DOE/ER-0091
Dist. Category UC-41

Comparative Health and Safety Assessment of the Satellite Power System and Other Electrical Generation Alternatives

December 1980

Prepared by:
Argonne National Laboratory
Argonne, Il. 60439

Under Contract No. 31-109-ENG-38

Prepared for
U.S. Department of Energy
Office of Energy Research
Solar Power Satellite Projects Division

DOE/NASA
Satellite Power System
Concept Development
and
Evaluation Program

ABSTRACT

The work reported here is an analysis of existing data on the health and safety risks of a satellite power system and six electrical generation systems: a combined-cycle coal power system with a low-Btu gasifier and open-cycle gas turbine; a light water fission power system without fuel reprocessing; a liquid-metal, fast-breeder fission reactor; a centralized and decentralized, terrestrial, solar-photovoltaic power system; and a first-generation design for a fusion power system. The systems are compared on the basis of expected deaths and person-days lost per year associated with 1,000 MW of average electricity generation. Risks are estimated and uncertainties indicated for all phases of the energy production cycle, including fuel and raw material extraction and processing, direct and indirect component manufacture, on-site construction, and system operation and maintenance. Also discussed is the potential significance of related major health and safety issues that remain largely unquantifiable. The appendices provide more detailed information on risks, uncertainties, additional research needed, and references for the identified impacts of each system.

PREFACE AND ACKNOWLEDGMENTS

This report contains the final results from the health and safety studies conducted as part of the Comparative Assessment component of the Satellite Power System Concept Development and Evaluation Program established by the SPS Project Division of the U.S. Department of Energy. Analogous comparative assessments of the SPS and alternative energy systems were also conducted for major technical, economic, environmental, institutional, and societial issues, and the overall conclusions of these studies are published in *An Assessment of the Satellite Power System and Six Alternative Technologies* (Draft, July 1980).

Preliminary results of the health and safety study were published as DOE/ER-0053, Health and Safety: *Preliminary Comparative Assessment of the Satellite Power System (SPS) and other Energy Alternatives,* April 1980. This report represents a major update of that preliminary study in several aspects, although a similar format was used in both reports for evaluating individual energy technologies. A liquid-metal, fast breeder reactor system and decentralized ("rooftop") terrestrial photovoltaic system were added to the previous study to extend the range of alternatives evaluated. The much more thorough evaluation of risks related to both direct and indirect industrial activity to produce system components represents an important addition to the previous report because of the capital intensive nature of several of the technologies considered. The cumulative impacts in the updated report associated with alternate future SPS energy scenarios provides a new perspective on the significance of the differences between technologies, even though definitive conclusions from the scenario analysis are limited due to uncertainties. The data presented in the previous report were also subjected to detailed review in view of additional information obtained relative to health and safety risk factors and as the result of both major and minor changes in the reference design characterizations for each of the technologies.

Acknowledgment is due to the following reviewers who provided valuable suggestions through a formal review of the draft manuscripts; reviewer affiliation is given for informational purposes and does not necessarily imply endorsement by those institutions: N. Barr, Office of Health and Environmental Resources, DOE; B. Cohen, University of Pittsburgh; J. Crow, Chairman, National Academy of Science Committee on Health and Safety Impacts of Coal and Nuclear Energy, and University of Wisconsin; W. Ellet, Office of Radiation Programs, Criteria and Standards Division, EPA; D. Miller, Radiation Safety Officer, Sargent and Lundy Engineers; R. Wyzga, Program Manager, Integrated Assessments, Electric Power Research Institute; and M.A. Zerivas, Occupational Safety and Health Consultant. Unfortunately, given the resource limitations of the program, some of the useful comments supplied by these reviewers could not be incorporated into the report. In particular, several reviewers suggested that we use a more thorough and consistent evaluation and documentation of the range of published data and uncertainties. The authors acknowledge the validity of this comment but must defer an adequate response to a future, as yet unplanned, follow-up study.

EXECUTIVE SUMMARY

The work reported here is part of the Satellite Power System Concept Development and Evaluation Program (SPS CDEP), established by the SPS Project Office of the U.S. Department of Energy. The purpose of that program was to generate information from which decisions can be made regarding development of SPS technology after fiscal year 1980. One phase of the SPS CDEP is the comparative assessment of the SPS and selected alternative energy systems with regard to the technical, economic, environmental, societal, and institutional issues surrounding the deployment of these technologies. The health and safety risks associated with the SPS and six alternative electrical generation systems are assessed here.

The approach developed and used in this assessment is oriented toward providing information useful for decision making. Data available from the literature were used initially to make an evaluation of the public and occupational health and safety risks of a light water reactor (LWR) fission power system without fuel reprocessing; a coal-gasification combined-cycle (CG/CC) power system with a low-Btu gasifier and open-cycle gas turbine; a liquid-metal, fast-breeder reactor (LMFBR) with fuel reprocessing; both a centralized (CTPV) and decentralized (DTPV), terrestrial, solar photovoltaic power system; the satellite power system; and a first-generation fusion system. The overall assessment approach consists of (1) the identification of health and safety issues in each phase of the energy cycle from raw material extraction through electrical generation, waste disposal, and system deactivation; (2) quantitative or (if limited by data availability) qualitative evaluation of impact severity and uncertainties and (3) the cumulative occupational risks from construction, operation, and maintenance for 2000-2020 U.S. electrical supply scenarios with and without the SPS. Because of the capital intensive nature of advanced technologies, in particular, solar technologies, an important aspect of the evaluation was the estimation of occupational risks related to both direct and indirect industrial activity to produce system components. The indirect industrial activity requirements are based on input-output matrices of the U.S. economy.

In contrast to the apparent public willingness to accept limited known risks of energy systems, those risk that are less quantifiable or predictable but perceived as major risks by the public may restrict or completely halt energy system deployment if adequate assurances of very low impact probability cannot be given. For this reason in this study potentially major, but unquantified, risks are given prominence comparable to the quantified risks. Evaluation of unquantifiable issues also serves as a means of identifying needed research.

The presentation of the health and safety issue comparisons between technologies utilizes (1) diagrams showing system components, related health and safety issues, and issue impact and uncertainty ratings; (2) issue summary tables with quantitative impact values and qualitative descriptors; and (3) detailed separate descriptions of the basis for evaluation of each issue.

The results of the quantitative risk analysis for the SPS and six alternative electrical generation systems are summarized in Table 1. The major potentially high impact unquantified issues are listed in Table 2.

Table 1. Summary of Quantified Average Fatalities per Year per 1000-MW Generation, 30-Year Plant Lifetime

	LWR	Coal (CG/CC)	LMFBR	CTPV	DTPV	SPS	Fusion
Total	0.26-1.4	6.6-79	0.24-1.1	0.43-0.73	1.92-4.4	0.26-0.67	0.22-0.44
Population Affected							
Public	0.03-0.18	5.4-76	0.03-0.18	U[a]	U	U	0.0001
Occupational	0.24-1.2	1.3-3.1	0.21-0.94	0.43-0.73	1.92-4.39	0.26-0.67	0.22-0.44
Impact Period							
Manufacture and Construction[b]	0.10-0.16	0.11-0.18	0.12-0.20	0.31-0.55	1.04-1.94	0.19-0.55	0.16-0.38
Operation and Maintenance	0.16-1.2	6.5-79	0.12-0.92	0.12-0.18	0.88-2.45	0.07-0.12	0.03-0.06
Impact Cause							
Accidents and Non-Radiation Disease	0.21-0.67	6.6-79	0.17-0.51	0.43-0.73	1.9-4.4	0.26-0.67	0.22-0.44
Radiation	0.05-0.70	0.0023	0.07-0.61	U	U	U	U

[a]U - Unknown or negligible.

[b]Total impacts averaged over 30-year lifetime.

Table 2. Summary of Potentially Major but Unquantified Issues

Solar Technologies (CTPV, DTPV, SPS)	Nuclear Technologies (LWR, LMFBR, Fusion)
1. Exposure to Cell Production Emissions	1. System Failure with Major Public Radiation Exposure
2. Hazardous Waste From Disposal or Recycle of Cell Materials	2. Occupational Exposure to Chemically Toxic Materials during Fuel Cycle
3. Chronic Low-level Microwave Exposure to Large Populations (SPS only)	3. Diversion of Fuel or By-product for Military or Subversive Uses
4. Space Vehicle Crash into Urban Area (SPS only)	4. Liquid Metal Fire (LMFBR, Fusion only)
5. Exposure to HLLV Emissions (SPS only)	
Coal Technologies (CG/CC)	
(None Identified)	

Public Risks, Operation and Maintenance. The largest operations and maintenance phase public risks quantified for this study are those related to the coal technology, and these are almost entirely due to coal transport accidents and air pollutants. The estimates for air pollutant impacts include long-range transport, and the uncertainty range is based on a 60% confidence level for incidence rates of health effects. Although small, estimated public impacts from the fission and fusion systems are thought to represent an upper level of probable impact from low-level radiation.

Occupational Risks, Construction Phase. For each unit value of industrial output required to directly supply system components for each of the energy systems, an additional indirect output in other industries in the range of 0.5-0.9 units is required. This significant requirement for indirect industrial output is a significant addition to the overall component production impacts. The total component production risks combined with on-site construction risks in Table 1 illustrate the higher construction phase risk of the solar and, to a lesser extent, the fusion technologies due to the more capital intensive nature of these technologies. The centralized terrestrial photovoltaic system requires over 19 units at 200-MW peak capacity and 26% load factor to produce an average 1000 MW electrical generation, and the SPS requires extensive ground and space facilities to construct and maintain the orbiting satellites.

Occupational Risks, Operation and Maintenance. Quantified risks of operation and maintenance (O&M) are largest for the coal technology, primarily due to the risks of accidents and illness during coal mining. A major uncertainty in mine risk estimates is the as yet unknown long-term effect of recent regulations for reducing the levels of dust in coal mines. Approximately one-half of the O&M risks of the fission systems are related to conventional occupational hazards and the other half are due to uncertain impacts of low-level radiation. The O&M occupational risks of the advanced fusion, SPS, and centralized terrestrial solar systems have no historical basis and are projected from conventional risk levels for existing similar occupations and estimates of the number of O&M employees required.

Unquantified Health and Safety Issues. Table 2 is a listing of potentially major but unquantified issues identified for the technologies considered.

Estimates of expected health and safety impact levels for catastrophic events (i.e., events of low occurrence probability, but high impact per event) were included as unquantified issues in this study because of inherently high uncertainties associated with predicting occurrence rate and impact per occurrence. Furthermore, averaging expected catastrophic impacts over plant lifetime does not indicate the full significance of these potential events. The issues of catastrophic fission reactor accidents, potential fission system fuel diversion for weapons use, and SPS space transport vehicle crash into urban areas are included in the potential catastrophic event category. Through engineered safeguards, the probability of occurrence of these events can be reduced to very low levels, but essentially zero probability is very difficult if not impossible to achieve at reasonable cost.

A further important distinction concerning unquantified issues is whether the potentially affected persons are part of the general public or are workers producing or operating the system. Issues in the latter category (e.g., emissions from solar cell production, emissions of toxic materials from the fission system fuel cycle, LMFBR and fusion liquid metal fire hazards) primarily affect a well-defined group, i.e., occupational workers, and those impacts can be more easily monitored and mitigating actions implemented. Risk from these hazards are often considered voluntary, in which the exposed person has the choice to accept the risk for pay. In contrast, impacts from low-level microwave radiation, if they exist, may be difficult to identify because of their potentially small and subtle nature within a large exposed group. Public risks are involuntary in nature, with a different perceived acceptability.

Table 2 does not attempt to rank the unquantified issues, although, for example, potential radiation release from fission is expected to be greater than that from fusion.

Cumulative Risks from National Energy Scenarios. In comparing 2000-2020 energy scenarios with and without SPS implementation, the SPS scenario has slightly higher estimated initial cumulative occupational impacts due to relatively high construction and manufacturing risks compared to non-solar technologies. However, by 2020 the cumulative occupational risks of the SPS scenario are as low or lower than for the non-SPS scenario because of low O&M risks.

The addition of quantified public risks to the occupational risks in the scenario analysis, in particular those from coal, would favor the SPS scenario with reduced conventional generation. However, the unquantified risks to the public in Table 2 restrict the delineation of definitive conclusions related to total scenario risks.

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

The Satellite Power System (SPS) is one of several new energy systems being studied to replace or supplement current fossil and nuclear fueled systems. Each of these alternatives will have both similar and unique impacts on society, industry, and the economy, and developing an understanding of the relative significance of these impacts has become widely accepted as a necessary prerequisite to a committment to proceeding with future deployment of these alternatives.

Among the more important potential impacts requiring careful attention is an assessment of the associated health and safety risks. The primary objective of this study is to evaluate the health and safety risks of the SPS in comparison to risks from a selected group of alternative electrical generation technologies projected to also be potentially available for deployment in the post-2000 period. This study is one component of the broader SPS Concept Development and Evaluation Program (CDEP) established by the SPS Project Division of the U.S. Department of Energy.[1] As part of that program, comparative assessments of the SPS and the selected alternative energy systems were also conducted in regard to other technical, economic, environmental, institutional, and societal issues.[2]

The assessment approach developed and used in this study is specifically intended to provide information useful for decision making regarding development of SPS technology after fiscal year 1980. An initial task was thus to develop a taxonomy for the health and safety comparative assessment and a format for presenting information in a manner most useful to decision making. This taxonomy and format are described in Sec. 2. Because of major deficiencies in essential data that prohibit definitive conclusions on relative technology risks, the taxonomy includes measures of uncertainty that are expected to be useful in the evaluation of the SPS and other alternatives.

In addition to the SPS, the alternative baseload electrical generation systems considered are a light water fission reactor system without fuel reprocessing (LWR); a low-Btu coal gasification system with an open cycle gas turbine combined with a steam topping cycle (CG/CC); a liquid-metal, uranium-plutonium, fast breeder reactor system (LMFBR); a central station terrestrial photovoltaic system (CTPV); and a first generation fusion system with deuterium-tritium fuel and a lithium blanket. Additionally, risk from a decentralized "roof-top" photovoltaic system (DTPV) with 6 kW peak capacity and battery storage was also evaluated to provide a preliminary comparison to nonbaseload technologies. The health and safety impacts for these individual systems are discussed in Sec. 3 on the basis of 1000 MW average annual electrical generation. The results of the CDEP characterization of each system on an equivalent cost and engineering basis were important inputs to this analysis.[3,4]

The final section (Sec. 4) summarizes the impacts of each unit technology in comparison to each other technology. A further perspective on the significance of relative technology risk is provided in Sec. 4 through an analysis of the cumulative occupational risks for total baseload electrical generation in the 2000-2020 time period. Two scenarios are evaluated: one with the SPS system and one without the SPS.

2 APPROACH

The major components of the health and safety assessment procedure are discussed in this section. These major components in the procedure are the identification, categorization, and impact estimation of major health and safety issues (Sec. 2.1) and a detailed analysis of the direct and indirect occupational impact that are of major significance for the more capital intensive technologies (Sec. 2.2).

2.1 ISSUE IDENTIFICATION AND EVALUATION

The first step in issue identification and evaluation was the compilation of all known and potential major health and safety issues that could be unambiguously defined and discussed. In order to produce an easily comprehensible list of issues for each technology, similar impacts were grouped together, and quantitatively negligible impacts were excluded.

Each segment of the complete energy cycle was considered, including raw material extraction, material processing, component fabrication, transportation, facility construction, facility operation and maintenance, waste disposal, and plant deactivation. This comprehensive procedure is illustrated in Fig. 2.1. The raw materials considered in the extraction and processing segment include fuels as well as materials such as cement, iron, copper, bauxite, and gallium aluminum arsenide, which are used in facility construction. The mining and processing of these materials and their use in component production are major factors, in particular for the solar technologies, and the approach to their evaluation is discussed in more detail in the next section.

An evaluation of each health or safety issue identified was conducted and documented according to the format shown in Table 2.1. The results of these evaluations, contained in the appendices, provide a direct link to the assumptions and references used in overall technology assessments and comparisons.

Issue categorization in an important aspect of the evaluation. It is generally accepted that the impacts on human health and safety are among the most important considerations in a comparative evaluation of alternative technologies. General acceptance of a high priority for health and safety issues does not imply, however, that quantification of all such effects will give common values for straightforward ranking of energy systems. Each component of energy production differs from others not only in the level, but also in the manner in which health and safety effects are incurred. These distinctions affect society's perception of "acceptable" health and safety effects and therefore should be preserved in the analysis. Accordingly, for this preliminary analysis, each issue was categorized along the dimensions given in Table 2.2.

Catastrophic events (defined in this study as single events potentially leading to over 1,000 deaths) constitute a prime example of the need for categorization. Because of the engineered low risk of occurrence for these

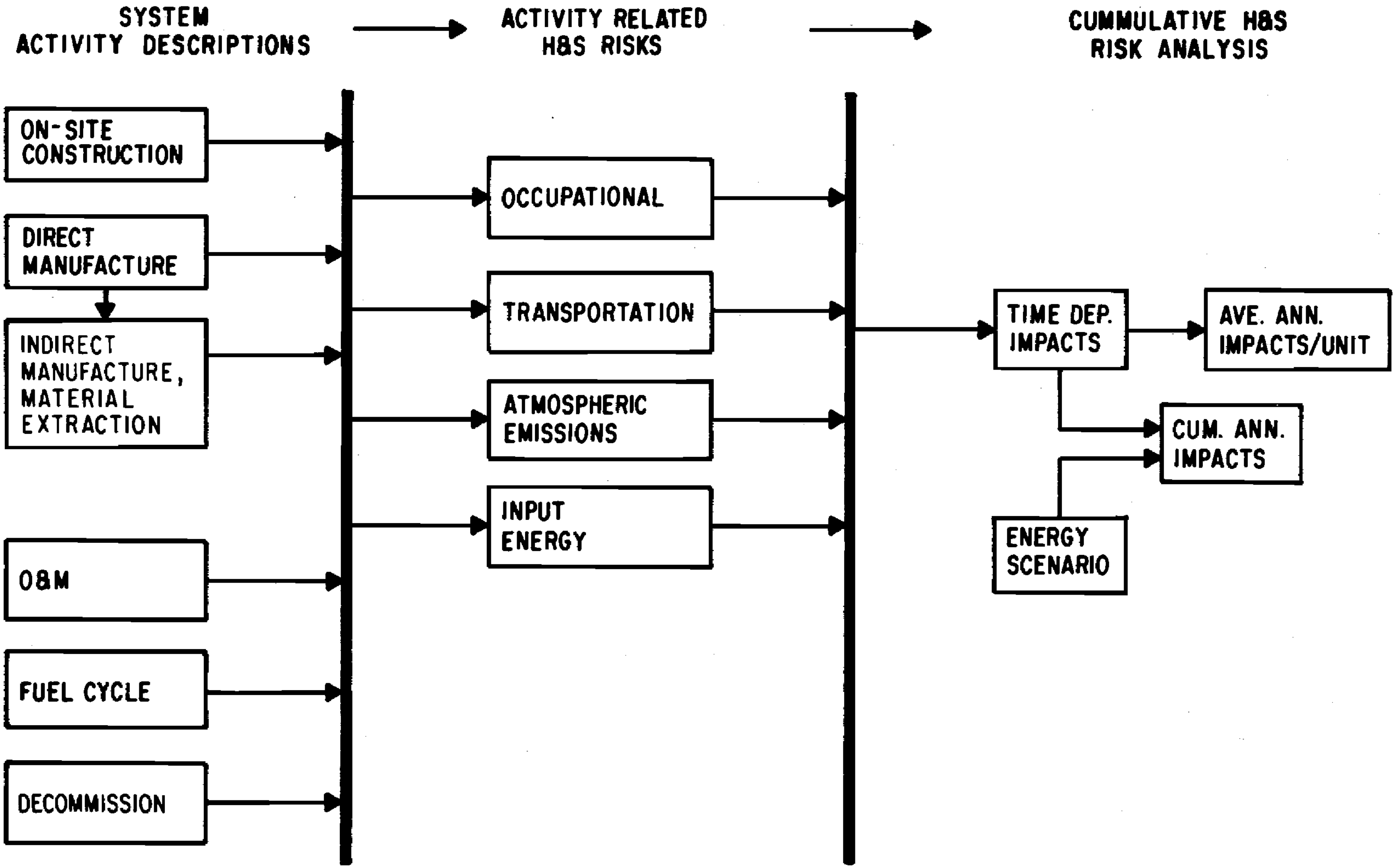


Fig. 2.1. Components of Comprehensive Health and Safety Impact Analysis

Table 2.1. Format for Issue Identification and Evaluation[a]

Evaluation Component	Description
TECHNOLOGY	Light water or fast breeder fission reactors, combined-cycle coal, centralized or decentralized terrestrial photovoltaic, satellite power system, and fusion.
ISSUE NUMBER	
PROCESS	Raw material or fuel extraction, material processing, component fabrication, transportation, facility operation and maintenance, waste disposal, or deactivation.
IMPACT CATEGORY	Categorization of issues along dimensions given in Table 2.2.
GENERAL DESCRIPTION	Description of factors or conditions producing health or safety risk and description of the nature of impact on human health or safety, e.g., carcinogenic, mutagenic, or toxic effects.
QUANTITATIVE IMPACT ESTIMATE	Assumptions and methodology leading to quantitative impact estimate.
MAJOR UNCERTAINTIES REQUIRING R&D	Major areas of uncertainty requiring further research and development that would provide a definitive issue evaluation or risk quantification. These uncertainties may in some cases go beyond those assumed in the quantitative impact estimate.
REGULATORY STATUS	Current regulations and potential for additional regulation to mitigate impact.
SEVERITY INDEX	Relative impact rating using index described in Table 2.3.
UNCERTAINTY INDEX	Relative uncertainty in issue impact evaluation using index described in Table 2.4.
REFERENCES	References used in conducting issue identification and evaluation.

[a]See appendices.

Table 2.2. Categorization of Health and Safety Issues

Affected Population
Public
Occupational
Impact Period
Intermediate Term (Component Production and Plant Construction)
Long Term (Plant O&M, Waste Management)
Short Term (Catastrophic Events)
Impact Cause
Accidents (Falls, Electrical Shock, etc.)
Chemical Pollutant (Toxic, Carcinogenic)
Radiation (Ionizing, Nonionizing)
Impact Severity
Fatalities
Person Days Lost (Nonfatalities)

events, the number of expected deaths per year, averaged over the lifetime of the plant, may be lower than that from continuous low-impact risks, but the public perception of the significance of these potential events may critically affect the acceptability of a technology.

Categorization thus precludes the possibility that the rankings of the health and safety impacts for each technology will be combined into a single normative factor that would allow definitive ranking of the alternative energy systems. The technologies are compared using various indicators described in the following and in Sec. 4, but the final comparison must be reserved for the authorities responsible for evaluating issues in terms of broad societal objectives.

The principal measure of the severity of health and safety impacts is the estimated range of expected person-days lost and deaths per unit period or per event attributable to the energy system or system segment. In addition to this quantitative measure, the separate issues identified for each system are assigned to impact level and uncertainty categories (Tables 2.3, 2.4).

Table 2.3 defines severity ratings on the basis of the annual level of health and safety impacts averaged over the 30-year lifetime of a power plant (1,000 MW average annual generation). In addition to defining severity ratings for quantifiable impacts, the rating procedure in Table 2.3 also applies to issues that were unquantified. These issues are rated largely on the basis of a qualitative understanding of the potential hazards, for which

Table 2.3. Index of Severity of Health and Safety Impacts

Hazard Category	Level of Impact (x, Fatalities/1000 MW/yr)	Severity Rating
Quantified	x > 0.1	1
	0.1 > x > 0.01	2
	x < 0.01	3
Unquantified	High (may be significant, x > 0.01)	A
	Low (probably insignificant, x < 0.01)	B

Table 2.4. Uncertainty Indices

Description	Uncertainty Index	Risk Evaluation
Causal relationship and impact levels relatively well established (e.g., coal mining accidents)	1	Quantified Range
Established but poorly quantified causal relationship (e.g., low-level ionizing radiation)	2	Quantified Range
Cause-effect association established, but extremely variable impact level estimates (e.g., ground water pollution, catastrophic events)	3	Qualitative Range (A,B)*

*See Table 2.3.

impact data are not readily available because of lack of sufficient operating experience in a present technology or a lack of analogy between existing and future technologies. An (A) severity rating is given to a potential hazard for which a reasonable operating scenario can be envisioned in which human interactions could result in a significant number of injuries or disease occurrences. An event of low probability of occurrence and of limited impact is assigned a (B) severity rating.

To gain a perspective on the relative societal implications of the health and safety issues within each of these severity categories, it is useful to compare the range of impact levels within the categories with other health and safety risks to which the general population is exposed.

Since the U.S. electrical power consumption per 10^6 persons is approximately 1000 MW,[86] the units of fatalities/1000 MW/yr can be considered equivalent to fatalities/yr/10^6 persons for purposes of comparison with other risks. (This is only strictly true when risks are evaluated on the basis of the average for a generic population since the electricity users of a specific facility are not necessarily the group that incurs the risk from that facility.) As illustrated in Fig. 2.2, this comparison indicates that the risks from air pollution, background radiation, saccharin, urban drinking water, and lightning, to which a large segment of the population is exposed, would all receive a "high" or "1" severity rating under the energy system issue categorization chosen.

In addition to reflecting the range in quantitative estimates, the uncertainty index assigned to each severity rating (Table 2.4) is based on the degree to which the cause-effect relationship of the hazard-impact has been established and on the reliability of the impact quantification or impact potential. Ratings assigned the lowest level of uncertainty (1) were those for which strong arguments could be made regarding the existence of a cause-effect relationship and for which the degree of impact was well defined, primarily through historical data. Issues rated at higher uncertainty (2) were those for which cause-effect relationships are established but not reliably quantified. The highest uncertainty (3) was assigned to those issues for which only cause-effect associations could be made or for which impact levels were not readily quantifiable or extremely variable. Categorization of an issue with uncertainty index 3 does not imply that quantification is not possible, only that such quantification requires an analysis and review, beyond the scope of this study, of often obscure literature.

2.2 OCCUPATIONAL IMPACTS

Compared to the more conventional coal and fission technologies, the advanced solar and fusion technologies present a tradeoff of reduced fuel requirements but higher initial capital and construction requirements. Furthermore, the industries producing the energy system components in turn require certain commodity inputs (e.g., copper mining to produce electrical equipment), and the risks associated with the production of these indirect requirments must be considered in the overall risk analysis. Figure 2.3 illustrates the overall analytical procedure for computing on-site construction impacts and the direct and indirect system component manufacture impacts.

The direct labor requirements for plant construction for each of the technologies was provided by the technology characterization study. These requirements, as given in the following section, consist of two components. The most significant component in terms of health and safety risks includes all craft labor, i.e., electricians, carpenters, plumbers, concrete workers, steel workers, etc. The range of assumed risk for this category (Table 2.5) was based on historical statistics for the combined contract construction industry (Standard Industrial Classification Categories 15, 16, 17). The second category of plant construction occupational risks is related to indirect construction and engineering services. Labor requirements for these services were estimated by assuming that 50% of the estimated service costs were for direct hourly wages. The relatively low health and safety risks of office workers were assumed applicable for this category (Table 2.5).

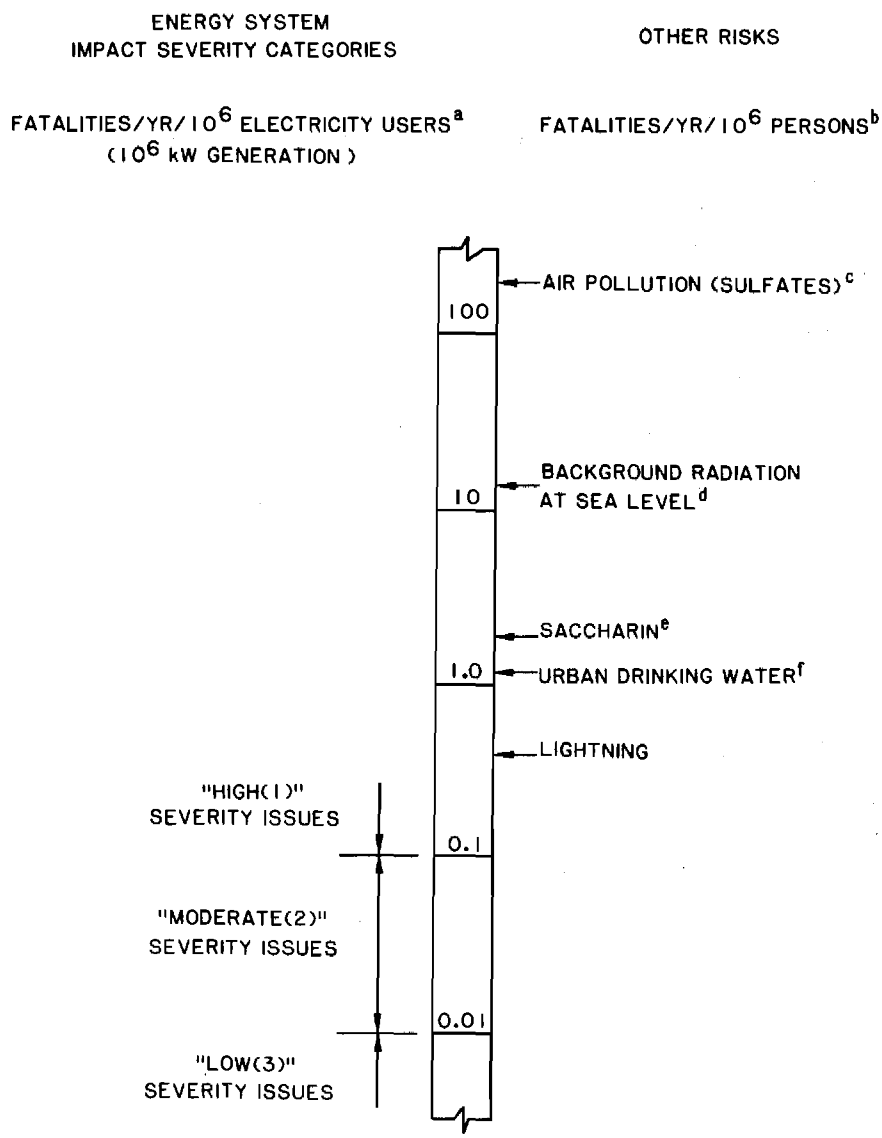


Fig. 2.2. Impact Severity Categories for Energy System Health and Safety Issues in Comparison to Estimated Risks from Other Causes

a) Estimated fatalities from electrical generation do not necessarily occur within user group.

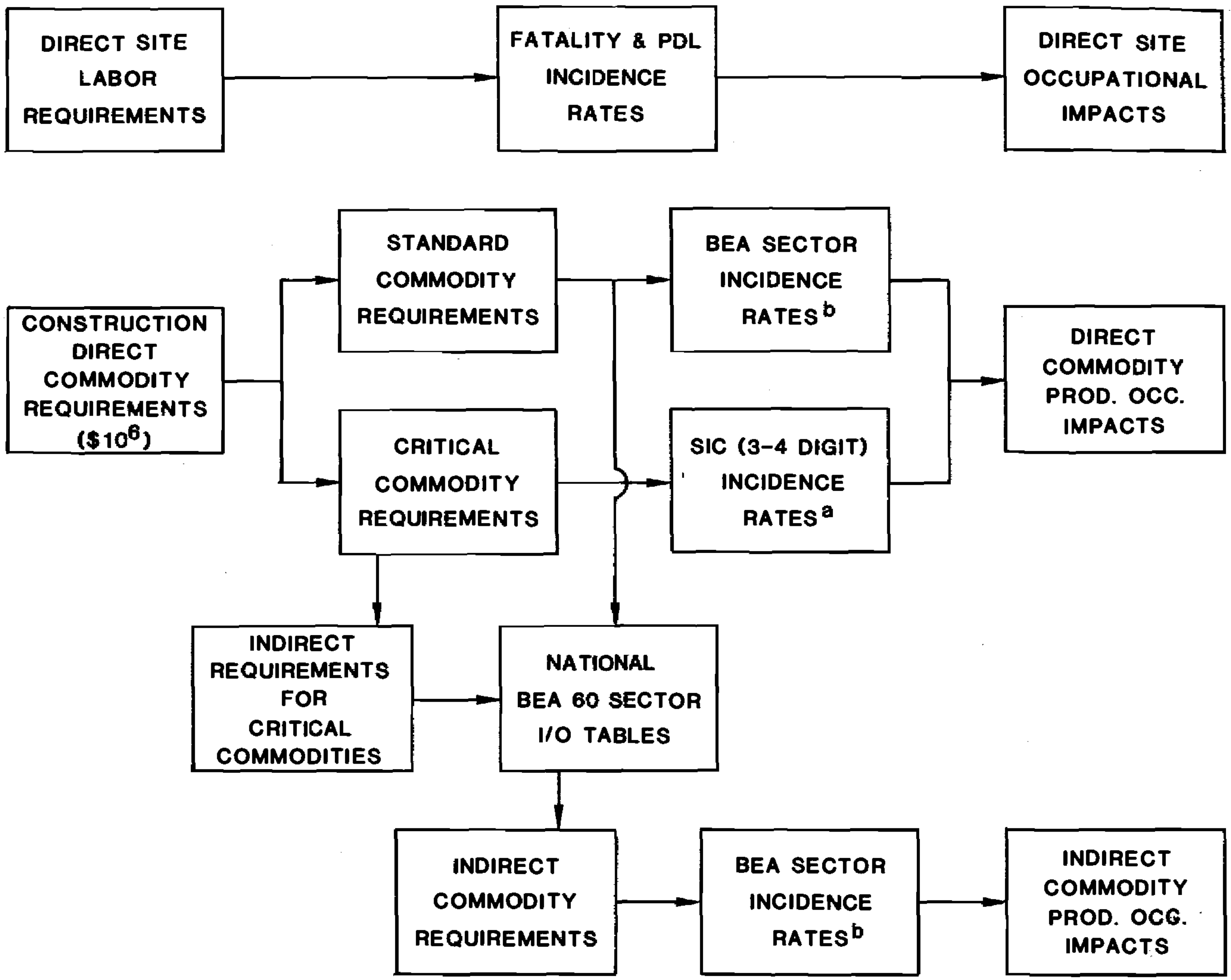
b) From Ref. 87.

c) Based on average U.S. exposure.

d) No. of cancers based on linear extrapolation of human epidemiological data.

e) No. of cancers based on average U.S. consumption and linear extrapolation of animal data.

f) No. of cancers based on multistage extrapolation from animal data with Miami and New Orleans drinking water.



[a] Fatalities, PDL per $\$10^6$ SIC sector output

[b] Aggregated from SIC data

Fig. 2.3. Occupational Health and Safety Impacts Analysis Procedure

Table 2.5. Assumed Occupational Accident and Disease Incidence Rates for Energy System Construction, Operation, and Maintenance

	Annual Fatalities per 100 Workers[a]	Annual PDL per 100 Workers[b]	SIC[c] Categories
Direct Site Labor	0.033-0.051	99-108	15,16,17
Indirect Site Labor	0.003-0.006	28-32	70,72,73,75,76, 78,79,80,82,84, 86,89
Plant Maintenance	0.033-0.051	99-108	15,16,17
Plant Operations	0.003-0.006	28-32	70,72,73,75,76, 78,79,80,82,84, 86,89

[a]Range based on 1972-1975 data (Ref. 6).

[b]Range based on 1975-1976 data (Ref. 6); PDL = person-days lost.

[c]Standard Industrial Classification

Risks to maintenance personnel from conventional hazards during plant operation were assumed to be at the same level per employee as for the construction workers in Table 2.5. Nonconventional hazards, e.g., radiation in nuclear power plants and potentially carcinogenic substances in coal gasification plants are evaluated separately in Sec. 3.

Plant operations personnel were assumed to incur risks per employee at the level of office workers (Table 2.5).

The procedure for estimating occupational health and safety risks associated with off-site manufacturing of components and materials used in facility construction (Fig. 2.3) required as input the percentage of system capital cost for commodities produced by the various predesignated industrial categories listed in Table 2.6. These industrial categories are adapted from the groupings developed by the U.S. Department of Commerce Bureau of Economic Analysis (BEA) for use in the study of the input-output structure of the U.S. economy in 1972.[5] Table 2.6 only includes those categories that are most affected directly or indirectly by construction of the energy technologies considered in this study. Also given in Table 2.6 are the coefficients for fatalities and nonfatal person-days-last per $\$10^6$ output for each of the industrial categories. These values were averaged from similar values for the indicated SIC subcategories within the designated grouping using the 1975 SIC sector total ouput[7,8] as a weighting factor. Parameters used to obtain the SIC sector incidence rates per $\$10^6$ ouput were the 1972 productivity levels (employees/$\$10^6$) [SIC 74,75] and 1975 statistics for occupational health and safety risk.[6]

The requirement for an increased industry category output to directly supply energy technology plant construction will result in secondary or

Table 2.6. Industry Groupings and Occupational Fatality and PDL Incidence Rates per $\$10^6$ Output for Direct and Indirect Impact Estimation

Industry Category	Fatalities per $\$10^6$ Output[a]	PDL per $\$10^6$ Output[a]	SIC Categories
Iron and ferroalloy ore mining[b]	0.0155	13.0	101,106
Nonferrous ore mining[b]	0.0152	17.2	102-5, pt. 108,109
Coal mining[c] (Underground)	0.0072-0.0166	8.7	12
(Surface)	0.0020	1.5	12
Crude petroleum and natural gas[b]	0.0045	5.2	131,132, pt. 138
Stone and clay mining and quarrying[b]	0.0207	23.5	141-5, pt. 148,149
Maintenance and repair construction	0.0100	27.2	pt. 15-17, pt. 138
Ordnance and accessories	0.0020	21.4	3482-4,3489,3761, 3795
Lumber and wood products, except containers	0.0021	47.8	241-3,2448,249
Printing and publishing	0.0025	13.0	27
Chemicals and selected chemical products	0.0010	7.0	281,286-7,289
Plastics and synthetic materials	0.0012	5.5	282
Petroleum refining and related industries	0.0003	3.0	29
Rubber and miscellaneous plastic products	0.0021	33.1	30
Glass and glass products	0.0021	27.5	321-3
Stone and clay products	0.0020	31.4	324-9
Primary iron and steel manufacturing	0.0016	24.4	331-2,339,3462
Primary nonferrous metals manufacturing	0.0011	16.9	333-6,3463
Heating, plumbing, and fabricated structural metal products	0.0020	33.4	343-4
Screw machine products and stampings	0.0020	23.2	345,3465-6,3469

Table 2.6. (Cont'd)

Industry Category	Fatalities per $\$10^6$ Output[a]	PDL per $\$10^6$ Output[a]	SIC Categories
Other fabricated metal products	0.0023	30.5	342,347,349
Engines and turbines	0.0015	10.3	351
Construction and mining machinery	0.0017	23.6	3531-3
Materials handling, machinery and equipment	0.0020	22.4	3534-7
Metalworking machinery and equipment	0.0025	21.1	354
General industry machinery and equipment	0.0022	22.5	356
Miscellaneous machinery, except electrical	0.0029	30.4	359
Electrical transmission equipment and industrial apparatus	0.0019	47.6	361-2,3825
Electric lighting and wiring equipment	0.0022	17.6	364
Radio, TV, and communication equipment	0.0021	7.9	365-6
Electronic components and accessories	0.0027	9.9	367
Miscellaneous electrical machinery, equipment and supplies	0.0020	16.1	369
Motor vehicles and equipment	0.0009	8.2	371
Aircraft and parts	0.0020	9.2	372
Other transportation equipment	0.0021	48.6	373-5,3792,3799 2451
Professional, scientific, and controlling instruments and supplies	0.0025	12.4	381,3822-4,3829, 384

[a]Except where noted, based on total industry output dollar value (1972 dollars), and number of employees (Ref. 7) and incidence rates/100 employees (Ref. 6).

[b]Total industry output dollar value and number of employees from (Ref. 8).

[c]Adapted from (Ref. 9) based on \$50/ton of coal.

indirect output increments in industry categories because of the interdependence of these industries in the U.S. economy. The levels of these indirect increments per unit final output demand have been conveniently provided through the generation of "input-ouput" matrices.[5] For example, a $\$10^6$ final demand output from the "engines and turbines" category in Table 2.6 will result in a cumulative output of $\$1.77 \times 10^6$ for all categories.

Because of the range of subcategories in the industry groupings in Table 2.6, the risks of major specific energy technology commodity production requirements may be inaccurately estimated using the above procedure. For this reason production risks of certain specific critical commodities were evaluated with the slightly revised procedure indicated in Fig. 2.3. For these critical commodities, the direct production risks were evaluated using more specific SIC category incidence rates. Manufacture of lead acid storage batteries required in the DTPV system is an example of a commodity evaluated with this more detailed approach. Risks, both direct and indirectly associated with producing inputs to the manufacture of these critical commodities (e.g., lead for storage batteries) were then evaluated using the broader industry categories in Table 2.6.

In applying the above procedure, compatibility with 1978 cost data in Sec. 3 required adjusting the 1972 productivity levels by the 1972-1978 U.S. Dept. of Commerce Implicit GNP Deflator of 1.46.

The above procedure for estimating direct and indirect commodity production occupational risks contains various uncertainties that must be recognized. The uncertainties include use of the Bureau of Labor Statistics data for occupational injury and illness.[29] Although these data are considered the best for these factors, they are not very accurate because of underreporting and misdiagnosis. In particular, these statistics do not adequately reflect chronic disease. Other uncertainties include use of the 1972 input-output structure of the economy to estimate indirect requirements for facilities to be constructed in the post-2000 period; uncertainties in plant construction requirements; potential changes in employee productivity; and potential changes in risk levels per worker. Because of these uncertainties overall risks of commodity production were assigned error bounds of ±20% for most developed technologies (LWR, CG/CC), ±35% for the intermediate technologies (LMFBR, CTPV, DTPV) and ±50% for the least developed technologies (fusion, SPS).

Further direct and indirect impacts of component manufacture could be attributed to pollutants released during the manufacturing processes and because of the energy requirements of those processes. These secondary impacts are not included.

3 INDIVIDUAL ENERGY SYSTEM ASSESSMENTS

This section summarizes the results of the issue identification and evaluation for each of the seven technologies considered in the evaluation: light water reactors; liquid-metal, fast-breeder reactors; combined-cycle coal system; centralized and decentralized terrestrial photovoltaic system; satellite power system; and fusion. Each technology is described briefly; more detailed characterizations are developed in another component of the SPS Comparative Evaluation Program.[3,4]

The first level of display of the health and safety assessment consists of compact flow diagrams of health and safety issues as they relate to the processes associated with the complete cycle of each technology. These diagrams are compact, comprehensive summaries of issues and their potential significance. Each issue shown in a diagram is accompanied by issue categories (public or occupational and health or safety), severity ratings, and uncertainty ratings.

Summary tables represent the next level of detail. In addition to the information included in the flow diagrams, the tables indicate quantified ranges of estimated impacts and a short statement on causes of uncertainty.

The issue descriptions and evaluations in Appendices B-F provide detailed analysis of the issues for each technology, including citation of data sources. Appendix A includes data on construction commodity requirements disaggregated by industrial sectors.

3.1 FISSION POWER SYSTEMS

3.1.1 System Descriptions

Light Water Reactor without Fuel Reprocessing

Light water reactor (LWR) technology dominates the U.S. nuclear power industry. In this system, heat is generated by uranium fission. The thermal energy produced is transferred to a working fluid to produce high-temperature, high-pressure steam, which passes through a turbine generator to produce electric power. Apart from the nature of its fuel, the basic operation of a fission power station is similar to that of a fossil-fueled steam-electric plant.

The two common LWR options are the pressurized water reactor (PWR) and the boiling water reactor (BWR). Both reactors use light water as a coolant and moderator. In the BWR, water is circulated through the reactor core, where it is converted under pressure to steam. This steam is passed directly through the turbine, cooled, and recirculated to the reactor. The PWR is operated at a pressure high enough to ensure that water passed through the reactor does not boil. The thermal energy in this primary coolant loop is transferred to the working fluid of a secondary steam loop, which is routed through the turbine.

Natural uranium occurs as the oxide U_3O_8, which contains only 0.7% of the fissile isotope ^{235}U. To be useful as reactor fuel, the fissile isotope concentration must be raised to between 2% and 3%. This is accomplished through fuel processing, during which the oxide is converted by chemical reaction with HF to UF_6. The fluoride is then processed through a gaseous diffusion plant, which produces an enriched product. The enriched UF_6 is then converted to UO_2, the form in which it is fabricated into fuel pellets. In this technology the spent fuel is stored as a waste rather than being reprocessed.

Additional design parameters relevant to this study include:[3,4]

Unit Capacity	1250 MW
Annual Load Factors	70%
Direct Equipment and Construction Material Costs*	$333.7 x 10^6 (1978 $)
Indirect Construction Costs	197.1 x 10^6 (1978 $)
On-site Direct Construction Labor	15.5 x 10^6 person-hours
Plant Operations Staff	136 persons
Plant Maintenance Staff	79 persons
Overall efficiency	33.4%
Unit lifetime	30 years
Fuel Burnup	50 MW-days/kg U
Radionuclide Emissions	
Air	4,195 Ci/yr
Solids and Sludges	11,000 Ci/yr
Liquid	438 Ci/yr
Scaling Factor for 1000 MW Average Generation	1.143

Figure 3.1 is a simplified representation of a boiling water reactor.

Liquid Metal Fast Breeder Reactor

The principal difference between the liquid-metal, fast-breeder reactor (LMBFR) and the present generation light water reactor (LWR) is that the LMFBR, in producing heat for electric power production, can also create excess nuclear fuel by breeding more than it consumes in energy generation. By the breeding process the LMFBR can convert most of the nonfissile natural uranium, which can not be used as fuel, into plutonium, which can be recycled for when use. Specific design differences between the LMFBR and LWR include the following considerations.

*Excludes plant land costs ($2.2 x 10^6)

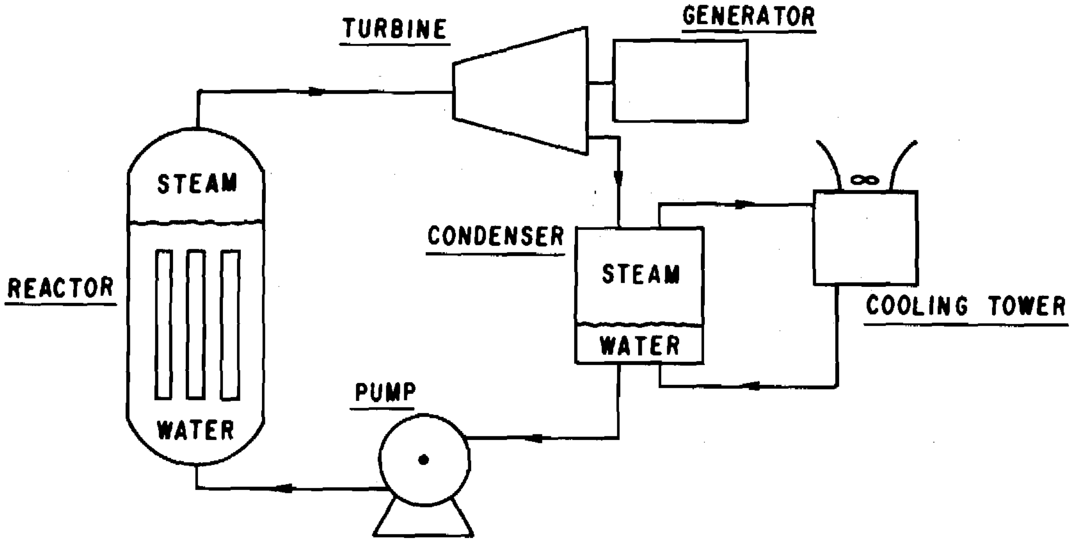


Fig. 3.1. Light Water Reactor

Whereas the LWR uses fuel with a 2 to 3% fissile material component the breeder requires 15 to 30% either as ^{235}U or ^{239}Pu. A breeder core is made up of pins of fissile material surrounded by a blanket of nonfissionable (fertile ^{238}U) material. As the control rods are removed the fissile materials are bombarded by neutrons releasing heat and high energy neutrons. Breedings occurs when these unmoderated "fast" neutrons penetrate the ^{238}U blanket. The capture of neutrons by the fertile uranium blanket forms ^{239}Pu which can later be removed through reprocessing of the blanket material and be recycled as nuclear fuel. In the fast breeder, 2.9 neutrons are released for every fissioning nucleus as compared to 2.4 for the LWR. This slight surplus allows the breeder to produce more fuel than it consumes and is responsible for the economic incentives for LMFBR technologies.

The LMFBR depends for its cooling on liquid sodium metal. The choice of sodium was determined by the closely packed fuel and high power density inherent in the breeder. Sodium has good heat transfer characteristics and does not slow down neutrons as does water, nor does it absorb as many neutrons as water. Sodium becomes highly radioactive; therefore the LMFBR requires a secondary sodium loop for heat transfer to the steam generation cycle and the radioactive containment of the steam loop is avoided. Figure 3.2 defines the major components of a present generation breeder reactor.

The economic viability of the LMFBR requires the services of a separate fuel cycle. Such a fuel cycle would require a substantial commitment for fuel reprocessing and should be considered to be an integral part of the LMFBR system.

Relevant design parameters include:[3,4]

Unit capacity	1250 MW
Annual Load Factor	70%

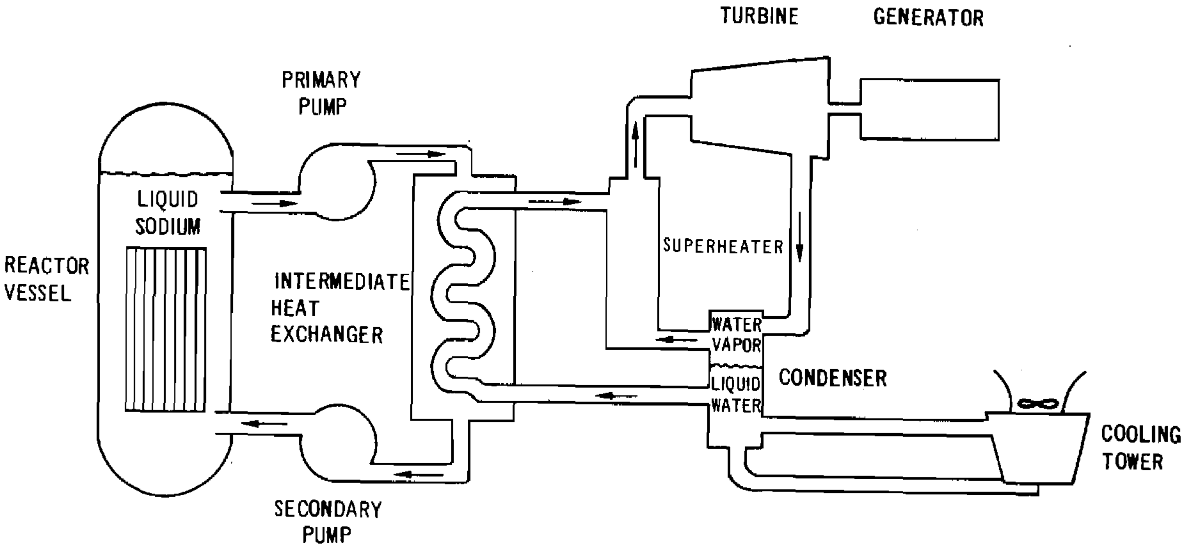


Fig. 3.2. Liquid-Metal, Fast-Breeder Reactor

Direct Equipment and Construction Material Costs*	\$535.2 x 10^6 (1978 \$)
Indirect Construction Costs	\$262.6 x 10^6 (1978 \$)
On-Site Direct Construction Labor	\$14.5 x 10^6 person-hours
Plant Operations Staff	146 persons
Plant Maintenance Staff	79 persons
Overall Efficiency	36.6 persons
Unit Lifetime	30 years
Radionuclide Emissions	
Air	409,550 Ci/yr
Solids	33,000 Ci/yr
Liquids	480 Ci/yr
Scaling Factor for 1000 MW Average Generation	1.143

A schematic illustration of an LMFBR system is shown in Fig. 3.2.

3.1.2 Summary of Health and Safety Issues

The major health and safety issues identified for the LWR and LMFBR are illustrated in Fig. 3.3 and summarized in Table 3.1. The nuclear fuel cycle, as it pertains to electrical power generation, carries a set of health

*Excludes plant land costs (\$2.2 x 10^6)

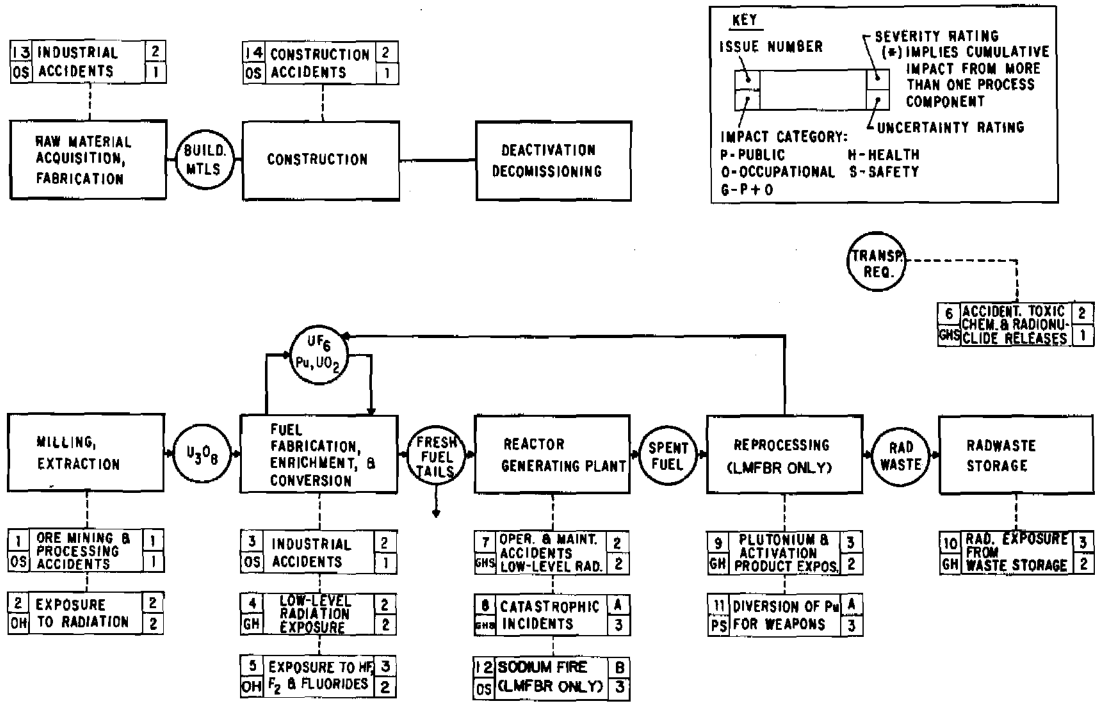


Fig. 3.3. Flow Diagram of Health and Safety Issues of the Light Water Reactor Power System with Fuel Reprocessing

and safety risks both for workers and for the general population.[10,11] Although the radiological hazards of nuclear energy have received wide attention, the nuclear fuel cycle contains nonradiological risks as well. The principal health issues related to the fuel cycle are associated with the physical hazards of fuel handling and radiological hazards that result in general population exposures. Estimates of the impact of the annual operational and fuel cycle requirements of both LWR and LMFBR 1,000-MW reactor are on the order of 0.2-0.7 fatal injury per year from physical hazards and 0.05-0.7 fatalities per year attributable to ionizing radiation exposure (Table 3.1).

The major portion of the impact of physical hazards to the occupational population occurs during ore extraction. In recent years, uranium miners have experienced roughly the same risk (on a person-hour basis) as coal miners.[75] However, on an energy basis, injury rates from uranium mining are much lower than coal mining owing to the high energy content of nuclear fuel. The remainder of work force injury is associated primarily with fuel processing or reprocessing (LMFBR) and power plant operation. Injuries in these processes result from the usual array of industrial accidents. For the LMFBR, the occupational hazards from uranium mining and milling are primarily only related to the initial phase of the fuel cycle since reprocessed fuels are used primarily in the established technology.

Materials transport is required in all steps of the nuclear fuel cycle. Since the transportation mode is primarily by truck with some rail

Table 3.1. Issue Summary for Nuclear Fission Reactors (LWR, LMFBR)

	Issue	Process	Categories[a] Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
1.[b]	Accidental injury.	Ore extraction and U_3O_8 milling.	O	OM	AD	0.05 - 0.2 fatalities/yr. (For LMFBR: applies only to start-up phase)	Future use of lower-grade ore will require larger mining and milling operations.	1
2.[c]	Lung cancer as a result of exposure to radon and other decay products of natural uranium.	Ore extraction, U_3O_8 milling.	O P	OM OM	IR IR	0.001 - 0.1 fatalities/yr. 0.0045 fatalities/yr (For LMFBR: applies only to start-up phase)	Exposure levels prior to establishment of standards are not known precisely. Effectiveness of ventilation for the removal of ^{222}Rn.	2
3.[d]	Accidental injury.	Fuel fabrication: U_3O_8 conversion, UF_6 enrichment, UO_2, PuO_2 fabrication.	O	OM	AD	0.003 - 0.2 fatalities/yr.	Occupational accident potential for nuclear fuel preparation.	1
4.[e]	Low-level radiation exposure.	Fuel fabrication: U_3O_8 conversion, UF_6 enrichment, UO_2, PuO_2 fabrication.	O P	OM OM	IR IR	0.008 - 0.33 fatalities/yr 0.0003 fatalities/yr	Generic to all segments of the fuel cycle; the actual human response to low-level exposures is hypothetical.	2
5.[f]	Exposure to HF, F_2.	Fuel fabrication: U_3O_8 conversion, UF_6 enrichment, UO_2, PuO_2 fabrication.	O	OM	C	0.005 fatalities/yr from severe injury or lung damage, osteofluorosis from continuous exposure.	Possible high level exposure from industrial mishaps; Population response to excess fluorides.	2
6.[g]	Accidental injury possible; radiation hazard and chemical toxicity from UF_6 spill.	Transportation.	O P	OM OM	AD AD	0.002-0.036 fatalities/yr 0.01 fatalities/yr.	Transport distances and modes; trip frequencies.	1

[a]O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operation and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

Sources: [b]12; [c]13,18; [d]14; [e]15,16; [f]12,17; [g]14,18-21.

Table 3.1. (Cont'd)

		Categories[a]					
Issue	Process	Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
7.[h] Low-level radiation hazard, accidents.	Reactor operation.	P O O	OM OM OM	IR AD IR	0.01-0.16 fatalities/yr 0.034-0.055 fatalities/yr 0.024-0.1 fatalities/yr	Health impacts of low-level radiation.	2
8.[i] Acute and delayed effects from catastrophic accidents.	Reactor operation.	P	OM	IR	3,500 acute fatalities; 45,000 eventual deaths/ incident; one incident per 10^6 plant/yr	The operating experience of large power reactors is small. Catastrophic risk estimates are based on this experience.	3-A
9.[j] Low-level radiation.	Reprocessing (LMFBR only).	O P	OM OM	IR IR	0.006 fatalities/yr, 0.009 deaths/yr.	Extent of exposure.	2
10.[k] Delayed response to low-level radiation exposure.	Radioactive-waste storage.	O P	OM OM	IR IR	0.006 fatalities/yr, 0.0003-0.001 fatalities/yr	Ability to contain radioactive wastes over long periods of time.	2
11.[l] Intentional misuse of nuclear materials resulting in general population injury.	Fuel or by-product theft.	P	OM	IR,C	One small dirty terrorist bomb could destroy one city block with 50,000 casualties.	Accessibility to nuclear materials under future reprocessing requirements, use of non-explosive toxic materials.	3-A
12.m Liquid metal fire	Reactor operations (LMFBR only).	O	OM	AD	Not available.	Initiating events, including intentional	3-A
13.[n] Accidents and disease	Direct and indirect material extraction and component manufacture.	O	C	AD	Total fatalities: LWR: 0.79-1.18; LMFBR:1.02-2.12	General manufacturing incidence rates.	1
14.[o] Accidents and disease	Construction on-site	O	C	AD	Total fatalities: LWR: 2.29-3.62; LMFBR:2.56-4.04	General construction incidence rates	1

Sources: [h]3,4,11,12,18,20,21; [i]20,22; [j]18; [k]23; [l]15,24, [m]25,26; [n,o]3,4,6 transport, it is assumed that general population interactions and resulting physical injuries within the fuel cycle are in proportion to the use of these modes.[9]

The principal health effects of exposure to ionizing radiation are acute radiation sickness, cancer, and genetic defects. There have been seven reported fatalities from acute radiation sickness in the United States (none since 1961).[27] The Biological Effects of Ionizing Radiation report[13] gives estimates of low-level radiation effects in terms of cancer deaths and eventual genetic defects. These estimates predict 180 x 10^{-6} cancer deaths per rem and 150 x 10^{-6} genetic defects per rem of whole-body population exposure and are used to predict the delayed effects of the nuclear fuel cycle.

Low-level radiation exposure is inherent in ore components of the nuclear fuel cycle. Uranium miners and handlers are exposed to uranium daughter products, including ^{222}Rn, which are known to present carcinogenic risks.[28] Radiation-induced lung cancers have been observed in underground miners exposed to radon decay products. Ore tailings also contain measurable quantities of radium and radon and have been identified as a potential source of radiation exposure to the general public as well as to occupational populations.

Low-level radiation exposure occurs during operation and routine maintenance of nuclear facilities. Both plant workers and the general public are exposed to low-level radiation from normal releases and minor leaks in the system piping. These emissions consist of uranium fission products and activation products from the structural components of the reactor system. Of particular concern are the gaseous emissions of ^{14}C, ^{85}Kr, ^{131}I, and ^{3}H.

The magnitude of risk associated with radiation levels caused by these releases continues to be the subject of much debate. However, for the operation of a 1,000-MWe power plant, it is tentatively estimated that plant workers will have 0.024-0.1 fatal disease cases per year and that there will be 0.01-0.016 fatal disease cases per year in the general population, from cancer and genetic defects.[18]

Other major issues associated with fission reactors are not as easily quantifiable. The primary issue relating to plant operation and maintenance is that of a catastrophic event (Issue 8).[20,22] Although the probability of a core meltdown or significant release of radiation is projected to be minimal, any such occurrence would be highly visible and would significantly affect the reactor industry. Similar situations are addressed by Issues 5, 10, and 11, the potential exposure of workers and the public to hydrogen fluoride during fuel enrichment and fabrication,[9,29] exposures to radioactive wastes, and the diversion of plutonium for weapons.[15] Although the probability of occurrence is low and can be minimized by preventive procedures, the possibility of such an occurrence with accompanying impacts is a significant issue potentially limiting the nuclear technology.

For the most part, health and safety issues relevant to the LMFBR will be those similar in character and magnitude to those encountered in the LWR system. During normal operations, the LMFBR and LWR operate in much the same way. Because they share the same characteristics regarding sabotage, operator and maintenance error, and other human factor elements, the LMFBR faces the same level of uncertainty with regard to public health risk as does the LWR.

An issue that presents a substantial hazard unique to the LMFBR is the use of liquid sodium as the system coolant and heat transfer medium for steam generation. Sodium is extremely active chemically. It can react with air, water, and concrete by releasing large quantities of chemical energy in the form of heat. During normal operations, the reactor coolant circuits are operated above the temperature of spontaneous oxidation of sodium in air. A sodium fire in the reactor caused by air entering the primary coolant circuit could have grave consequences. Design parameters such as an inert gaseous environment surrounding the primary coolant loop would eliminate the possibility of sodium fire within the core in the event of a primary break. However, sodium-water reactions are possible in the secondary sodium loop. This steam generator circuit requires dose proximity of the two constituents with the heat exchanges and although it is generally accepted that a sodium-water reaction would not pose a major public safety risk, it would pose a danger for plant maintenance workers by exposing them to caustic fumes and explosive overpressures.

The LMFBR also carries a hazard that is beyond those associated with its operation and malfunction. A 1000 MW system would contain roughly 2500 kg of plutonium and would discharge more than 1500 kg per year. Over its 30 year lifetime, such an operation would recycle more than 108 kg of plutonium. The plutonium hazard is neither new nor unique to the LMFBR. However, it is the magnitude of the overall requirement and the need for a large-scale reprocessing component that adds substantial health and safety risk to the LMFBR concept. Safeguarding nuclear materials from diversion and intentional misuse becomes an inherent requirement of a mature LMFBR system. Because of the long lived alpha-emitting radionuclides of plutonium a long-term health risk is also associated with waste management storage.

3.2 COMBINED-CYCLE COAL POWER SYSTEM WITH LOW-BTU GASIFIER AND OPEN-CYCLE GAS TURBINE

3.2.1 System Description

The conceptual design for a combined-cycle coal power plant used in the analysis (see Fig. 3.4) was adapted from the National Aeronautics and Space Administration's Energy Conversion Alternatives Study.[3,4,30] Since year-2000 technologies are the basis for the SPS evaluation program, we used a design based on gaseous fuel emissions of 0.2 lb $SO_2/10^6$ Btu gas or 0.326 lb $SO_2/10^6$ Btu coal. According to this design, fixed-bed gasifiers generate low-Btu gas, which is chemically treated in a gas-cleanup system so that the fuel combusted and supplied to the gas turbine can meet the SO_2 emission standard. The system does not generate synfuels for use outside of the plant. Preprocessed Illinois No. 6 coal is fed to the gasifier. In the bottoming cycle, thermal energy from the gas turbine exhaust is used to generate steam to drive a turbine generator. Approximately two-thirds of the energy output is generated by the gas turbine and one-third by the steam turbine. The conceptual unit

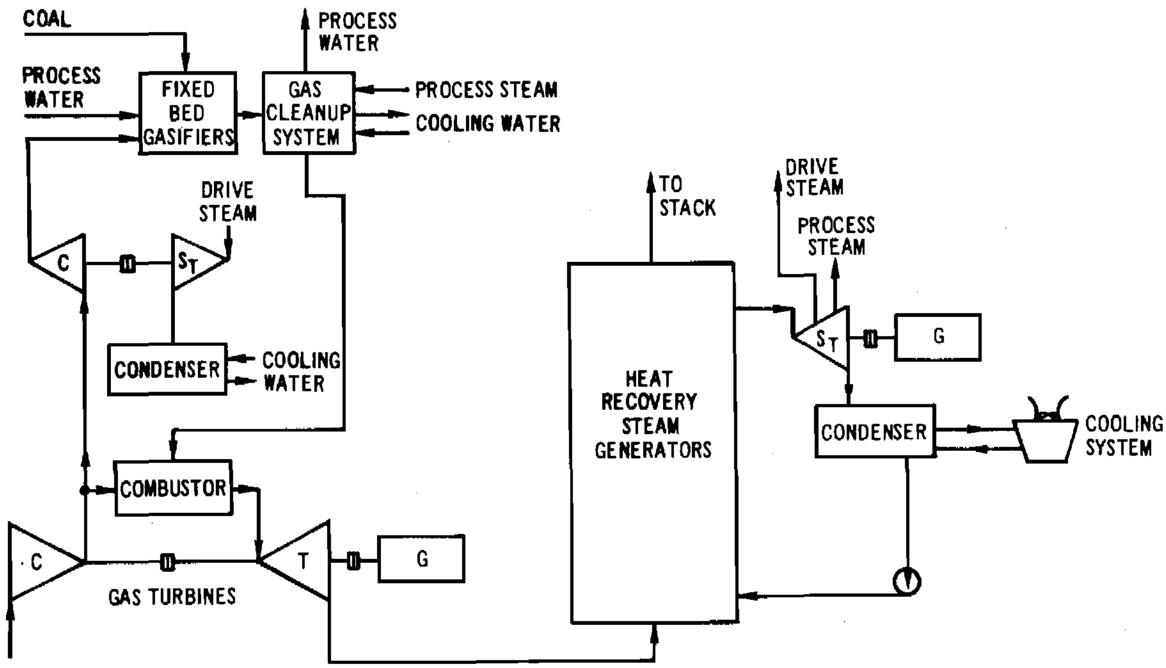


Fig. 3.4. Combined-Cycle Coal Power System with Low-Btu Gasifier and Open-Cycle Gas Turbine

design for 585 MW net output[30] was scaled to two 625 MW units for this study.[3,4]

Additional design parameters relevant to this study include:[3,4]

Unit Capacity	2 x 625 MW
Annual Load Factor	70%
Direct Equipment and Construction Material Costs*	\$356.2 x 10^6 (1978 \$)
Indirect Construction Costs	\$132.7 x 10^6 (1978 \$)
On-Site Direct Construction Labor	13.4 x 10^6 person-hours
Plant Operation Staff	147 person
Plant Maintenance Staff	189 persons
Overall Efficiency	38.5%
Unit Lifetime	30 years
Coal Feed (Full load)	1.00 x 10^6 lb/hr
SO_2 Emissions (Full load)	3600 lb/yr
NO_2 Emissions (Full load)	760 lb/hr

*Excludes plant land costs (\$2.2 x 10^6)

Sludge Disposal (50% water, Full load)	6080 lb/hr
Scaling Factor for 1000 MW Average Generation	1.143

3.2.2 Summary of Health and Safety Issues

The major health and safety issues identified are illustrated in Fig. 3.5 and summarized in Table 3.2. The major quantifiable impact for the combined-cycle coal system is related to continuous public exposure to atmospheric emissions (Issue 5: 4-70 deaths/year from long range SO_2 and SO_4 transport.[31]) Although air pollutants from coal conversion (SO_x in particular) have been shown to correlate statistically with health effects, considerable uncertainty remains as to the actual impact mechanisms and the role of synergistic effects from specific combinations of pollutants that would be emitted from new combined-cycle technologies. The estimate of health effects is based on a 60% confidence range for the pollutant dose-response; the 90% confidence range has zero impacts as a lower range.[31] This estimate is also directly proportional to assumed emission rates of SO_2, and further reductions in these emissions are technically feasible, although at cost penalties.

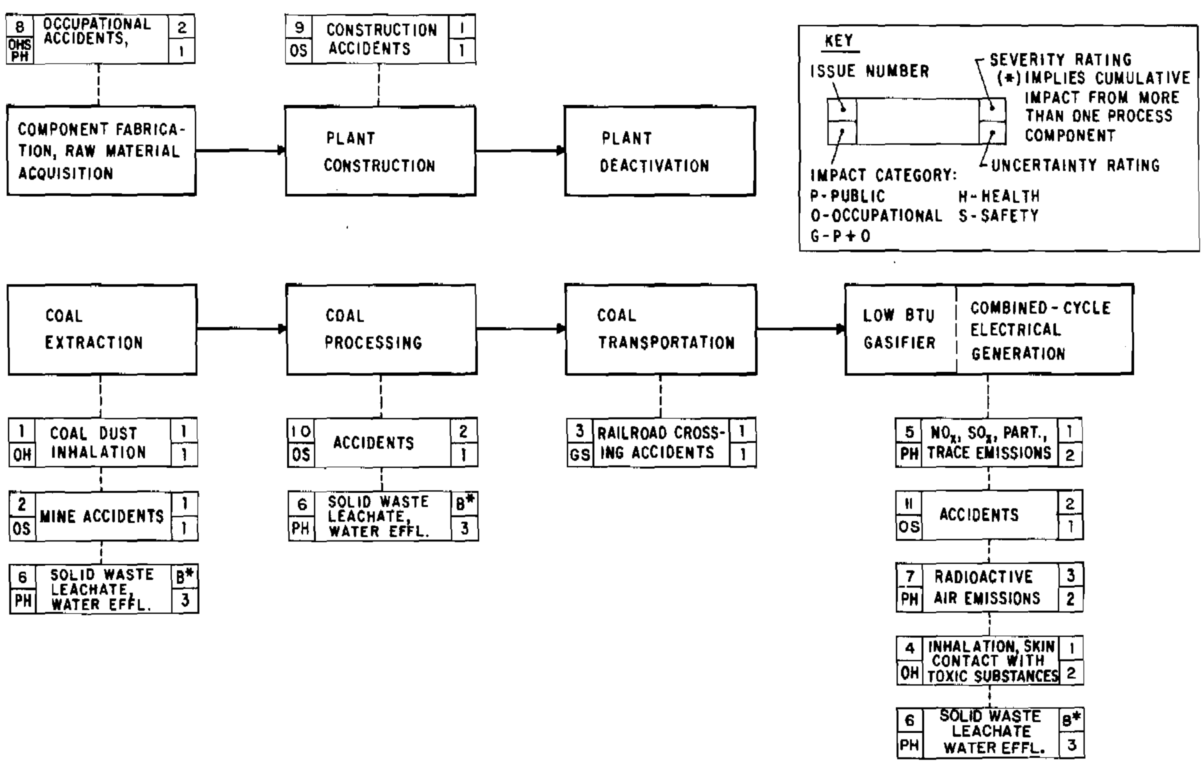


Fig. 3.5. Flow Diagram of the Health and Safety Issues of the Combined-Cycle Coal Power System with Low-Btu Gasifier and Open-Cycle Turbine

Table 3.2. Issue Summary for Combined-Cycle Coal System

Issue	Process	Categories[a] Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
1.[b] Coal dust inhalation.	Underground coal mining. (75% of total)	O	OM	AD	0-1.2 fatalities/yr.	Impact of regulations reducing dust levels.	1
2.[c] Mining accidents.	Surface (25%) and underground (75%) coal mining.	O	OM	AD	0.94-1.2 fatalities/yr.	Large no. of inexperienced miners, new mining techniques.	1
3.[d] Railroad crossing accidents.	Coal transport.	O P	OM OM	AD AD	0.07-0.17 fatalities/yr, 0.78-1.9 fatalities/yr.	Transport routes and distances.	1
4.[e] Inhalation and skin contact with toxic substances and carcinogens.	Plant operation and maintenance.	O	OM	AD	0-0.2 fatalities/yr.	Commercial facility in-plant exposures, impact of low level exposure.	2
5.[f] Atmospheric emissions, long-range transport.	Plant operation; 0.326 lb $SO_2/10^6$ Btu coal input emissions.	P	OM	AD	4.6-75 fatalities/yr; 60% confidence interval for dose response.	Long-range pollutant transport; low-level exposures; impact mechanism and pollutant synergisms.	2
6.[g] Chemical pollutants in aqueous effluents and solid waste leachates.	Coal extraction and processing, plant operation.	P	OM	AD	Not available.	Health impact of small increments of pollutants; effluent characteristics of gasification facilities.	3-B

[a]O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operation and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

Sources: [b]31,35,36; [c]31; [d]6,31-34; [e]37-43; [f]31,44-46; [g]37-39,47.

Table 3.2. (Cont'd)

Issue	Process	Categories[a] Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
7.[h] Exposure, inhalation, and dietary intake of radioactive coal constituents.	Plant air emissions	P	OM	IR	0.0023 fatalities/yr; 0.002 eventual genetic defects/ yr within an 88.5 km site radius.	Effects of low-level radiation; fate and impact of solid waste radioactive leachates. Effect of transport and exposure over longer distances.	2
8.[i] Occupational health and safety.	Direct and indirect material extraction, processing and component fabrication.	O	C	AD	0.82-1.2 fatalities total .	Component needs and associated risks for commercial gasification facilities.	1
9.[j] Construction accidents	On-site plant construction.	O	C	AD	2.6-4.0 fatalities total.	Total and skill-specific labor requirements.	1
10.[k] Occupational accidents.	Coal processing.	O	OM	AD	0.073 fatalities/yr.	Year 2000 coal processing practices.	1
11.[l] Occupational accidents.	Plant operation and maintenance.	O	OM	AD	0.066-0.10 fatalities/yr.	Lack of experience with gasification facilities.	1

Sources: [h]16,48,49; [i]6,50; [j]3,4,6; [k,l]3,4,6,31.

Next to the effects of air pollutants, the largest public impact results from railroad grade-crossing accidents associated with coal transport (Issue 3).[6,32-34] This impact is different in nature from air-pollutant effects in that a direct cause-effect relationship can be established.

The issue of chemical pollutants in water effluents (Issue 6) was given a high uncertainty rating (3) because of lack of data for quantification. In the past, coal-related effluents (e.g., mine effluents) have created significant water quality problems[47] and may create additional issues (e.g., gasification effluents).[37-39] However, since these are expected to be controllable with available technology as mandated by existing water quality legislation,[47] a low subjective severity rating was specified (B).

The safety and health impacts of coal mining on occupational populations[35,36] (Issues 1 and 2) are also of major importance, although there is uncertainty as to the future effects of recent mining health and safety protection regulations.

The estimate of occupational accident risk associated with generating-plant operations[3,4,6,31] (Issue 11) was large enough (up to 0.1 death/yr) to place this issue in the category with the highest severity rating, although the accident estimates are considerably lower than those for coal mining.

The preprocessing, gasification, and combustion of coal in the combined-cycle facility results in various products that can be carcinogenic and toxic if inhaled or in contact with skin over extended periods.[37-42] The potential concentrations of these substances are uncertain, but estimates of potential effects based on pilot plant operations place this issue in a high severity category (Issue 4).

3.3 CENTRALIZED AND DECENTRALIZED TERRESTRIAL PHOTOVOLTAIC POWER SYSTEM

3.3.1 System Descriptions

Centralized Terrestrial Photovoltatic Power System (CTPV)

Several system designs have been proposed for terrestrial photovoltaic central power systems. Although the conceptual frameworks of these designs are similar, significant variations exist in facility size, photovoltaic array geometry, and type of photovoltaic cells used. The system design used in this assessment is based on a characterization done by TRW for the Satellite Power System Comparative Assessment.[3,4,51] A unit facility size of 200 MW peak capacity was used for the present study. Major components include eight 25-MW arrays of photovoltaic cells arranged in a rectangular configuration with gross linear dimensions of approximately 1,300 x 3,000 m, a DC-AC converter station adjacent to this module, and a centrally located switching transformer station to interface the facility with the utility grid (Fig. 3.6). A dedicated energy storage system was not included in this study under the assumption that energy storage is more efficient if integrated into the full utility system.

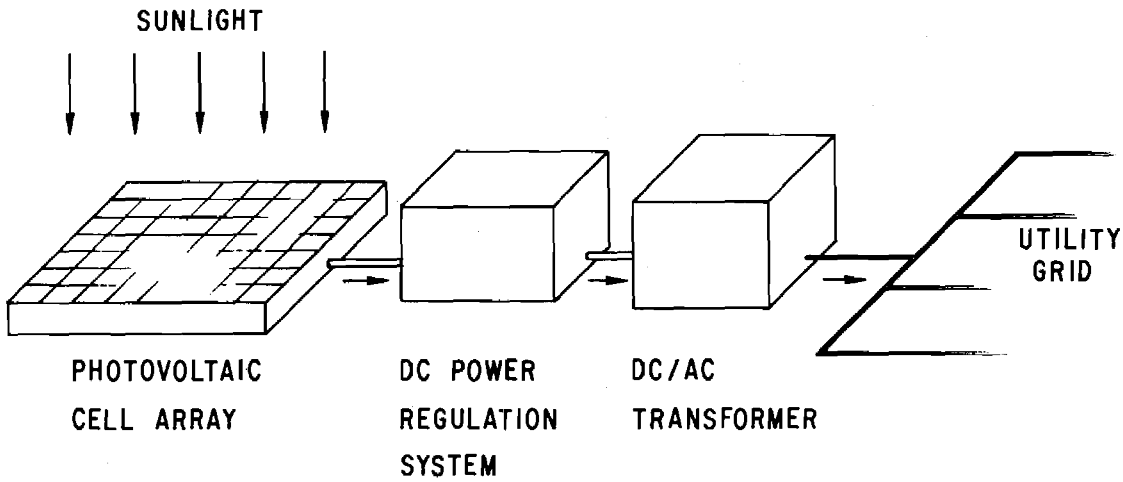


Fig. 3.6. Central Terrestrial Photovoltaic Power System

The types of photovoltaic cells making up the arrays are not specified in the TRW design[51] but are assumed to be silicon with possible options of cadmium/silicon (Cd/S), or gallium aluminum arsenide (GaAlAs).[52] The arrays are of the flat plate type.

Other design parameters relevant to this study include:[3,4]

Unit Peak Capacity	200 MW
Annual Load Factor (% of peak for Phoenix, Ariz.)	25.8%
Direct Equipment and Construction Material Costs*	\$90.1 x 10^6 (1978 \$)
Indirect Construction Costs	\$29.0 x 10^6 (1978 \$)
On-site Direct Construction Labor	1.7 x 10^6 person-hours
Plant Operation Staff	8.5 persons
Plant Maintenance Staff	17 persons
Unit Lifetime	30 years
Scaling Factor for 1000 MW Average Generation	19.4

Decentralized Terrestrial Photovoltaic Power System (DTPV)

The decentralized or "rooftop" photovoltaic system presents a basic conceptual difference in approach from the CTPV in supplying electrical demand. The CTPV represents only a small fraction of the utility's generating capacity demand with the objective of allowing the utility to reduce operating costs by displacing fossil-fueled generation. In contrast, the decentralized

*Excludes plant land costs (\$4.6 x 10^6)

residential system is conceived to satisfy the bulk of consumer requirements as they occur, i.e, it is load oriented. Because of this basic difference in approach, the comparison of DTPV and CTPV involves many factors other than health and safety (costs, ownership, rate structure, etc.) and the two systems can be viewed as complementary rather than competitive in appropriate settings.

The DTPV system considered in this study[53] has a peak capacity of 6 kW and supplies 7220 kWh/yr of baseload demand for a Phoenix residence (lights and appliances). Hot water heating and space conditioning requirements are not supplied. To meet the demands of these appliances (7220 kWh/yr total) with a minimal reliance on utility grid back-up, 20 kWh of battery storage capacity is required. Silicon photocells mounted in a shingle array are assumed. A system schematic is shown in Fig. 3.7.

Design parameters relevant to this study include:[53]

Unit Peak Capacity	6 kW
Annual Load Factor (% of peak for Phoenix, Ariz.)	12.2%
Direct Equipment and Construction Material Costs (including initial batteries)	$7168 (1978 $)
On-site Direct Construction Labor	96 person-hours
System Maintenance	3-9 person-hours/yr
Battery Replacement Cost	$1260 (1978 $)

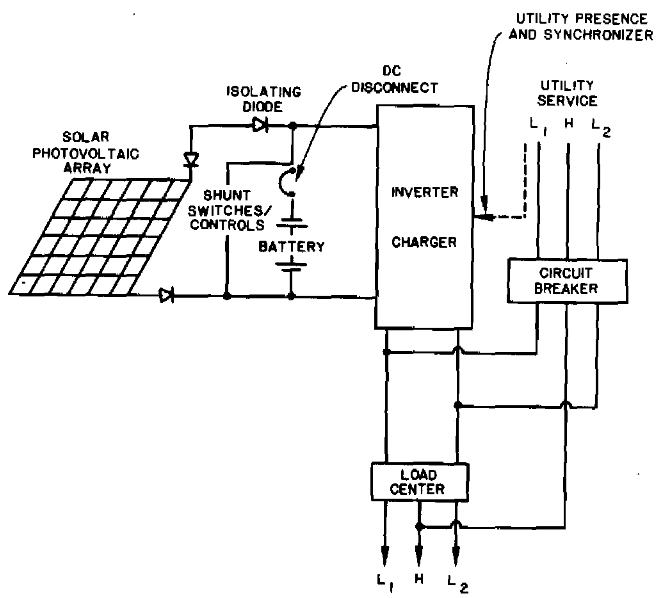


Fig. 3.7. Decentralized Terrestrial Photovoltaic System (Source: Ref. 86, p.21)

Battery Lifetime	10 years
Unit Lifetime	30 years
Scaling Factor for 1000 MW Average Generation	1,366,000

3.3.2 Summary of Health and Safety Issues

Five major health and safety issues (Fig. 3.8, Table 3.3) have been identified for central, terrestrial photovoltaic (TPV) power systems. Health impacts of three are currently quantifiable, two are not. Issue 1 pertains to procurement of raw materials and manufacture of photovoltaic cells. Although some experience with silicon cells has been accumulated, primarily through the space program, what is known about worker health and safety and public exposure to toxic substances is based on limited-scale applications. The proposed use of advanced Cd/S or GaAlAs cells would further increase the uncertainty of efforts to quantify health impacts due to lack of data on pathways of human exposure and toxicity. However, the relative risk of workers involved in TPV cell production activities is among the highest in the U.S. (averaging over 100 person days lost per year per 100 full-time workers compared to the U.S. industry average of 55 person days lost per 100 full-time workers (See Appendix D, Issue 1A).[6]

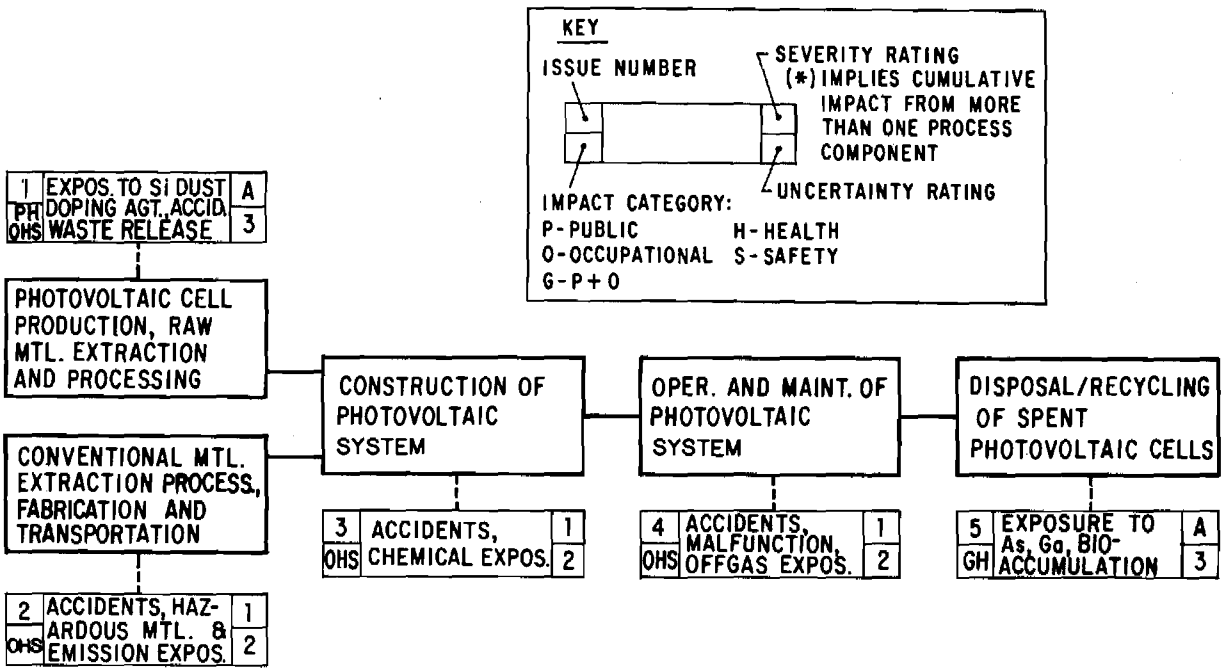


Fig. 3.8. Flow Diagram of the Health and Safety Issues of the Centralized and Decentralized Terrestrial Photovoltaic Power Systems

Table 3.3. Issue Summary for Centralized and Decentralized Terrestrial Photovoltaic Power System

	Issue	Process	Categories[a] Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
1.[b]	Exposure to Si dust, doping agents, process chemicals.	Raw material production and manufacture of photovoltaic cells.	O,P	C	AD	Potential exposure to Si dust and toxic chemicals including, phosgene, boron trichloride, Cd, Ga, As, $HFNO_3$, SnO_x, NH_3, phenols. CdO, $ZnSO_4$, Al_2O_3 and other processing chemicals.	Emission levels, bioaccumulation potentials of released wastes, volume of wastes.	3-A
2.[c]	Accidents, exposure to toxic process chemicals and environmentally released wastes.	Direct and indirect material extraction and component manufacture.	O	C	AD	3.4-7.2 fatalities, total (central.); 14-30 fatalities, total (decentral.)	Material and manpower requirements.	2
3.[d]	Accidents, exposure to toxic chemicals.	Construction.	O	C	AD	5.9-9.3 fatalities, total (central) 17-28 fatalities, total (decentral.)	Manpower requirements of sectors involved in construction activities.	2
4.[e]	Accidents, system malfunction.	Operation and maintenance.	O	OM	AD	0.12-0.18 fatalities/yr. (central.); 0.88-2.4 fatalities/yr. (decentral.); Includes battery replacement every 10 years for decentralized unit.	Manpower requirements and system malfunction potential.	2
5.[f]	Exposure to toxic substances.	Disposal of spent photovoltaic cells.	O,P		AD	Disposal or reuse of cells will increase worker and public risks to exposure of doping agents including As, Cd, and Ga.	Disposal and recycling techniques. Regulations to control disposal of small decentralized units.	3-A

[a]O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operation and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

Sources: [b,d]25,54; [c,d]53,55; [e]13,52,53; [f]52,54.

Environmental effluents emitted during cell production contain potentially toxic substances (e.g., As, Cd, Pb, phenols, and silicon dust). Many toxic substances concentrate through food chains, thus increasing toxicity. Large-scale development of TPV could result in significant releases of these toxic substances and subsequent public health exposure.[52] As a result of these considerations, Issue 1 rates an (A) severity ranking with a (3) uncertainty level.

Issue 5, exposure to toxic substances from disposal of spent photovoltaic cells, is another issue for which health and safety impacts are difficult to quantify. Doping agents in advanced photovoltaic cells (As, Ga, and Cd) are toxic. Although the lifetime of a TPV is projected to be 30 years, photovoltaic cells are projected to last an average of 5 years.[88] In order to produce 1,000 MW of energy per year from the centralized system, 1.27×10^7 kg of GaAlAs polycrystal will be required, or 9.8×10^3 kg of Cd/S.[45] These requirements will create the need to dispose of or recycle large amounts of potentially toxic material, thus increasing occupational and public risk of exposure to toxic substances. These potential problems are further magnified for the decentralized system for which control of the disposal of many small systems could be very difficult to regulate. For these reasons, Issue 5 is given an (A) severity rating with a (3) uncertainty rating.

Issue 2, impacts from extraction, processing, and transportation of conventional materials (e.g., glass, cement, and steel) for use in TPV, have been quantified using the methods described in Sec. 2.2. These systems, in particular the decentralized unit, have large material requirements in comparison to more conventional technologies with a resultant high occupational impact. The number of projected impacts justifies giving this issue a (1) severity rating. The wide range in estimates due to lack of historical data accounts for the uncertainty rating of (2).

Similarly, the relatively high on-site construction requirements result in higher construction risks per unit energy generated than for other non-solar technologies. The primary construction trades involved (cement, electrical, roofing, and sheet metal) are high-risk occupations. Estimates of occupational health and safety impacts from cleaning lenses, maintaining transformers, and operation activities also vary considerably. Maximum estimates of impacts justify a (1) severity rating for both issues, and the lack of experience in impact data dictates rating both at an uncertainty level of (2).

In contrast to the high construction phase occupational impacts the terrestrial solar systems present very low public risks during operation and maintenance. The decentralized system however has a significant potential for occupational O&M risks (Issue 4) based on the assumption of 3-9 hours per unit annual maintenance and storage battery replacement every 10 years.

3.4 SATELLITE POWER SYSTEM

3.4.1 System Description

Major components of the NASA satellite reference system design considered in this study include a satellite composed of a graphite composite structure, silicon solar cells, a power amplifier/transmission system utilizing a klystron for baseline power amplification and DC-RF power conversion, a graphite/epoxy transmitting antenna, and a pilot-beam directional system (Fig. 3.9). Use of gallium aluminum arsenide solar cells has also been considered as an alternative by NASA. Total surface area of the satellite, which is located in geosynchronous orbit (GEO), is about 50 km^2.[1,56] The terrestrial receiving station (rectenna), which receives and rectifies the microwave power beam, consists of a series of rectifying diodes on steel mesh ground planes mounted on steel and concrete structures. Total active panel area per rectenna is projected to be 80 km^2, and a surrounding exclusion zone will result in land requirements of approximately 150 km^2 per site.[1] A considerable amount of space transportation will be required during construction and maintenance. Heavy-lift launch vehicles (HLLV) will be used to transport materials to low earth orbit (LEO), and personnel orbital transfer vehicles (POTV), possibly propelled by ion thrusters, will be used between LEO and GEO.

The current reference SPS calls for construction of two 5-GW systems per year for 30 years, with initial operation after 2000 and a total system capacity of 300 GW.[1]

Design parameters relevant to this study include the following:[1,56]

Unit Capacity	5000 MW
Annual Load Factor	90%

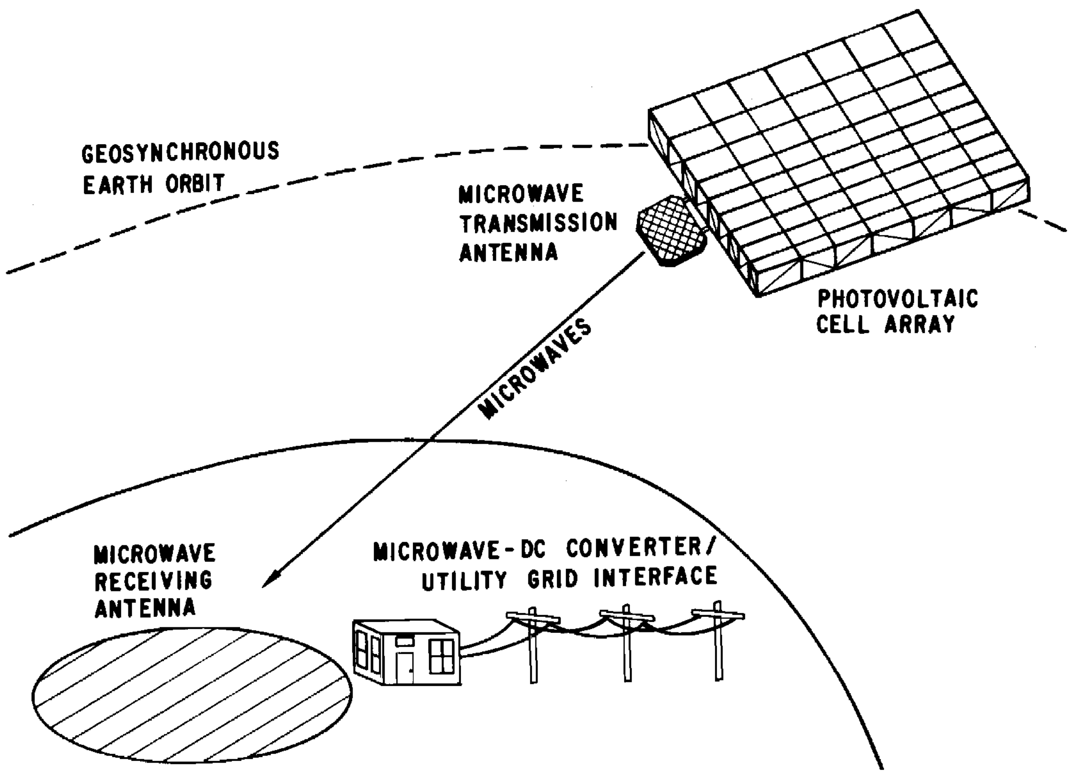


Fig. 3.9. Satellite Power System

Direct Equipment and Construction Material Costs*	$13,421 x 10^6 (1978 $)
Construction Phase Labor:	
Orbiting Crew	0.70 x 10^6 person-hours
Launch Area Operations	2.83 x 10^6 person-hours
Launch Area Maintenance Labor	4.22 x 10^6 person-hours
Receiving Antenna Construction Labor	15.0 x 10^6 person-hours
Operation and Maintenance Phase Labor:	
Orbiting Crew	4.5 persons
Launch Area Operations	19.8 persons
Launch Area Maintenance	29.4 persons
Receiving Antenna Operation Staff	9.5 persons
Receiving Antenna Operations Staff	10 person
SPS Unit Lifetime	30 years
Power Beam Operating Frequency	2.45 GHz
Power density levels	
Center transmitting antenna	22 kW/cm^2
Edge transmitting antenna	2.4 kW/cm^2
Center rectenna	23 mW/cm^2
Edge rectenna	1 mW/cm^2
Grating lobe levels	<0.01 mW/cm^2
Scaling Factor for 1000 MW Average Generation	0.222

3.4.2 Summary of Health and Safety Issues

The major health and safety issues associated with the SPS are identified in Fig. 3.10. Due to the uncertain nature of the SPS design and lack of experience relating to large-scale space projects using SPS technologies, estimation of the extent of many identified health and safety issues involves a great deal of extrapolation. However, a good data base does exist for the technologies and processes needed to supply conventional materials and services (e.g., cement, steel, mining, and construction) for the reference SPS design. SPS requirements for conventional materials and services are large,[57] and the size of these requirements is reflected in Issue 1 in Table 3.4. Increased production will be required from industrial sectors such as ore mining and steel production, which have relatively high accident rates

---

*Average for 60 units, including investment phase costs. Excludes receiving antenna land ($125 x 10^6/unit) and estimated labor costs ($327 x 10^6/unit).[56]

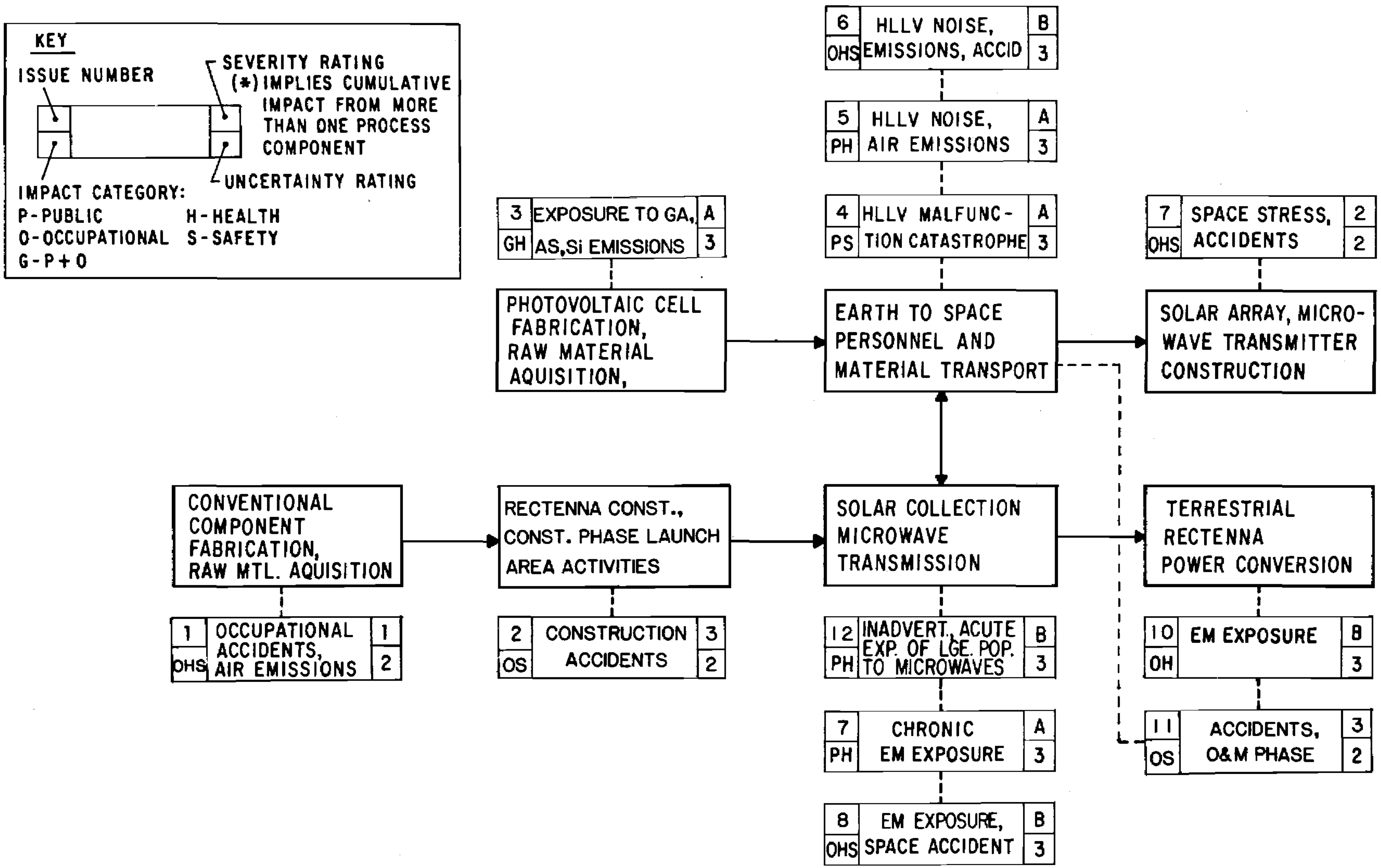


Fig. 3.10. Flow Diagram of Health and Safety Issues of the Satellite Power System

Table 3.4. Issue Summary for Satellite Power System

	Issue	Process	Categories[a] Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
1.[b]	Occupational accidents and disease.	Direct and indirect material and component fabrication.	O	C	AD	5-15 fatalities, total.	Changes in SPS components and thus in conventional technology (e.g., materials extraction and processing) may result from SPS demand.	2
2.[c]	Construction accidents and disease.	O&M of ground launch and recovery areas during construction phase; rectenna construction.	O	C	AD	0.72-1.1 fatalities, total	Total and skill specific labor requirements.	2
3.[d]	Exposure to Si dust, doping agents, process chemicals.	Raw material production and manufacture of photovoltaic cells.	O,P	C	AD	Potential exposure to Si dust and toxic chemicals including, phosgene, boron trichloride, Cd, Ga, As, $HFNO_3$, SnO_x, NH_3, phenols. CdO, $ZnSO_4$, Al_2O_3 and other processing chemicals.	Emission levels, bioaccumulation potentials of released wastes, volume of wastes.	3-A
4.[e]	Catastrophic Events e.g., HLLV malfunction.	Transportation of materials and personnel to low earth orbit (LEO).	P	C,OM	AD	Maximum accident may exceed 1000 fatalities. Approximately 40 flights per 1000 MW capacity during construction phase.	Frequency potential for launch and navigational malfunction.	3-A
5.[f]	Public exposure to fuel emissions, noise from HLLV.	Transportation of materials and personnel to LEO.	P	C,OM	AD	95 dBa at 6 km distance during launch event. Overpressure level of sonic boom during ascent and descent of sufficient magnitude to cause nonprimary structural damage at 125 km distance.	Dispersion patterns and concentration of toxic fuel components.	3-A
6.[g]	Occupational exposure to noise, fuel emissions, malfunctions during HLLV and PLV launch.	Transportation of materials and personnel to LEO and GEO.	O	C,OM	AD	Explosion of heavy-lift launch vehicle (HLLV) could produce ignition of combustibles and first degree burns at 300 m. HLLV launch sound pressure levels exceed pain threshold at 130 dB in launch area.	Toxic chemical exposure potential. System malfunction probability.	3-B

[a]O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

Sources: [b]1,6,56,57; [c]6,56; [d]52,54; [e]1,59,60; [f]57-62; [g]57,60,61,63.

Table 3.4. (Cont'd)

	Issue	Process	Categories[a] Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
7.[h]	Stress of life in space, accidents.	Construction of photovoltaic array and microwave transmission system.	O	C	AD	0.002-0.068 fatalities, total. Based on range of incidence rates in conventional occupations; 640 persons in orbit for 1/2 year to construct 5000 MW satellite.	Potential for system malfunction events, radiation exposure, and vehicle collisions with space debris.	2
8.[i]	Electromagnetic radiation exposure, accidents.	Operation and maintenance of photovoltaic array and microwave transmission system.	O	OM	AD	0-0.003 fatalities/yr. Based on range of incidence rates in conventional occupations; approx. 1400 maintenance crew in orbit for 300 GWe system.	Effects of high-energy particle exposure. Effects of chronic low-level microwave exposure; peak exposure potential of 2400 mW/cm^2.	2
9.[j]	Electromagnetic radiation exposure, chronic and acute.	Operation and maintenance of microwave transmission system.	P	OM	ER	Effects of chronic low-level exposure unquantified.	Effects of large-population exposure to low levels of microwave radiation.	3-A
10.[k]	Electromagnetic radiation exposure.	Operation and maintenance of ground station rectennae.	O	OM	ER	Accidental exposures, power beam reflections would be less than the maximum beam density of 23 mW/cm^2.	Effects of long term exposure to low levels of microwaves and low-frequency electromagnetic radiation.	3-B
11.[l]	Conventional occupational accidents and disease.	Operation and maintenance of ground rectennae, launch and recovery areas.	O	OM	AD	0.07-0.12 fatalities/yr.	Limited historical data on space travel support requirements.	2
12.[m]	Acute exposure to power beam.	Operation and maintenance of satellite power system.	P	OM	ER	Current reference design has low probability for acute public exposure to peak power beam density of 23 mW/cm^2.	Accessibility of final design SPS directional controls to subversive factions. Reliability of directional system shutdown controls.	3-B

[a]O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operation and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

Sources: [h]6,15,51,56,64; [i]6,15,48,56,64; [j]15,51,64; [k]15,64; [l]16,56; [m]15,48,51.

and levels of occupational exposure to hazardous physical and chemical agents. In addition, increased public risks will occur through release of hazardous environmental pollutants. Incremental increases in both public and occupational health effects resulting from meeting SPS demands for conventional materials and services are expected to account for a significant portion of total SPS health impacts. Because of the modular design concept of the SPS, a relatively larger portion of the total construction occupational impacts occur off-site related to direct and indirect commodity production as opposed to on-site construction accidents (Issue 2) as with more conventional technologies.

A high degree of uncertainty is attached to health and safety impacts of other identified issues in Fig. 3.10 and Table 3.4. Despite this uncertainty, several issues appear to pose nonnegligible risks to public and occupational health and safety. Other issues are less significant because of the availability of mitigation strategies such as use of safety devices and system planning.

Issue 9, chronic public exposure to the power beam, warrants both a high severity designation (A) and a high uncertainty ranking (3). The impact on human health from long-term exposure to low-level microwave radiation (<1 mW/cm^2) is not well understood. Studies suggest that chronic exposure may have teratologic, reproductive, genetic, immunologic, and neurologic effects.[61] The level of exposure needed to manifest an effect is not certain. A threshold level may not exist.

Scatter and reradiation from rectenna surfaces and energy from grating lobes are the primary SPS-related sources of public exposure to low levels of microwave radiation. The SPS reference system may, depending on proximity of rectenna sites to high-density population areas, expose significant numbers of people to low-level (<0.1 mW/cm^2) microwaves.[1]

Issue 12 -- acute public exposure to microwaves -- addresses issues such as unexpected excursions of the power beam above the design density of 23 mW/cm^2 and inadvertent or surreptitious focusing of one or more beams outside of rectenna boundaries. For comparison, the OSHA standard prohibits excursions above 25 mW/cm^2 and 8-hour average exposure above 10 mW/cm^2 in the workplace. The current reference design includes a retrodirective phase-control system, an encoded pilot beam, and a ground-based, beam-detection system. Thus the probability of acute exposure of the public is expected to be very low.[1] However, this potential issue deserves continued concern, because details of the final working design, or need for alternative approaches, are still uncertain. The combination of low risk (as currently perceived) and high uncertainty is consistent with a (B) severity rating and a (3) uncertainty rating.

Issue 3, the impacts of production of photovoltaic cells in sufficient quantity to meet SPS demand, is of high uncertainty (level 3) due to the experimental nature of the production techniques that would be required. The SPS reference design includes a gallium aluminum arsenide (GaAlAs) photovoltaic cell option, for which there are even fewer production characterization data than for silicon cells. Since components of GaAlAs cells are toxic,[52] and since exposure levels to occupational personnel and to the public are potentially significant during the production cycle, Issue 3 has been given an (A) severity rating.

Issues 4 and 5, both of which have been given (A) severity ratings and high uncertainty ratings, relate to the public health and safety impacts of transportation of personnel and materials to and from GEO and LEO. A single catastrophic event involving propellant or guidance system malfunction of a transport vehicle (Issue 4) could result in extensive public or occupational fatalities and injuries. Noise and atmospheric emissions produced by transport vehicles (Issue 5), will have impacts of a more continuous, less immediate nature. Noise from launch and flight operations may result in high annoyance levels and potentially hazardous structural damage in the vicinity of the launch area and along the flight path. Atmospheric emissions, potentially toxic themselves, may also have indirect effects on public health if they alter the upper atmosphere so as to produce changes in radiation and weather patterns.[61]

Other identified issues received low severity ratings due to potential mitigation strategies that could keep health risks at low levels. These four issues, 6, 7, 10, and 11, involve occupational risk where procedures such as personnel screening, use of safety equipment, limiting exposure periods, and continuous maintenance of SPS system components would minimize risk.[61]

3.5 FUSION POWER SYSTEM

3.5.1 System Description

A demonstration-size nuclear fusion power reactor is projected to be at least 20 years from completion, and an operating commercial unit will require an additional 10 to 15 years.[65,66] These predictions assume that solutions can be found to difficult technical questions that continue to hamper development of controlled nuclear fusion for commercial power generation.

Selecting a representative fusion system is difficult since it is not possible to identify the specific configuration a working reactor will take. The two research directions under active investigation are magnetic confinement as typified by the Tokamak design and inertial confinement using high-power lasers.[67,68] To date most effort has been directed at the Tokamak concept,[69] and it would appear that the Tokamak design has the best chance of becoming the initial working design. The Tokamak commercial design developed by the University of Wisconsin has been selected as the reference system in the present analysis.[3,4,70]

Figure 3.11 illustrates a Tokamak fusion power reactor coupled through an intermediate heat exchanger to a conventional steam cycle. The primary side of this heat exchanger extracts the heat delivered by neutrons from the fusion reactor to the fusion blanket.

All of the fusion designs currently under consideration would utilize a deuterium/tritium (D/T) fuel cycle. It has been estimated that a fusion system fueled by the earth's natural resource of deuterium could supply the present world power demand for the next 64 x 10^9 years.[71]

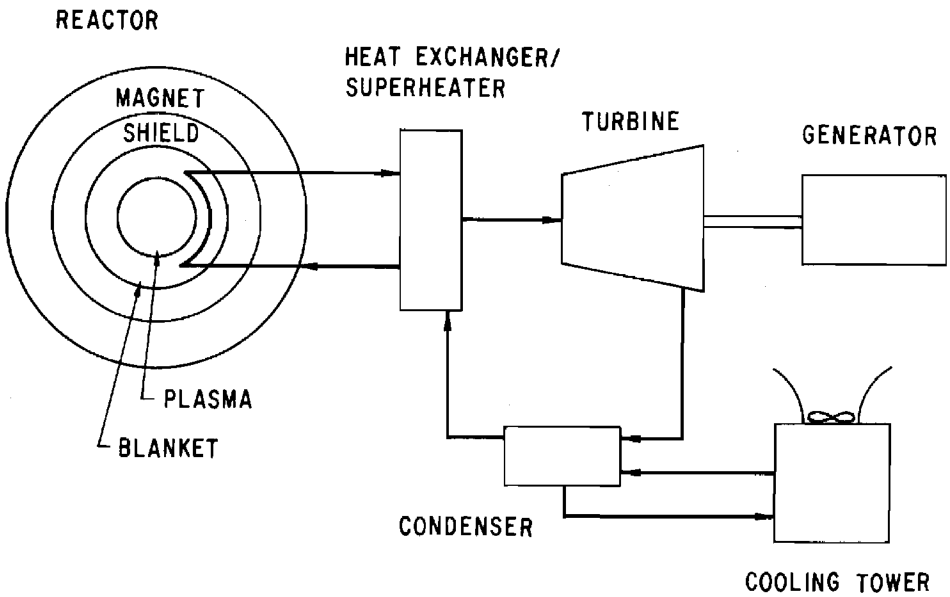


Fig. 3.11. Fusion Power System

A number of fusion reactions are possible, but the one that is most likely to be used in initial fusion reactor designs[65] is as follows:

$$ {}^{2}_{1}D + {}^{3}_{1}T + \underset{(10\ \text{keV})}{\text{plasma energy}} \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + \underset{(17{,}600\ \text{keV})}{\text{fusion energy}} $$

The products of this reaction are a 14.1-meV neutron and a 3.5-meV alpha particle. As the neutron is slowed down, its kinetic energy is given up in the form of heat in the blanket region of the reactor adjacent to the plasma. The energy from the alpha particle is used to maintain the plasma temperature. Because there is no significant source of tritium on earth, the required tritium supply would have to be bred from lithium (Li) in the following reactions:

$$ {}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + 4.8\ \text{meV} $$

$$ {}^{7}_{3}Li + {}^{1}_{0}n \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + {}^{1}_{0}n $$

These reactions would take place within the reactor during normal operations, and since more tritium is produced then is burned up, an excess of fuel would be generated.

To start up a fusion power plant, an initial charge of deuterium and tritium will be needed; after that a continuous supply of deuterium and lithium at about one kilogram per day will be required. An estimated 3 x 10^5 kg of lithium will be required per 1,000 MWe/year.[65]

Relevant design parameters include:[3,4]

Unit Capacity	2 x 660 MW
Annual Load Factor	70%
Direct Equipment and Construction Material Costs*	$1253.9 x 10^6 (1978 $)
Indirect Construction Costs	$628.6 x 10^6 (1978 $)
On-Site Direct Construction Labor	17.4 x 10^6 person-hours
Plant Operation Staff	136 persons
Plant Maintenance Staff	79 persons
Overall Efficiency	31.5%
Unit Lifetime	30 years
Radionuclide Emissions	
Air	730 Ci/yr
Solids and Sludges	9000 Ci/yr
Scaling Factor for 1000 MW Average Generation	1.082

3.5.2 Summary of Health and Safety Issues

The identified major health and safety issues are illustrated in Fig. 3.12 and summarized in Table 3.5. The health and safety issues of a fusion system, like those of a fission system, can be divided between those with and those without a radioactive nature. Safety issues are primarily those associated with hazards of fuel and component preparation, transportation, and general occupational experience during plant operations.

Fusion is often compared favorably to fission as a self-limiting process without the problem of radioactive waste disposal.[67] This statement is only partially true. Although the fusion reaction will not release waste products from fuel use, it does not preclude radioactive wastes from non-fuel-system components such as activation products in the first wall of the reactor. Even though the reaction would cease if a malfunction were to occur, it would be possible for the vacuum vessel to fail during operation and to release tritium.

Tritium is the principal radiological concern in the fusion system.[72,89] This radionuclide is considered a relatively low-level hazard because of its low-energy beta emission and short biological half-life. However, release of a large quantity of tritium as a result of system failure must be guarded against.

---

*Excludes plant land costs ($2.2 x 10^6)

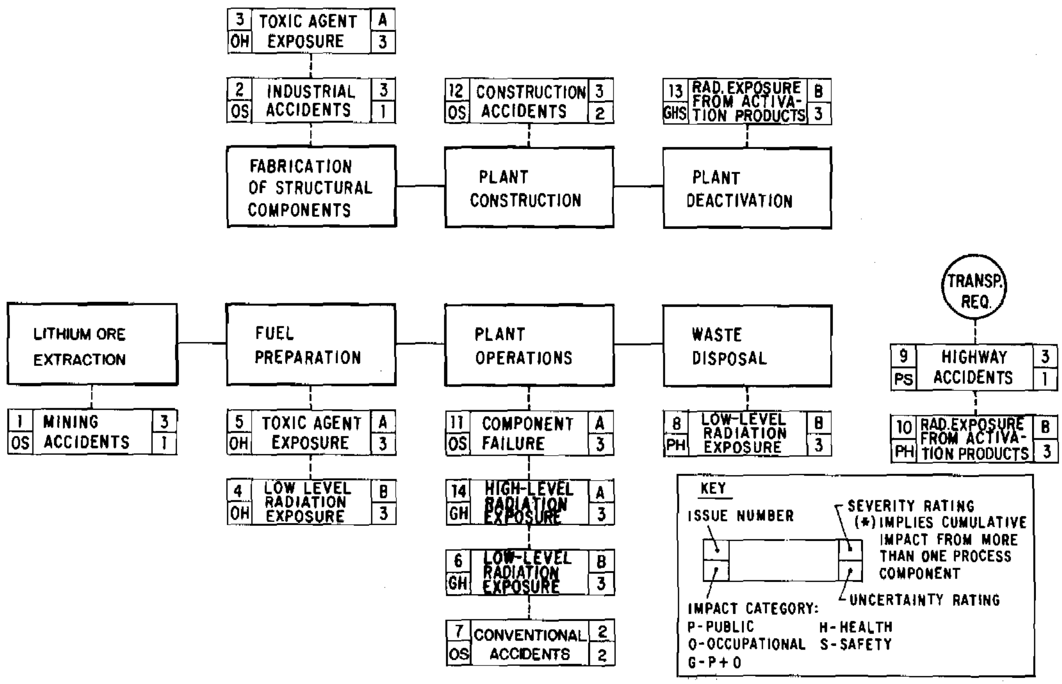


Fig. 3.12. Flow Diagram of the Health and Safety Issues of the Fusion Power System

A more localized yet greater concern during mechanical failure would be a liquid-lithium spill or fire. Such a situation could conceivably release energy equivalent to 1.5 million liters of fuel oil.[69]

An issue unique to the fusion system is the biological effect of high magnetic fields. Studies are presently under way to determine the nature and extent of responses to long-term exposure.[73,74] It appears likely that electromagnetic radiation effects will be limited to the portion of the plant population directly exposed to the field.

Other health issues related to occupational exposures include toxic exposures during fuel processing and fabrication of system components. Hydrogen sulfide exposure during deuterium extraction and acid leaching of lithium ore can result in health impacts to workers in such operations. Beryllium, an identified workplace hazard, will be used in the fusion vessel blanket for enhanced neutron production. Workers likely to be exposed to this metal or its compounds during fabrication must be protected from adverse response.[72]

Issues of a general safety nature include accidents and exposure to toxic chemicals and radiation hazards during lithium ore extraction and processing, system fabrication, plant construction and demolition, fuel and component transportation, and waste disposal. These activities would be expected to exhibit impacts similar to fission systems except for fuel transport and waste disposal.

Table 3.5. Issue Summary for the Fusion Power System

		Categories[a]					
Issue	Process	Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
1.[b] Safety of open pit and brine pumping operations.	Lithium ore extraction and processing (5% yield).	O	OM	AD	1.8 x 10^{-3} fatal accidents/yr, 6.8 x 10^{-3} nonfatal accidents/ yr.	Injury and disease incidence rates of lithium ore extraction.	1
2.[c] Occupational health and safety	Material extraction and fabrication of structural components, direct and indirect.	O	C	AD	1.8-5.5 fatalities, total.	Choice of system design and facility size will influence the quantity and identity of structural components.	2
3.[d] Toxic agent exposure.	Component fabrication.	O	C	AD	Threshold limit value (TLV) for Be: 0.002 mg/m^3.	Satisfactory protection by workplace exposure standards.	3-A
4.[e] Low-level radiological hazards.	Fuel preparation, Tritium.	O	OM	AD	Tritium required for plant startup only.	Size of tritium production facilities and worker exposure levels.	3-B
5.[f] Toxic agent exposure.	Fuel preparation, H_2S exposure.	O	OM	AD	TLV for H_2S: 15 mg/m^3.	H_2S exposure specific to the Girdler process for deuterium extraction.	3-A
6.[g] Low-level radiation exposure. Exposure to high EM fields.	Plant operation.	O,P	OM	IR,ER	Tritium; maximum dose downwind of plant: 1 rem/year. EM effects data inconclusive.	Tritium exposure level inside of plant. EM field health effects.	3-B
7.[h] Occupational accidents and disease, conventional.	Plant operation.	O	OM	AD	0.034-0.055 fatalities/yr.	Plant O&M requirements.	2
8.[i] Exposure to activation products.	Waste disposal, damage repair.	O,P	OM	IR	First wall and blanket finite lifetime due to radiation damage, nonvolatile components.	Capability and migration potential of wastes.	3-B

[a] O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operation and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

Sources: [b] 65,75; [c] 3,4,6; [d] 43,72,76; [e] 77,78; [f,g] 65,67; [h] 3,4,6; [i] 71

Table 3.5. (Cont'd)

	Issue	Process	Categories[a] Impacted Group	Phase	Primary Cause	Impact Estimation/ 1000-MW Generation	Uncertainties	Uncertainty Rating
9.[j]	Highway safety.	Transportation of materials, fuel, and waste.	P	OM	AD	Truck transport 1.3×10^{-4} fatal accidents/yr, 1.1×10^{-3} nonfatal accidents/yr.	Amount and mode of required transportation.	2
10.[k]	Low-level radiation exposure.	Transport of materials, fuel, and waste.	O,P	OM	IR	Unknown.	Amount and mode of required transportation.	3-B
11.[l]	Component failure, plant safety, liquid metal fires and spills, pressure and thermal explosions, missile generation due to magnet or vacuum failure.	Operation and maintenance.	O	OM	AD	Similar to other industrial experience with high-energy material.	System reliability and likelihood of a fire or explosion.	3-A
12.[m]	Occupational accidents and disease.	Plant on-site construction.	O	C	AD	3.8-6.0 fatalities, total.	Materials and construction personnel requirements.	2
13.[n]	Radiation exposure from activation products.	Plant deactivation.	O,P		IR	Nonvolatile nature of activation products suggests a low level of impact for this issue.	Human response to low-level exposure uncertain. Exposure scenario of unknown probability.	3-B
14.[o]	High-level radiation exposure.	Catastrophic event.	O,P		IR	Unknown.	Likelihood of exposure during such an event.	3-A

Sources: [j]75,79; [k]68,72; [l]65; [m]4,3,6; [n]66,68,80; [o]65,67,68,77,78.

A final issue that does not lend itself to quantification is the impact of fusion technology on nuclear safeguards. Unlike fission technology, which could conceivably be diverted to produce material for nuclear weapons, fusion has a nearly self-contained fuel cycle and nonvolatile radioactive waste products.[67] As such, a fusion system would not produce nuclear materials on a level comparable to that of the LMFBR system from which weapons could be fabricated. However, through plasma confinement techniques, fusion technology could aid in the spread of knowledge pertinent to weapons development, a by-product of energy research with an indirect safety impact.

4 SUMMARY AND ENERGY SYSTEM COMPARISONS

The results of the quantitative risk analysis for the SPS and six alternative electrical generation systems are summarized in Table 4.1 and Figs. 4.1-4.3. The major (Severity Category A) unquantified issues are listed in Table 4.2. The following is a discussion of major features from those results.

Occupational Risks of the Construction Phase. For each unit value of industrial output required to directly supply system components for each of the energy systems, an additional indirect output in other industries in the range of 0.5-0.9 units is required. This significant requirement for indirect industrial output results in a significant addition to average unit component production impacts, as illustrated in Fig. 4.1. The combined direct and indirect impact per unit component requirement in Fig. 4.1 is within the same range for each technology, and, as a result, the total component requirement per 1000-MW generation is the over-riding factor in determining component production risk. The total component production risks, combined with on-site construction risks are shown in Fig. 4.2 and illustrate the higher construction phase risk of the solar and, to a lesser extent, the fusion technologies due to the more capital intensive nature of these technologies. The centralized terrestrial photovoltaic system requires nearly 20 units at 200-MW peak capacity and 26% load factor, and the SPS requires extensive ground and space facilities to construct and maintain the orbiting satellites.

Although not shown, similar results are obtained for the number of work days lost (see Appendix A). For this parameter, more disaggregated data on risk levels is available for individual industrial categories.

Occupational Risks of the Operation and Maintenance Phase. The total quantified fatality risk, averaged over an assumed 30-year lifetime, is shown for each technology in Fig. 4.3. Quantified risks of operation and maintenance (O&M) are largest for the coal technology, primarily due to the risks of accidents and illness due to coal mining. A major uncertainty in mine risk estimates derives from the currently unknown long-term effect of recent regulations for reducing the levels of dust in coal mines. Additional occupational O&M risks of energy production from coal are related to rail transport of the coal, accidents in the coal processing and electrical generation plants, and exposure to potential carcinogenic emissions from the coal gasification process. The estimate for the risk from potential in-plant gasification emissions (0.0-0.2 fatalities/1000 MW-yr) is based on the estimated number of workers in the plant and on historical data from pilot plants with limited control measures.[40] Approximately one-half of the O&M risks of the fission systems are related to conventional occupational hazards and the remaining one-half are due to low-level radiation exposure, the impacts of which are uncertain. The O&M occupational risks of the advanced fusion, SPS, and centralized terrestrial solar systems have no historical basis and are projected from conventional risk levels for existing similar occupations and estimates of the number of O&M employees required.[3,4]

Table 4.1. Summary of Quantified Average Fatalities per Year per 1000-MW Generation, 30-Year Plant Lifetime

	LWR	Coal (CG/CC)	LMFBR	CTPV	DTPV	SPS	Fusion
Total	0.26-1.4	6.6-79	0.24-1.1	0.43-0.73	1.92-4.4	0.26-0.67	0.22-0.44
Population Affected							
Public	0.03-0.18	5.4-76	0.03-0.18	U[a]	U	U	0.0001
Occupational	0.24-1.2	1.3-3.1	0.21-0.94	0.43-0.73	1.92-4.39	0.26-0.67	0.22-0.44
Impact Period							
Manufacture and Construction[b]	0.10-0.16	0.11- 0.18	0.12-0.20	0.31-0.55	1.04-1.94	0.19-0.55	0.16-0.38
Operation and Maintenance	0.16-1.2	6.5-79	0.12-0.92	0.12-0.18	0.88-2.45	0.07-0.12	0.03-0.06
Impact Cause							
Accidents and Non-Radiation Disease	0.21-0.67	6.6-79	0.17-0.51	0.43-0.73	1.9-4.4	0.26-0.67	0.22-0.44
Radiation	0.05-0.70	0.0023	0.07-0.61	U	U	U	U

[a]U - Unknown or negligible.

[b]Total impacts averaged over 30-year lifetime.

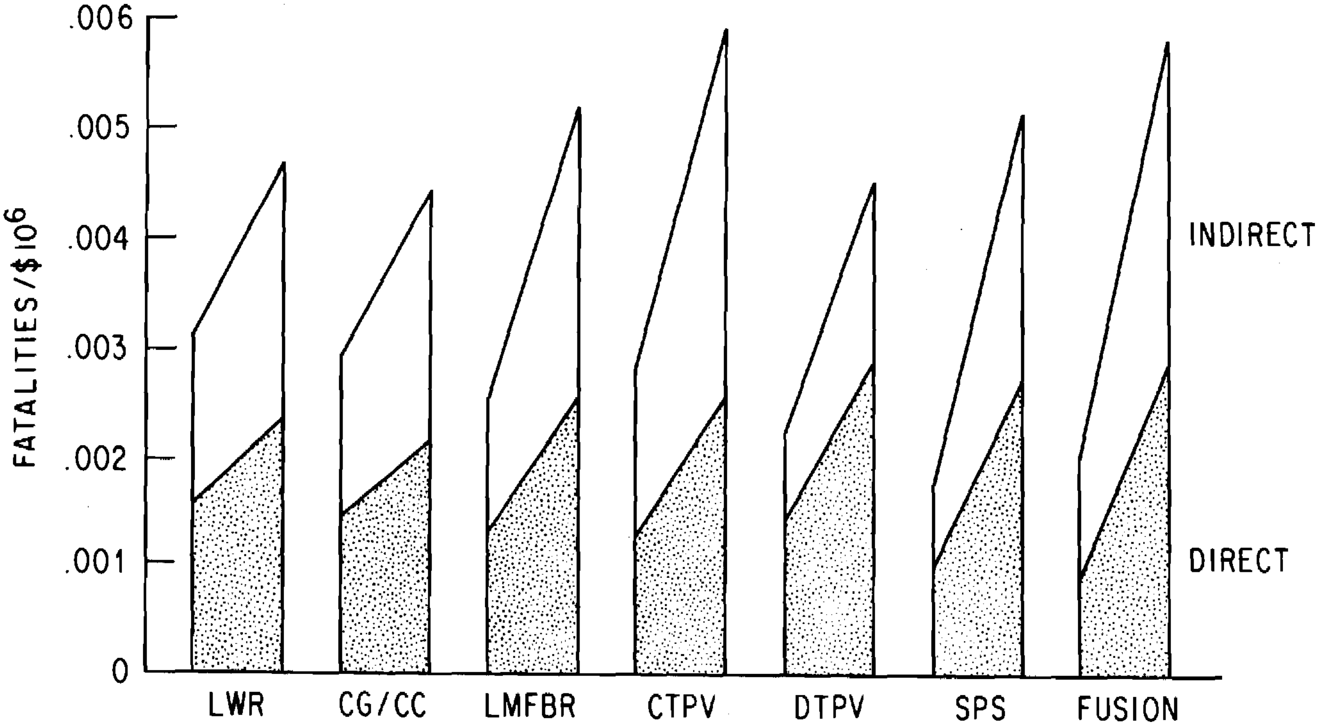


Fig. 4.1. Direct and Indirect Occupational Fatalities from Unit (10^6) Facility Component Production

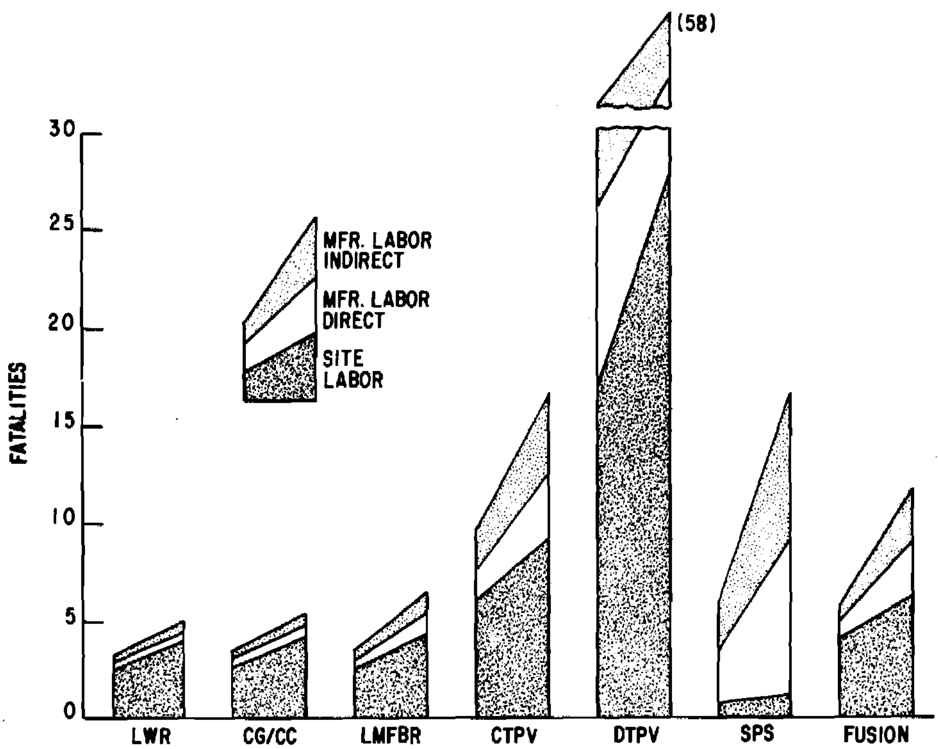


Fig. 4.2. Total Occupational Fatalities in Construction Phase of System with 1000-MW Average Generation

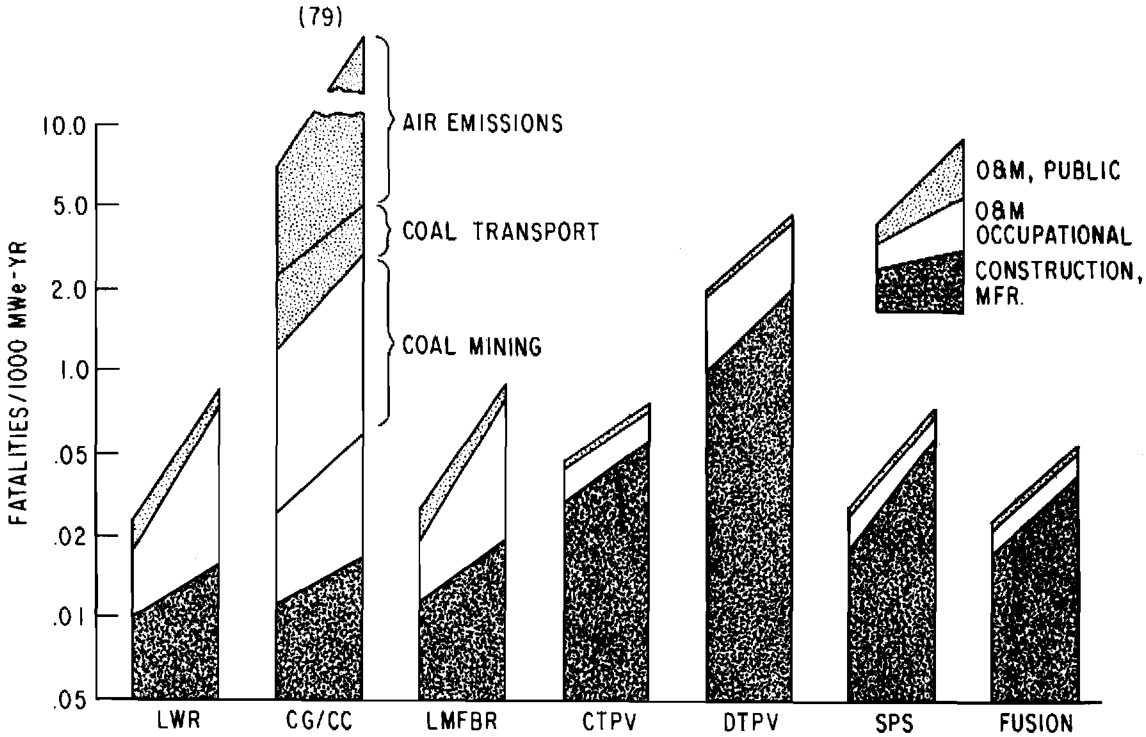


Fig. 4.3. Total Quantified Construction and O&M Fatalities per 1000 MW-yr

Table 4.2. Summary of Potentially Major but Unquantified Issues

Solar Technologies (CTPV, DTPV, SPS)	Nuclear Technologies (LWR, LMFBR, Fusion)
1. Exposure to Cell Production Emissions	1. System Failure with Major Public Radiation Exposure
2. Hazardous Waste From Disposal or Recycle of Cell Materials	2. Occupational Exposure to Chemically Toxic Materials during Fuel Cycle
3. Chronic Low-level Microwave Exposure to Large Populations (SPS only)	3. Diversion of Fuel or By-product for Military or Subversive Uses
4. Space Vehicle Crash into Urban Area (SPS only)	4. Liquid Metal Fire (LMFBR, Fusion only)
5. Exposure to HLLV Emissions (SPS only)	
Coal Technologies (CG/CC)	
(None Identified)	

Public Risks of the Operation and Maintenance Phase. The largest O&M phase public risks quantified for this study are those related to the coal technology, and these are almost entirely due to coal transport accidents (0.8-1.9 fatalities/1000 MW-yr) and air pollutants (4.6-75 fatalities/1000 MW-yr). The estimates for air pollutant impacts include long-range transport, and the uncertainty range is based on a 60% confidence level for incidence rates of health effects (adapted from Ref. 31). It should be noted that a similar procedure using 90% confidence levels for air pollutant dose-response gives a range including zero impacts. Low levels of public impacts (less than 0.2 fatality/1000 MW-yr) can be attributed to normal O&M of the fission and fusion systems, and these impacts are primarily due to low-level radiation, which has a high uncertainty level. The quantified solar O&M public impacts are negligible.

Unquantified Health and Safety Issues. In contrast to the apparent public willingness to accept limited known risks of energy systems, recent experience with light water fission systems indicates that perceived major risks that are less quantifiable or predictable may restrict or prevent energy system deployment if adequate assurances of very low impact probability cannot be given. For this reason potentially major, but unquantified, risks should be given prominence comparable to the quantified risks discussed above. Table 4.1 is a listing of potentially major (Category A) but unquantified issues identified for the six technologies considered.

Estimates of expected health and safety impact levels have been developed for certain catastrophic events (i.e., events of low occurrence probability, but high impact per event), in particular, for fission reactor systems.[81] However, these impacts were not included as quantified issues in this study because of inherently high uncertainties associated with predicting occurrence rate and impact per occurrence. Furthermore, averaging expected catastrophic impacts over plant lifetime does not indicate the full significance of these potential events. The issues of potential fission system fuel diversion for weapons use and SPS space transport vehicle crash into urban areas are also included in the potential catastrophic event category. Through engineered safeguards, the probability of occurrence of these events can be reduced to very low levels, but essentially zero probability is very difficult if not impossible to achieve at reasonable cost.

A further important distinction concerning unquantified issues is whether the potentially affected persons are part of the general public or are workers producing or operating the system. Issues in the latter category (e.g., emissions from solar cell production, emissions of toxic materials from the fission system fuel cycle, LMFBR and fusion liquid metal fire hazards) affect a well-defined group, i.e., occupational workers, and those impacts can be more easily monitored and mitigating actions implemented. In contrast, impacts from low-level microwave radiation, if they exist, may be difficult to identify because of their potentially small and subtle nature within a large exposed group.

In general, the more defined technologies (e.g., CG/CC, LWR) have a greater number of quantifiable risks and fewer unquantifiable risks. The opposite is true for the less-defined technologies (e.g., fusion, SPS).

Table 4.2 does not attempt to rank the unquantified issues, although, for example, potential radiation release from fission is expected to be greater than that from fusion.[78]

Cumulative Risks From National Energy Scenarios. A further perspective on the significance of relative technology risks is provided by Fig. 4.4, which indicates the range of annual occupational risks for 2000-2020 scenarios of energy production with and without the SPS system. A nearly constant total electrical energy generation is assumed in this period for the scenarios (Table 4.3). The SPS units were assumed to operate at the design load factor of 90%. However, because of the large SPS unit size (5000 MW), it is assumed that because of reliability requirements, the overall capacity, including conventional technologies, is the same for the SPS scenario as for the non-SPS scenario in which the overall load factor was assumed to be 70%. In the SPS scenario, the non-SPS technologies serve in part as back-up for the SPS and operate at less than 70% load factor.

Because of high construction and manufacturing impacts, the SPS scenario has higher initial value for the mean occupational health and safety risks. By 2020, in this scenario, these occupational risks have dropped to nearly the same values as those for the non-SPS scenario.

The addition of quantified public risks to the occupational risks in Fig. 4.4, in particular those from coal, would favor the SPS scenario with

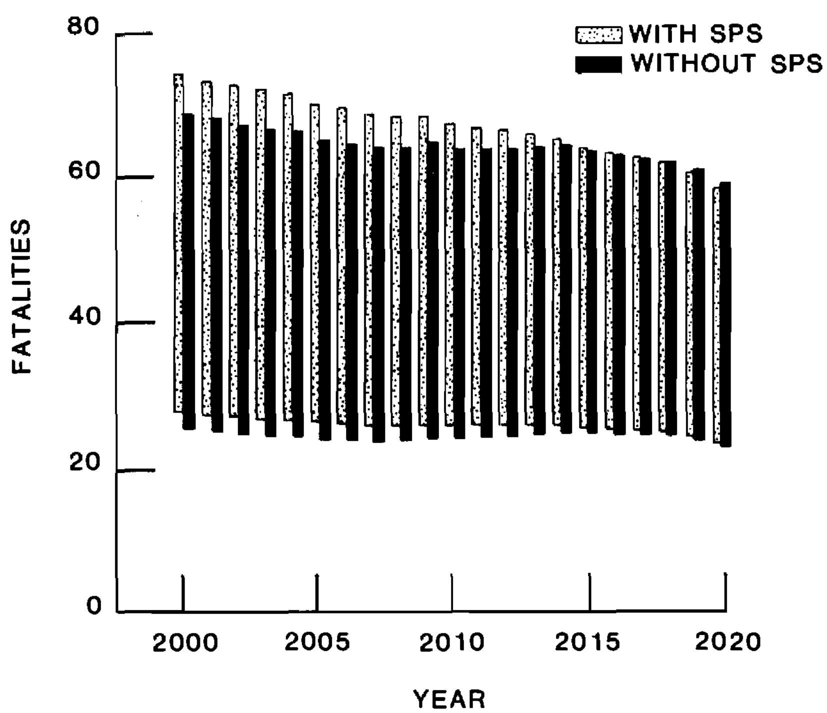


Fig. 4.4. Annual Construction and O&M Occupational Fatalities from Baseload Scenarios With and Without SPS

Table 4.3. Scenario Baseload Capacities and Electrical Generation

Year	Capacity (GW)						Generation
	LWR	CG/CC	LMFBR	SPS	Fusion	Total	Total/(GW-yr)
2000	263	238	34	0	0	535	375
2020 (SPS)	199	145	96	100	19	549	384
2020 (W/O SPS)	213	159	140	0	37	549	384

reduced conventional generation. However, the unquantified risks to the public in Table 4.2 restrict the delineation of definitive conclusions related to total scenario risks.

Conclusions. Of the various systems considered, the coal technology has the largest overall quantified risk primarily due to coal extraction, processing and transport, and air emissions, although large uncertainties remain in the actual effect of the air emissions. On the other hand, additional issues that are potentially major but remain largely unquantifiable were not identified for the coal system. Quantified risks from the remaining technologies (fission, fusion, SPS, and centralized terrestrial photovoltaic) are comparable within the range of quantified uncertainty. The occupational risks for component production, both direct and indirect, are a substantial fraction of the total risk, in particular for the advanced, capital-intensive solar and fusion technologies.

Of potential major significance for public acceptance of new energy systems, but not included in the quantification, is the possibility of catastrophic incidents that exist for the fission and fusion systems. Unique unquantified issues of concern also exist for the SPS in relation to the use of microwave transmission of energy and extensive space travel.

APPENDIX A

TECHNOLOGY CHARACTERIZATION AND HEALTH AND SAFETY IMPACT DATA SUMMARIES

Table A.1. Major Characteristics of Alternative Energy Technologies

	LWR	CG/CC	LMFBR	CTPV	DTPV	SPS	Fusion
Unit Capacity (MW)	1250	1250	1250	200	0.006	5,000	1320
Total Direct Commodity Cost per Unit ($\$10^6$)[a]	333.7	356.2	535.2	90.1	0.00717	13,421	1253.8
Average Annual Load Factor (%)	70	70	70	25.8	12.2	90	70
Indirect Capital Cost per Unit ($\$10^6$)[b]	197.1	132.7	262.6	20.0	-	-	628.6
On-site Construction Labor per Unit (10^6 person-hrs)	13.1	15.2	14.5	1.7	96×10^{-6}	(c)	22.1

[a]Delivered costs for components, structures, and materials. Land and labor costs excluded. Values are 1978 dollars.

[b]Temporary site construction facilities, payroll insurance and taxes, and other construction services, such as home and field office expenses, field job supervision, and engineering services. Specifically excluded are fees for permits, taxes, interest on capital, and price escalation. Values are 1978 dollars.

[c]Rectenna - 15.0; Construction in orbit - 0.7; Launch area maintenance - 4.2; Launch area operations - 2.8.

Table A.2. Dissaggregation of Energy Technology Component Cost by Producing Industry Category (Percentage)

Industry Category	LWR,LMFBR, Fusion	CG/CC	CTPV	DTPV	SPS
Stone and clay mining and quarrying	1.9	1.8	0.2		0.4
Plastics and synthetic materials			0.8		29.9
Glass and glass products					0.4
Stone and clay products	1.6	1.8	0.3		1.1
Primary iron and steel manufacturing	14.0	2.6			
Primary nonferrous metals manufacturing	3.4	1.9	68.4	(4.0)[a]	6.7
Heating, plumbing and fabricated structural metal products	48.6	47.4	7.6		2.9
Other fabricated metal products	3.4	1.1	0.1		
Engines and turbines	15.9	26.0			
Materials handling machinery and equipment		8.3			
General industry machinery and equipment	1.4	2.8			
Electrical transmission equipment and industrial apparatus	5.6		4.3	19.2	25.6
Electric lighting and wiring equipment	0.7	5.4		5.0	
Electronic components and accessories			18.2	30.3	1.7
Miscellaneous electrical machinery, equipment and supplies				45.5[b]	
Aircraft and parts					31.1[c]
Professional, scientific, and controlling instruments and supplies	3.5	0.9	0.1		0.2

[a]Lead use in lead-acid storage batteries.

[b]Includes batteries (17.6% of total components cost). Occupational risks for manufacture of batteries evaluated separately.

[c]Material and personnel space transport vehicles.

Table A.3. Summary of Quantified Health and Safety Impacts for Alternative Technologies

Activity	Population	Impact	LWR	CG/CC	LMFBR	CTPV	DTPV	SPS	Fusion
O&M[a]	Public	Fatalities	0.063 - 0.064	5.4 - 76.4	0.072 - 0.073	-[b]	-	-	-
O&M[a]	Occ.	Fatalities	0.12 - 0.66	1.15 - 2.91	0.13 - 0.66	0.12 - 0.18	0.88 - 2.45	0.07 - 0.12	0.036 - 0.057
	"	PDL[c]	130 - 150	1400 - 16,000	140 - 150	380 - 420	6100 - 13,000	250 - 290	140 - 150
On-site constr.[d]	Occ.	Fatalities	2.29 - 3.62	2.59 - 4.05	2.56 - 4.04	5.92 - 9.30	16.85 - 28.09	0.72 - 1.18	3.80 - 5.95
"	"	PDL	7700 - 8400	8300 - 9100	8800 - 9700	20,000 - 65,000	46,000 - 77,000	9300 - 10,000	15,000 - 35,000
Component Prod.,[d] Direct	Occ.	Fatalities	0.39 - 0.58	0.40 - 0.60	0.50 - 1.04	1.55 - 3.22	9.15 - 19.07	2.68 - 8.05	0.90 - 2.72
"	"	PDL	5600 - 8400	5600 - 8400	7300 - 15,000	20,000 - 41,000	105,000 - 220,000	23,000 - 68,000	13,000 - 39,000
Component Prod.,[d] Indirect	Occ.	Fatalities	0.40 - 0.60	0.42 - 0.63	0.52 - 1.08	1.91 - 3.96	5.29 - 11.02	2.38 - 7.15	0.93 - 2.82
"	"	PDL	3000 - 4600	3700 - 5500	3900 - 8200	7300 - 15,000	57,000 - 118,000	10,000 - 30,000	7100 - 21,000

[a]Impacts are given per 1000 MW-yr generation.

[b]Not estimated or negligible.

[c]Work days lost from nonfatal accidents or disease.

[d]Impacts are total for construction of capacity producing 1000 MW-yr/yr.

APPENDIX B

FISSION: ISSUE IDENTIFICATION AND EVALUATION

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 1

PROCESS: Uranium ore extraction and milling.

IMPACT CATEGORY: Occupational, O&M, accidents.

GENERAL DESCRIPTION: The mine environment -- irrespective of the product being extracted -- has historically been identified with clearly defined physical hazards. Underground uranium mining utilizes heavy machinery, explosives, and high-power electrical equipment, generally in confined, poorly lighted work areas. A continuous hazard also exists from rock slides and roof falls. Surface processing of the ore also presents opportunities for adverse health interactions from the requirement of large-scale materials-handling activities.

QUANTITATIVE IMPACT ESTIMATE: Occupational risks from physical hazards during mining and milling operations are roughly comparable to those of the coal industry. Over the six-year interval between 1964 and 1969, the injury rates per million person hours were 1.02 for fatal* and 39.2 for nonfatal accidental injuries as compared to 1.01 and 42.6 for the coal industry during the same period. For the LMFBR, the occupational hazards of ore extraction and milling are primarily only related to the initial phase of the fuel cycle since reprocessed fuels are used primarily in the established technology.

MAJOR UNCERTAINTIES REQUIRING R&D: The future extent of worker exposure to extraction and milling operations is highly dependent on advances in the industry and availability of specific grades of ore. Lower grade ores will require greater hazard exposure.

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCE: 12

---

*Estimated impact 0.05 to 0.2 fatality per yr per 1,000 MWe

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 2

PROCESS: Uranium ore extraction and milling.

IMPACT CATEGORY: Occupational, O&M, radiation.

GENERAL DESCRIPTION: Underground mining of uranium can expose the miner to dust containing naturally-occurring radionuclides. These dusts, together with radon gas, ^{222}Rn, pose an occupational hazard to the miner. To a lesser degree this hazard exists during milling as well.

Increased rates of lung cancer have been documented in underground uranium miners. Evidence supports the relationship between exposure to alpha-emitting radionuclides such as ^{222}Rn and induction of lung tumors in man. Dose-response relationship: $0.63/10^6$ person/yr/rem excess cases of lung cancer in U.S. uranium miners between 1951 and 1971.

QUANTITATIVE IMPACT ESTIMATE: During the past 20 years more than 100 uranium miners have died from lung cancer in the U.S.; 500-1,500 miners who were exposed prior to establishment of occupational safety standards may die from similar radiation-related disease. Estimated impact, 0.001-0.1 fatality per year per 1,000-MWe generation. For the LMFBR, the occupational hazards of ore extraction and milling are primarily only related to the initial phase of the fuel cycle since reprocessed fuels are used primarily in the established technology.

MAJOR UNCERTAINTY REQUIRING R&D: Radiation exposures before establishment of national standards are not known precisely; they have been estimated at several thousand times the present exposure limits.

REGULATORY STATUS: International Commission on Radiological Protection (ICRP) 1959 limit: 0.3×10^{-8} μCi of ^{222}Rn/ml of air, maximum permissible concentration. U.S. exposure limit, 4 months of occupational exposure per year (10^{-7} μCi of ^{222}Rn/ml of air).

SEVERITY RATING: 2

UNCERTAINTY RATING: 2

REFERENCES: 13, 18

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 3

PROCESS: U_3O_8 conversion, UF_6 enrichment, UO_2 fabrication.

IMPACT CATEGORY: Occupational, O&M, accidents.

GENERAL DESCRIPTION: The industrial processes required to take milled U_3O_8 from its natural state to enriched UO_2 in reactor fuel bundles permit the possible exposure to toxic fumes and physical hazards in the workplace.

Initial conversion of U_3O_8 to $U(NO_3)^6$ can also expose workers to an explosive hazard.

QUANTITATIVE IMPACT ESTIMATE: Occupational injury during uranium processing: 0.003-0.2 fatal and 0.568 nonfatal injuries per year associated with the fuel requirement of 1,000-MWe generation.

MAJOR UNCERTAINTIES REQUIRING R&D: Specific data are needed on the work force accident experience related to the fuel preparation activities of the nuclear fuel cycle.

REGULATORY STATUS: Both NRC and OSHA regulations cover various aspects of the workplace throughout the nuclear industry.

SEVERITY RATING: 2

UNCERTAINTY RATING: 1

REFERENCE: 14

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 4

PROCESS: Fuel processing; conversion, enrichment, fabrication.

IMPACT CATEGORY: Public and occupational, O&M, radiation.

GENERAL DESCRIPTION: Low-level radiation exposure is associated with all phases of the nuclear fuel cycle. The purpose of fuel processing is to bring the U-235 content of the fuel up from about 0.7% in its natural state to 3 or 4% in the enriched fuel. Both the fabricated fuel product and process wastes (including mine tailings) present possible sources of radiation exposure. The quantity of such wastes is expected to increase with expansion of the nuclear industry.

The health impacts generally associated with low-level radiation exposure are cancer and genetic defects. These impacts are classified as delayed effects in that they occur long after the initial exposure. A general latency period for most cancers associated with radiation is about 15 years. Genetic effects occur in the offspring of the exposed individual.

QUANTITATIVE IMPACT ESTIMATE: A Biological Effects of Ionizing Radiation (BEIR) report estimates for low-level radiation effects are calculated at 180×10^{-6} cancer deaths per rem and 150×10^{-6} eventual genetic defects per rem exposure of the entire population. Estimated occupational impacts: 0.008 - 0.33 occupational fatality/1000 MWe-yr; 0.0003 fatality/1,000 MWe-yr among general public.

MAJOR UNCERTAINTIES REQUIRING R&D: No data exist on radiation-induced genetic defects in man. All evidence has been derived from animal experimentation.

REGULATORY STATUS: The ICRP recommends dose limits for the general public: genetic dose < 5 rem from all sources over the normal time period for child-bearing.

SEVERITY RATING: 2

UNCERTAINTY RATING: 2

REFERENCES: 15, 16

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 5

PROCESS: Fuel processing; conversion, enrichment, fabrication.

IMPACT CATEGORY: Occupational, O&M, chemical pollutants.

GENERAL DESCRIPTION: Increasing the ^{235}U content of fuel (enrichment) requires U_3O_8 concentrate to be converted to UF_6. This step is accomplished by hydrofluorination with HF and F_2. Process emissions contain fluorides.

Hydrogen fluoride is a known eye and lung irritant. Fluorosis and chronic fluorine toxicity can result in degenerative bone lesions and osteofluorosis.

QUANTITATIVE IMPACT ESTIMATE: Fluoride concentrations in forage in the vicinity of UF_6 production facilities have been measured as high as 10 ppm. The chemical hazard to humans from HF outweighs the radiological hazard of exposure to UF_6. Exposure to levels of HF exceeding 400 mg/m^3 for short time periods can cause death; 25 mg/m^3 can result in severe lung damage. The level of impact from accidental releases of large quantities of fluorine can be estimated by comparing it to the experience with chlorine. In four separate incidents in which chlorine releases between 15 to 30 tons were involved, a range of 7 to 60 fatalities has been recorded. A similiar level of impact might be expected from fluorine. The four incidents referred to occurred over a time interval of 50 years.[17] Estimates of 0.005 fatalities/1000 MWe-yr attributable to major fluorine releases.

MAJOR UNCERTAINTIES REQUIRING R&D: Accidents and explosions accompanied by fire in chemical process equipment could release hydrogen fluoride.

REGULATORY STATUS: 1977 threshold limit value for airborne fluorides in the workplace: 2.5 mg/m^3 for fluorine, 2 mg/m^3 as a time-weighted average.

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCES: 9, 17

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 6

PROCESS: Transportation requirements of the fuel cycle.

IMPACT CATEGORY: Occupational and public, O&M, accidents.

GENERAL DESCRIPTION: Transportation accidents occur over a range of frequency and severity. Most accidents occur at low vehicle speeds. Severe accidents generally involve some combination of impact, puncture, and fire. Even if the hazardous nature of the cargo is not a factor, accidents often result in injury. Transport requirements exist throughout the nuclear fuel cycle.

The general public and transportation workers are both at risk of transportation-related accidents. Accidents occur whether shipments contain hazardous materials or not, but accidents involving components of the nuclear fuel cycle contain toxic chemical and radiological health hazards as well.

QUANTITATIVE IMPACT ESTIMATE: Accident rates: truck $1.5/10^6$ km, rail $8.1/10^6$ km. To date there have been no injuries or deaths of a radiological nature due to the transportation of nuclear materials. The DOT estimates that 20 to 30 accidents involving transportation of nuclear materials occur each year. In 1972 injury rates were estimated for trucks at 0.65 injury and 0.03 death per accident; for rail transportation, 2.4 injuries and 0.26 death per accident. Estimated impact is 0.002-0.036 fatality and 0.14-0.45 nonfatal injury and disease occurrence per year per 1,000 MWe for transportation workers and 0.0003-0.002 fatalities for the public.

MAJOR UNCERTAINTIES REQUIRING R&D: Risk analysis of transportation requirements of the nuclear fuel cycle is based on theoretical hazards.

REGULATORY STATUS: Transportation of nuclear materials is subject to NRC regulations and to DOT hazardous materials regulations.

SEVERITY RATING: 2

UNCERTAINTY RATING: 1

REFERENCES: 14, 18-21

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 7

PROCESS: Reactor plant operations.

IMPACT CATEGORY: Public, O&M, radiation; occupational, O&M, accidents.

GENERAL DESCRIPTION: Routine operation of the reference power reactor requires a manpower level of 136 (LWR) or 146 (LMFBR) for operations and 79 for maintenance. Daily work activities related to operation, maintenance, and repair of the facility expose workers to a typical range of industrial accidents. The presence of nuclear materials presents an additional hazard. Release of such materials exposes the work force and general public to a continuous level of low-dose radiation.

QUANTITATIVE IMPACT ESTIMATE: Using the accident and disease incidence rates in Table 2.5, the in-plant occupational risks for 1000 MW-yr generation are 0.034-0.056 fatalities and 132-150 PDL. Estimated impact from routine emissions of radionuclides is on the order of 0.01-0.16 public fatalities and 0.024-0.1 occupational fatalities per 1000 MWe-yr.

MAJOR UNCERTAINTIES REQUIRING R&D: Specific accidental injury data occurring during routine plant operation, further experimental data relating low-level radiation exposure to disease states in humans.

REGULATORY STATUS: The Nuclear Regulatory Commission requires that no member of the public receive a radiation dose greater than 5 rem/yr from power plant emissions. Maximum permissible occupational dose for workers in nuclear facilities is 12 rem/yr.

SEVERITY RATING: 2

UNCERTAINTY RATING: 2

REFERENCES: 3, 4, 11, 12, 18, 20, 21

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 8

PROCESS: Reactor operations.

IMPACT CATEGORY: Public and occupational, O&M, catastraphic incidents.

GENERAL DESCRIPTION: Given the appropriate set of conditions, it is possible to conjecture situations in which an appreciable fraction of the radioactivity produced by a reactor would be released in an uncontrolled manner. Such an accident would cause the reactor core to melt down and release the contained radioactive components of the fuel.

Immediate and latent health effects (acute radiation sickness and eventual cancer deaths) would be expected as a result of a catastrophic accident at a nuclear facility.

QUANTITATIVE IMPACT ESTIMATE: Worst-case estimates for a single accident are 3,500 fatalities from acute radiation sickness and an eventual 45,000 cancer deaths. Such an accident has an estimated probability of occurrence of about once in a million plant-years (0.02-0.56 fatality/year).

MAJOR UNCERTAINTY REQUIRING R&D: Impact estimates are based on the small number of operational hours of experience with large power reactors.

REGULATORY STATUS: NRC reactor-licensing regulations specify safe operating procedures and conditions.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 20, 22

TECHNOLOGY: Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 9

PROCESS: Fuel reprocessing.

IMPACT CATEGORY: Public and occupational, O&M, low-level ionizing radiation.

GENERAL DESCRIPTION: The objective of nuclear fuel reprocessing is to recover plutonium (produced in the reactor) and unburned uranium for reuse in the fuel cycle. Activities within the reprocessing step can result in public and worker exposure to fission products.

Because of the nature and quantity of the material handled during fuel reprocessing, worker contamination with radioactive products is possible. Increased public and occupational exposure to such radiation would increase carcinogenic and genetic health risks.

QUANTITATIVE IMPACT ESTIMATE: Currently there are no operating fuel-reprocessing facilities in the U.S. However, estimates indicate that impacts from low-level radiation exposure would be approximately 0.006 death per year/1,000 MW for occupational exposures and 0.009 death per year/1,000 MW for public exposures.

MAJOR UNCERTAINTIES REQUIRING R&D: The extent of workplace exposure, especially during accidental radiation release, needs to be quantified. Future levels of facility operations are unknown.

REGULATORY STATUS: Processing plants are governed by NRC licensing procedures.

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCE: 18

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 10

PROCESS: Radioactive waste disposal.

IMPACT CATEGORY: General population and occupational delayed response to low-level radiation; long term risk during and after plant operation.

GENERAL DESCRIPTION: High-level wastes accumulate as a result of spent fuel storage or reprocessing. The principal hazard presented by disposal of material is that it may eventually contact and contaminate ground water, move through aquifers, and eventually reach drinking water supplies.

All segments of the population would be at risk from the hazard presented by leached radioactive-wastes and their potential carcinogenic action.

QUANTITATIVE IMPACT ESTIMATE: Duration times for hazards associated with radioactive wastes range from 10^3 to 10^6 years. Impacts are estimated at 0.006 occupational death/yr and 0.0003-0.001 public death/yr per 1,000 MW.

MAJOR UNCERTAINTY REQUIRING R&D: Ability to predict material or geological stability over containment times necessary for long-lived components.

REGULATORY STATUS: NRC regulations require conversion and storage of radioactive wastes and licensing of deep geologic repositories.

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCE: 23

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 11

PROCESS: Safeguarding of reprocessed fuel, diversion of fissile materials.

IMPACT CATEGORY: General population safety risk during plant operation.

GENERAL DESCRIPTION: Plutonium is a by-product of the reprocessing of spent nuclear fuel. Reactor-grade plutonium can be used to fabricate low-yield nuclear weapons. Airborne plutonium is also hazardous because of its recognized carcinogenic acivity.

It is generally accepted that an explosive device fabricated from diverted nuclear materials would have sufficient power to destroy a city block. A single large power reactor discharges annually enough plutonium to support the construction of about 100 explosive weapons on the order of 0.1 to 1 kiloton yield. Diversion of nuclear materials and their possible health consequences are not limited to the effects of nuclear explosives. The same constituents can also form the basis of radiological weapons that would not depend on blast effects for their impact. A finely-divided aerosol would also be an effective weapon due to the substantial toxicity of plutonium when inhaled and deposited in the lower respiratory tract.

QUANTITATIVE IMPACT ESTIMATE: Detonated within a modern skyscraper, an explosive device capable of destroying a city block could cause 50,000 civilian casualties through blast effect alone.

MAJOR UNCERTAINTY REQUIRING R&D: There is no concensus on the level of risk associated with unlawful diversion of reprocessed nuclear materials and their eventual criminal misuse.

REGULATORY STATUS: NRC safeguard procedures and regulations for processing of spent fuel are continuations of programs for improving security initiated by the Atomic Energy Commission (AEC).

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 15, 24

TECHNOLOGY: Liquid-Metal, Fast-Breeder Reactor

ISSUE: 12

PROCESS: Reactor operations; sodium metal coolant circuit requirement.

IMPACT CATEGORY: Occupational, O&M, accidents.

GENERAL DESCRIPTION: The liquid-metal, fast-breeder reactor depends on sodium (Na) metal in the liquid state for heat transfer from the reactor core. Na is highly efficient for this purpose; however it is also extremely active chemically and for various postulated initial conditions substantial fractions of the thermal energy would be converted to mechanical work capable of damaging the reator core and breaching the containment vessel. The LMFBR cooling circuit operates at temperatures above the spontaneous ignition temperature of Na in air and in the case of a spray fire due to the explosive introduction of Na into the surrounding atmosphere an uncontrolled burn could result. If exposed to liquid water or steam, as would be the case in a steam generator leak, it would react violently, releasing heat, hydrogen, and corrosive reaction products. Such an incident occurred at the Soviet test LMFBR BW350 in 1973 resulting in severe damage to the facility. A similar occurrence may have taken place in 1979 in the Soviet installation at Belogask. It has been reported that a fire occured at that facility and was not brought under control until "everything that could possibly burn was completely burned up" and in which several firefighters lost their lives while combatting the blaze.

QUANTITATIVE IMPACT ESTIMATE: In the one reported incident, several fire fighters were killed.[26]

MAJOR UNCERTAINTIES: Design features (reduced pressure, inert atmosphere) of the LMFBR reduce the likelihood of major consequences of failure in the primary coolant system. An LWR heat exchanger failures can be expected, but the severity of such a failure in the LMFBR remains to be quantified.

REGULATORY STATUS: Good engineering practice reduces the likelihood of coolant circuit failure to a minimum but not to zero.

SEVERITY: B

UNCERTAINTY: 3

REFERENCES: 25, 26

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 13

PROCESS: Direct and indirect component manufacture activities.

IMPACT CATEGORY: Occupational, construction, accidents and disease.

GENERAL DESCRIPTION: Large amounts of concrete, steel, and other conventional materials are needed for construction of nuclear reactors.

QUANTITATIVE IMPACT ESTIMATE: Total system capital costs, commodity subcategory percentages, and other relevant data are given in Table A.1 and A.2. Using procedures outlined in Sec. 2.2, occupational deaths from direct and indirect manufacturing are -0.69-1.03 (LWR) and 0.89-1.86 (LMFBR) total deaths per 1250 MWe capacity. Ranges in value were based on ±20% uncertainty for LWR and ±35% for LMFBR. Additional details of risk estimates results are given in Table A.3.

MAJOR UNCERTAINTY REQUIRING R&D: Precise evaluation of manpower demands of raw material acquisition.

SEVERITY RATING: 2

UNCERTAINTY RATING: 1

REFERENCES: 3, 4, 6

TECHNOLOGY: Light Water Reactor, Liquid-Metal, Fast-Breeder Reactor

ISSUE NO. 14

PROCESS: Plant construction.

IMPACT CATEGORY: Occupational, construction, accident and disease.

GENERAL DESCRIPTION: Reactor system on-site construction will require a substantial commitment of manpower. The construction trades have traditionally had higher than average injury rates compared to industrial operations in general. Activities related to the construction of a nuclear plant can be assumed to demonstrate injury rates comparable to those for other heavy-construction projects and industrial manufacturing operations.

QUANTITATIVE IMPACT ESTIMATE: Construction of a 1250 MWe LWR nuclear power plant is estimated to require 13.1 x 10^6 person-hours (14.50 x 10^6 for LMFBR) of on-site construction labor and 8.6 x 10^6 person-hours (11.5 x 10^6 for LMFBR) of indirect construction services (see Table A.1). Using procedures outlined in Sec. 2.2, total occupational construction fatalities are 2.00-3.17 (LWR) and 2.240-3.54 (LMFBR). Additional details of risk estimate results are given in Table A.3.

MAJOR UNCERTAINTY REQUIRING R&D: The actual nature of on-site operations for plant construction must be evaluated more precisely.

SEVERITY RATING: 2

UNCERTAINTY RATING: 1

REFERENCES: 3, 4, 6

APPENDIX C

COMBINED-CYCLE COAL SYSTEM: ISSUE IDENTIFICATION AND EVALUATION

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 1

PROCESS: Underground coal mining.

IMPACT CATEGORY: Occupational, O&M, disease.

GENERAL DESCRIPTION: Coal workers' pneumoconiosis (CWP) results after about about 15 years of coal dust buildup in the lungs. In progressive massive fibrosis (PMF), an advanced form of CWP, fibers are developed in the lung tissue as a reaction to the coal dust and continue to develop without further exposure to dust. A 1970 survey showed that 10% of miners had CWP and one-third of those had PMF.[36] The cold, damp conditions in mines are also associated with high rates of chronic bronchitis and emphysema.

QUANTITATIVE IMPACT ESTIMATE: In a review of recent studies of underground coal miner disease, 0.07 deaths/10^6 tons was taken as the best estimate with a range of 0-0.47.[31] In that study, the incidence of chronic respiratory disease in miners was suggested to be 12 times the number of deaths. Assuming these risks for the reference system with 1000 MWe annual average generation consuming 3.52 x 10^6 tons of coal, 75% of which is obtained from underground mines, it is estimated that there will be 0-1.2 deaths/yr and 0-14.9 incidences of chronic respiratory disease.

MAJOR UNCERTAINTIES REQUIRING R&D: Due to the long latency period for development of CWP and other mine-related health effects, the actual impact of recent regulations on coal dust levels is uncertain.

REGULATORY STATUS: The Federal Coal Mine Health and Safety Act of 1969 limits the average concentration of respirable dust in mine air to 2 mg/m^3. In 1969 the average dust concentration in U.S. mines was reported as 7 mg/m^3.[35]

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCES: 31, 35, 36

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 2

PROCESS: Underground and surface coal mining.

IMPACT CATEGORY: Occupational, O&M, accidents.

GENERAL DESCRIPTION: Physical hazards associated with underground mining operations, e.g., operation of heavy machinery, often in poorly lighted and confined areas; use of explosives; rock slides; roof falls; high-voltage electrical wiring.

QUANTITATIVE IMPACT ESTIMATE: The following incidence rates were obtained from Ref. 31:

Type of Incident	Number/10^6 tons
Underground Mining	
Deaths	0.36
Disabling Injuries	27.6
Surface Mining	
Deaths	0.10
Disabling Injuries	5.0

Assuming these risks for the 1000 MWe generation reference system consuming 3.52×10^6 tons coal per year with 75% obtained from underground mines and 25% from surface mines, it is estimated that there will be 0.94-1.16 fatalities/yr (including ±10% uncertainty) and 69-91 disabling injuries.

MAJOR UNCERTAINTIES REQUIRING R&D: Impact of large influx of new, inexperienced miners accompanying increased coal demand; increased mechanization; new mining techniques.

REGULATORY STATUS: Occupational safety regulations enforced by Mining Enforcement and Safety Administration under the Federal Coal Mine Health and Safety Act of 1969 as amended in 1977.

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCE: 31

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 3

PROCESS: Transportation of coal.

IMPACT CATEGORY: Public and occupational, O&M, accidents.

GENERAL DESCRIPTION: Coal electrical generation technologies require transport of large quantities of materials over distances ranging from less than a kilometer for mine-mouth plants to over 2000 kilometers for eastern plants using western coal. The most widely used transport mode is railroads, and their close proximity to populated areas creates public hazards at road crossings. Barge transport of coal is economically competitive with railroads and historically is less hazardous, but this mode of transport is also less extensive and accessible to various coal regions. Coal slurry pipelines are considered potentially the least hazardous per unit energy transported on the basis of similarities to oil pipelines; however the extent to which this transport mode will be used in the future remains uncertain.

The table below gives the 1970-1972 average deaths and injuries per ton mile and per train mile. It is interesting to note that there are about 100 employee nonfatal injuries for every death, whereas there are fewer than 3 nonemployee, nonfatal injuries for every death. This is probably an indication of the severity of grade-crossing accidents, where most of the nonemployee accidents occur.

Average Rate of Fatal and Nonfatal Railroad Injuries[a]

	No./10^9 tonne-km	No./10^6 train-km
Employee deaths	0.12	0.20
Employee injuries	12.3	20
Nonemployee deaths	1.4	2.3
Nonemployee injuries	3.6	5.9

[a]Based on accidents for freight trains and collisions between freight and passenger trains, 1970-1972 data (Source: Ref. 34).

For comparison, barge transport is estimated to result in 0.037 deaths and 3.6 injuries per 10^6 tonnes of coal transported, and for slurry pipelines, 0.0043 deaths and 3.92 injuries per 10^6 tonnes coal transported.[31] These figures are not broken down into employee and public impacts.

QUANTITATIVE IMPACT ESTIMATE: The reference CG/CC system consumes 3.20 million tonnes (3.52 million tons) of coal per year at an average output rate of 1000 MW. The average railroad coal shipment haul distance is reported to be 480 km (300 miles), and this is assumed appropriate for the reference system which uses eastern bituminous coal. Assuming 90% of shipments in the year 2000 are by rail and 10% by slurry pipeline gives 1.38 x 10^9 tonne-km by railroad and 0.32 x 10^6 tonnes by pipelines. Alternatively assuming unit trains of 100 cars (the average freight train is 60-70 cars) with 90 tonnes/car and a round trip of 960 km (600 miles) gives 0.34 x 10^6 train-km. Person days lost (PDL) per "last workday case" is assumed to be 14 for railroad workers and 19 for pipeline workers based on 1976 data.[6] For nonemployee injuries a higher value of 200 PDL per injury is assumed on the basis of greater severity of non-employment injuries as indicated by the fatal to nonfatal injury ratio. Pipeline injuries are assumed to be all employee-related.

Combining these assumptions, the estimates for annual injury rates from reference system coal transport are as follows, with the lower level based on train-km injury rates, and the higher values based on tonne-km rates:

Employee Fatalities	Employee PDL	Nonemployee Fatalities	Nonemployee PDL
0.07-0.17	98-240	0.78-1.9	28-70

MAJOR UNCERTAINTIES REQUIRING R&D: Accident rate estimates are adapted from haulage of all national railway freight and may vary according to train length, distance transported, population density along transport routes, and existence and maintenance of crossing-safety devices. For comparison, estimates of number of deaths from increased coal rail transport originating in less populated western areas are 8 deaths for 74.5 million tons of coal, or 0.38 deaths/3.52 million tons of coal required annually for the reference plant.[50] This estimate compares favorably with the lower estimate above, which includes round trips and is based on a national average.

REGULATORY STATUS: No regulations specific to coal transport.

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCES: 6, 31-34, 50

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 4

PROCESS: Plant operation: Exposure to carcinogens from coal preprocessing, gasification, gas cleanup, steam cycle.

IMPACT CATEGORY: Occupational, O&M, disease.

GENERAL DESCRIPTION: During plant operations there is a potential for: inhalation of fugitive emissions of gases and particulates formed in the gasification process; during maintenance, skin exposure to formed sludges and condensed products inside the components; during disposal, skin exposure to solid and liquid wastes that contain condensed or absorbed toxic substances.

POTENTIAL IMPACTS INCLUDE: CWP from coal dust; coal dust fires; cancers from inhalation and exposure to certain polynuclear aromatic hydrocarbons and nitrogen-containing compounds; toxicity and lung irritant effect of various sulfur, hydrocarbon, and trace element compounds.

QUANTITATIVE IMPACT ESTIMATE: Lack of experience with gasification systems makes estimation difficult. However, the following health effects were estimated for workers in a pilot coal-conversion plant from 1952 to the late 1960s:

> "In reporting the clinical effects in a group of 359 coal hydrogeneration workers who were examined regularly over a 5-year period, it was found that the exposure of these men varied from a few months to 23 years, and all of the (skin) lesions of significance were discovered in those workmen with less than 10 years exposure. ... the incidence of cancer in these men was between 16 and 37 times that reported in the literature."[40]

In 1976 the reported incidence rate of malignant skin melanoma in the total U.S. population of approximately 200 x 10^6 was 9300 cases, with 5000 deaths.[82] Assuming an upper bound of 25 times this rate for the coal system workers and 384 plant workers for 1000 MW average generation, a maximum of 0.2 fatalities and 0.4 total cases of skin cancer are estimated. Since the in-plant levels of carcinogens in a modern gasification plant may be expected to be significantly lower than those in pilot plants, a reasonable lower bound estimate is zero impact.

MAJOR UNCERTAINTIES REQUIRING R&D: In-plant concentration levels, synergistic effects of multiagent exposure, effects of long-term, low-level exposure.

REGULATORY STATUS: OSHA standards have been promulgated for the following materials known to be present in coal gasification plants: As, benzene, Be, Cd, CO_2, CS_2, Cr, H_2S, phenol, and V. Additional standards are anticipated.

SEVERITY RATING: 1

UNCERTAINTY RATING: 2

REFERENCES: 37-42, 82

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 5

PROCESS: Power plant operation, atmospheric pollutant emissions.

IMPACT CATEGORY: Public, O&M, disease.

GENERAL DESCRIPTION: Coal contains numerous noncarbon constituents in various concentrations. These constituents can be converted to gaseous forms during gasification and combustion phases and emitted from the stack. Of these, SO_x, NO_x, and particulates from ash have been the major focus of environmental control regulations, and for this issue analysis it is assumed that SO_x and NO_x are emitted at levels equal to those currently permitted in gases from fossil-fuel electrical generation plants. Particulates can be expected to be reduced to nearly negligible levels by the low-Btu gas-cleanup system. Production and emission of hydrocarbons classified as polycyclic organic material (POM) are of concern because of their toxic and carcinogenic properties;[44] however, emission levels have not been established for this type of process. Similarly, trace components of coal, such as Cd, Hg, As, and U may be emitted -- in particular, those such as Hg, which are volatilized and not collected with other particulates. However, the levels of emissions of these components and their possible pathways to humans are uncertain.

Airborne effluents from coal combustion have been associated with increases in both the incidence of new cases and the mortality from existing cases of emphysema, bronchitis, asthma, pneumonia, influenza, and malignant diseases. Sulfur emissions, particularly after atmospheric transformation to sulfates, have been shown to correlate statistically with increased mortality and morbidity, although the physical mechanisms of the impacts are not well understood. These correlations, as used in the quantitative impact estimates below, should be viewed as indicators of complex mechanisms involving other pollutants as well.

QUANTITATIVE IMPACT ESTIMATE: A recent study of a U.S. coal use scenario for the year 1990 projected 23,797,000 tons/year national SO_2 emissions from industrial and utility coal combustion. On the basis of an air pollutant dispersion model that includes long range transport and conversion of SO_2 to sulfates, 8,600-140,000 fatalities per year were estimated to result from coal emissions. The range of estimates is based on a 60% confidence level for the human dose-response relationship; uncertainty in the dispersion and exposure modeling is not included in this range.[31]

Assuming linearity, the 12,700 tons/yr SO_2 emissions from the 1000 MW generation by the reference coal system would result in an estimated 4-70 fatalities. It should be noted that the 90% confidence interval for the human dose response from reference[31] includes a minimum of zero fatalities/yr for the reference system. Also, the estimate of impacts is directly proportional to the assumed emission rates of SO_2, and further reductions in these emissions are technically feasible, although at added cost penalties.

MAJOR UNCERTAINTIES REQUIRING R&D: Characteristics and dose-response of specific pollutants emitted from combined-cycle plant, atmospheric transformation of pollutants, and effect of low-level exposures. The importance of individual dose response and impact resistance are also not well understood.

REGULATORY STATUS: The EPA has recently promulgated new standards[46] requiring 90% SO_2 control on a rolling monthly average basis for all fuels, with a maximum emission of 0.52 kg/10^9 J (1.2 lb/10^6 Btu), or 70% SO_2 control, with a maximum emission of 0.26 kg/10^9 J (0.6 lb/10^6 Btu). The particulate standard limits emissions to 0.013 kg/10^9 J (0.03 lb/10^6 Btu) and requires 99% reduction for solid fuels. The EPA also limits NO_x emissions to 0.26 kg/10^9 + J (0.6 lb/10^6 Btu) for bituminous coal and to 0.22 kg/10^9 J (0.5 lb/10^6 Btu) for gaseous fuel derived from coal.

SEVERITY RATING: 1

UNCERTAINTY RATING: 2

REFERENCES: 31, 44-46

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 6

PROCESS: Water pollutant effluents and solid waste from coal extraction and processing and plant operation.

IMPACT CATEGORY: Public, O&M, disease.

GENERAL DESCRIPTION: Effluents to public waterways and ground water result from coal mine drainage and seepage; runoff and leachates from coal storage piles, refuse piles, and surface-mine reclamation lands; blowdown from cooling towers and boilers; and discharge from metal cleaning, coal preparation, ash handling, and low-Btu gasification processes.[47]

The effluents potentially contain a large number of chemical constituents, which, when contained in domestic water supplies, could cause effects ranging from unpleasant odor and taste to toxic and carcinogenic effects. Of particular concern are chemical constituents of water in the coal gasifier, which are known to include carcinogens.[37-39]

QUANTITATIVE IMPACT ESTIMATE: A recent study of the water quality impacts for 22 pollutants from greatly increased coal use projected potential new surface-water quality standard violations or exacerbation of existing violations in many U.S. regions.[47] However, the projected increases in concentration due to coal use were small compared to existing concentrations. Technologies exist to control most pollutants at low levels, although control cost is an important factor.

MAJOR UNCERTAINTIES REQUIRING R&D: Dose-response information for estimating effects of low-level increases in water pollutants is generally not available. Estimates of effects from groundwater contamination are not available either.

REGULATORY STATUS: Water pollutants are controlled under the Federal Water Pollution Control Act, the Clean Drinking Water Act, the Toxic Substances Control Act, and the Resource Conservation and Recovery Act (solid waste disposal control). However, only a limited number of pollutants and technologies are currently regulated under these acts. In particular, federal guidelines for coal-gasification facilities and coal ash disposal have not been established.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 37-39, 47

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 7

PROCESS: Generating-plant operation; radioactive coal emissions.

IMPACT CATEGORY: Public, O&M, ionizing radiation continuous during plant operation.

GENERAL DESCRIPTION: Small quantities of ^{238}U, ^{235}U, ^{232}Th, and their radioactive daughter products occur naturally in coal. Average concentrations from various U.S. coals (799 samples) are 1.8 ppm for uranium and 4.7 ppm for thorium. Maximum measured values are 43 ppm for uranium and 48 ppm for thorium. The major portion of the radioactive products appears as a component of the ash during coal combustion or gasification and is either discharged through the stack or retained in the solid waste. Radioactive products may also be found in process water effluent from the gasifier.

Radionuclide exposure of humans occurs through inhalation of airborne particles, exposure from particles deposited on ground surfaces, water contamination from surface runoff of deposited atmospheric particles, leaching of solid wastes and radioactive plant effluents, and from ground deposits assimilated into the food chain. Radiation exposures may induce cancer deaths or genetic defects; however, the level of impact from the low levels anticipated from this source remain controversial. Principally at issue is the validity of extrapolation of known dose-response relations from higher levels of individual exposure.

QUANTITATIVE IMPACT ESTIMATE: Assuming 1 ppm uranium and 2 ppm thorium in the coal, 10% ash content, 0.5% emitted through a 300-m stack, and 0.38 kg coal/kWh, the population dose commitments within 88.5 km for a midwestern site from airborne releases at 1,000 MWe are estimated to be (rem/yr): whole body 1.4, bone 12.9, lung 1.4, thyroid 1.4, kidneys 2.4, liver 1.7, spleen 1.9. Assuming dose-response values given in Ref. 48, the above levels of whole-body irradiation would imply 0.0023 excess cancer death per year and 0.002 genetic defects per year in the surrounding population. An ash emission rate of 0.5% is conservative since the fuel gas is expected to be free of any particulate matter after its passage through the gas-cleanup system. Estimates of exposure from solid and aqueous effluents are not available.

MAJOR UNCERTAINTIES REQUIRING R&D: Effects of low-level radiation; leachate rate and fate of radioactive solid-waste constituents; exposure and impacts to populations beyond the 88.5 km radius considered in the referenced report.[48]

REGULATORY STATUS: No regulations for coal-fired plants. For comparison, NRC regulations are that no member of the public shall receive a radiation dose from light water nuclear reactors larger than 5 rem/yr to the whole body or 15 rem/yr to the thyroid.

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCES: 16, 48, 49

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 8

PROCESS: Direct and indirect material extraction, processing, and fabrication for process components.

IMPACT CATEGORY: Occupational, construction, accident and disease.

GENERAL DESCRIPTION: Significant quantitites of concrete, steel, and other metals and metal products are required for coal mining, transport, and processing and for plant construction.

Mining of raw materials (e.g., iron ore, coal used in steel manufacture), steel production, and component fabrication involve public and occupational health and safety risks from manufacturing emissions and transportation of products.

QUANTITATIVE IMPACT ESTIMATE: Total system capital costs, commodity subcategory percentages, and other relavent data are given in Tables A.1 and A.2. On the basis of procedures outlined in Sec. 2.2, occupational deaths from direct and indirect manufacturing are 0.1-1.08 total deaths per 1250 MW unit capacity. Ranges in value were based on ±20% uncertainty. Additional details of risk estimates are given in Table A.3.

MAJOR UNCERTAINTIES REQUIRING R&D: Estimates of component needs and of risk from component fabrication for gasification facilities have limited historical basis. Public risks from these activities are not included in the impact estimates above.

REGULATORY STATUS: Occupational health and safety regulations have been set for most conventional processes by OSHA and MESA. Regulations to control public exposure to emissions from conventional processes are promulgated by the EPA and related state organizations.

SEVERITY RATING: 2

UNCERTAINTY RATING: 1

REFERENCES: 6, 50

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUE NO. 9

PROCESS: General plant construction.

IMPACT CATEGORY: Occupational, construction, accidents and disease.

GENERAL DESCRIPTION: Physical hazards associated with major construction sites, e.g., work at high elevations, operation of heavy machinery, assembly of large unit components, high-voltage wiring.

QUANTITATIVE IMPACT ESTIMATE: Construction of a 1250 MW unit CG/CC is estimated to require 15.2 x 10^6 person-hours of on-site construction labor and 6.6 x 10^6 person-hours of indirect construction services. Using procedures outlined in Sec. 2.2, we estimate 2.59-4.05 total occupational construction fatalities per 1000 MW generation. Additional details of risk estimate results are given in Table A.3.

MAJOR UNCERTAINTIES REQUIRING R&D: Field labor requirements may vary from estimates, although experience in construction of related facilities minimizes the expected discrepancies.

REGULATORY STATUS: Construction site safety is regulated by OSHA standards.

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCES: 3, 4, 6

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine

ISSUES NO. 10, 11

PROCESS: Coal processing (10) and generation plant operation and maintenance (11).

IMPACT CATEGORY: Occupational, O&M, accident and disease.

GENERAL DESCRIPTION: Routine operation of the reference 1250 MW coal system requires a manpower level of 147 for operations and 189 for maintenance. Daily work activities related to operation, maintenance, and repair of the facility expose workers to a typical range of industrial accidents.

QUANTITATIVE IMPACT ESTIMATE: Using the accident and disease incidence rates in Table 2.5, the generation plant risks for 1000 MW-hr generation (Issue 10) are 0.066-0.105 fatality and 228-251 PDL. (Risks from exposure to potentially carcinogenic in-plant gasification products are considered separately in Issue 4). Occupational risks relating to the processing of 3.52 x 10^6 tons/yr of coal at this level of generation (Issue 11) are 0.073 fatalities and 4.6 disabling injuries.[31]

MAJOR UNCERTAINTIES REQUIRING R&D: Lack of experience with combined-cycle generation facilities.

REGULATORY STATUS: OSHA safety standards.

SEVERITY RATING: 10:2
11:2

UNCERTAINTY RATING: 10:1
11:1

REFERENCES: 3, 4, 6, 31

APPENDIX D

CENTRALIZED AND DECENTRALIZED TERRESTRIAL PHOTOVOLTAIC SYSTEMS: ISSUE IDENTIFICATION AND EVALUATION

TECHNOLOGY: Photovoltaic Power Systems

ISSUE NO. 1A

PROCESS: Raw-material extraction and processing for photovoltaic cells.

IMPACT CATEGORY: Occupational, construction, accidents, and disease.

GENERAL DESCRIPTION: Workers involved in extracting and refining silicon and doping agents for photovoltaic cells are exposed to hazardous materials and potential accident situations. Quartzite and sandstone extraction and silicon refining expose workers to large quantities of silicon dust, as well as to a high risk of accidents. Cd is recovered during Zn refining, Ga is a by-product of Al extraction from bauxite, and As is produced during Cu and Pb smelting. Workers involved in extraction and processing techniques that produce doping agents are at high risk of both accidents and exposure to refining acids and metal fumes.

Chronic exposure to silicon dust may result in silicosis, a disease which impairs respiratory function and predisposes victims to other respiratory diseases. Toxic impacts of exposure to Cd, Ga, As, and Pb include irreversible cardiovascular, renal, and neurological damage. Exposure to acids and their vapors used in metal refining can result in chemical burns and respiratory dysfunction.

QUANTITATIVE IMPACT ESTIMATE: No quantitative estimates are currently available; however, the relative risks of industries extracting and processing materials needed for photovoltaic cell production are among the highest of all U.S. industries:

Industry	Person Days Lost/ 100 Full-Time Workers[a]
U.S. -- All Industries	54-56
Lead and Zinc Mining	156-168
Nonferrous Primary Smelting	116-140
Nonferrous Costing	111-140

[a]Values for accidents and injuries, 1974-1975.

MAJOR UNCERTAINTIES REQUIRING R&D: The impact of increased production of photovoltaic materials on worker productivity and extraction and refining technology. Such changes could significantly affect occupational exposures to metals and increase the risk of accidents.

Material requirements for commercial-level production of photovoltaic cells have not been determined.

REGULATORY STATUS: OSHA standards regulate exposure of occupational populations to most gases, dusts, fumes, and vapors released during production of photovoltaic materials and also establish safety procedures to control accidents.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 6, 52, 54, 55, 75

TECHNOLOGY: Photovoltaic Power Systems

ISSUE NO. 1B

PROCESS: Raw-material extraction and processing for photovoltaic cells

IMPACT CATEGORY: Public, construction, accident and disease.

GENERAL DESCRIPTION: Production of raw materials for photovoltaic cells results in a release of atmospheric, aquatic, and solid waste products with potential adverse human health impacts. Specific releases vary with type of cell being produced. All cells currently considered for use consist primarily of silicon with p- and n-type dopants. Refining of silicon requires combustion of large amounts of coke with corresponding environmental releases of particulates and SO_x. Proposed dopants include phosphorus/boron, cadmium sulfide, and gallium aluminum arsenide. Production of Si and dopants releases significant quantities of cadmium, gallium, and silicon dust to the atmosphere and increases the potential for an aquatic discharge of cadmium and arsenic and other production-related trace metals such as copper, lead, selenium, and zinc.

Chronic exposure to silicon dust results in silicosis, a degenerative respiratory disease. Exposure to excess levels of trace metals results in a variety of physiological disorders ranging from emphysema to renal dysfunction to cancer. Many trace elements exhibit tendencies to accumulate through food chains, thus increasing the toxic potential at each trophic level.

QUANTITATIVE IMPACT ESTIMATE: Quantitative estimates of public health impacts from environmental releases of photovoltaic cell material during extraction and refining are not well established. Potentially significant releases include:

Atmospheric emissions: particulates, SO_x, NO_x, and HC

Aquatic effluents: NH_3 phenols, As, TSS, Cd, Cu, Pb, Se, Zn, and oil

Solid wastes: CdO, $ZnSO_4$, SiO, and Al_2O_3

MAJOR UNCERTAINTIES REQUIRING R&D: Impact of increased demand for photovoltaic cells on raw material extraction, refining and production techniques, and subsequent environmental emissions.

Human health effects and dose-response relationships of effluents from applicable raw material and refining technologies.

REGULATORY STATUS: Environmental releases of silicon dust, arsenic, and cadmium are controlled under Effluent Limitation Guidelines and New Source Performance Standards for quartzite, zinc, lead, copper and aluminum extraction and smelting industries.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 6, 52, 54, 55, 75

TECHNOLOGY: Photovoltaic Power Systems

ISSUE NO. 1C

PROCESS: Production of photovoltaic cells.

IMPACT CATEGORY: Occupational, construction, accidents and disease.

GENERAL DESCRIPTION: Production of silicon photovoltaic cells will expose workers to silicon dust, process chemicals, and doping agents including phosphine and boron trichloride. Proposed Cd/S and GaAlAs cell concepts have not progressed beyond bench-scale production techniques. Commercial-scale production may alter exposure significantly, but potential exists for worker exposure to silicon dust, SnO_x, $HFNO_3$, Cd/S, and GaAlAs, as well as acids and degreasing solvents.

Silicosis, a degenerative respiratory disease, is a well-documented effect of silicon dust inhalation. Exposure to cadmium fumes and dusts is known to cause pulmonary edema, emphysema, and hypertension. GaAlAs is a potential carcinogen. Other chemicals related to photovoltaic cell production may be equally toxic.

QUANTITATIVE IMPACT ESTIMATE: No quantitative impact estimates currently exist. Risk from exposure to materials used in photovoltaic cell production has been recognized, and occupational standards have been set for several production materials including silicon dust, phosgene, arsenic, and cadmium. Exposures may be kept to a minimum through design engineering and use of protective equipment.

MAJOR UNCERTAINTIES REQUIRING R&D: Commercial-scale production techniques and resulting worker exposure to toxic substances.

REGULATORY STATUS: OSHA standards have been set for many chemicals and materials of potential use in photovoltaic cell production.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 52, 54

TECHNOLOGY: Photovoltaic Power Systems

ISSUE NO. 1D

PROCESS: Production of photovoltaic cells.

IMPACT CATEGORY: Public health.

GENERAL DESCRIPTION: Production of photovoltaic cells involves toxic substances including silicon dust, SnO_x, $HFNO_3$, Cd, As, and Ga. Release of these toxic substances to the environment via atmospheric emissions, aquatic effluents, and solid waste during photovoltaic cell production poses threats to public health through direct exposure (inhalation, water ingestion). Some toxic photovoltaic substances (e.g., As, Cd) accumulate through food chains, thus increasing indirect exposure and potential adverse health impacts.

QUANTITATIVE IMPACT ESTIMATE: No quantitative estimates of the impact currently exist.

MAJOR UNCERTAINTY REQUIRING R&D: Potential for environmental release of toxic substances from photovoltaic cell production.

REGULATORY STATUS: No effluent standards currently exist for the photovoltaic industry.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 52, 54

TECHNOLOGY: Photovoltaic Power Systems

ISSUE NO. 2

PROCESS: Direct and indirect extraction, material processing, component fabrication.

IMPACT CATEGORY: Occupational, construction, accidents and disease.

GENERAL DESCRIPTION: Substantial amounts of conventional materials, e.g., aluminum, glass, steel, cement, and storage batteries (decentralized only) are required by photovoltaic power systems. Fulfilling these requirements involves extraction, refining, fabrication, and transportation of raw and finished goods as well as the use of large amounts of electricity.

Production of these materials for use in photovoltaic power systems will require significant numbers of workers in high-risk occupations such as mineral mining and primary and secondary metal production. Hazards more specific to photovoltaic cell production are discussed in Issue 1.

QUANTITATIVE IMPACT ESTIMATE: Total system capital costs, commodity subcategory percentages, and other relevent data are given in Section 3.3 and Tables A.1 and A.2. On the basis of procedures outlined in Sec. 2.2, occupational deaths from direct and indirect manufacturing are 0.17-0.36 total deaths per 200 MW centralized unit capacity and (1.05-2.20) x 10^{-5} total deaths per kW decentralized unit capacity. Ranges in value were based on $\pm$35% uncertainty. Additional details of risk estimate results are given in Table A.3.

MAJOR UNCERTAINTIES REQUIRING R&D: Conventional material and manpower requirements for photovoltaic central power systems.

REGULATORY STATUS: Most industries and processes contributing materials to photovoltaic central power systems will be regulated by one or more of the following: NSPS, OSHA, RECRA, TOSCA, CAA, and WPCA.

SEVERITY RATING: 2 (Centralized), 1 (Decentralized)

UNCERTAINTY RATING: 2

REFERENCES: 3, 4, 6, 53, 55, 83

TECHNOLOGY: Photovoltaic Power System

ISSUE NO. 3

PROCESS: Construction of centralized and decentralized systems.

IMPACT CATEGORY: Occupational, construction, health and safety.

Construction of photovoltaic power systems requires large amounts of manpower. Primary trades involved in construction include cement, electrical, roofing, sheet metal, and miscellaneous contracting.

GENERAL DESCRIPTION: Construction of photovoltaic power systems requires large amounts of construction and support service manpower in relation to other energy technologies. This is primarily due to relatively low load factors of 25.8% for centralized and 12.2% for decentralized).

Construction activities involve worker exposure to potential accident situations and to toxic chemicals. The types of exposures experienced during construction will be similar to those normally associated with each trade involved.

QUANTITATIVE IMPACT ESTIMATE: Construction of a 200 MW centralized unit is estimated to require 1.7×10^6 person-hours of on-site construction labor and 1.08×10^6 person-hours of indirect construction services. The 6 kW decentralized unit is estimated to require 96 hours of on-site construction labor. On the basis of procedures outlined in Sec. 2.2, total occupational construction fatalities are 0.31-0.48 per 200 MW centralized unit and $(1.23\text{-}2.05) \times 10^{-5}$ per 6 kW decentralized unit. Additional details of risk estimate results are given in Table A.3.

MAJOR UNCERTAINTIES REQUIRING R&D: Refinement of manpower requirements during the construction phase of photovoltaic central power plant. Characterization of hazardous material exposures of construction personnel.

REGULATORY STATUS: OSHA health and safety regulations will apply to construction site operation.

SEVERITY RATING: 2 (Centralized), 1 (Decentralized)

UNCERTAINTY RATING: 2

REFERENCES: 3, 4, 6, 53, 55, 83

TECHNOLOGY: Photovoltaic Power System

ISSUE NO. 4

PROCESS: Operation and maintenance of photovoltaic power systems.

IMPACT CATEGORY: Occupational, O&M, accidents and disease.

GENERAL DESCRIPTION: Daily operation and upkeep procedures, e.g., cleaning cell lenses, maintaining transformers and transmission lines, and repairing periodic system malfunctions (such as, array overheating) will result in health and safety risk to occupational personnel.

Major sources of health and safety impacts include physical trauma resulting from accidents occurring during routine operation and maintenance procedures and exposure to gases during episodes of array overheating and release of toxic doping agents (e.g., As, Cd, and Ga).

QUANTITATIVE IMPACT ESTIMATE: Routine operation of the reference 200 MW central solar unit is assumed to require a manpower level of 8.5 persons for operations and 17 persons for maintenance. According to the accident and disease incidence rates in Table 2.5, the generation plant risks for 1000 MW-yr generation (19.4 units) are 0.12-0.18 fatalities and 384-421 PDL.

Each decentralized 6 KW unit unit is assumed to require 3-9 hours of professional maintenance per year, or 2049-6147 person-years for the 1,370,000 units producing 1000 MW-yr/yr. According to the maintenance worker incidence rates in Table 2.5, the estimated annual impact from these units is 0.68-2.03 fatalities. Additionally, the decentralized units are expected to require storage battery replacement every 10 years. Using procedures outlined in Sec. 2.2, occupational deaths from direct and indirect manufacture of these batteries is 2.05-4.27 deaths ($\pm$35% uncertainty), or 0.205-4.27 deaths per year average per 1000 MWh generation.

MAJOR UNCERTAINTIES REQUIRING R&D: Manpower needs of operation and maintenance activities, potential for system malfunction.

REGULATORY STATUS: Exposure to toxic gases in centralized systems will be regulated by OSHA.

SEVERITY RATING: 1

UNCERTAINTY RATING: 2

REFERENCES: 3, 4, 6

TECHNOLOGY: Photovoltaic Power System

ISSUE NO. 5

PROCESS: Disposal or recycling of spent photovoltaic cells.

IMPACT CATEGORY: Occupational and public health, decommissioning, accidents and disease.

GENERAL DESCRIPTION: Photovoltaic central power stations are projected to have 30-year lifetimes. Photovoltaic cells are projected to have much shorter lifetimes as short as 10 years for silicon and GaAlAs cells, 5 years for Cd/S cells. 1,000 MW of GaAlAs cells will contain approximately 1.27×10^7 kg of GaAlAs polycrystal. 1,000 MW of Cd/S cells will contain approximately 9.8×10^5 kg of Cd/S. As a result, large amounts of potentially toxic Ga, As, and Cd will need to be recycled or disposed of during the lifetime of a power station.

Problems of disposal of inoperative cells may also become particularly acute for decentralized systems, which will be difficult to regulate because of their large numbers and small, dispersed nature.

Disposal or recycling of photovoltaic cells could pose Ga, As, and Cd exposure threats to workers dealing with spent cells via direct contact and inhalation of gas or particulates and to the public via leaching from disposal sites and subsequent bioaccumulation.

QUANTITATIVE IMPACT ESTIMATE: No quantitative impact estimates are currently available.

MAJOR UNCERTAINTIES REQUIRING R&D: Procedures and technologies for reuse or disposal of spent photovoltaic cells.

REGULATORY STATUS: RECRA regulations requiring "cradle to grave" maintenance of toxic substances will apply to toxic substances in photovoltaic cells.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 52, 54

APPENDIX E

SATELLITE POWER SYSTEM: ISSUE IDENTIFICATION AND EVALUATION

TECHNOLOGY: Satellite Power System

ISSUE NO. 1

PROCESS: Direct and indirect extraction, material processing, and fabrication activities.

IMPACT CATEGORY: Occupational and public, construction, accident and disease.

GENERAL DESCRIPTION: Significant quantities of conventional products (e.g., cement, steel, aluminum, copper, glass, and ceramics) will be required. Conventional assembly techniques are assumed. The incremental public and occupational health impacts of these requirements will be nonnegligible.

These commodity production impacts are proportionally higher than those for other systems because of the large fraction of system module construction that occurs off-site. On the other hand, on-site construction is lower as a result (Issue 2). Occupational hazards more specifically related to photocell production are discussed in Issue 3.

Acquisition of materials and components will require significant numbers of workers in high-risk activities such as primary metal production, mineral mining, and concrete production, with resultant incidents of injury and illness.

There is a potential for public health impacts from toxic air emissions, water effluents, and solid wastes generated during production of materials and components and transportation of raw materials and finished goods to launch and rectenna sites.

QUANTITATIVE IMPACT ESTIMATE: Total system capital costs, commodity, subcategory percentages, and other relavent data are given in Section 3.4 and Tables A.1 and A.2. On the basis of procedures outlined in Sec. 2.2, occupational deaths from direct and indirect manufacturing are 22.8-68.4 total deaths per 5000 MW unit capacity. Ranges in values were based on ±50% uncertainty. Additional details of risk estimates are given in Table A.3.

Public health impacts have not been quantified.

MAJOR UNCERTAINTIES REQUIRING R&D: System component needs and material requirements need better definition.

Changes in conventional processes, technologies, and emission controls may result from SPS demands.

REGULATORY STATUS: Occupational health and safety regulations have been set for most conventional processes by the Occupational Safety and Health Act (OSHA) and the Mining Enforcement and Safety Administration (MESA). Regulations to control public exposure to potentially dangerous emissions from conventional processes are promulgated by the U.S. Environmental Protection Agency (EPA) and related state organizations.

SEVERITY RATING: 1

UNCERTAINTY RATING: 2

REFERENCES: 1, 6, 56, 57, 61, 84

TECHNOLOGY: Satellite Power System

ISSUE NO. 2

PROCESS: Ground-based launch area operations and maintenance during construction, receiving antenna on-site construction.

IMPACT CATEGORY: Occupational, construction, accident and disease.

GENERAL DESCRIPTION: A major commitment of manpower is required to support activities at the space vehicle launch and recovery area. These activites include fueling, maintenance, cargo loading, and various scheduling and logistics operations.

Receiving antenna construction involves site preparation, antenna module base construction, and assembling modules and associated electrical power conditioning and distribution equipment. On-site antenna construction is minimizied by off-site manufacture of major modules (Issue 1).

QUANTITATIVE IMPACT ESTIMATE: During the 30-year construction phase for the 300 GW reference SPS system, the launch and recovery area is projected to require 3,800 person-yrs per year for maintenance activities and 2,600 for operations,[56] or an average per 5000 MW unit of 2100 person-years total for maintenance and 1400 for operations. According to the conventional operations and maintenance incidence rates in Table 2.5, the total impact per unit is 0.74-1.16 fatalities. Nonconventional hazards related to the launch and recovery areas are discussed in Issues 4-6.

Construction of a 5000 MW unit receiving antenna is estimated to require 15 x 10^6 person-hours of on-site construction labor. Using procedures outlined in Sec. 2.2, total occupational fatalities resulting from receiving antenna construction are 0.25-0.38. Additional details of risk estimate results are given in Table A.3.

MAJOR UNCERTAINTIES REQUIRING R&D: Specific labor requirements and associated hazards do not have an historical basis.

REGULATORY STATUS: OSHA Standards

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCES: 6, 56

TECHNOLOGY: Satellite Power System

ISSUE NO. 3

PROCESS: Material processing/fabrication; photovoltaic cell production.

IMPACT CATEGORY: Occupational and public, construction, accident and disease.

GENERAL DESCRIPTION: Production of silicon and gallium aluminum arsenide photovoltaic cells will result in potentially dangerous public and occupational exposure to silica dust, arsenic, gallium, sulfur oxides, and methacrylate doping agents. Atmospheric emissions of GaAlAs, arsenic-bearing particulates, and SO_2 may be a national pollution problem if GaAlAs cells are produced on a level needed for SPS use. Silicon production and cell fabrication will increase worker exposure to silicon, increasing the risk of silicosis, and to toxic doping agents, resulting in respiratory and carcinogenic effects.

QUANTITATIVE IMPACT ESTIMATE: It is estimated that approximately 156 kg of particulates and 459 kg of SO_x will be emitted during production of silicon for one MW of photovoltaic cells.[1] Sufficient data are not available for quantification of other emissions from GaAlAs cell production. Occupational exposure to toxic substances such as silicon dust may reach dangerous levels.

MAJOR UNCERTAINTIES REQUIRING R&D: Effectiveness of occupational exposure control measures during GaAlAs cell production. Impact of public health of emissions related to production of photovoltaic cells.

REGULATORY STATUS: OSHA regulations exist for toxic substances such as arsenic, cadmium, and silicon.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 1, 52, 54

TECHNOLOGY: Satellite Power System

ISSUE NO. 4

PROCESS: Transportation: material and personnel transfer from launch site to low earth orbit (LEO).

IMPACT CATEGORY: Public (catastrophic event potential), continuous risk during facility construction and operation and maintenance.

GENERAL DESCRIPTION: Malfunctions of propellant and navigational systems pose potential public health risks from explosion of fuels (liquid O_2, H_2, NH_4, hydrazine) during launch and from crash and/or explosion during flight and reentry of cargo and personnel vehicles.

QUANTITATIVE IMPACT ESTIMATE: Flash from explosion of heavy-lift launch vehicle (HLLV) fully fueled with liquid hydrogen is projected to cause first-degree burns at 300 m distance from explosion. Estimate of maximum deaths resulting from HLLV crash-and-burn scenario may exceed 1,000. Although approximately 400 HLLV flights, 30 personnel launch vehicle (PVL) flights, 30 cargo orbital transfer vehicle (COTV) flights, and 25 personnel orbital transfer vehicle (POTV) flights will be required per 5 GW of SPS capacity, current reference design projections include a very low probability for launch failure.

MAJOR UNCERTAINTIES REQUIRING R&D: Frequency potential for propellent and navigational system failure.

REGULATORY STATUS: No regulations currently applicable

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 1, 59-61

TECHNOLOGY: Satellite Power System

ISSUE NO. 5

PROCESS: Transportation: material and personnel transfer between launch site and low earth orbit (LEO).

IMPACT CATEGORY: Public, construction and O&M, noise exposure and atmospheric emission.

GENERAL DESCRIPTION: Noise impacts at both ascent and reentry may cause annoyance and nonprimary structural damage and may exceed ambient noise standards.

There is a potential for general population exposure to toxic levels of fuel emissions such as Al, hydrazine, NO_2, and CO from cargo and personnel transport vehicles.

Fuel exhaust may cause changes in the ionosphere and stratosphere such as ozone depletion leading to weather modification and increased radiation exposure and resulting health impacts, although current estimates project these effects to be small.[90]

QUANTITATIVE IMPACT ESTIMATE: 95 dBa sound pressure level (SPL) at 6 km from launch of HLLV, 65 dBa at 24 hour time-weighted concentration.

Overpressure level of sonic booms from ascent and reentry may cause nonprimary structural damage at distance of up to 185 km.

Emission concentrations in the ground cloud have not been quantified (would depend on fuel type and HLLV characteristics).

MAJOR UNCERTAINTIES REQUIRING R&D: Dispersion patterns and concentrations of toxic materials in launch ground cloud, impact of HLLV emissions on upper atmosphere.

REGULATORY STATUS: 70 dBa EPA day guideline, 50 dBa EPA night guideline; Committee on Toxicology has set recommendations for exposure to rocket propellant emissions.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 57, 59, 61, 62, 90

TECHNOLOGY: Satellite Power System

ISSUE NO. 6

PROCESS: Transportation: material and personnel transfer from launch site to low earth orbit (LEO) and from LEO to geosychronos earth orbit (GEO).

IMPACT CATEGORY: Occupational, construction and O&M, noise exposure and safety risks.

GENERAL DESCRIPTION: Conventional launch poses potential risk to workers from noise exposure and vehicle emissions. Explosion or fuel system malfunction creates a potential for physical, thermal, noise, and toxic-chemical exposure for terrestrial and space workers.

Malfunction of guidance and/or life-support systems in space poses physical risks to space workers.

QUANTITATIVE IMPACT ESTIMATE: HLLV spill/explosion episode would involve 850,000 gal of liquid hydrogen, with ignition of combustibles and first-degree burns at 300 m.

No quantification of in-transit system malfunction is currently available.

Sound pressure levels in launch area will exceed pain threshold (130 dB) during conventional launch.

MAJOR UNCERTAINTIES REQUIRING R&D: Identification of toxic exposure potential from used and unused fuels. Probability of malfunction of propellant, navigation, and life-support systems.

REGULATORY STATUS: Recommended exposure limits for rocket propellants by Committee on Toxicology and noise-exposure-limits regulation by OSHA.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 57, 60, 61, 63

TECHNOLOGY: Satellite Power System

ISSUE NO. 7

PROCESS: Construction: photovoltaic array, microwave transmission system in GEO and LEO.

IMPACT CATEGORY: Occupational, construction, accident and disease.

GENERAL DESCRIPTION: Absence of a life-supporting environment in space requires provisions for such needs as air, water, food, and shelter -- all subject to system failure.

High-energy heavy ions (HZE), electron-bremsstrahlung, excess ultraviolet radiation, and meteors are potential threats to personnel in space.

Limited social and recreational outlets, awareness of space-associated hazards, and weightlessness may affect the physiological and psychological health of workers.

QUANTITATIVE IMPACT ESTIMATE: No historical basis for quantitative estimates is currently available. However, throughout the 33 year, 60-unit construction phase, it is estimated that approximately 640 workers [200 in (low earth orbit) LEO, 440 in (geosynchronous earth orbit) GEO] will be in orbit in construction tasks, or approximately 352 person-years per 5 MW satellite. Current plans call for a 90-day maximum for workers to stay in space and a similar time period required for construction of each GEO satellite (see also Issue 8). Total elapsed time from implementation of material transport to LEO base construction to completion of GEO transmitting antenna is estimated to be 24 months per 5-GW station.

Assuming that the risks of space construction fall in the range between one of the most hazardous (coal mining: 0.068 fatalities and 211 PDL/100 person-years) and least hazardous (office workers: 0.003 fatalities and 28 PDL/100 person years) conventional occupations, the risk of constructing a unit 5 MW satellite is 0.011-0.24 fatalities and 99-743 PDL.

MAJOR UNCERTAINTIES REQUIRING R&D: Long-term impacts of exposure to radiation hazards in space, psychological reaction of contruction personnel to confines of life in space

REGULATORY STATUS: No regulations currently applicable.

SEVERITY RATING: 2

UNCERTAINTY RATING: 2

REFERENCES: 1, 6, 56, 57, 61

TECHNOLOGY: Satellite Power System

ISSUE NO. 8

PROCESS: Operation and maintenance: Space photovoltaic array, and microwave power transmission system in GEO and LEO.

IMPACT CATEGORY: Occupational, O&M, Electromagnetic radiation and accidents.

GENERAL DESCRIPTION: Diffraction and reflection of microwaves from transmission array and/or from leakage (e.g., structural failure, cracked waveguides) may result in excess thermal stress as well as biodysfunction. The impact of exposure to low-level microwaves is uncertain but of potential significance.

Physiological and mental stresses of life in space resulting from exposure to cosmic radiation (e.g., protons, alpha particles, HZE, and confinement of life-support quarters pose potential health risks to workers (see also Issue 6).

Assuming a range of risks for the orbiting crew as in Issue No. 7, the annual O&M impacts are 0.001-0.015 fatality and 6-48 PDL per year per 5 MW satellite. The impact of weightlessness (e.g., reduction of red cell mass, immunologic system changes, plasma volume decrease, loss of calcium from bones, and occurrence or threat of failure of life-support systems) increases psychological stress of workers in space (see also Issue 7).

QUANTITATIVE IMPACT ESTIMATE: Accidental microwave exposure in space could approach a power density of 2,400 mW/cm^2. The number of operation and maintenance personnel in space at any once time will be approximately 1360 (200 in LEO, 1160 in GEO) for 60 satellites. (Maximum stay in space will be 90 days).

MAJOR UNCERTAINTIES REQUIRING R&D: Effects of long-term low-level microwave exposure. Effects of exposure to space radiation hazards.

REGULATORY STATUS: OSHA standard for microwaves is 10 mW/cm^2 per 8-hr with no excursions > 25 mW/cm^2.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 6, 56, 57, 61, 85

TECHNOLOGY: Satellite Power System

ISSUE NO. 9

PROCESS: Operation and maintenance.

IMPACT CATEGORY: Public, O&M, electromagnetic radiation.

GENERAL DESCRIPTION: Populations outside of rectenna exclusion zone may be subject to low-level microwave exposure from grating lobes, reflection, and rectenna anomalies.

QUANTITATIVE IMPACT ESTIMATE: The effects of chronic exposure to low-level microwaves (< 1 mW/cm^2) at the operating frequency of 2.45 MHz are uncertain.

MAJOR UNCERTAINTIES REQUIRING R&D: Health effects of exposure to low-level microwaves.

REGULATORY STATUS: No current regulations applicable.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 1, 57, 61

TECHNOLOGY: Satellite Power System

ISSUE NO. 10

PROCESS: Operation and maintenance; receiving antenna, microwave reception, power transmission.

IMPACT CATEGORY: Occupational, O&M, electromagnetic microwave radiation.

GENERAL DESCRIPTION: There is potential risk to rectenna site workers from microwave dispersion and reflection at rectenna site due to atmospheric diffraction and rectenna anomalies and/or malfunctions.

Short-term exposure to of low-level microwave radiation may result in thermal stress.

QUANTITATIVE IMPACT ESTIMATE: Accidental exposures (e.g., power beam reflection) would result in maximum worker exposures somewhat less than the maximum power beam densities of 23 mW/cm^2. The effect of low-level, long-term microwave exposure to levels $<$ 1.0 mW/cm^2 is uncertain.

MAJOR UNCERTAINTIES REQUIRING R&D: Effects of long-term exposure to low-level microwaves.

REGULATORY STATUS: OSHA standard for microwave exposure is 10 mW/cm^2 per 8 hr weighted average, no excursions above 25 mW/cm^2.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 57, 61

TECHNOLOGY: Satellite Power System

ISSUE NO. 11

PROCESS: Ground-based launch and recovery area and rectenna operations and maintenance.

IMPACT CATEGORY: Occupational, O&M, accidents and disease.

GENERAL DESCRIPTION: Activities at the launch and recovery area will continue after the construction phase (Issue 2) in support of material and personnel transport for satellite maintenance.

Receiving antenna O&M activities include inoperational panel or other equipment, replacement, security, and operations.

QUANTITATIVE IMPACT ESTIMATE: The number of space vehicle launches during the O&M phase after all satellites are constructed are 46% of those during construction.[56] It is assumed that the operations and maintenance staff is reduced in the same proportion. With this assumption and others indicated in Issue 2, the annual launch area occupational impacts per 5 MW satellite are 0.010-0.016 fatalities and 33-38 PDL.

For each 5000 MW receiving antenna a maintenance staff of 9 persons and an operations staff of 10 persons is required.[56] Using incidence rates given in Table 2.5, the estimated annual impact per unit is 0.004-0.006 fatalities and 12-14 PDL.

MAJOR UNCERTAINTIES REQUIRING R&D: Specific O&M labor requirements and associated hazards do not have an historical basis.

REGULATORY STATUS: OSHA standards

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCES: 6, 56

TECHNOLOGY: Satellite Power System

ISSUE NO. 12

PROCESS: Operation and maintenance.

IMPACT CATEGORY: Public health, O&M, microwave radiation.

GENERAL DESCRIPTION: Excursion of power beam density beyond 23 mW/cm^2 reference system limit. Inadvertent or surreptitions focusing of beams outside of rectenna exclusion zone. It has been pointed out, however, that such redirection would be technically difficult according to the current reference concept in which the power beam could only be focused toward the origin of a pilot beam.[1] With this concept, the change in direction would require that a large transmitting antenna and high-power signal transmitter be constructed at the precise location where the beam is to be focused. The new transmitted pilot beam would have to simulate the original beam's code construction and transmit sufficient power to override the original signal. Furthermore, simultaneous failure or overriding of the ground monitoring system would be required to prevent detection of beam movement.

QUANTITATIVE IMPACT ESTIMATE: Limits on power beam densities (23 mW/cm^2) under the current reference system are based on theoretical atmospheric-heating constraints. OSHA standard (8-hr work day) is 10 mW/cm^2 with no excursions beyond 25 mW/cm^2.[85] Thermal effects in humans are noticeable at 100 mW/cm^2. The surface area of the power beam is 80 km^2.

MAJOR UNCERTAINTIES REQUIRING R&D: Reliability of system for directing and shutting down the beam, susceptibility of directional controls to redirection, theoretical 23 mW/cm^2 limit of power beam density. The reference system design has not been fully tested and thus its operational charcteristics are unknown. If major problems should be encountered, requiring redesign, the safety features could be affected. The combination of inherent safety in current design, but uncertainty in final design warrants a (B) severity rating for this issue.

REGULATORY STATUS: No regulations currently applicable.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 1, 61, 85

APPENDIX F

FUSION: ISSUE IDENTIFICATION AND EVALUATION

TECHNOLOGY: Fusion Power System

ISSUE NO. 1

PROCESS: Lithium ore extraction and processing.

IMPACT CATEGORY: Occupational, O&M, accidents.

GENERAL DESCRIPTION: Lithium extraction utilizes two techniques, open pit mining and brine pumping operations. The lithium concentration in the extracted product is in the range of 500 to 6,000 ppm; therefore ore processing is considered an integral part of the extraction process. These operations can be assumed to be similar to other industrial operations that utilize similar techniques such as uranium surface mine operations. As such, they can be expected to exhibit a similar accidental injury magnitude based on production levels.

QUANTITATIVE IMPACT ESTIMATE: On the basis of an annual estimated requirement of 3×10^5 kg of lithium for a power facility and an ore yield of 5%, assuming injury rates similar to the uranium processing industry, an estimated 0.0018 fatal and 0.0068 nonfatal injuries can be attributed to the annual lithium requirements of 1,000 MWe-yr fusion reactor operation.

MAJOR UNCERTAINTIES REQUIRING R&D: A more precise evaluation of the lithium extraction industry is required.

REGULATORY STATUS: Federal mine safety regulations cover operations such as those of surface mining.

SEVERITY: 3

UNCERTAINTY: 1

REFERENCES: 65, 75

TECHNOLOGY: Fusion Power System

ISSUE NO. 2

PROCESS: Direct and indirect component manufacture activities.

IMPACT CATEGORY: Occupational, construction, accident and disease.

GENERAL DESCRIPTION: Substantial industrial commitments will be required to supply the building materials and operating systems for fusion facility construction and maintenance. Accidents occurring in industries with a recognized involvement with these fusion requirements, such as cement and heavy machinery manufacturing, can then be attributed to the proven technology. Hazards more specific to fusion technology are considered in Issue 3.

QUANTITATIVE IMPACT ESTIMATE: Total system capital costs, commodity subcategory percentages, and other relevent data are given in Tables A.1 and A.2. On the basis of procedures outlined in Sec. 2.2, occupational deaths from direct and indirect manufacturing are 1.69-5.11 total deaths per 1320 MW unit capacity. Ranges in value were based on $\pm 50\%$ uncertainty. Additional details of risk estimate results are given in Table A.3.

MAJOR UNCERTAINTIES REQUIRING R&D: Industrial accident rates must be more specific to the actual requirements of fusion energy.

REGULATORY STATUS: Workplace safety is regulated by OSHA industrial safety standards.

SEVERITY RATING: 3

UNCERTAINTY RATING: 1

REFERENCES: 3, 4, 6

TECHNOLOGY: Fusion Power System

ISSUE NO. 3

PROCESS: Component fabrication.

IMPACT CATEGORY: Occupational, construction, disease.

GENERAL DESCRIPTION: Fabrication of a fusion reactor will require large quantities of refined metals for specific components. One such metal, beryllium, is known from industrial experience to be toxic and to be a cancer-causing agent. Construction of the first wall of the reactor could conceivably result in worker exposure to beryllium aerosols. Intermittent exposures to as little as 35 $^{mg}/m^3$ of Be for 6 months has experimentally induced lung cancer in 58% of a rat population. A similar concentration for 13 months resulted in 100% mortality to experimental rats.

QUANTITATIVE IMPACT ESTIMATE: The impact of worker exposure to beryllium during fabrication of a fusion reactor is not readily assessable. Since this metal is a recognized toxic agent, good industrial hygiene should insure that no worker contamination occurs. However, the potential for serious after-effects should be recognized in the event of inadvertent exposure.

MAJOR UNCERTAINTY REQUIRING R&D: The actual workplace experience that would be required to fabricate reactor components must be defined so that a more precise estimate of the potential of a beryllium hazard can be made.

REGULATORY STATUS: OSHA workplace standard for beryllium compounds: Threshold Limit Value (TLV) 0.002 mg/m^3.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 43, 72, 76

TECHNOLOGY: Fusion Power System

ISSUE NO. 4

PROCESS: Fuel preparation and handling.

IMPACT CATEGORY: Occupational, O&M, ionizing, radiation.

GENERAL DESCRIPTION: A fusion reactor will require a charge of tritium during initial start-up. After the start-up phase a continuous supply of tritium will be generated through a lithium-breeding reaction. The continuous handling requirement for fuel processing will result in occupational exposures to the radionuclide and present a potentially hazardous situation.

QUANTITATIVE IMPACT ESTIMATE: It is not possible to estimate the health impact of low-level workplace exposure to tritium at this time. Even though the radiological hazard of this radionuclide is relatively small it must be recognized as a possible source of radiation contamination.

MAJOR UNCERTAINTY REQUIRING R&D: The extent of exposure likely to occur as a result of tritium-handling activities.

REGULATORY STATUS: Standard radiological protection procedures.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 77, 78

TECHNOLOGY: Fusion Power System

ISSUE NO. 5

PROCESS: Fuel preparation.

IMPACT CATEGORY: Occupational, O&M, accident and disease.

GENERAL DESCRIPTION: Deuterium production by the girdler process requires hydrogen sulfide (H_2S) for deuterium separation. The toxic nature of H_2S is well documented. Good engineering practice and industrial hygiene will ensure that during normal operations the separation plant work place is protected from adverse H_2S exposure. However, in scaling up such operations, allowance must be made for mechanical failures resulting in very high exposure levels.

QUANTITATIVE IMPACT ESTIMATE: No impact estimates are available at this time, but they can be conjectured to be similar to those for other industrial operations requiring the use of toxic gases such as chlorine and hydrogen cyanide.

MAJOR UNCERTAINTIES REQUIRING R&D: The nature of unintentional serious exposures must be deferred to determine the seriousness of this hazard.

REGULATORY STATUS: OSHA workplace standard for worker exposure: TLV = 15 mg/m^3.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCE: 65

TECHNOLOGY: Fusion Power System

ISSUE NO. 6

PROCESS: Normal plant operations.

IMPACT CATEGORY: Occupational and public, O&M, ionizing and electromagnetic radiation.

GENERAL DESCRIPTION: A primary concern is over general population exposure to tritium (see Issue 4). A unique source of potentially adverse exposure for the plant work force is the high magnetic field associated with the plasma-containment requirement of the Tokamak design. The possibility exists for physiological reactions to such exposures.

QUANTITATIVE IMPACT ESTIMATE: Tritium has low radioactivity compared to most other radioactive nuclides. However large quantities of ^3H are involved in nuclear operations. The possibility that significant biological effects may result from chronic low-level exposure to ^3HOH is the main health concern regarding ^3H from nuclear fusion. However data for such exposures are largely unavailable. There continues to be a lack of agreement concerning tritium's relative biological effectiveness (RBE), although recent results give no indication that its RBE at low exposure levels appreciably exceeds four. Maximum ground-level dose downwind of the fusion plant: 1 rem/year. No quantitative estimate of the impact of high magnetic fields can be made at this time.

MAJOR UNCERTAINTIES REQUIRING R&D: Further clarification of the tritium dose term is needed. The biological effects of magnetic fields are being studied, but no information relating to fusion power is available.

REGULATORY STATUS: Maximum dose level allowed would be regulated by NRC standards for exposure.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 67, 68, 72, 89

TECHNOLOGY: Fusion Power System

ISSUE NO. 7

PROCESS: Normal plant operations.

IMPACT CATEGORY: Occupational, O&M, accidents and disease (other than radiation).

GENERAL DESCRIPTION: Routine operation of the reference 1320 MW fusion system is assumed to require the same manpower level as the LWR: 150 for operations and 90 for maintenance. Daily work activities related to operation, maintenance, and repair of the facility expose workers to a typical range of industrial accidents.

QUANTITATIVE IMPACT ESTIMATE: On the basis of the accident and disease incidence rates in Table 2.5, the generation plant risks for 1000 MW-yr generation are 0.034-0.055 fatality and 132-150 PDL.

MAJOR UNCERTAINTIES REQUIRING R&D: Specific operation and maintenance requirements for a commercial fusion system.

REGULATORY STATUS: None available.

SEVERITY RATING: 2

UNCERTAINTY RATING: 2

REFERENCES: 3, 4, 6

TECHNOLOGY: Fusion Power System

ISSUE NO. 8

PROCESS: Waste disposal, damage repair.

IMPACT CATEGORY: Public, O&M, ionizing radiation.

GENERAL DESCRIPTION: The severe environment of the interior of a fusion reactor results from the high temperatures and intense neutron flux required for operation. Materials subjected to such harsh conditions undergo degradation and require continuous replacement. Neutron bombardment will result in high levels of induced radiation in the components, requiring replacement, and will pose a significant radiation hazard to plant workers. Once replaced, the activated components must be disposed of in a fashion that will ensure that no residual radiological hazard exists. An average value of 180 + kg per year is estimated as the mass of neutron-activated reactor waste that must be disposed of for a single 1,000-MWe fusion facility.

QUANTITATIVE IMPACT ESTIMATE: It is not possible to assess the impact of fusion-activated waste. However, since the wastes are expected to be materials of a solid, nonvolatile nature, the radiological hazard for such waste products are anticipated to be less than those for nonfuel products of fission.

MAJOR UNCERTAINTIES REQUIRING R&D: More precise estimates of the radiological hazard will not be possible until an actual fusion design is evaluated. Only then will reasonable population-dose/commitment calculation be possible.

REGULATORY STATUS: NRC standards cover the handling and disposal of radioactive waste; the products of a fusion facility are not anticipated to require any unique regulatory action.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCE: 71

TECHNOLOGY: Fusion Power System

ISSUE NO. 9

PROCESS: Transportation of materials, fuels, and waste.

IMPACT CATEGORY: Public, O&M, accidents.

GENERAL DESCRIPTION: The fusion fuel cycle will be more closed than that for fission. The principal requirement will be for continuous replacement of lithium at roughly 130 + kg per 1,000 MWe. Since the lithium is nonradioactive, shielding would not be an issue for transportation; however, the cargo must be protected from exposure to air and water to keep the possibility of fire or explosion to a minimum.

QUANTITATIVE IMPACT ESTIMATE: An estimate of the possible impact to public safety can be made by assuming an accident impact for lithium transport similar to that for bulk fuels. Using such an approach the level of impact estimated would be on the order of 1.28×10^{-4} fatal and 1.1×10^{-3} nonfatal accidental injuries per 1,000 MWe/year.

MAJOR UNCERTAINTIES REQUIRING R&D: A more precise estimate is possible with further clarification of the actual yearly operating requirements for the fusion plant.

REGULATORY STATUS: The Interstate Commerce Commission (ICC) regulates interstate transit of dangerous materials. The lithium transportation requirements would be assumed under present regulatory action.

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCES: 75, 79

TECHNOLOGY: Fusion Power System

ISSUE NO. 10

PROCESS: Transportation of waste materials.

PROBLEM SOURCE: Public, O&M, ionizing radiation.

GENERAL DESCRIPTION: Because of the nonvolatile nature of the activation products, the general population dose associated with waste disposal requirements of a fusion facility should be less than those for a similar fission facility.

QUANTITATIVE IMPACT ESTIMATE: Impact estimates are not appropriate in the absence of more precise information concerning the disposal requirements of a fusion facility.

MAJOR UNCERTAINTIES REQUIRING R&D: The requirements for transport of waste from fusion facilities must be further evaluated.

REGULATORY STATUS: The radiologal hazard posed by transport of waste from fusion facilities should be covered by present NRC regulations on waste disposal.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 68, 72

TECHNOLOGY: Fusion Power System

ISSUE NO. 11

PROCESS: Operation and maintenance of reactor.

PROBLEM SOURCE: Occupational, O&M, accident and disease.

GENERAL DESCRIPTION: The energy content of an operating fusion reactor is estimated to be on the order of tens of thousands of gigajoules. The principal portion of this energy is contained in the circulating liquid lithium. However, other sources are the plasma itself, the vacuum in the reactor vessel, and the stored energy of the magnetic field. Primary concern is related to the possible instantaneous release of energy from any of these sources and the resulting damage to the operating system. It is estimated that a complete energy release for lithium would be equal to that of 1.5 million liters of fuel oil. Workers would be at risk from the ensuing explosive force, fire, and projectiles ejected from the failing subsystem.

QUANTITATIVE IMPACT ESTIMATE: A detailed quantitative estimate of accident consequences is not possible without more detailed reactor designs than are presently available.

MAJOR UNCERTAINTIES REQUIRING R&D: The probability and extent of consequences of hypothetical accident scenarios within an operating fusion power plant.

REGULATORY STATUS: None identified other than good engineering practice and OSHA workplace hazards regulations.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCE: 65

TECHNOLOGY: Fusion Power System

ISSUE NO. 12

PROCESS: Plant construction.

IMPACT CATEGORY: Occupational, construction, accidents.

GENERAL DESCRIPTION: Construction hazards of a fusion plant are assumed to be similar to those of conventional power plants.

QUANTITATIVE IMPACT ESTIMATE: Construction of a 1320 MW unit fusion plant is estimated to require 22.1×10^6 person-hours of on-site construction labor and 26.1×10^6 person-hours of indirect construction services. Using procedures outlined in Sec. 2.2, we estimated total occuapational construction fatalities to be 3.51 - 5.50. Additional details of risk estimate results are given in Table A.3.

MAJOR UNCERTAINTIES REQUIRING R&D: Future work force size and accident rates must be projected into the time frame of a year-2000 technology.

REGULATORY STATUS: No unique construction site requirements are known that would require workplace safety standards that are not presently in effect.

SEVERITY RATING: 3

UNCERTAINTY RATING: 2

REFERENCES: 3, 4, 6

TECHNOLOGY: Fusion Power System

ISSUE NO. 13

PROCESS: Plant deactivation.

IMPACT CATEGORY: Public and occupational, low-level ionizing radiation.

GENERAL DESCRIPTION: The possibility exists for significant levels of radiation to be released during decommissioning and subsequent dismantling of a fusion power plant. Exposure of members of the decommissioning team or general public can be hypothesized if proper precautions similar to those for fission plants are not observed. The activation inventory of the reactor is calculated to have levels on the order of thousands of curies and half-lives on the order of tens to hundreds of years. In light of these assumptions the most probable course of action would be for the plant to be mothballed or entombed so as to guarantee limited access to the potential radiation hazard.

QUANTITATIVE IMPACT ESTIMATE: No estimates are possible without more precise definitions of the fusion system and its operating characteristics.

MAJOR UNCERTAINTIES REQUIRING R&D: No information is available on the actual conditions a decommissioned fusion reactor would exhibit and from which human impacts could be inferred.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 66, 68, 80

TECHNOLOGY: Fusion Power System

ISSUE NO. 14

PROCESS: Catastrophic event potential.

IMPACT CATEGORY: Acute radiation exposure and continuous contamination of water supplies by toxic agents.

GENERAL DESCRIPTION: A general catastrophe sequence would involve explosive rupture of the fusion reactor vessel and release of its entire radioactive inventory. Other components of the reactor system would also be liberated into the surrounding air and water. Exposure of the general public to high levels of tritium could lead to increased incidence of cancer; a similar result could also occur from release of beryllium compounds in the first wall of the reactor.

QUANTITATAIVE IMPACT ESTIMATE: It is estimated that a critical dose of 4400 rem/Gw at 2 km from a maximum "Worst Case" accidental release would cause 4.6 deaths based on a population density of 1.5 x 10^4 persons/ km^2.[78]

MAJOR UNCERTAINTIES REQUIRING R&D: More detailed information is required on the types of failures possible under catastrophic situations and their potential impact on the general public.

REGULATORY STATUS: Regulatory aspects of a fusion facility would be expected to be similar to those for fission plants.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 65, 67, 68, 77, 78

REFERENCES

1. U.S. Department of Energy and NASA, *SPS CDEP Reference System Report*, DOE/ER-0023 (Oct. 1978).

2. Wolsko, T., *et al*., *A Methodology for the Comparative Assessment of the Satellite Power System (SPS) and Alternative Technologies*, DOE/ER-0051 (Jan. 1980).

3. Samsa, M.E., *Alternative Technolgies - Cost and Performance Review, DOE/NASA SPS Program Review*, Lincoln, Neb. (April 1980).

4. United Engineers and Constructors, *Satellite Power System and Alternative Technology Characterization*, UE&C-ANL-790831 (Aug. 1979).

5. Ritz, P.M., *The Input-Output Structure of the U.S Economy, 1972*, U.S. Dept. of Commerce, Survey of Current Business, *59*(2) (Feb. 1979).

6. *Occupational Injuries and Illnesses in the United States by Industry, 1975*, Bureau of Statistics, U.S. Department of Labor, Bulletin 1981, U.S. Government Printing Office, Washington, D.C. (1978).

7. *1972 Census of Manufactures*, Bur. of Census, U.S. Dept. of Commerce (Aug. 1976).

8. *Statistical Abstract of the United States, 1977*, Bur. of the Census, U.S. Dept. of Commerce (Sept. 1977).

9. Rhoads, R.E., and J.F. Johnson, *Risks in Transporting Materials for Various Energy Industries*, Nuclear Safety *19*(2):135-146 (March 1978).

10. Proc. 3rd Annual Illinois Energy Conference, University of Illinois (Sept. 1975).

11. Comer, C.L., and L.A. Sagan, *Health Effects of Energy Production and Conversion*, Ann. Rev. Energy *1*:581-599 (1976).

12. *Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy*, Report WASH-1224, Atomic Energy Commission, Washington, D.C. (1974).

13. *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation*, Report of the Advisory Committee on Biological Effects of Ionizing Radiation, Division of Medical Sciences, National Academy of Sciences, National Research Council (1972).

14. Council on Environmental Quality, *Energy and the Environment* (1973).

15. Cohen, B.L., *Impact of Nuclear Industry on Human Health and Safety*, Am. Scientist *64*:550-559 (Sept. 1976).

16. Cohen, B.L., *Conclusions of the BEIR and UNSCEAR Reports on Radiation Effects per Man-Rem*, Health Physics *30*:351 (1976).

17. Report by the Health and Safety Commission on the Hazards of Conventional Sources of Energy (1978).

18. U.S. Department of Energy, *Environmental Characterizations for Energy Technologies and End Uses*, Vol. 3, Characterization and Data in the Area of Nuclear and Coal Energy (Nov. 1978).

19. Department of Energy, *Shipments of Nuclear Fuel and Waste*, DOE/EV-0004/2, UC-71 (1978).

20. Cohen, B.L. and E.L. Lee, *A Catalog of Risks*, Health Physics, *36*:707-722 (1979).

21. AMA Council on Scientific Affairs, *Health Evaluation of Energy-Generating Sources: Council Report*, JAMA, *240*(20):2193-2195 (1978).

22. Study Group on Light Water Reactor Safety, American Physical Society, *Review of Modern Physics*, *47* (Suppl. 1) (1975).

23. Rochlin, G.I., *Nuclear Waste Disposal: Two Social Criteria*, Science *195*: 23-32 (Jan. 7, 1977).

24. Lovins, A.B., *Nuclear Weapons and Power Reactor Plutonium*, Nature, *283*: 817-823 (Feb. 1980).

25. Cochran, T.R., *The Liquid Metal Fast Breeder Reactor*, p. 171, John Hopkins University Press, Baltimore (1974).

26. Rich, V., *Fire Threatened Fast Reactor Cooling System, Editorial Nature*, *283*:420 (Jan. 1980).

27. Norwood, W.D., *Atomic Power Safety: A Common Sense Approach*, JAMA *221*(12):1392-1396 (1972).

28. U.S. Energy Research and Development Administration, *Conf. on Occupational Health Experience with Uranium*, ERDA 93 (April 1975).

29. Cralley, L.V., and J.P. Jewell, *Levels of Toxicity to Animals Provide Sound Basis for Fluoride Standards*, Envir. Sci. & Tech. *3*(8):721-730 (1969).

30. Harris, L.P., and R.P. Shah, *Energy Conversion Alternatives Study, General Electric Phase II Final Report*, Vol. 2, Part 3, NASA-CR Report 134949 (Dec. 1976).

31. *An Assessment of National Consequences of Increased Coal Utilization*, TID-29425, U.S. D.O.E. (Feb. 1979).

32. *Accident Bulletin No. 141*, Federal Railroad Administration, U.S. Department of Transportation (1972).

33. *Yearbook of Railroad Facts*, Association of American Railroads (1973).

34. Buehring, W.A., *A Model of Environmental Impacts from Electrical Generation in Wisconsin*, Ph.D. Thesis, U. of Wisc., Madison (1975).

35. Lee, D., *Coal Worker Pneumoconiosis--State of Knowledge and Research Needs*, J. Occupat. Med. *13*:183-192 (1971).

36. *Synopsis of the Work Proceedings, Spindletop International Conference on Coal Workers*, Arch. Environ. Health *21*:221 (1970).

37. Enviro. Control, Inc., *Recommended Health and Safety Guidelines for Coal Gasification Pilot Plants*, Environmental Protection Agency Report EPA-600/7-78-007 (Jan. 1978).

38. *Carcinogens Relating to Coal Conversion Processes*, TRW Energy Systems Report FE-2213-1 (June 1976).

39. Harper, W.C., *Experimental Carcinogenic Studies of Hydrogenerated Coal Oils, Fischer-Tropasch Oils*, J. Indust. Med. Surg., pp. 459-462 (Oct. 1956).

40. Ketcham, N.H., and W. Norton, *The Hazards to Health in the Hydrogeneration of Coal, III: The Industrial Hygiene Studies*, Arch Environ. Health *1*:194-207 (1960).

41. Sikles, J.E., II, et al., *Literature Survey of Emissions Associated with Emerging Energy Technologies*, EPA-600/7-77-104, Research Triangle Institute, Research Triangle Park, N.C. (1977).

42. Hamersma, J.W., and S.R. Reynolds, *Review of Process Measurements for Coal Gasification Process*, TRW Doc. 24916-6018-RU-00 (1975).

43. Groth, D.H., et al., *Carcinogencity of Beryllium Hydroxide and Alloys*, *Environmental Research*, *21*:63-84, 1980.

44. *Particulate Polycyclic Organic Matter*, National Academy of Sciences (1972).

45. Lundy, R.T., and D. Grahn, *Predictions of the Effects of Energy Production on Human Health*, Proc. Am. Statistical Assn. Annual Mtg., Chicago, Ill. (1977).

46. *New Stationary Source Performance Standards; Electric Utility Steam Generating Units*, Federal Register, *44*(113) June 11, 1979.

47. Chiu, S.Y., et al., *The Water Quality Impacts of Increased Coal Utilization*, Argonne National Laboratory Report ANL/EES-TM-74 (April 1979).

48. McBride, J.P., et al., *Radiological Impact of Airborne Effluents of Coal-Fired and Nuclear Power Plants*, Oak Ridge National Laboratory Report 5135 (1977), Triangle Park, N.C. (1977).

49. Swanson, V.E., et al., *Collection, Analysis, and Evaluation of Coal Samples in 1975*, U.S. Department of the Interior, Geological Survey, Open-File Report, 76-468 (1976).

50. *A Technology Assessment of Coal Slurry Pipelines*, Office of Technology Assessment, Congress of the United States (March 1978).

51. Kortman, P.J., et al., *SPS Comparative Assessment Technology Comparisons*, Energy Systems Group, TRW (Dec. 1979).

52. Gandel, M.G., et al., *Assessment of Large Scale Photovoltaic Materials Production*, Lockheed Missiles and Space Co. Report PB 272-064 (1968).

53. *Characterization of Residential Solar Photovoltaic Energy Systems*, Mittelhauser Corp., Downers Grove, Ill. (Feb. 1980).

54. U.S. Department of Energy, *Commercialization ERD/EDP: Photovoltaics*, OTI/OTA Dept. of Energy (1978).

55. Inhaber, H., *Risk of Energy Production*, Atomic Energy Control Board, Ottawa, Canada (1977).

56. Harron, R.J., and R.C., Wadle, *Solar Power Satellite Costs Estimate*, draft (Feb. 1980).

57. Poon, T.Y., et al., *Preliminary Examination of Satellite Power System Occupational Health Impacts*, Jet Propulsion Laboratory Report 900-820 Rev. A, Pasadena, Calif. (1979).

58. Jet Propulsion Laboratory, *Preliminary Satellite Power System Impacts and Benefits Study*, Pasadena, Calif. (March 1978).

59. Stephens, J.B., and R.B. Stewart, *Rocket Exhaust Effluent Modeling for Tropospheric Air Quality and Environmental Assessments*, National Aeronautics and Space Administration Report TR-R-473 (1977).

60. National Aeronautics and Space Administration, *NASA Environmental Impact Statement: Space Shuttle Program* (July 1977).

61. *Environmental Assessment for the Satellite Power System (SPS) Concept, Development and Evaluation Program (CDEP)*, U.S. Dept. of Energy, DOE/ER-0069 (August 1980).

62. Environmental Protection Agency, *Interim Guidelines on Air Quality Models*, Office of Air Quality Planning Report 1.2-080 (1977).

63. *Code of Federal Regulations*, 40CFR50.

64. *Nuclear Power and the Environment*, International Atomic Energy Agency, Vienna (1973).

65. Dingee, D.A., *Fusion Power: Special Reports*, Chem. Engineer. News, *19*:32-45 (April 2, 1979).

66. Electric Power Research Institute, *Capturing a Star; Controlled Fusion Power*, EPRI J. *2*(10):2-15 (1977).

67. Kulcenski, G.L., et al., *Energy for the Long Run: Fission or Fusion?* Am. Scientist *67*:78-89 (1979).

68. Post, R.F., and F.L. Ribe, *Fusion Reactors as Future Energy Sources*, Science *186*(4162):397-407 (1974).

69. Atomic Energy Commission, *Fusion Power: An Assessment of Ultimate Potential*, Div. of Controlled Thermonuclear Research, AEC, Wash 1239 (1973).

70. *NUWMAK, A Tokamak Reactor Design Study*, UWFDM-330, U. of Wisc., Madison, Wis. (March 1979).

71. Hafele, W., et al., *Fusion and Fast Breeder Reactors*, International Institute for Applied Systems Analysis, RR-77-8 (1977).

72. Strand, J.A., and Poston, T.M., *Biological Effects of Activation Products and Other Chemicals Released from Fusion Power Plants*, Battelle Northwest Laboratories, BNWL-20-23 (1976).

73. *Proc. of the Biomagnetic Effects Workshop*, Lawrence Berkeley Laboratory, LBL-7452 (April 6-7, 1978).

74. *The Biological Effects of Magnetic Fields; a Bibliography*, Los Alamos Scientific Laboratory, LA-7723-MS (March 1979).

75. *Work Injury and Illness Rates*, National Safety Council (1978).

76. Atomic Energy Commission, *Project Independence, Nuclear Energy*, Task Force on Nuclear Energy, Federal Energy Administration, AEC (1974).

77. *Tritium in the Environment*, NCRP Monograph #62 (1979).

78. Holdren, J.P., *Environmental Considerations of Fusion Power*, presented at the Symposium, The Prospects of Fusion as a Commercial Energy Source, January 8, 1980.

79. *National Energy Transportation*, Congressional Research Service, pub. 95-15, U.S. Senate (1977).

80. Easlerty, C.E., *ORNL Health Physics Annual Report*, Oak Ridge National Laboratory, ORNL-5171 (1976).

81. *Reactor Safety Study: An Assessment of Accident Risks in U.S Commercial Nuclear Power Plants*, Nuclear Regulatory Commission Report WASH-1400, Washington, D.C. (1975).

82. *Ca-A Cancer Journal for Clinicians*, American Cancer Society, *26*:1 (Jan., Feb. 1976).

83. *Requirements of Photovoltaic Power Plants in Electric Utility Systems*, EPRI ER-685, Vol. 1, 2, 3, (June 1978).

84. *SPS System Definition Study*, Phase II, Vol. IV, Tech. Anal. Dept. D180-25461-4, Boeing Aerospace, Seattle, Wash. (1979).

85. American Conference of Governmental Industrial Hygienists, *Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment*, ACGIH (1977).

86. Federal Power Commission, *FPC News*, *9*(43):23,27 (Oct. 22, 1976).

87. Hutt, P., *Unresolved Issues in the Conflict between Individual Freedom and Government Control of Food Safety*, Ecotoxicol. Environ. Safety *2*: 447-469 (1978). The estimates of risk in this reference are derived from *Wilson: Direct Testimony Before the Occupational Safety and Health Administration*, OSHA Docket No. H-090 (Feb. 1978).

88. *An Integrated Assessment of Increased Coal Use in the Midwest: Impacts and Constraints*, Argonne National Laboratory Report ANL/AA-11 (Oct. 1977).

89. Dowson, R.L., *Low-Level Chronic Exposure to Tritium: An Improved Basis for Hazard Evaluation*, In Biological and Environmental Effects of Low-Level Radiation, Vol. I, Proc. Symp., Chicago, 3-7 Nov. 1975, IAEA-SM-202/304, pp. 57-62 (1976).

90. Rote, D.M., K.L. Brubaker, and J.-L. Lee, *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program: Atmospheric Effects*, U.S. Department of Energy Report, in press (Sept. 1980).

BIBLIOGRAPHY

Accidents and Unscheduled Events Associated with Non-Nuclear Energy Resources and Technology, Environmental Protection Agency EPA 600/7-77-016, EPA, Washington, D.C. (1977).

Assistant Secretary for Environment, *Coal Extraction and Preparation*, Department of Energy Environmental Readiness Document, Department of Energy (1978).

Baldewicz, W., et al., *Historical Perspectives on Risk for Large-Scale Technological Systems*, UCLA-ENG-7485, University of California at Los Angeles (1974).

Bridbord, C., *Carcinogenic and Mutagenic Risks Associated with Fossil Fuels*, NIOSH, Rockville, Md. (1976).

Buechley, R.W., et al., *SO_2 Levels and Perturbations in Mortality*, Arch. Environ. Health *27*(3) (Sept. 1973).

Ehrenberg, L., and G. Lafroth, *A Review of Current Progress, Basic Problems, and Available Technologies: Impact on Human Health*, presented at Conf. on Impacts and Risks of Energy Strategies: Their Analysis and Role in Management, Stockholm, Sweden, 1978.

Energy, the Environment, and Human Health, AMA Congress on Environmental Health, Acton, Mass. (1974).

Frigerio, N.A., K.F. Eckerman, and R.S. Stowe, *The Argonne Radiological Impact Program (ARIP), Part I. Carcinogenic Hazard from Low-Level, Low-Rate Radiation*, ANL/ES-26, Part I (Sept. 1973).

Gotchy, R.L., *Health Effects Attributable to Coal and Nuclear Fuel Cycle Alternatives*, U.S. Nuclear Regulatory Commission NUREG-0332 (1977).

Gregor, J., *Intra-Urban Mortality and Air Quality: An Economic Analysis of the Costs of Pollution Induced Mortality*, Environmental Protection Agency Report 600/5-77-009 (July 1977).

Hamilton, L.D., and S.C. Morris, *Health Effects of Fossil Fuel Power Plants*, presented at 8th Midyear Topical Symp. of the Health Physics Soc., Oct. 21-24, 1974, Brookhaven National Laboratory Report BNL-19265 (1974).

Hamilton, L.D., ed., *The Health and Environmental Effects of Electricity Generation--A Preliminary Report*, Brookhaven National Laboratory Report BEAG-HE/EE 12/74 (July 1974).

Handy, R., and A. Schnindlev, *Estimation of Permissible Concentrations for Continuous Exposure*, Environmental Protection Agency Report EPA/600/2-76-155, RTI (June 1976).

Health Consequences of Sulfur Oxides -- a Report from Chess 1970-1971, Environmental Protection Agency Report EPA 650/1-74-004 (1974).

Electric Power Research Institute, *Health Effects of Nitrogen Oxides*, EPRI 571-1A (Feb. 1976).

Electric Power Research Institute, *Health Effects of Selenium*, EPRI-571-1A (Feb. 1976).

Health, Environmental Effects, and Control Technology of Energy Use, Proc. EPA/ORD/OEMI Conf., Feb. 9-11, 1976, Washington, D.C.

Herrera, G., ed., *Assessments of RD&D Resources, Health and Environmental Effects, O&M Costs, and Other Social Costs for Conventional and Terrestrial Solar Electric Plants*, Jet Propulsion Laboratory Report 900-782 (Jan. 1977).

Hittman Associates, Inc., *Environmental Impacts, Efficiency, and Cost of Energy Supply and End Use*, Report HIT-593 (1974-1975).

Hub, K., et al., *Social Costs for Alternative Electrical Power Generation for 1980 and 1990*, Argonne National Laboratory Report ANL-8082 (1973).

Hub, K., *Preliminary Assessment of Health and Environmental Impacts of FBC of Coal as Applied to Electric Utility System*, Argonne National Laboratory Report ANL/EES-TM-7 (1977).

Hub, K.A., and R.A. Schlenker, *Health Effects of Alternate Means of Electrical Generation*, International Atomic Energy Agency, IAEA-SM-184/18 (May 1974).

Impact of Coal Mine Health and Safety Research, Bureau of Mines, U.S. Department of Interior (1977).

Jaksch, J.A., et al., *Outpatient Medical Costs Related to Air Pollution in the Portland, Oregon Area*, Environmental Protection Agency, Report EPA 600/5-74-017, Oregon State University (July 1974).

Kornreich, M.R., *Coal Conversion Processes: Potential Carcinogenic Risk*, MITRE Corp., Report MTR-7155 (March 1976).

Lave, L.B., and L.C. Freeburg, *Health Effects of Electricity Generation from Coal, Oil and Nuclear Fuel*, Nucl. Safety *14*:409-428 (1973).

Lave, L.B., and E.P. Seskin, *Air Pollution on Human Health*, John Hopkins University Press, Baltimore, Md. (1977).

Liv, B., and Y. Siu-hung, *Air Pollution Damage Functions and Regional Damage Estimates*, Techomic Press, Westport, Conn. (1977).

Liv, B., et al., *Physical and Economic Damage Functions for Air Pollutants by Reception*, EPA-600/5-76-011, MRI (Sept. 1976).

Loyd, J.W., *Long-Term Mortality Study of Steelworkers, V. Respiratory Cancer in Coke Plant Workers*, J. Occup. Med. *13*(2):53-67 (1971).

Energy Research and Development Administration, *Annual Environmental Analysis Report*, Vol. 4, Office of Environment and Safety, ERDA (Sept. 6, 1977).

Morris, S.C., *Comparative Effects of Coal and Nuclear Fuel on Mortality*, Draft report, Brookhaven National Laboratory (1977).

Nuclear Power and Its Fuel Cycle, Proceedings of an Internat. Conf. on Nuclear Power and its Fuel Cycle held by Internat. Atomic Energy Agency in Salzburg, Austria, May 2-3, 1977, Vol. 7.

Occupational Injuries and Illnesses in the U.S. by Industry, 1975, Bureau of Statistics Bulletin 1981, Department of Labor, (1978).

Ramsay, W., and Milton Russel, *Time Adjusted Impacts from Electricity Generation*, Public Policy *26*(3) (1978).

Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, Nuclear Regulatory Commission Report WASH-1400, Washington, D.C. (1975).

Sagan, L.A., *Health Costs Associated with the Mining, Transport, and Combustion of Coal in the Steam Electric Industry*, Nature *250*:107-111 (1974).

Safety Statistics--1976, Safety Department, Ontario-Hydro, Toronto, Canada (1977).

Salmon, E.J., *Comparative Assessment of Health, Safety, and Environmental Impacts of Coal Use*, for DTA/OTI, draft, Department of Energy (1978).

Sexton, R.J., *Hazards to Health in the Hydrogeneration of Coal*, Arch. Environ. Health *6* (1960).

Smith, K.R., J. Weyant, and J.P. Holdren, *Evaluation of Conventional Power Plants*, Energy and Resources Program Report ERG 75-5, University of California, Berkeley, Calif. (1975).

Smith, L., *Manpower Requirements for Construction of Various Solar Plants*, Jet Propulsion Laboratory Report 342-76-13-905 (1976).

United Nations Scientific Committee on Effects of Atomic Radiation; Sources and Effects of Ionizing Radiation: Report to the General Assembly, United Nations (1977).

☆U.S. GOVERNMENT PRINTING OFFICE: 1981-341-060/368