individual.

What will be discussed here is the importance of separating tasks (1) and (2), the set of information that should be transferred from (1) to (2), and the potential for feedback and interaction from task (2) back to task (1).

First, it should be emphatically stated that it is most important to make as clear a division between the engineering work and the policy work as is possible. Qualitative or subjective arguments imbedded in the results of engineering assessments not only reduce the usefulness of those assessments but render them suspect in the view of people with slightly different judgmental perspectives.

The question then arises as to what in fact is the necessary and sufficient information about an energy technology that can be made available by an engineer that will allow the policy makers to make the most intelligent R&D decisions. Here there are basically three types of information needed:

1) Assumptive information
   - exactly what is the basis of the assessment, has there been scaling up from small facilities, what sort of economic judgments are imbedded in the cost information, what exactly are the fuel, the plant design, and modeling assumptions;
2) Assessment information
   - expected values of all of the economic and engineering data, reduced to their most usable form but not incorporating any hidden subjective trade-offs between unlike quantities; and
3) Probabilistic information
   - in many cases it is more important to know the size and shape of the distribution of possible values of data than it is to know exactly what the expected value may happen to be.

<u>Assumptive Information</u>

The assumptive information should consist of descriptive and numerical information, specifically that information which must be assumed to develop assessment numbers. Some of the many types of assumptions that may be involved are included in Table 4. Of course, in making comparisons between

Table 4 Example List of Assumptive Information [from Gruhl, et al., 1976]

1) Basic Assumptions

A. Year (if a particular year is to be the time for the comparison) - example: 1988

B. Regional Considerations

- Fuel
  - example: fuel from Western Kentucky
- Plant
  - example: located in New England, rural site
- Load/Demand
  - example: customers in New England, load shape typical of New England.

C. Power System

- example: power system is small, predominately oil-fired, this would then reflect upon the usefulness of this particular facility with respect to the power generation mix available on this type of power system and the replacement cost of power that would be likely.

2) Economics

Whether or not, and which, economic factors should be available as parametric factors would depend entirely upon the sophistication of the modeling of accounting procedures that is desired. Possible levels of accounting sophistication include:

0th Order - Exact accounting procedure to be used would be specified as would the exact values for ecomonic factors, such as cost of capital.

1st Order - Ability to use parameterization of economic factors and different accounting procedures for the major expenditure items, such as construction, licensing, equipment, and other

Table 4 (continued)

primary investments. Secondary expenses, such as transportation investments that would affect transportation costs as passed on to the utilities would be handled as described in Zeroth Order procedure.

2nd Order - Primary and secondary (or indirectly affecting) expenditures could be modeled with parameterized economic factors and various accounting procedures and tertiary influences would use prespecified procedure as in Zeroth Order.

3) Performance

   A. Capacity Factor (design)

      - example: 65% (i.e. baseload)

   B. Exact descriptions of Equipment Designs and Assumptions.

4) Environmental

   A. Emission Standards

      - example: current standards

   B. Ambient Standards

      - example: disregard

different energy technologies, it is not sufficient to use the same assumptions for all technologies, since some assumptions will tend to bias the comparison.

The comparison of energy technologies on the basis of economic evaluations is a conventional practice. It is rarely, however, that these comparisons can be made on common economic assumptions, and more rarely that competing technologies can be compared using a series of assumptions about several values of key economic parameters. Some of the most detailed models that are capable of handling such sensitivity studies for conventional coal, oil, gas, and nuclear fueled facilities are available from the Department of Energy and Oak Ridge National Laboratory. Examples of these models are the CONCEPT, PLANT, and ORCOST programs. In most projects it is likely that some options and some parameters will inevitably be fixed in an accuracy versus complexity trade-off.

In a Zeroth Order effort no economic factors could be parameterized, they would all be pre-fixed. In a 1st Order procedure, such as in the ECAS study (NASA, 1976), examples of parametric economic factors would include those shown in Table 5.

In many cases, such as cost of capital, assumptions must be made in order to develop meaningful cost information. Since the exact numbers are unknown, sensitivity studies with respect to these parameters are essential.

Assessment Information

Here some attempt is made at displaying the set of quantitative performance information that should ideally be passed from the engineering studies to the policy studies. Table 6 shows a list of potential categories.

Ideally, persons with widely differing perspectives could find in Table 6 the performance information about the energy technology that they would need in order to make comparative judgments from their particular, and unavoidable, set of biases. If this set of information is called a set of performance factors, then it could be a meaningful exercise just to examine all of the entries in this list, but presumably more useful investigations would result from the side-by-side comparative examinations

Table 5 Example List of Economic Information That Might be Parametrically Varied, [principally from the ECAS study (NASA, 1976)].

A. Accounting Procedures
   1) Depreciation Options:
      a) straight line
      b) sum-of-the-years-digits
      c) combination of (a) and (b) switching at a given year
   2) Fraction of Year to Discount Annual Expenses
      - example: 0.50
   3) Time Factors
      a) base year for escalations
         - example: 1971.0
      b) year construction started
         - example: 1971.0
      c) year of commercial operation
         - example: 1979.5
      d) length of workweek (hrs)
         - example: 40.0
      e) year for present-worthing of dollars
         - example: 1975.0

B. Treatment of Debt and Equity
   1) Bond Repayment Options
      a) proportional case
      b) uniform principal reduction
      c) uniform annual payment
      d) delayed uniform principal reduction, include starting year for delayed option
   2) Annual Interest Rate on Debt (%)
      - example: 7.5%
   3) Fraction of Initial Investment Raised by Debt
   4) Earning Rate on Equity (after tax)
   5) Debt/Equity Ratio

C. Escalation Rates
   1) Initial Equipment Escalation Rate (%)
      - example: 5.0%
   2) Equipment Escalation Rate (%)
      - example: 5.0%

Table 5 (continued)

3) Initial Material Escalation Rate (%)
   - example: 5.0%
4) Material Escalation Rate (%)
   - example: 5.0%
5) Initial Labor Escalation Rate (%)
   - example: 10.0%
6) Labor Escalation Rate (%)
   - example: 10.0%
7) Uniform Overall Escalation Rate (%)
   - example: 0.0%
8) Escalation Rate on O&M Cost (%/yr)
   - example: 0.0%
9) Escalation Rate on Fuel Cost (%/yr)
   - example: 0.0%

D. Indexes for Uniform Parameterization

1) Site Labor Productivity Index
   - example: 1.0
2) Equipment Cost Index
   - example: 1.0
3) Materials Cost Index
   - example: 1.0
4) Labor Cost Index
   - example: 1.0

E. Insurance

1) Property Insurance (fraction of plant investment/yr)
   - example: 0.001
2) Additional Liability Insurance (for nuclear accidents, oil conflagrations, etc., \$/yr or \$/yr/MWh)
   - example: 0.000

F. Taxes

1) Federal Income Tax Rate (fractional)
   - example: 0.041
2) State Income Tax Rate (fractional)
3) State Gross Revenue Tax Rate (fractional)
4) Property Tax Rate on Plant (fraction/yr)
5) Other Taxes (fraction/yr)

Table 6 Quantitative Assessment Information about the Performance of Energy Technologies [from Gruhl, et al., 1976].

1) Economic Resultant Factors
   1) Total Investment ($)
   2) Capital Investment Normalized ($/1000MWe)
   3) Operating Cost
      A. Fixed Operating Cost ($/MWe/yr)
      B. Variable Operating Cost ($/MWh)
   4) Annualized Cost ($/yr)
   5) Total Cost per Unit Output (mills/kWh)
2) Performance Resultant Factors
   1) Capacity (MWe)
   2) Production (MWh/yr)
   3) Design Capacity Factor (%)
   4) Operating Capacity Factor (%)
   5) Availability (%)
   6) Energy Efficiency (overall losses and ancillary, %)
   7) Expected Lifetime of Unit (yrs)
3) Applicability Resultant Factors
   1) Commercialization Date (2000MWe production capacity, yr)
   2) Operating Experience (MWe/yr)
   3) Licensing and Construction Time (yrs)
   4) Maximum Rate of Installation (MWe/yr)
   5) Potential for Advancement of Technology (e.g., mills/kWh reduction in output price per year after commercialization)
   6) Probability of Technological Feasibility (fraction of 1)
4) Resource Requirements
   1) Renewable Energy (as % of primary energy)
   2) Land Use (acres/MWe or/yr)
      A. On-site Requirements
      B. Waste Disposal and Other
      C. Pondage Requirements
   3) Manpower Requirement (non-operating, man-yrs)
   4) Water Consumption (gallons/MWh)
   5) Materials Requirements (tons/MWyr/material)
   6) By-products (disposal costs or sales, $/MWyr)

Table 6 (continued)

5) <u>Environmental Consequences</u>

- 1) Emission Standards (% of each standard)
- 2) Emissions (normal and upset)
  - A. Air pollutants (tons, BTU/MWyr for specific pollutants)
  - B. Water pollutants (tons, BTU/MWyr for specific pollutants)
  - C. Waste solids (tons, BTU/MWyr for specific wastes)
  - D. Radioactive pollutants (curies/MWyr)
  - E. Noise (decibels/full load at plant boundary)
- 3) Upset Conditions (hrs/MWyr)
- 4) Ambient Standards (% of each standard)
- 5) Occupational Health
  - A. Mortalities (deaths/yr/MW)
  - B. Morbidities (illnesses/yr/MW)
  - C. Work-days Lost (work-days/yr/MW)
  - D. Occupational Health Costs ($/yr/MW)
- 6) Public Health
  - A. Mortalities (deaths/yr/MW)
  - B. Morbidities (illnesses/yr/MW)
    - i. Chronic Respiratory (cases)
    - ii. Aggravated Heart-lung Symptoms (person-days/yr/MW)
    - iii. Asthma Attacks (cases)
    - iv. Children's Respiratory (cases)
- 7) Pollution-Related Damage Costs (total health and other)
  - A. Public Health Costs ($/yr/MW)
  - B. Biota Costs ($/yr/MW)
  - C. Material Damage Costs ($/yr/MW)
  - D. Aesthetic Cost ($/yr/MW)

of sets of performance factors from two or more energy technologies.

The portion of the list in Table 6 that perhaps requires more amplification is the specification of the set of pollutants that should be included. The argument that is generally put forward to define the set of pollutants to be investigated involves including every pollutant about which there exists adequate emission information. This, of course, strongly biases the investigation in favor of the technologies about which the least information is available, and this bias need not necessarily be accepted as inevitable. One can avoid this bias by not allowing question marks or "unknown" to show up in the list of performance factors, and instead forcing a speculation on the possible levels, even if it is just "zero to worst case".

Of course, it is impossible to include levels of emissions for all pollutants in the list of performance factors, there are more than 602 inorganic and 491 organic air emissions from coal facilities, so some aggregation is unavoidable. Table 7 displays a systematic example of determining which pollutants should be incorporated in a comparative evaluation.

From these types of lists some priorities can be developed concerning which pollutants to investigate. For example, highest priorities for incorporation should go to those items that consistently occur in these different lists, such as compounds of sulfur, nitrogen, beryllium, arsenic, and uranium/radioactivity. In this way the size of the bookkeeping and manipulation efforts in the assessment procedure can be kept reasonable.

From the perspective of commercialization potential, another set of pollutants which should receive consideration is those that are now and may in the future be regulated. Some foresight as to what these pollutants may be can be gleaned from several sources: the revised Clean Air Act Amendments, the concerns expressed by members of the epidemiological, toxicological, and regulatory communities, the lowest emissions levels from available control technologies, and the pollutants investigated in various mechanisms aimed at policy evaluations, see Table 8.

Probabilistic Information

It is largely a matter of chance if a decision maker can make the correct choice in the absence of probabilistic information. The ideal format for this information would be in the form of probability density

Table 7 Different Ways in Which Pollutants are Shown to be of Concern in a Comparative Assessment [from Gruhl, et al., 1976]

<u>Great Variability among Coal</u>

1) Arsenic (sometimes 100 to 1000 times national average)
2) Barium (1 to 3000 ppm)
3) Beryllium (0.1-1000 ppm)
4) Boron (100-1000 ppm)
5) Germanium (25-3000 ppm)
6) Uranium (1-200 ppm)
7) Sulfur (3000-120000 ppm)
8) Nitrogen
9) Chromium
10) Cobalt
11) Copper
12) Lead
13) Manganese
14) Molybdenum
15) Nickel
16) Vanadium
17) Zinc
18) Zirconium

<u>Escape Pollution Control Equipment Due to Volatility (or other properties)</u>

1) Mercury (about 100%)
2) Arsenic (about 80%)
3) Beryllium (about 100%)
4) Nitrogen (about 100%)
5) Sulfur (about 99%)

<u>Relative National Importance of Power Plants as an Emission Source</u>

(Goldberg, 1973) and (Starr, Greenfield and Hausknecht, 1972)

1) SO_x (73.5%)
2) Beryllium (68.0%)
3) Chromium (53.5%)

Table 7 (continued)

4) Selenium (50.5%)
5) NO_x (43.8%)
6) Vanadium (34.2%)
7) Boron (32.2%)
8) Particulates (31.4%)
9) Nickel (26.8% but mostly oil)
10) Barium (24.8%)
11) Mercury (22.0%)
12) Flourides (17.7%)
13) Magnesium (8.5%)
14) Lead (7.7%)
15) Arsenic (5.5%)
16) Tin (4.5%)

<u>Approaching Ambient Standards or Recommended Levels (site specific)</u>

1) SO_x
2) Total Suspended Particulates
3) NO_x
4) Ozone/Oxidants
5) Hydrocarbons
6) Beryllium (20% of recommended levels)
7) Radiation (10% of recommended levels)

<u>Important from Standpoint of Health Effects Research</u>

1) SO_x
2) Particulate Sulfates
3) Sulfuric Acid Aerosols
4) NO_x
5) NO
6) Ammonia
7) Particulate Hydrocarbons (carcinogenic potency ++++)
8) Particulate Hydrocarbons (carcinogenic potency +++)

Table 7 (continued)

9) Particulate Hydrocarbons (carcinogenic potency ++)

10) Particulate Hydrocarbons (carcinogenic potency +)

11) Heat

12) Radionuclides

13) SiO

14) Arsenic

15) Asbestos

16) Beryllium

17) Chromium

18) Lead

19) Mercury

20) Nickel

21) Tin

22) Vanadium

23) Zinc

<u>Synergistic Pollutants - Potentiators</u>

1) SO_x

2) NO_x

3) Total Suspended Particulates

4) Ozone

5) Reactive Gaseous Hydrocarbons

6) Metal Oxides

7) Iron

<u>Synergistic Pollutants - Antagonizers (possibly beneficial to health)</u>

1) Arsenic

2) Cadmium

3) Copper

4) Manganese

5) Particulates Hydrocarbon (carcinogenic potency -)

6) Selenium

7) Titanium

8) Water Hardness

Table 8 List of Pollutants Collected for Use in the SEAS Mechanism (USEPA, 1975)

The system consists of a nine-digit code, as follows:

1st and 2nd digits: Residual Category		3rd and 4th digits: (Continued)	
Particulates	01	Antimony	03
Sulfur Oxides	02	Appliances	04
Nitrogen Oxides	03	Arsenic	05
Hydrocarbons	04	Asbestos	06
Carbon Monoxide	05	Ash	07
Photochemical Oxidants	06	Automobiles	08
Other Gases and Mists	07	Bacteria	09
Odors	08	Barium-140	10
Biological Oxygen Demand	09	Beryllium	11
Chemical Oxygen Demand	10	Boron	12
Total Organic Carbon	11	Botanical Insecticides	13
Suspended Solids	12	Cadmium	14
Dissolved Solids	13	Carbamate Insecticides	15
Nutrients	14	Cesium-134	16
Acids	15	Cesium-137	17
Bases	16	Cesium-144	18
Oils and Greases	17	Chloramine	19
Surfactants	18	Chlorine	20
Pathogens	19	Chromium	21
Waste Water	20	Cobalt-60	22
Thermal Loading	21	Concrete, Masonry	23
Combustible Solid Waste	22	Copper	24
Non-Combustible Solid Waste	23	Copper Fungicides	25
Bulky Waste	24	Crop Waste	26
Hazardous Waste	25	Cyanide	27
Mining Waste	26	Dithiocarbamate Fungicides	28
Industrial Sludges	27	Ferric Chloride	29
Sewage Sludge	28	Ferric Sulfate	30
Herbicides	29	Ferrous Metals	31
Insecticides	30	Fluorine	32
Fungicides	31	Food Waste	33
Miscellaneous Pesticides	32	Garden Waste	34
Radionuclides to Air	33	Glass	35
Radionuclides to Water	34	Household Furniture	36
Radionuclides to Land	35	Hydrogen-3	37
		Inorganic Herbicides	38
3rd and 4th digits:		Inorganic Insecticides	39
Residual Component		Iodine-129	40
		Iodine-131	41
Not Applicable	00	Krypton-85	42
Aluminum	01	Lanthanum-140	43
Ammonium Hydroxide	02	Lead	44

Table 8 (continued)

3rd and 4th digits: (Continued)	
Leather	45
Livestock Waste	46
Mercury	47
Mine Overburden	48
Mine Tailings	49
Miscellaneous Fungicides	50
Nitrates	51
Non-Ferrous Metals, Miscellaneous	52
Organic Herbicides	53
Organic Mercury Fungicides	54
Organochlorine Insecticides	55
Organophosphorus Insecticides	56
Other Synthetic Organic Insecticides	57
Paper	58
Phenols	59
Phosphates	60
Pthalimide Fungicides	61
Plastics	62
Radium-266	63
Radon-222	64
Rubber	65
Ruthenium-106	66
Sand, Stone, Soil	67
Selenium	68
Slag	69
Strontium-90	70
Tellurium	71
Textiles	72
Thalium	73
Tires	74
Vanadium	75
Viruses	76
Water, Cooling	77
Water, Process	78
Wood	79
Zinc	80

5th digit: Carrier Medium/ Reporting Category	
Air	1
Water	2
Land	3
Leachate	4
Pesticide	5
Radiation	6
6th digit: Source	
Point	1
Area	2
Mobile	3
7th digit: Product of Combustion	
Yes	1
No	2
8th digit: Type of Economic Activity	
Extraction	1
Production	2
Distribution	3
Consumption	4
Disposal	5
9th digit: Toxicity	
None	1
Low	2
Medium	3
High	4

functions for each of the entries in the list of performance factors, Table 6. It may seem as though these data are not obtainable, but there is, fortunately, a great deal that can be done to rectify the apparent lack of information. Take, for example, the fact that lanthanum levels in a specific coal seam may be unknown. First, the parts per million (ppm) level is certainly greater than or equal to zero. Average distribution of lanthanum in the crust of the earth is known to be about 20 ppm. Lanthanum ores may generally be in the range of 600 to 1000 ppm. Levels in oil shale are known to be about 30 ppm, so there appears to be some concentration in the natural energy storage process. Thus, as a crude estimate one might set the range at 10 ppm to 600 ppm with a mean possibly at 40 ppm. If this range of levels indicates potential problems in the overall assessment, then there is clearly a need for research to reduce this uncertainty.

There are different types of information that are contained in the same probabilistic curve. For example, a variation in beryllium emissions may in part be due to an intentional procedure for describing the range of beryllium that would be experienced in the use of U.S. coals, and it may in part be due to uncertainties about the fate of beryllium in the combustion process. For this reason some methods of tracing the uncertainties back to their sources are necessary. Such methods are discussed in Section III.

An example of some of this probabilistic information is available from a computerized model that has been developed at the MIT Energy Laboratory and that has the capability of simulating the siting of many electric power generation technologies. This model, AEGIS - Alternative Electric Generation Impact Simulator, gives output that displays the range of uncertainty associated with each of 109 performance measures. An open cycle MHD simulation is shown in Table 9. Negative numbers, such as -1, indicate that these are performance values not predicted by the particular modules chosen by the user.

Ordering Techniques

Having gathered a hundred or more performance measures for each of several competing energy technologies, it would be an impossible task to push these characterizations through a comprehensive national energy model. Fortunately, there are simpler, approximate methods of comparing technologies and these involve direct side-by-side examinations of the various performance characterizations. Even a comparison of two sets of

Table 9 Display to user of the assumptions that will be used in this particular session.

```
|--------------|
| ASSUMPTIONS |
|--------------|
  SIZE<MWE>                    1900.0
  YEAR COMPL                   1998.0
  FUEL TYPE               NAT RANGE BITUMINS COALS
  PRECL TYPE              NONE
  GENERATYPE              COALFIRED OPEN CYCLE MHD
    DES CAPAC FAC<%>           70.000
    STORAGE CAP<MWH>           .0
    SORBENT TYPE          NONE
  ABATE TYPES:
    PART TYPE             NONE
    SCRUB TYPE            NONE
    STACK HT<M>                235.00
  MET SITE TYPE           STANDARD AMBIENT SCALING
  AEROCHEM MODELS:
    SULFATION TYPE        NONE
    SMOG TYPE             NONE
  DENSITY PATTERN         INDIAN POINT IN 1980 EST
    SCALED BY                  .90000
  HEALTH/IMPACTS:
    CHEM HEALTH MOD       LINEAR ADD MORT MODEL
    RAD HEALTH MOD              NONE
    POLLUTION INDEX             NONE

FOR CHANGES NQ=4,OTHERWISE NQ=3
 &PRINT NQ &END
 &print nq=3 &end
```

Table 9. Performance measures for the technology/site options chosen for this simulation.

CUMULATIVE PROB MEASURES PROB VALUE < THIS VALUE	MINIMUM .0000	1 DEV LO .1587	MEDIAN .5000	1 DEV HI .8413	MAXIMUM 1.0000
ECONOMIC FACTORS					
INVEST COST<MIL $>	1219.8	1364.2	1529.5	2095.7	2736.0
NORMALIZED INVEST<$1000/MWE>	642.00	718.00	805.00	1103.0	1440.0
OPERATING COSTS:					
FIXED OPER COST<$/MWE/YR>	.11248E+06	.12579E+06	.14104E+06	.19325E+06	.25229E+06
VARIABLE OPER COST<$/MWH>	7.4159	8.8692	11.229	14.377	19.852
OP&MAIN<$/MWH>	1.6000	1.7000	2.8000	3.2000	4.0000
FUEL<$/MWH>	5.8159	7.1692	8.4289	11.177	15.852
COST OF ELECT<MILS/KWH>	25.759	29.383	34.229	45.892	60.995
CAP COST<MILS/KWH>	18.343	20.514	23.000	31.514	41.143
OP COST<MILS/KWH>	1.6000	1.7000	2.8000	3.2000	4.0000
FUEL COST<MILS/KWH>	5.8159	7.1692	8.4289	11.177	15.852
PERFORMANCE FACTORS					
OPER CAP FAC<%>	55.000	63.000	68.000	70.000	75.000
ENERGY EFF ONSITE<%>	39.819	43.347	46.147	48.068	49.867
APPLICABILITY					
COMMERC YR<2000MWE ONLINE>	1995.0	1996.0	1999.0	2003.0	2021.0
INSTALLED CAP<MWE>	583.00	583.00	583.00	583.00	583.00
LARGEST FACILITY<MWE>	500.00	500.00	500.00	500.00	500.00
RESOURCE REQUIREMENTS					
LAND USE ONSITE<ACRES>	70.490	96.900	370.50	659.30	1187.5
LAND DISTURB FUEL<ACRES/YR>	63.776	99.243	120.60	146.74	179.70
LAND DISPOSE WASTE<ACRES/YR>	59.850	86.450	119.70	151.62	196.84
WATER CONSUMP<MIL GAL/YR>	2394.0	2926.0	4123.0	5985.0	7315.0
ENVIRONMENTAL CONSEQUENCES					
AIR EMIS ONSITE<GM/MIN>:					
SOX	101.82	1287.7	42475.	.12990E+06	.48523E+06
SULFATES	8.1452	90.141	2973.3	9093.0	33819.
SULF ACID AEROS	1.2727	12.877	504.40	1515.5	5661.0
NOX	5700.0	14250.	17100.	29450.	64600.
NO	5700.0	14250.	17100.	29450.	64600.

Table 9 Continued display of performance measures.

O3, OXID	.64600E-03	.20900E-02	.64600E-02	.20330E-01	.64600E-01
PART TOTAL	9690.0	47500.	77900.	98800.	.11590E+06
PART RESPIR	7030.0	32300.	55100.	68400.	81700.
CO	15960.	53200.	.15960E+06	.53200E+06	.15960E+07
CO2	.38000E+07	.47500E+07	.57000E+07	.76000E+07	.11400E+08
HC TOTAL	3.0400	9.8800	30.400	98.800	304.00
INERT HC	2.4320	7.9800	24.320	79.800	243.20
REACTIVE HC	3.0400	.98800	3.0400	9.8800	30.400
OXYG HC	.30400E-01	.98800E-01	.30400	.98800	3.0400
POLY ORG MAT	.26600	.89300	2.6600	8.9300	27.360
TRACE ELEM:					
ARSEN	.34397E-01	3.8291	23.482	150.89	398.10
BERYL	.13759E-01	.79669	5.1235	14.164	32.105
CAD	.68794E-02	.37236	6.9642	134.90	452.14
CHROM	.27518	8.5587	57.575	163.29	577.89
COB	.68794E-01	2.5087	32.058	104.33	368.13
LEAD	.27518	8.0305	58.253	372.98	933.18
MANG	.41276	12.199	206.85	695.96	1937.0
MERC	.13759E-02	.23272E-01	.83745E-01	.29607	1.7123
NICK	.20638	11.500	88.225	256.64	847.57
SELEN	.30957E-01	.45614	2.6128	7.3554	24.721
TIN	.68794E-01	2.2683	20.057	131.24	540.32
VANAD	.75673	19.251	95.875	244.22	584.31
ZINC	.41276	30.254	820.91	9270.6	41223.
RADIOACT TO AIR<CUR/YR>	.31402E-03	.29245E-01	.11002	.23652	.58511
WATER EMIS ONSITE<TONS/YR>	.44245E+06	.52351E+06	.60302E+06	.71259E+06	.88853E+06
INORGANIC<TONS/YR>	.39860E+06	.47140E+06	.54272E+06	.64197E+06	.79868E+06
ORGANIC<TONS/YR>	43846.	52103.	60302.	70617.	88853.
THERMAL<10*12 BTU/YR>	25.510	28.119	30.151	33.016	36.939
RADIOACT TO WAT<CUR/YR>	.0	.0	.0	.0	.0
SOLID WASTES<TONS/YR>	.60753E+06	.26624E+07	.38457E+07	.53221E+07	.11083E+08
RADIOACT SOLIDS<CUR/YR>	.0	.0	.0	.0	.0
ATMOS DILU FAC<UG/M3/G/MIN>					
GASEOUS:					
1 HOUR	.83301E-06	.14072E-05	.33154E-05	.66555E-05	.11353E-04
3 HOUR	.15048E-05	.25421E-05	.59892E-05	.12023E-04	.20509E-04
8 HOUR	.19885E-05	.33592E-05	.79143E-05	.15887E-04	.27101E-04
24 HOUR	.25796E-05	.43578E-05	.10267E-04	.20611E-04	.35158E-04
3 DAY	.32783E-05	.55381E-05	.13048E-04	.26193E-04	.44680E-04
1 MON	.44069E-05	.74446E-05	.17540E-04	.35210E-04	.60062E-04
ANNUAL	.53742E-05	.90788E-05	.21390E-04	.42939E-04	.73246E-04
PARTICULATES:					
1 HOUR	.57056E-06	.74611E-06	.19311E-05	.34233E-05	.51789E-05
3 HOUR	.10307E-05	.13478E-05	.34885E-05	.61841E-05	.93554E-05
8 HOUR	.13620E-05	.17810E-05	.46098E-05	.81719E-05	.12363E-04
24 HOUR	.17669E-05	.23105E-05	.59802E-05	.10601E-04	.16038E-04
3 DAY	.22454E-05	.29363E-05	.75999E-05	.13473E-04	.20381E-04
1 MON	.30184E-05	.39472E-05	.10216E-04	.18111E-04	.27398E-04
ANNUAL	.36810E-05	.48136E-05	.12459E-04	.22086E-04	.33412E-04

Table 9 Completion of display; -1.0 values indicate information not predicted by modules chosen.

OCCUP HEALTH:					
MORT ONSITE<PER YR>	.63776E-01	.82703E-01	.10768	.13757	.17970
MORB ONSITE<PER YR>	.63776	.87665	1.8521	3.3016	4.4926
DAYS LOST ONSITE</YR>	239.16	364.72	792.55	1283.9	1797.0
MORT OFFSITE<PER YR>	.79720E-01	.41351	.86146	1.3757	2.1964
MORB OFFSITE<PER YR>	2.1524	4.7140	54.617	87.583	100.83
DAYS LOST OFFSITE</YR>	53.731	154.65	294.62	3466.7	9584.2
PUBLIC HEALTH<ROUTINE>:					
MORTALITIES<PER YR>	.94463E-01	1.0952	6.3197	18.926	56.097
CANCER<TOTAL>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
CARDIOVAS	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
BRONCHOPULM	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
CNS	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MUTATIONS<TOTAL>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MORBIDITIES<PER YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
RESPIR	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
ASTHMA	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
PNEUM	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
CHRONIC	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
CHILDREN	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
THYROID	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
CARDIOVAS	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MANDAYS LOST<PER YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
PUBLIC HEALTH<OFFSITE>:					
MORTALITIES<PER YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
CANCER<TOTAL>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MUTATIONS<TOTAL>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MORBIDITIES<PER YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MANDAYS LOST<PER YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
PUBLIC HEALTH<CATAST>:					
PROB OF OCCUR<PER YR>	.79720E-07	.39697E-06	.68917E-06	.11739E-05	.15974E-05
MORTALITIES<PER YR>	.63776	1.2405	1.5506	1.9259	2.7954
CANCER<TOTAL>	.39860E-05	.25638E-04	.56857E-04	.35767E-03	.86856E-03
BRONCHOPULM	.11958E-04	.49622E-04	.21537E-03	.50441E-03	.11980E-02
CARDIOVAS	.79720E-04	.37216E-03	.86146E-03	.20176E-02	.89851E-02
MUTATIONS<TOTAL>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MORBIDITIES<PER YR>	6.3776	17.368	24.121	32.099	40.932
THYROID	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MANDAYS LOST<PER YR>	637.76	1736.8	2412.1	3209.9	4093.2
INDEXES AND COSTS:					
PUBLIC HEALTH COSTS<$/YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
BIOTA COSTS<$/YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
MAT DAMAGE COSTS<$/YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
AESTH COSTS<$/YR>	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
SUBJECTIVE INDEXES	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000

FOR ANOTHER RUN TYPE: DO OR: NOT

not

END

probabilistic information for a hundred or more performance measures can be an extremely difficult and subjective task. This, however, is a true reflection of the difficulty faced by the decision maker. It would be unusual to find a policy maker who would feel more comfortable with a smaller set of information, knowing that the reduction in size of the set had been accomplished in a relatively arbitrary manner in which several other people had introduced their own biases.

There is in fact a systematic way in which this mass of comparative data can be reduced. Figure 2 shows a flow chart of how this might be accomplished using a computerized interactive mechanism, although a manual use of this flowchart would also be possible. There are also other techniques for making such systematic comparisons (Burnett, et al., 1974).

The use of the probabilistic information not only allows for various levels of risk aversion to be met, but it also makes it possible to quantify the risk of an error being made in the decision. Take for example, the comparison of a single measure of desirability for two different alternatives, where there is no correlation between the uncertainties and the uncertainties are real, rather than described by ranges. Figure 3 shows cases where the probabilities of decision errors are 45% and 1.5%.

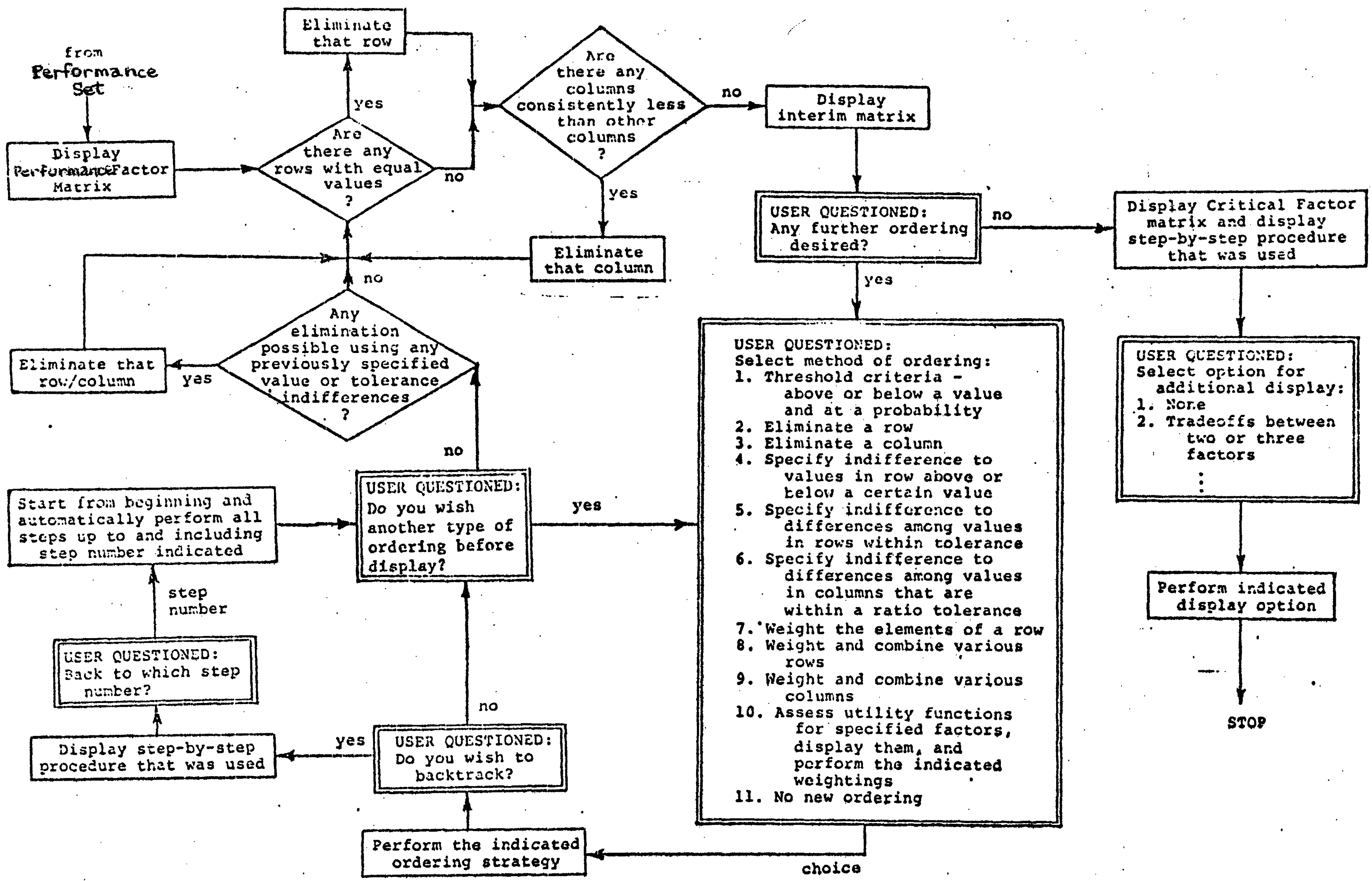

Figure 2 Flowchart showing the decisions, actions, and questioning that could be performed to develop priorities between lists of performance measures.

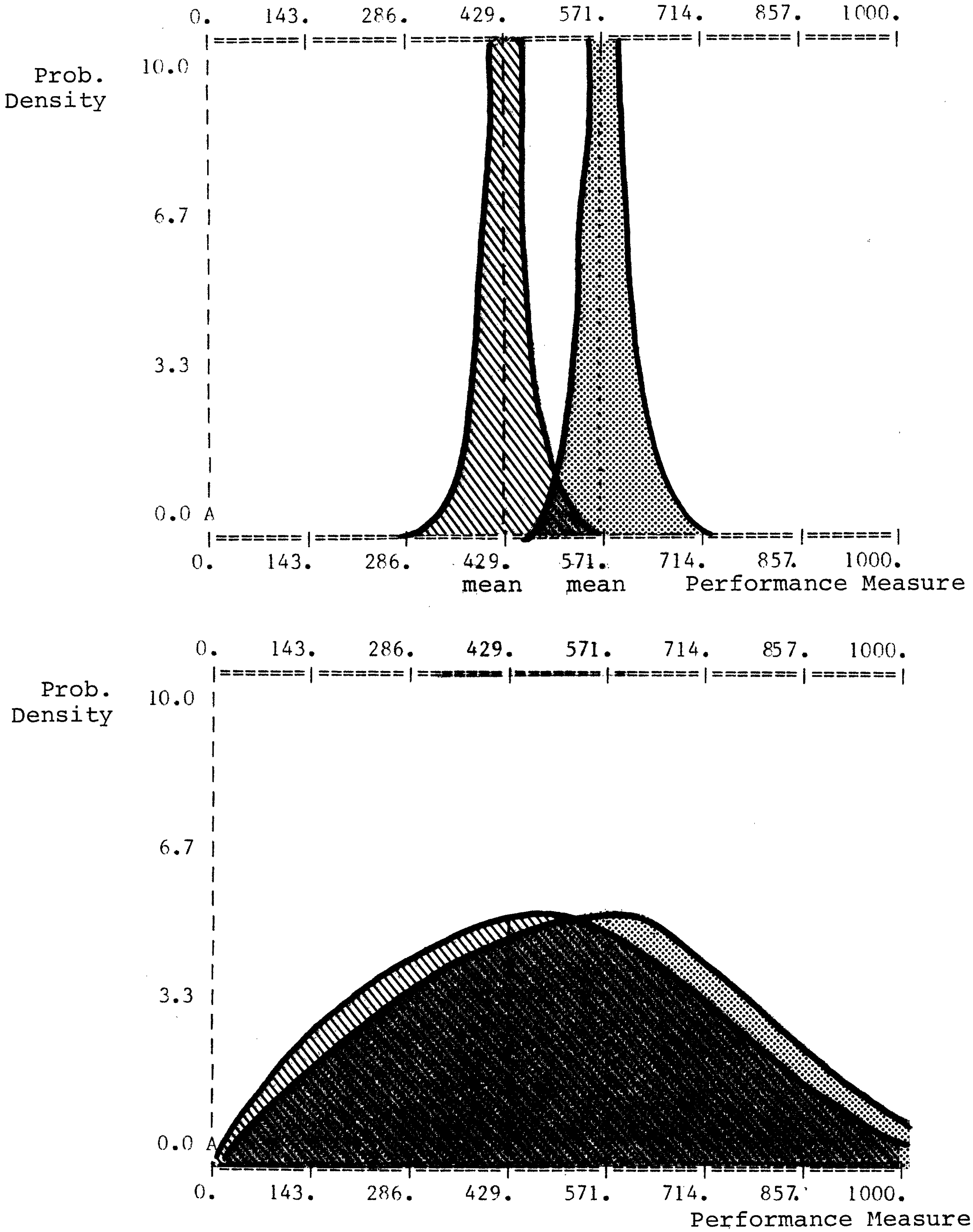

Figure 3 Comparison of two probabilistic displays of performance measures.

III. PRIORITIES FOR R&D FUNDING

There are two different methods for selecting high priority research projects. One method involves comparison of a performance measure with some absolute standard and the other results from reducing uncertainty involved in the choice between two or more alternative energy technologies. Hypothetical examples will be used to demonstrate these two possibilities.

External Performance Thresholds

Direct inspection of the list of performance measures can lead to the identification of key research projects. For example, regardless of how uncertain a piece of information is, if it does not approach recognition levels then there is no urgent research need to reduce that uncertainty. On the other hand, if a performance measure has a significant probability of violating an absolute standard, see Figure 4, then research to reduce this uncertainty would be important. Suppose there is a 48% chance of violating the standard and a 10% chance of missing the standard by a factor of two (note that an expected value approach would tend to show this as a satisfactory situation), then a quantitative level of urgency can be associated with the task of reducing this level of uncertainty relative to other important tasks that are identified. To identify the specific experiments necessary to effect this reduction requires tracing back this uncertainty to the responsible components, see Table 10 for example.

Table 10 Hypothetical Example of Tracing Uncertainty Back to its Components

	Geometric Standard Deviation
Geometric Standard Deviation of Emission Level	= 1.80
Unexplained variation due to variation in coal source	= 1.20
Unexplained variation due to combustion design differences	= 1.12
Effect of fluidizing velocity	= 1.22
Ca/S ratio effect	= 1.04
Temperature effect	= 1.07
Knowledge of background concentrations	= 1.15
Dispersion modeling inaccuracies	= 1.05

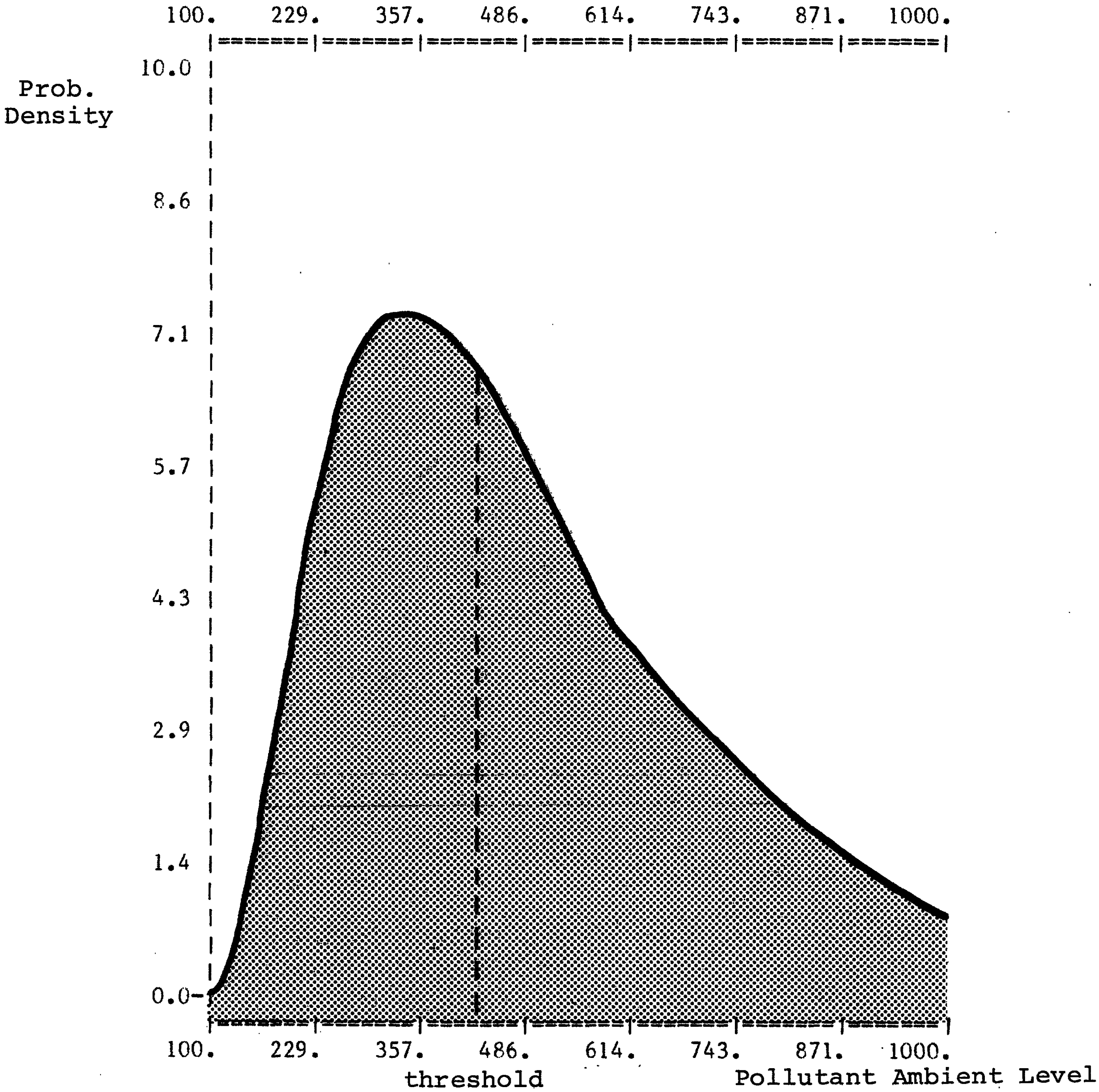

Figure 4 Distribution of uncertainty about an ambient threshold pollution standard

Here it is possible to identify as possibly most important the effects of fluidizing velocity and the unexplained variation due to different coal sources. However, at this stage, in order to make accurate quantitative measures of the priorities of various projects it would be necessary to have dollar cost estimates associated with various probabilities of reducing the same amount of uncertainty in the different areas.

Comparative Performance Advantages

This other method involves comparison of alternate energy technologies from the standpoint of deciding between them. Again, the uncertainties in both cases can be traced back to the responsible components, but here the difference is that there may well be a high degree of correlation between uncertainties in the two cases. For example, background levels of pollutants may be very uncertain but they are identical for two energy technologies proposed for the same site. As another example, the choice between an atmospheric fluidized bed combustor with or without physical coal cleaning might appear to have too much uncertainty to allow for any assurance about the decision. Due to the high degree of correlation between these similar processes, however, the decision may not be risky at all.

Again here, it is a formidable problem to develop quantitative priority levels for different research projects. The information that is needed for this comparison includes:

(1) dollar costs of the different projects,

(2) amount of reduction in uncertainties probable upon execution of those projects, and

(3) quantified levels of the importance of reducing those various uncertainties.

Point (3), the levels of urgency, are developed as discussed, either by comparison with absolute standards or by comparison among technologies. Developing the dollar costs in Point (1) can be a time consuming task but these numbers can be gathered with some certainty of being good predictions (West, 1970), (Weinberger, 1963). Point (2) is a difficult quantity to establish because it will usually depend upon the relative success of the research project. Estimates of probabilities of various reductions may be necessary.

Identifying Key Projects

Another area of great interest involves inverting the procedure of evaluating specific research projects as discussed above, by first identifying the performance uncertainties that are to be reduced and then designing the best R&D projects for those purposes. This type of effort is largely an art; however, where good empirical models exist, it may be possible to reduce a specific uncertainty by solving for the next best experiment or the next best design. Here again, it is important that "best" be uniquely defined. Surveys of the R&D literature, (Chen, Kirkwood, Lathrop, Pollock, 1977) and (Gruhl, et al., 1976), show that there are seven broad categories of objectives that might be used to define "best". These were listed before and include:

1. economics, in terms of cost of unit energy output, investment and operating costs;
2. timeliness, availability for commercial use and fit into energy-economic context;
3. resource comsumption, including use of unpolluted air and water, materials, fuels, manpower, and capital;
4. environmental, safety, and health characteristics;
5. basic research, meaning those contributions that will also apply to other processes;
6. institutional, factors such as public image and government-industry interference and cooperation; and
7. national security enhancement, primarily in aiming at replacing or avoiding cartel-vulnerable products, such as foreign oil or rare imported metals, and avoiding disruptions that could affect the survival of the establishment.

A quick look at this list points out the strict limitations of most empirical models of energy technologies, which can at most be used to tune in on best designs only with respect to cost, efficiency, and emission performance measures. There is, however, no reason why some of those other performance measures could not be modeled and thus considered in the design of experiments. It must also be noted that empirical models that focus only upon expected values will be very much limited in applicability because decision makers are generally very risk averse with regard to many of the important performance indexes. Measures of uncertainty are required for these instances where a lower risk region such as a broadly level hill of high performance is much preferred compared to the absolute optimum performance that may be closely surrounded by disastrous chasms. The standard gradient search procedures for identifying optimal designs can easily be modified for consideration of risk aversion by using average or minimum performance over a range of uncertainty.

Aside from experiments aimed at best performance there are also experiments that are aimed at making the greatest reduction in the uncertainties in our knowledge about a technology. It is highly unlikely that the experiment that will provide the best performance will also reduce the most important uncertainties. Thus, this is a classic dual control problem where the designer must divide, by relative weightings, his interest between maximizing performance and obtaining useful information. As a new technology matures and becomes better understood, that weighting will slowly shift from entirely informational to entirely beneficial.

Except for the easy cases where measurement errors are known to be responsible, the designing of experiments to most reduce the key uncertainties is a very difficult process that requires:

1. prespecified priorities or weightings of the relative importance of the different types of uncertainties, weightings that will usually vary over the range of the variables, that is, have regions where the uncertainty is more critical;
2. measures of the difficulties (including absolute constraints), such as costs, involved in changing the various variables (for example it may be less costly to change temperature than design), both for the specific experiment and for any subsequent final design; and
3. obtaining all of the available validation information about the empirical model, because the validation procedure is very similar to the process of reducing uncertainty.

With these pieces of information, some simple directions toward key data can be made, such as: (1) resolving discrepancies by repeating experiments, (2) performing tests on the experiments with the largest residuals, (3) interpolating between experiments, (4) aiming at reducing measurement errors with parametric investigations, and (5) developing correction factors that can be traced to new variables. Reducing widespread, persistent uncertainty is, however, still a formidable problem. A well-constructed empirical model will generally, by definition, not be able to offer clues for reducing that type of uncertainty, because the modeler should previously have followed through on, and factored out, all these clues. Such widespread uncertainty may point toward missing, unmeasured variables which, of course, can only be identified by validation procedures and not by any other hints from the model. Apart from validation approaches, perhaps the only avenue remaining for exploring persistent uncertainty is through the highlighting of the most sensitive variables. One possible method is to trace the uncertainties back through the model to find the minimum weighted distance change in inputs that could account for the uncertainties. Indications of which input variables may be responsible for the uncertainties might then come from identification of the input variables that seem to be most persistently accountable for the uncertainties. This procedure involves the study of the minimum compensating change in $\underline{x}_n$, called $\Delta\underline{x}_n$, using weights of the certainty with which its effects are felt to have been modeled $\underline{W}$ (a diagonal matrix of weights that may be composed of robust, measurement, or other confidence indicators), where $\Delta\underline{x}_n$ is such that

$$y_n = F(\underline{x}_n + \Delta\underline{x}_n, \underline{p})$$

with $\Delta\underline{x}'_n \underline{W} \Delta\underline{x}_n$ minimized. Although this is not a panacea for the problem of persistent uncertainties, it will show in some sense where the responsibility for the uncertainties can be most easily relegated.

The design of the next best <u>facility</u> is completely analogous to the design of the next best <u>experiment</u>. For the next best experiment, the design parameters are generally fixed, and the optimization takes place in the operating variable space; for the next best facility the optimization takes place over design and operating variable space; the situations are otherwise identical.

A summary of these ideas and how they relate back to the comparative assessments is given in Table 11.

Table 11 Outline for Unraveling the Task of R&D Planning

1. Individual Technology R&D Guidance - assigning funding priorities for a technology where the GOAL is the most cost effective path of EXPERIMENTS and DESIGNS for:

   1.1 Reducing Uncertainties - INFORMATION
   - -identify discrepancies - over all pairs of experiments maximize the ratio (difference in arithmetic or geometric residuals):(distance between the pair measured in n-dimensional exogenous model variable space)
   - -identify effects of measurement errors
   - -sensitivity analysis to focus on information about the key variables
   - -comparison with analytic models, with understanding, or with data split models, to identify problem areas and missing variables
   - -correction factors for designs, coals, sorbents, and so on, to trace back to new variables

   must divide attentions

   1.2 Maximize Desirability Measure - PERFORMANCE
   - -ECONOMICS - cost of unit energy output, investment and operating costs
   - -RESOURCE CONSUMPTION - unpolluted air and water, materials, fuels, manpower, and capital
   - -ENVIRONMENTAL - ecology, safety, and health considerations
   - -TIMELINESS - availability for commercial use and fit into energy/economic context
   - -BASIC RESEARCH - contributions that will apply to other processes
   - -INSTITUTIONAL - factors such as public image and government/industry interference and cooperation
   - -NATIONAL SECURITY - primarily aiming at replacing or avoiding cartel-vulnerable materials, such as oil or imported metals, and avoiding disruptions that could affect the survival of the establishment

   for thresholds and relative importance must go to comparison

2. Comparative Technology Assessment - assigning funding priorities among competing technologies by sponsoring a MIX that is APPROPRIATE and FLEXIBLE

IV. REFERENCES AND BIBLIOGRAPHY

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