

# **HEALTH AND SAFETY: PRELIMINARY COMPARATIVE ASSESSMENT OF THE SATELLITE POWER SYSTEM (SPS) AND OTHER ENERGY ALTERNATIVES**

April 1980

**U.S. Department of Energy**  
Office of Energy Research  
Satellite Power System Project Division

**DOE/NASA**

SATELLITE POWER SYSTEM  
Concept Development  
and  
Evaluation Program

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Under Contract No. 31-109-ENG-38

Prepared for:

**U.S. Department of Energy**  
Office of Energy Research  
Satellite Power System Project Division  
Washington, D.C. 20545

## **DOE/NASA**

SATELLITE POWER SYSTEM  
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## ACKNOWLEDGMENTS

Grateful acknowledgment for direction and support in the development of this report is given to F. Koomanoff, director of the DOE SPS Project Office; M. Riches, DOE project officer for the SPS Comparative Assessment; and T. Wolsko, ANL project manager for the SPS Comparative Assessment. The authors also express their appreciation to L. Doak, A. Harris, and B. Salbego for typing the manuscript, and to J. Korn, M. Koelbl, and L. Samek for preparation of the drawings.

Acknowledgment is also due to the following reviewers who provided valuable suggestions through a formal review of the draft manuscript; 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.

## DEFINITIONS OF UNIT SYMBOLS

Btu:	British thermal unit
Ci:	curie (unit of radioactivity: $3.7 \times 10^{10}$ disintegrations per second)
cm:	centimeter
dBa:	decibel (adjusted)
gal:	gallon
GHz:	gigahertz ( $10^9$ cycles per second)
GW:	gigawatt ( $10^9$ watts)
J:	joule
keV:	kiloelectron-volt
kg:	kilogram
kW:	kilowatt
kWh:	kilowatt hour
lb:	pound
m:	meter
meV:	millielectron-volt
mg:	milligram
ml:	milliliter
mW:	milliwatt
MW:	megawatt
MWe:	megawatt (electric)
$\mu$ Ci:	microcurie
$\mu$ g:	microgram
ppm:	part per million
rem:	roentgen equivalent, man (unit of ionization - i.e., tissue damage - due to radiation)
V:	volt
W:	watt
yr:	year

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## 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 is to generate information from which rational 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. Environmental issues concern the health and safety risks associated with energy systems, and the SPS and four alternative electrical generation systems are assessed here with regard to such risks. This report presents the results of an initial phase of the health and safety assessment.

The approach developed and used in this assessment is intended to provide information useful for decision making. Data readily available from the literature were used to make an initial comparison of the health and safety risks of a fission power system with fuel reprocessing; a combined-cycle coal power system with a low-Btu gasifier and open-cycle gas turbine; a central-station, terrestrial, solar photovoltaic power system; the satellite power system, and a first-generation fusion system. The 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 (3) the rating of each issue with regard to known or potential impact level and level of uncertainty. Evaluation of unquantifiable issues 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 descriptions of each issue. The last component provides the basis for the evaluation.



Table 1 summarizes the results of this evaluation in terms of expected deaths per year associated with 1,000 MW of electricity generation averaged over a 30-year plant lifetime. This table also contains the number of issues identified as being potentially significant but unquantifiable because of lack of information.

When the systems are compared directly by total quantifiable deaths per year, systems in a more advanced stage of development generally exhibit higher impact or risk levels. The usefulness of this straightforward comparison, however, is limited by the uncertainties of poorly quantified or unquantified impacts. The quantified impacts of the terrestrial photovoltaic system and the satellite power system are more uncertain than those of the coal and light water reactor systems. The major quantified impacts of the

Table 1. Quantifiable Health and Safety Impacts and Number of Potentially Major but Currently Unquantifiable Issues<sup>a</sup>

Category	Expected Deaths per Year, 30-Year Plant Lifetime				
	Fission Energy System	Coal System	Terrestrial Photovoltaic System	Satellite Power System	Fusion Energy System
Total	0.65(3)	5.84(2)	1.46(2)	0.31(4)	0.004(4)
Public	0.55(3)	3.70(1)	0.03(2)	- (4)	- (1)
Occupational	0.10(2)	2.14(1)	1.43(2)	0.31(1)	0.004(4)
Long Term	0.65(1)	5.75(2)	1.33(1)	- (2)	0.0002(2)
Intermed.Term <sup>b</sup>	- (-)	0.92(-)	0.13(2)	0.31(2)	0.004(1)
Short Term (Catastrophic)	- (2)	- (-)	- (-)	- (1)	- (1)
Accidents	0.25(3)	4.30(-)	1.43(1)	0.3 (2)	0.004(1)
Disease	- (-)	1.54(2)	0.03(2)	0.01(3)	- (1)
Radiation	0.39(3) <sup>c</sup>	0.0023(-) <sup>c</sup>	- (-)	- (1) <sup>d</sup>	- (2) <sup>c</sup>

<sup>a</sup>Numbers of potentially major but unquantifiable issues in parentheses.

<sup>b</sup>Occurring during raw material extraction, processing, fabrication for component production, and system deactivation. Estimates are plant lifetime total for 1,000-MW generation.

<sup>c</sup>Ionizing radiation.

<sup>d</sup>Microwave radiation.

terrestrial photovoltaic system are projected to occur mainly during construction and maintenance of the large arrays of solar collectors; however, no historical precedents for such activities exist. In addition, the SPS and fusion systems, which have the lowest level of quantifiable impacts, have the largest number of unquantifiable issues.

Similarly, when the systems listed in Table 1 are compared on the basis of quantifiable public (non-occupational) impacts, a higher level is again estimated for the more developed or near-term technologies. However, the number of unquantifiable public impacts is greatest for fusion and the satellite power system and least for coal energy systems.

For the impacts of component production and facility construction, averaged over a 30-year plant lifetime, the solar technologies have the greatest impact because of their larger labor requirements compared to those of the coal and light water reactor technologies.

It may be unrealistic to evaluate catastrophic events in terms of an averaged death risk per year of plant operation because the significance of such events is perceived differently by the public. A major factor in the determination of the future viability of a new technology may be the real or perceived potential for the occurrence of a catastrophic event even though the more continuous, low-risk hazards may be minor. Therefore, this assessment treats the potential for catastrophic events in a separate evaluation; because of the large uncertainty in the estimates of impacts from catastrophic events, these issues are included in the list (Table 2) of unquantifiable issues.

Results of this first phase of the health and safety assessment will be used in the second phase, which will include the evaluation of cumulative health and safety impacts of the alternative technologies within an energy scenario. This analysis will account for the effects of achievable load factors for the technologies and will include analyses of health and safety impacts from required back-up and storage systems. The second phase will also reassess the assumptions on which first-phase analyses were based, and revisions to the estimates will be made on the basis of additional information. A further extension will be the analysis of a decentralized or small-scale electric energy technology.

Table 2. Potentially Major but Unquantifiable Health and Safety Issues

System	Currently Unquantifiable Issues	Potential Catastrophic Events
Satellite Power System	Exposure to emissions of photovoltaic cell production Exposure to emissions and noise from space transport vehicles Exposure to electromagnetic radiation from microwave transmission Inadvertent, acute exposure of a population to the microwave beam	Malfunction of heavy-lift launch vehicle
Combined-Cycle Coal System	Occupational exposure to toxic substances and carcinogens during plant operation and maintenance Long-range transport of atmospheric pollutants	
Light Water Reactors with Fuel Reprocessing	Exposure to HF and F <sub>2</sub> during fuel conversion, enrichment, and fabrication	Core meltdown, radiation release during plant operation Subversive use of fuel and wastes
Terrestrial, Photovoltaic, Central-Power Stations	Exposure to emissions from photovoltaic cell production Exposure to toxic substances from photovoltaic cell recycling and disposal	
Fusion System	Exposure to toxic substances during component fabrication Exposure to H <sub>2</sub> S during fuel preparation Liquid metal fires, system failure during plant operation	High-level radiation exposure from malfunction of operational system

## ABSTRACT

The work reported here is an analysis of existing data on the health and safety risks of a satellite power system and four electrical generation systems: a combined-cycle coal power system with a low-Btu gasifier and open-cycle gas turbine, a fission power system with fuel reprocessing, a central-station, 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 and on the number of health and safety risks that are identified as potentially significant but unquantifiable. The appendices provide more detailed information on risks, uncertainties, additional research needed, and references for the identified impacts of each system.

## 1 INTRODUCTION

Among the more important considerations in a comparative assessment of the SPS and alternative systems are the impacts of these technologies on human health and safety. This assessment is being conducted in two phases, and this report presents the results of the preliminary phase. The objectives of this preliminary phase were as follows:

- (1) To develop a taxonomy for the comparative assessment and a format for presenting information in a manner useful for comparing the health and safety impacts of the Satellite Power System (SPS) and alternative technologies. The taxonomy and format are described in Sec. 2.
- (2) To conduct a preliminary assessment of the SPS and four alternative energy systems by organizing available information using this taxonomy and format. The energy systems considered are a light water fission reactor (LWR) with fuel reprocessing, a combined-cycle coal system (CG/CC) with a low-Btu gasifier and open-cycle gas turbine, a central-station, terrestrial photovoltaic system (TPV), and a first-generation fusion system with deuterium-tritium fuel and a lithium blanket. Assessment of additional technologies and revisions to these technologies will be part of the second phase of the assessment. The health and safety impacts for the individual systems are discussed in Sec. 3, and the impacts of the systems are compared in Sec. 4.
- (3) To identify those aspects of health and safety impact definition that will require analysis and research so that more definitive comparisons of the technologies can be made. These aspects of the assessment are discussed in Sec. 3 and listed in the appendices.

In addition to providing an initial comparison of health and safety impacts, this assessment will provide input to a forthcoming second-phase assessment that will be more comprehensive. For example, the preliminary

assessment focuses on the identification of death risks, whereas the second phase will also evaluate person-days lost through nonfatal accidents and disease. A major objective of the second phase should be the evaluation of the cumulative health and safety impacts of the alternative technologies for national energy scenarios. That analysis should account for the effects of achievable load factors for the technologies and include an analysis of the health and safety impacts of required back-up and storage systems.

The estimates of health and safety impacts compiled in this preliminary assessment rely heavily on other studies. A subsequent phase of this assessment should consider in more detail the assumptions on which these analyses were based, and revisions to the estimates should be made on the basis of additional information.

## 2 APPROACH

The major components of the health and safety assessment are discussed in this section. The components described are the identification and categorization of major health and safety issues (Sec. 2.1) and the assignment of ratings of impact severity and uncertainty for each issue (Sec. 2.2).

### 2.1 ISSUE IDENTIFICATION AND CATEGORIZATION

The first step in issue identification and categorization 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. 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 are major components of the solar technologies considered in this report.

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 used in overall technology assessments and comparisons. This link will facilitate the subsequent phase of the assessment that will include more detailed and updated analyses of major issues.

Issue categorization is 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

Table 2.1. Format for Issue Identification and Evaluation<sup>a</sup>

Evaluation Component	Description
TECHNOLOGY	Light water reactors, combined-cycle coal, 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, and deactivation.
IMPACT CATEGORY	Categorization of issues along dimensions given in Table 2.2.
PROBLEM SOURCE	Description of factors or conditions producing health or safety risk.
HEALTH AND SAFETY IMPACT	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 requiring further research and analysis that would provide a definitive issue evaluation or risk quantification.
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.

<sup>a</sup>See appendices.

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.



Table 2.2. Categorization of Health and Safety Issues

Categorization Component	Description of Categories
Persons Affected	The general public Energy-related workers
Impact Duration and Rate	Intermediate term, moderate level (e.g., occurs during component raw material extraction, processing and transport; component fabrication; plant construction; or plant deactivation) Long-term, low-level (e.g., occurs during fuel extraction, plant operation and maintenance, waste disposal, or waste management) Short-term, high-level (e.g., catastrophic events)
Impact Cause	Accidents Disease (e.g., chemical pollutants causing disease through toxicity or carcinogenesis) Radiation (ionizing radiation and nonionizing radiation from microwaves)
Impact Severity	Fatalities Person-days lost (nonfatal accidents and disease)

Catastrophic events (defined in this study as single events 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 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 viability 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 Sec. 4, but the final comparison must be reserved for the decision maker who will use formal or informal decision analysis to evaluate issues in terms of a broad set of perceived societal objectives.

## 2.2 INDICES OF SEVERITY AND UNCERTAINTY

The principal measure of the severity of health and safety impacts is the estimate 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. By separating the hazards that are quantifiable and clearly defined from those that are of potential significance but are currently unquantifiable, the rating system helps to focus the SPS evaluation on the most significant issues. The index of uncertainty is a subjective measure based on the verifiability of the cause-effect relationship that determines the impact and on the degree of reliability of the impact estimate for each health issue. 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). Table 2.4 defines the uncertainty ratings.

In addition to defining severity ratings for quantifiable impacts, the rating procedure in Table 2.3 also applies to issues that are unquantifiable. These issues are rated largely on the basis of a qualitative understanding of the potential hazards, for which impact data are not 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

Table 2.3. Index of Severity of Health and Safety Impacts

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

Table 2.4. Index of Uncertainty of Health and Safety Impacts

Causal Relationship and Impact Level	Uncertainty Index	Severity Rating Options
Causal relationship and impact levels relatively well established (e.g., coal mining accidents)	1	1,2,3
Established but poorly quantified causal relationship (e.g., low-level ionizing radiation)	2	1,2,3
Cause-effect association established, but extremely variable impact level estimates (e.g., ground water pollution, catastrophic events)	3	A,B

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,<sup>1</sup> 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. 2.1, 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.

The uncertainty assigned to each severity rating 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

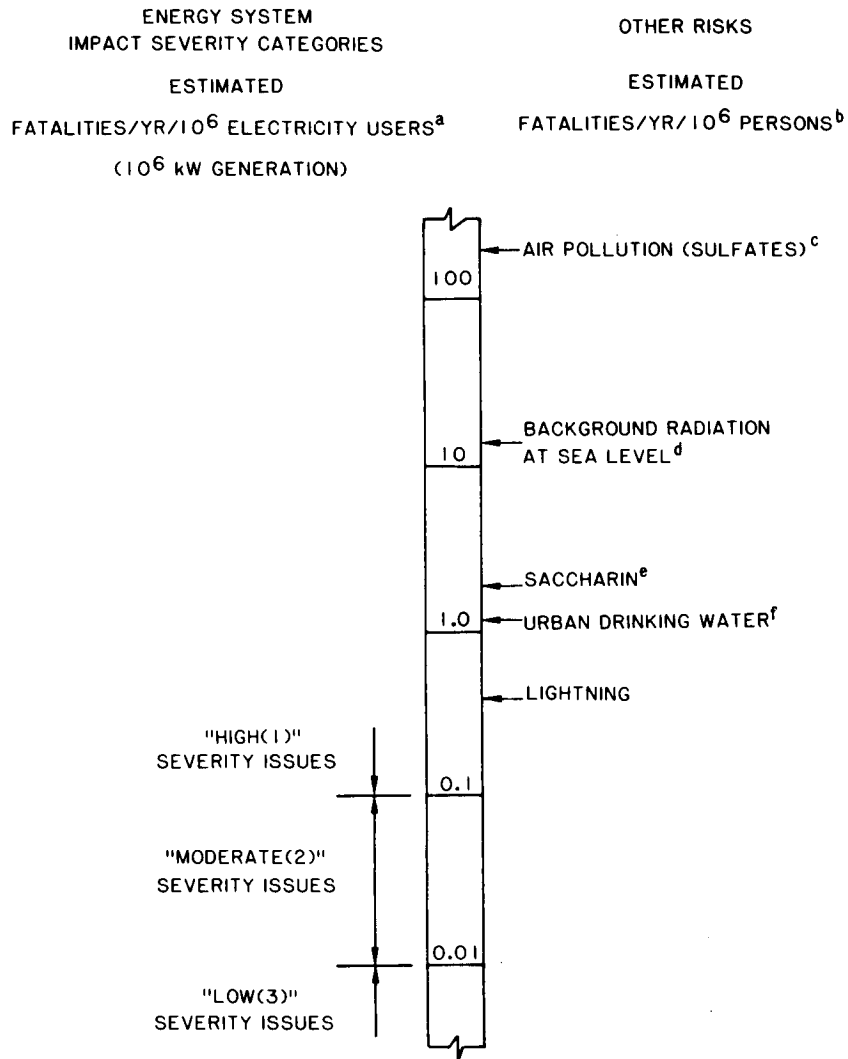


Fig. 2.1. Impact Severity Categories for Energy System Health and Safety Issues in Comparison to Risks from Other Causes

- a) Estimated fatalities from electrical generation do not necessarily occur within user group.
- b) From Ref. 2.
- 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.

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 between existence of the hazard and the occurrence of resulting impacts 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 unquantifiable or extremely variable.

### 3 INDIVIDUAL ENERGY SYSTEM ASSESSMENTS

This section summarizes the results of the issue identification and evaluation for each of the five technologies considered in the preliminary evaluation: light water reactors, combined-cycle coal system, centralized, terrestrial photovoltaic system, satellite power system, and fusion. Each technology is described briefly; more detailed characterizations are being developed in another component of the SPS Comparative Evaluation Program,<sup>3</sup> and the descriptions in this report are subject to change in the final assessment on the basis of those characterizations.

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 represent the most compact and easily comprehensible summary 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 whether an impact is continuous (occurring more or less uniformly over the lifetime of the plant) or short term (occurring over relatively short periods such as during plant construction or as the result of catastrophic events). Also included are a summary of the impact quantification and a description of uncertainties in the impact definition or quantification.

The issue descriptions and evaluations in the appendices provide the most detailed analysis of the issues for each technology, including citation of data sources.

#### 3.1 FISSION POWER SYSTEM WITH FUEL REPROCESSING

##### 3.1.1 System Description<sup>4</sup>

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. Reprocessing involves dissolving the spent fuel in aqueous acid, followed by a series of solvent extractions and ion exchange operations that remove fission products and separate the plutonium from the uranium and then purify the two products. The two advantages of reprocessing are the conservation of fuel resources and reduction of the volume of waste to be isolated.

For this study a 1,000-MWe boiling water reactor is used. Additional design parameters relevant to the study include:

Overall efficiency	33%
Unit lifetime	30 years
Uranium ( $UO_2$ , enriched)	129 metric tons (31 metric tons replaced, 1 metric ton consumed)
Emissions	
$^3H$	16,900 Ci
$^{85}Kr$	290,000 Ci
$^{133}Xe$	580 Ci

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

### 3.1.2 Summary of Health and Safety Issues

The major health and safety issues identified are illustrated in Fig. 3.2 and summarized in Table 3.1. The nuclear fuel cycle, as it pertains to electrical power generation, carries a set of health and safety risks both for workers and for the general population.<sup>5,6</sup> 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 requirements of a 1,000-MWe light water reactor are on the order of 0.334 fatal injury per year from physical hazards and 0.005-0.134 fatality per year attributable to ionizing radiation exposure.<sup>7</sup>

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.<sup>8</sup> 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

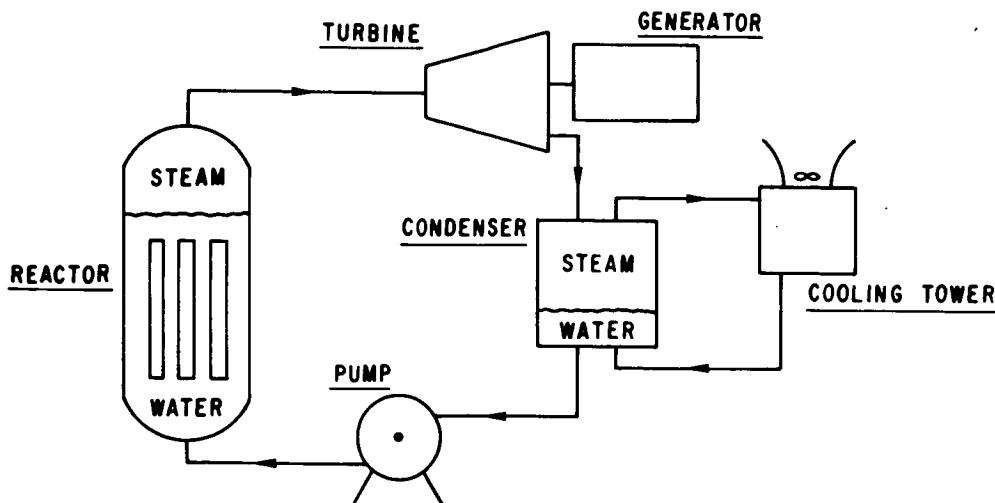


Fig. 3.1. Light Water Reactor



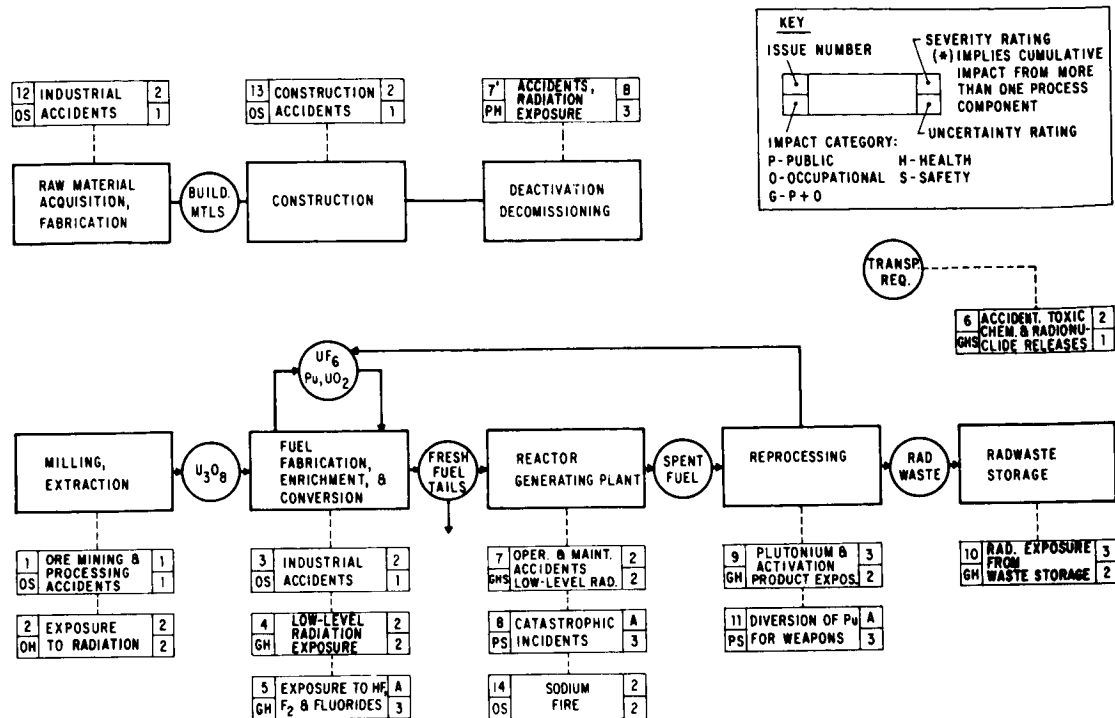


Fig. 3.2. Flow Diagram of Health and Safety Issues of the Light Water Reactor Power System with Fuel Reprocessing

and power plant operation. Injuries in these processes result from the usual array of industrial accidents.

Materials transport is required in all steps of the nuclear fuel cycle. Since the transportation mode is primarily by truck with some rail 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.<sup>9</sup>

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).<sup>10</sup> The Biological Effects of Ionizing Radiation report<sup>11</sup> gives estimates of low-level radiation effects in terms of cancer deaths and eventual genetic defects. These estimates predict  $180 \times 10^{-6}$  cancer deaths per rem and  $150 \times 10^{-6}$  genetic defects per rem of whole-body population exposure and are used to predict the delayed effects of the nuclear fuel cycle.

Table 3.1. Issue Summary for Light Water Reactors with Fuel Reprocessing

Issue	Process	Impact Category			Impact Quantification/ 1000 MW	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Continuous				
1. <sup>a</sup> Accidental injury.	Ore extraction and U <sub>3</sub> O <sub>8</sub> milling.	X	X	X	0.05 - 0.2 deaths/yr.	1	Future use of lower-grade ore will require larger mining and milling operations.	1
2. <sup>b</sup> Lung cancer as a result of exposure to radon and other decay products of natural uranium.	Ore extraction and U <sub>3</sub> O <sub>8</sub> milling.	X	X	X	0.001 - 0.1 fatalities/yr.	2	Exposure levels prior to establishment of standards are not known precisely. Effectiveness of ventilation for the removal of <sup>222</sup> Rn.	2
3. <sup>c</sup> Accidental injury.	Raw material acquisition and fabrication, U <sub>3</sub> O <sub>8</sub> conversion, UF <sub>6</sub> enrichment, UO <sub>2</sub> fabrication, Reactor operations, construction, decommission.	X	X	X	0.003 - 0.2 fatalities/yr.	2	Occupational accident potential for nuclear fuel preparation.	1
4. <sup>d</sup> Low-level radiation exposure.	U <sub>3</sub> O <sub>8</sub> conversion, UF <sub>6</sub> enrichment, UO <sub>2</sub> fabrication.	X	X	X	Occupational: 0.013 - .033 deaths/yr, public 0.0003 deaths/yr.	2	Generic to all segments of the fuel cycle; the actual human response to low-level exposures is hypothetical.	2
5. <sup>e</sup> Exposure to HF, F <sub>2</sub> .	U <sub>3</sub> O <sub>8</sub> conversion, UF <sub>6</sub> enrichment, UO <sub>2</sub> fabrication.	X	X	X	Possible severe injury or lung damage, osteofluorosis from continuous exposure.	A	Possible high level exposure from industrial mishaps; Population response to excess fluorides.	3
6. <sup>f</sup> Accidental injury possible; radiation hazard and chemical toxicity from UF <sub>6</sub> spill.	Transportation.	X	X	X	0.002 - 0.036 occupationally-related deaths/yr; 0.01 public deaths/yr.	2	Transport distances and modes; trip frequencies.	1

Sources: a12; b11; c13; d7,14; e12; f13,15-18.

Table 3.1. (Cont'd)

Issue	Process	Impact Category			Impact Quantification/ 1000 MW	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Short Term				
7.8 Low-level radiation hazard, accidents.	Reactor operation (Issue 7). Decommission (Issue 7').	X	X	X	Public risks: ~0.05 fatalities/yr. Occupational impact: ~0.024 fatalities/yr from accidents.	2(7) B(7') low-level radiation.		2(7) 3(7')
8. h Acute and delayed effects.	Core melt down, Catastrophic accidents, Worst case.	X		X	~3,500 acute fatalities; ~45,000 eventual deaths/incident (= 0.02-0.056 fatalities/year).	A	The operating experience of large power reactors is small. Catastrophic risk estimates are based on this experience.	3
9. i Low-level radiation.	Reprocessing	X	X	X	0.006 deaths/yr, occupational; 0.009 deaths/yr, public.	3	Extent of exposure.	2
10. j Delayed response to low-level radiation exposure.	Radioactive-waste storage.	X	X	X	Occupational: 0.006 deaths/yr, public: 0.0003-0.009 deaths/yr.	3	Ability to contain radioactive wastes over long periods of time.	2
11. k Intentional misuse of nuclear materials resulting in general population injury.	Safeguards, Plutonium theft.	X		X	One small dirty terrorist bomb to destroy one city block with 50,000 casualties.	A	Accessibility to nuclear materials under future reprocessing requirements.	3
12. l Accidents	Raw material acquisition.		X	X	~0.01 fatalities.	2	General manufacturing accident rates.	1
13. m Accidents	Construction		X	X	0.002 - 0.004 fatalities.	2	General construction accident rates.	1

Sources: 812,17,18; h17,19; i15; j20; k7; l.m8.

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  $^{222}\text{Rn}$ , which are known to present carcinogenic risks.<sup>21</sup> 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  $^{14}\text{C}$ ,  $^{85}\text{Kr}$ ,  $^{131}\text{I}$ , and  $^3\text{H}$ .

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 0.012-0.024 fatal disease case per year from lung cancer and that there will be 0.01-0.16 fatal disease case per year in the general population, from cancer and genetic defects.<sup>15</sup>

Other major issues associated with light water reactors are not as easily quantifiable. The primary issue relating to plant operation and maintenance is that of a catastrophic event (Issue 8).<sup>17,19</sup> 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 LWR industry. Similar situations are addressed by Issues 11 and 5, the diversion of plutonium for weapons,<sup>7</sup> and the potential exposure of workers and the public to hydrogen fluoride during fuel enrichment and fabrication.<sup>9,22</sup> Although the probability of occurrence of either event 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 LWR.

### 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. 3.3) was obtained from the National Aeronautics and Space Administration's Energy Conversion Alternatives Study.<sup>23</sup> Since the basis for the SPS evaluation program are year-2000 technologies, a design based on appropriate gaseous fuel emission standards was used ( $0.086 \text{ kg SO}_2/10^9 \text{ J}$  input). 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  $\text{SO}_2$  emission standard. Pre-processed 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 design is for 585 MWe net output and was scaled linearly to 1,000 MWe for this study.

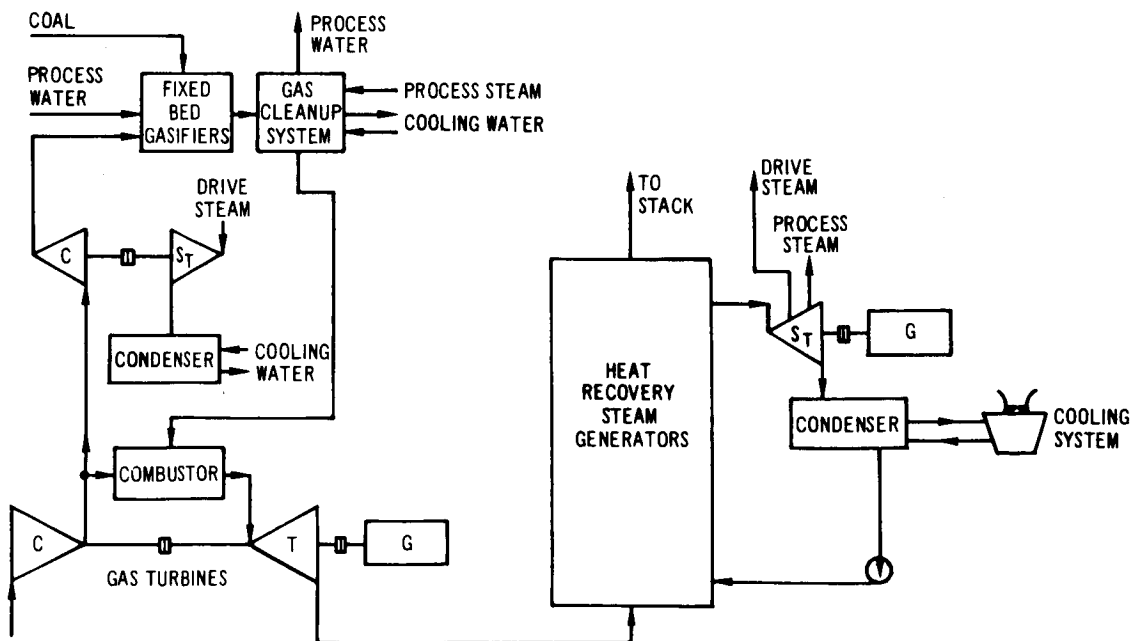


Fig. 3.3. Combined-Cycle Coal Power System with Low-Btu Gasifier and Open-Cycle Gas Turbine

Additional design parameters relevant to this study include:

Overall efficiency	39.6%
Unit lifetime	30 years
Coal	0.38 kg/kWh
SO <sub>x</sub> emissions	0.085 kg/10 <sup>9</sup> J
NO <sub>x</sub> emissions	0.08 kg/10 <sup>9</sup> J
Ash disposal	0.36 kg/kWh
Water discharge	0.34 kg/kWh
Sludge	0.001 kg/kWh

### 3.2.2 Summary of Health and Safety Issues

The major health and safety issues identified are illustrated in Fig. 3.4 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 6: 1 death/year within an 80-km radius).<sup>24</sup>

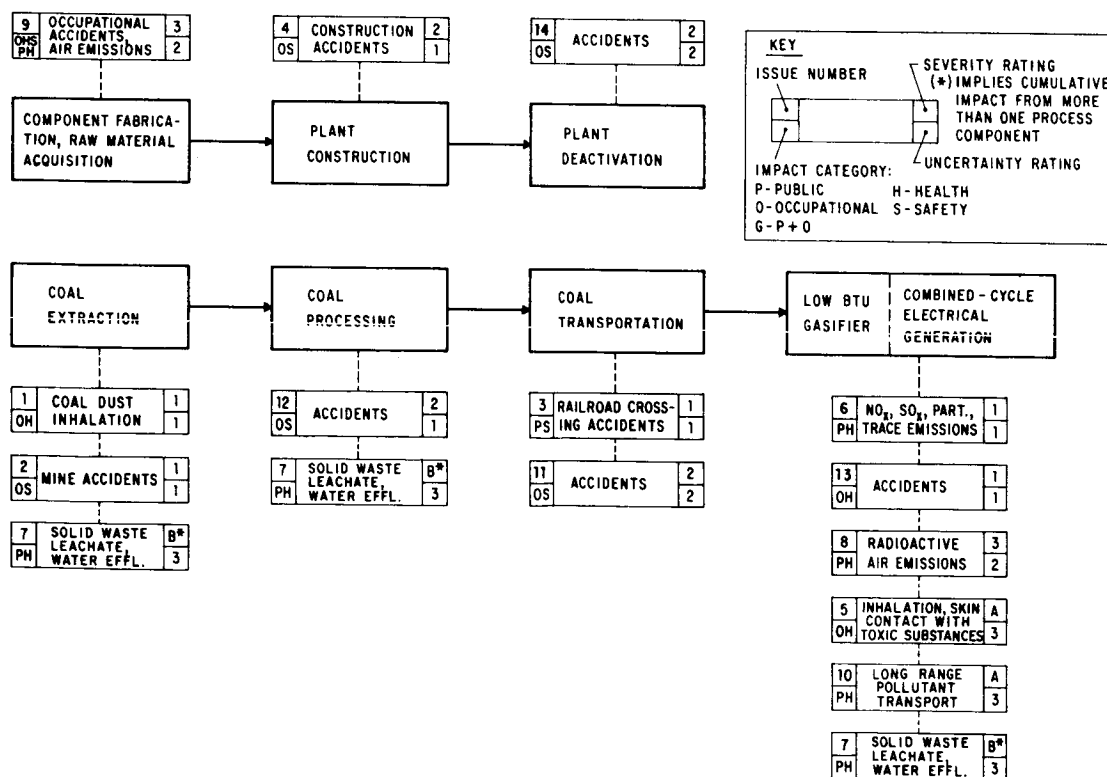


Fig. 3.4. Flow Diagram of the Health and Safety Issues of the Combined-Cycle Coal Power System with Low-Btu Gasifier and Open-Cycle Turbine

Table 3.2. Issue Summary for Combined-Cycle Coal Power System with Low-Btu Gasifier and Open-Cycle Turbine

Issue	Process	Impact Category			Impact Quantification/ 1000 MW	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Continu- ous	Short Term			
1. <sup>a</sup> Coal dust inhalation.	Underground coal mining.		X	X		1	Impact of regulations reducing dust levels.	1
2. <sup>b</sup> Mining accidents.	Surface and underground coal mining.		X	X		1	Large no. of inexperienced miners, new mining techniques.	1
3. <sup>c</sup> Railroad crossing accidents.	Coal transport,	X		X		1	Transport routes and distances.	1
4. <sup>d</sup> Construction accidents.	Plant construction.		X		X	2	Total and skill-specific labor requirements.	1
5. <sup>e</sup> Inhalation and skin contact with toxic substances and carcinogens.	Plant operation and maintenance.		X	X		A	Commercial facility in-plant exposures, impact of low level exposure.	3
6. <sup>f</sup> Atmospheric emissions.	Plant operation.	X		X		1	Long-range pollutant transport; low-level exposures; impact mechanism and pollutant synergisms.	1
7. <sup>g</sup> Chemical pollutants in aqueous effluents and solid waste leachates.	Coal extraction and processing, plant operation.	X		X		B	Health impact of small increments of pollutants; effluent characteristics of gasification facilities.	3

Sources: a<sup>24</sup>, 25, 26; b<sup>24</sup>; c<sup>24</sup>, 27, 28; d<sup>23</sup>, 29; e<sup>30-35</sup>; f<sup>24</sup>, 36-38; g<sup>30</sup>, 31, 32, 39.

Table 3.2. (Cont'd)

Issue	Process	Impact Category			Impact Quantification/ 1000 MW	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Continuous				
8. <sup>h</sup> Exposure to, inhalation, and dietary intake of radioactive coal constituents.	Plant air emissions	X		X	0.0023 deaths/yr; 0.002 eventual genetic defects/yr within an 88.5 km site radius.	3	Effects of low-level radiation; fate and impact of solid waste radioactive leachates.	2
9. <sup>i</sup> Occupational health and safety, public exposure to industrial air emissions.	Material extraction, processing and fabrication of fuel cycle components.	X	X	X	Approximately 69.7 x 10 <sup>6</sup> kg of steel products, 67.4 x 10 <sup>3</sup> kg of concrete required for plant construction: 0.53 fatalities, 4,410 PDL from nonfatal illnesses and injuries. Example: 0.01 µg/cm <sup>3</sup> SO <sub>4</sub> in New York from 1000-MW plant in Ohio. <sup>10</sup>	2	Component needs and associated risks for commercial gasification facilities.	2
10. <sup>j</sup> Long-range transport of air pollutants.	Plant air emissions.	X		X		A	Long-range transport model; low-level exposure effects.	3
11. <sup>k</sup> Occupational accidents.	Coal transport.		X	X	0.024 deaths and 9.2 disabling injuries/100 workers/yr.	2	No. of workers, coal haul distance.	2
12. <sup>l</sup> Occupational accidents.	Coal processing.		X	X	0.076 deaths, and 4.7 disabling injuries/yr.	2	Year 2000 coal processing practices.	1
13. <sup>m</sup> Occupational accidents.	Plant operation and maintenance.		X	X	0.1 deaths and 4.3 disabling injuries/yr.	1	Lack of experience with gasification facilities.	1
14. <sup>n</sup> Occupational accidents.	Plant deactivation.		X	X	Assumed equal to construction: 1.1 deaths, 550 disabling injuries (total during deactivation).	2	Lack of historical data.	2

Sources: h<sup>1</sup>, 40, 41; i<sup>1</sup>, 42; j<sup>1</sup>, 43, 44; k<sup>1</sup>, n<sup>1</sup>, 24, 44.



Although air pollutants from coal conversion ( $\text{SO}_x$  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. Increased public exposure from long-range transport of pollutants (Issue 10) could also substantially increase impact estimates.<sup>43,44</sup>

Next to the effects of air pollutants, the largest public impact results from railroad grade-crossing accidents associated with coal transport (Issue 3).<sup>27,28</sup> 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 effluents (Issue 7) 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<sup>39</sup> and may create additional issues (e.g., gasification effluents).<sup>30-32</sup> However, since these are expected to be controllable with available technology as mandated by existing water quality legislation,<sup>39</sup> a low subjective severity rating was specified (B).

The safety and health impacts of coal mining on occupational populations<sup>25,26</sup> (Issues 1 and 2) are of the same order of magnitude as those on the public due to exposure to coal combustion emissions.

The estimate of occupational accident risk associated with generating-plant operations<sup>24,29,44</sup> (Issue 13) was large enough (over 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.<sup>30-35</sup> The potential concentrations of these substances are uncertain, but they are of sufficient concern to warrant an (A) severity rating for Issue 5.

### 3.3 CENTRAL TERRESTRIAL PHOTOVOLTAIC POWER SYSTEM

#### 3.3.1 System Description

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.<sup>3</sup> Unit facility size was 200 MW, which was linearly scaled to 1,000 MW 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 1,336 x 3,038 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. 3.5).

The types of photovoltaic cells making up the arrays are not specified in the TRW design<sup>3</sup> but are assumed to be one of three types -- cadmium/silicon (Cd/S), silicon, or gallium aluminum arsenide (GaAlAs).<sup>45</sup> The arrays may be of the flat plate or concentrating type. Other cell characteristics include:

Dimensions	0.05 x 0.05 m
Voltage	0.4 VDC
Current	0.72 A
Power	0.3 - 0.5 W
Cell lifetime	5-10 yr <sup>6</sup>

#### 3.3.2 Summary of Health and Safety Issues

Five major health and safety issues (Fig. 3.6, 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 Cd/S or GaAlAs cells further increases 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 130 person days lost per year per 100 full-time workers compared to the U.S. industry average of 59 person days lost per 100 full-time workers).<sup>29</sup>

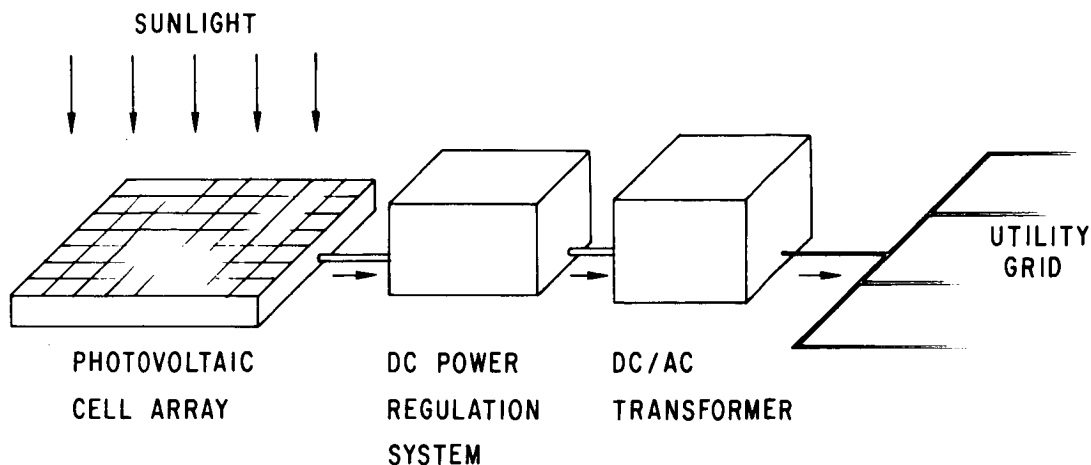


Fig. 3.5. Central Terrestrial Photovoltaic Power System

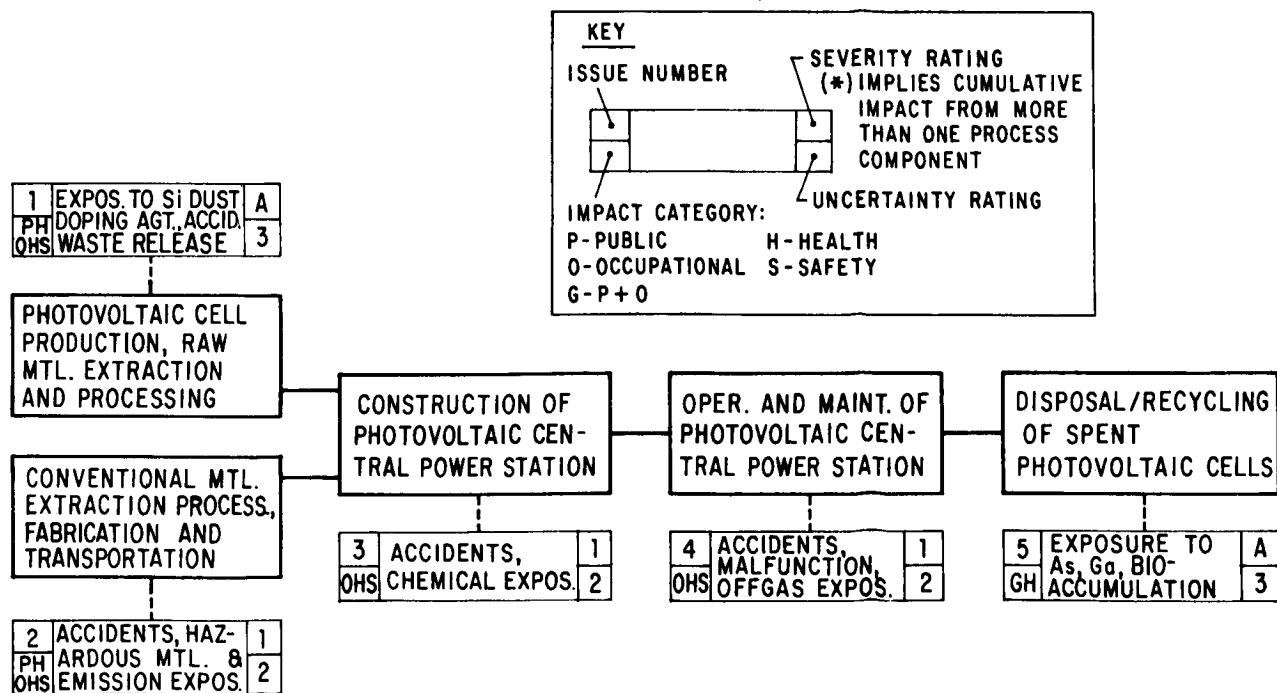


Fig. 3.6. Flow Diagram of the Health and Safety Issues of the Central Terrestrial Photovoltaic Power Systems

Table 3.3. Issue Summary for Central Terrestrial Photovoltaic Power System

Issue	Process	Impact Category			Impact Quantification/ 1000 (HW)	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Contin-uous				
1. <sup>a</sup>	Occupational exposure to Si dust, accidents.							
	Raw material production for photovoltaic cells.							
			X	X	Industry Quartzite mining 113 Nonferrous primary smelting 120 Lead, zinc mining 180 All U.S. industry 59 PDL/100	A	Photovoltaic cell production material requirements.	3
1A. <sup>b</sup>	Exposure to environmentally released wastes.							
	Raw material production for photovoltaic cells.	X		X	Atmospheric emissions: Particulates, SO <sub>x</sub> , NO <sub>x</sub> , HC. Aquatic effluents; NH <sub>3</sub> , phenols. Solid wastes; CdO, ZnSO <sub>4</sub> , Al <sub>2</sub> O <sub>3</sub>	A	Impact of increased demands for materials or quantities of wastes produced.	3
1B. <sup>c</sup>	Exposure to Si dust, doping agents, process chemicals.							
	Photovoltaic cell production.		X	X	Potential exposure to Si dust and toxic chemicals including, phosphene, boron trichloride, Cd, Ga, As, HfNO <sub>3</sub> , SnO <sub>2</sub> , and processing acids and solvents.	B	Worker exposure.	3
1C. <sup>d</sup>	Exposure to environmentally released wastes.							
	Photovoltaic cell production.	X		X	Production of cells on a commercial level will result in large volumes of atmospheric, aquatic, and solid wastes.	B	Bioaccumulation potentials of released wastes, volume of wastes.	3
2. <sup>e</sup>	Accidents, exposure to toxic process chemicals and environmentally released wastes.							
	Conventional material production.	X	X	X	Process Deaths/1000 HW/year Materials acquisition 0.06-0.47 0.03 Transportation 3.2 0.7 Occupational Public	1	Material and manpower requirements.	2
3. <sup>f</sup>	Accidents, exposure to toxic chemicals.							
	Construction	X	X	X	Impacts/1000 HW/year Deaths PDL: 0.037-7.91 Illness 4.0-350 Injury 310-24,600	1	Manpower requirements of sectors involved in construction activities.	2
4. <sup>g</sup>	Accidents, system malfunction.							
	Operation and maintenance.		X	X	Operations and maintenance will include risk of electrical and physical trauma and of exposure to off gases during episodes of array overheating.	1	Manpower requirements and system malfunction potential.	2
5. <sup>h</sup>	Exposure to toxic substances.							
	Disposal of spent photovoltaic cells.	X	X	X	Disposal or reuse of cells will increase worker and public risk to exposure of doping agents including As, Cd, and Ga.	A	Disposal and recycling techniques.	3

Sources: a<sub>8</sub>,29,42,45,46; b<sub>8</sub>,29,42,45-47; c<sub>8</sub>,45,47; e<sub>8</sub>,f<sub>8</sub>,42,46; g<sub>11</sub>,42,45; h<sub>45</sub>,47.

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.<sup>45</sup> 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.<sup>47</sup> In order to produce 1,000 MW of energy per year,  $1.27 \times 10^7$  kg of GaAlAs polycrystal will be required, or  $9.8 \times 10^3$  kg of Cd/S.<sup>45</sup> 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. For these reasons, Issue 5 is given an (A) severity rating with a (3) uncertainty rating.

Issue 2, extraction, processing, and transportation of conventional materials (e.g., glass, cement, and steel) for use in TPV, can be partially quantified. The public and occupational health and safety impacts of the issue have been estimated by Inhaber<sup>46</sup> and Caputo<sup>42</sup> by applying injury and illness statistics to TPV material and transportation needs. The number of projected impacts justifies giving this issue a (1) severity rating. The wide range in estimates accounts for the uncertainty rating of (2).

Inhaber and Caputo have also estimated occupational health and safety impacts of TPV construction (Issue 3) and operation and maintenance (Issue 4).<sup>42,46</sup> Estimates of construction manpower requirements vary significantly (80.8 - 33,700 man hours/MW) between sources. 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 variance in impact estimates dictates rating both at an uncertainty level of (2).

### 3.4 SATELLITE POWER SYSTEM

#### 3.4.1 System Description

Major components of the NASA satellite power system reference design include a satellite composed of a graphite composite structure, gallium aluminum arsenide (GaAlAs) 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. 3.7). Total surface area of the satellite, which is located in geosynchronous orbit (GEO), may exceed  $55 \text{ km}^2$ .<sup>48</sup> 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  $80 \text{ km}^2$ ,<sup>48</sup> and a surrounding exclusion zone will result in land requirements in excess of  $100 \text{ km}^2$  per site.<sup>48</sup> A considerable amount of space

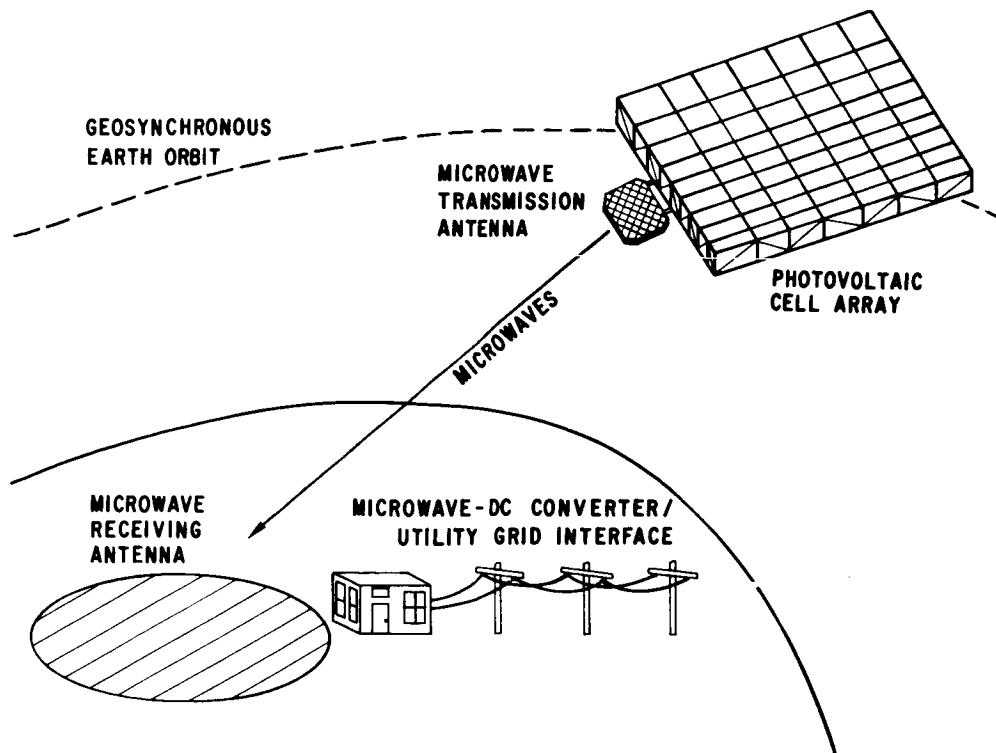


Fig. 3.7. Satellite Power System

transportation will be required during construction, operation, and maintenance. Heavy-lift launch vehicles (HLLV) ( $\text{LCH}_4$ - or  $\text{LO}_2$ -propelled) will be used to transport materials to low earth orbit (LEO), and personnel orbital transfer vehicles (POTV) propelled by ion thrusters will be used between LEO and GEO.

The current SPS Reference Design calls for construction of two 5-GW systems per year for 30 years, with initial operation beginning in 2000 and a total sytem capacity of 300 GW achieved by 2030.<sup>48</sup>

Additional design parameters relevant to this study include the following:

SPS unit lifetime	30 years
Power Beam operating frequency	2.45 GHz
Power density levels <sup>48</sup>	
Center transmitting antenna	22 kW/cm <sup>2</sup>
Edge transmitting antenna	2.4 kW/cm <sup>2</sup>
Center rectenna	23 mW/cm <sup>2</sup>
Edge rectenna	1 mW/cm <sup>2</sup>
Grating lobe levels	<0.01 mW/cm <sup>2</sup>

### 3.4.2 Summary of Health and Safety Issues

The major health and safety issues associated with the SPS are identified in Fig. 3.8. 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,<sup>49</sup> 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 metal mining and steel production, which have relatively high accident rates 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

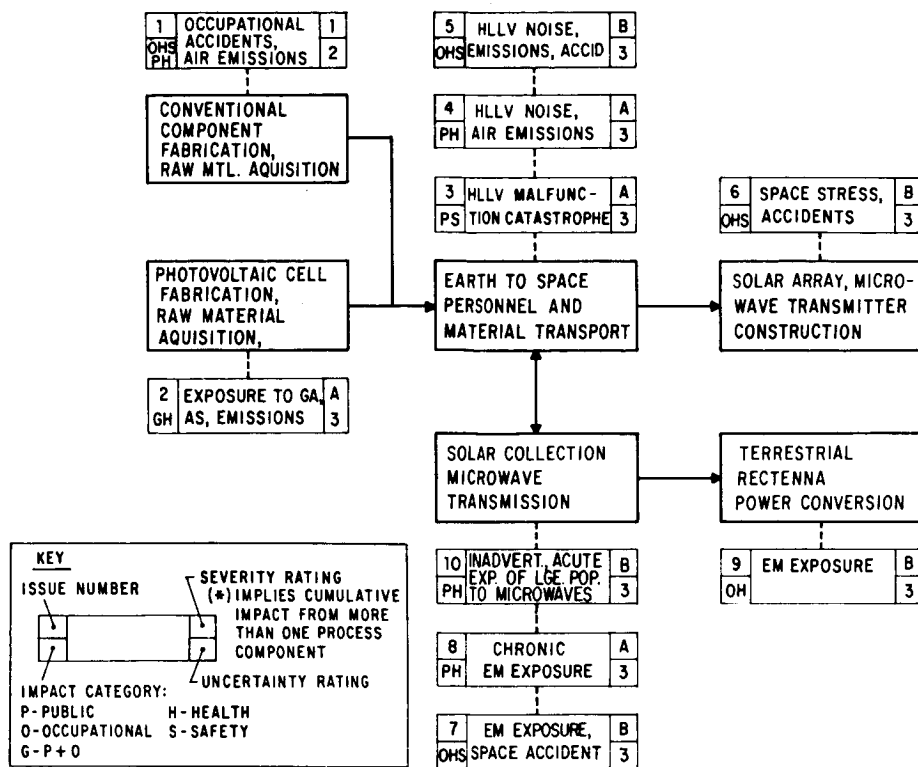


Fig. 3.8. Flow Diagram of Health and Safety Issues of the Satellite Power System

materials and services are expected to account for a significant portion of total SPS health impacts.

A high degree of uncertainty is attached to health and safety impacts of other identified issues in Fig. 3.8 and Table 3.4. Despite this uncertainty, several issues appear to pose nonnegligible threats 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 8, 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 ( $<1 \text{ mW/cm}^2$ ) is not well understood. Studies suggest that chronic exposure may have teratologic, reproductive, genetic, immunologic, and neurologic effects.<sup>50</sup> The level of exposure needed to manifest an effect is not certain. A threshold level may not exist.



Table 3.4. Issue Summary for Satellite Power System

Issue	Process	Impact Category			Impact Quantification/ 1000 MW	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Continuous				
1. a Accidents and exposure to emissions.	Extraction, material processing, fabrication, construction, transportation, operation.	X	X	X	0.3 fatalities, occupational injury. 0.01 fatalities, occupational illnesses. No quantification for public impacts currently available.	1	Changes in SPS components and thus in conventional technology (e.g., materials extraction and processing) may result from SPS demand.	2
2. b Exposure to emissions e.g., GaAs	Photovoltaic cell production.	X	X	X	1.6 x 10 <sup>5</sup> kg of particulates and 4.6 x 10 <sup>5</sup> kg of SO <sub>x</sub> emitted during production of photovoltaic cells.	A	Effectiveness and institution of environmental effluent controls. Extent of occupational exposures to toxic substances.	3
3. c Catastrophic Events e.g., HLLV malfunction.	Transportation of materials and personnel to low earth orbit (LEO).	X	X	X	Maximum accident may exceed 1000 deaths. Approximately 40 flights per 1000 MW capacity during construction phase.	A	Frequency potential for launch and navigational malfunction.	3
4. d Public exposure to fuel emissions, noise from HLLV.	Transportation of materials and personnel to LEO.	X	X	X	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.	A	Dispersion patterns and concentration of toxic fuel components.	3
5. e Occupational exposure to noise, fuel emissions, malfunctions during HLLV launch.	Transportation of materials and personnel to LEO and GEO.	X	X	X	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 lbs in launch area.	B	Toxic chemical exposure potential. System malfunction probability.	3

Sources: a 29, 42, 48-50; b 45, 47, 48; c 48, 50-53; d 49-54; e 49, 51, 53, 55.

Table 3.4. (Cont'd)

Issue	Process	Impact Category				Impact Quantification/ 1000 MW	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Continuous	Short Term				
6.f Stress of life in space, accidents.	Construction of photovoltaic array and microwave transmission system.		X	X		9.4 workers exposed: 7.4 in LEO and 2.0 in GEO during 90 day construction period.	B	Potential for system malfunction events, radiation exposure, and vehicle collisions with space debris.	3
7.g Electromagnetic radiation exposure, accidents.	Operation and maintenance of photovoltaic array and microwave transmission system.		X	X		6.5 workers exposed: 0.5 in LEO, 6 in GEO in maximum allowable time in space--90 days; accidental exposure to microwave approaching 2500 mW/cm <sup>2</sup> .	B	Effects of high-energy particle exposure. Effects of chronic low-level microwave exposure.	3
8.h Electromagnetic radiation exposure, chronic and acute.	Operation and maintenance of microwave transmission system.	X		X		Effects of chronic low-level emission exposure unquantified.	A	Effects of exposure to low levels of microwave radiation.	3
9.i Electromagnetic radiation exposure.	Operation and maintenance of ground station rectennae.		X	X		Accidental exposures, power beam reflections could result in exposures of almost 23 mW/cm <sup>2</sup> under normal operating conditions.	B	Effects of long term exposure to low levels of microwaves and low-frequency electro-magnetic radiation.	3
10.j Acute exposure to power beam.	Operation and maintenance of satellite power system.	X		X	X	Excursion of power beam density beyond 23 mW/cm <sup>2</sup> reference system limit; inadvertent or surreptitious focusing of one or more beams outside rectenna sites.	B	Accessibility of SPS directional controls to subversive factions. Reliability of directional system shutdown controls. Theoretical 23 mW/cm <sup>2</sup> limit on power beam.	3

Sources: f3,4,7; 84,7,40; h3,4,7; i4,7; j3,7,40.

Scatter and reradiation 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 microwaves.<sup>48</sup>

Issue 10 -- acute public exposure to microwaves -- addresses issues such as unscheduled excursions of the power beam above the design density of  $23 \text{ mW/cm}^2$  and inadvertent or surreptitious focusing of one or more beams outside of rectenna boundaries. For comparison, the OSHA standard prohibits excursions above  $25 \text{ mW/cm}^2$  and 8-hour average exposure above  $\sim 10 \text{ mW/cm}^2$  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.<sup>48</sup> However, this potential issue deserves continued concern, because details of the final working design are still highly 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 2, 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 current production. The SPS reference design includes a gallium aluminum arsenide (GaAlAs) photovoltaic cell option, for which there are fewer production characterization data than for commercially available silicon cells. Since components of GaAlAs cells are toxic,<sup>45</sup> and since exposure levels to occupational personnel and to the public are potentially significant during the production cycle, Issue 2 has been given an (A) severity rating.

Issues 3 and 4, 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. It is estimated that a single catastrophic event involving propellant or guidance system malfunction of a transport vehicle (Issue 3) could result in as many as 1,000 deaths. Noise and atmospheric emissions produced by transport vehicles (Issue 4), 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.<sup>51</sup>

Other identified issues received low severity ratings due to potential mitigation strategies that could keep health risks at low levels. These four issues, 5, 6, 7, and 9, 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.<sup>51</sup>

### 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.<sup>57,58</sup> 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.<sup>59,60</sup> To date most effort has been directed at the Tokamak concept,<sup>61</sup> and it would appear that the Tokamak design has the best chance of becoming the initial working design. Thus, the Tokamak design has been selected as the reference system in the present analysis.

Figure 3.9 illustrates a Tokamak fusion power reactor coupled through an intermediate heat exchanger to a conventional steam cycle. The primary side of this heat exchange 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  $64 \times 10^9$  years.<sup>62</sup>

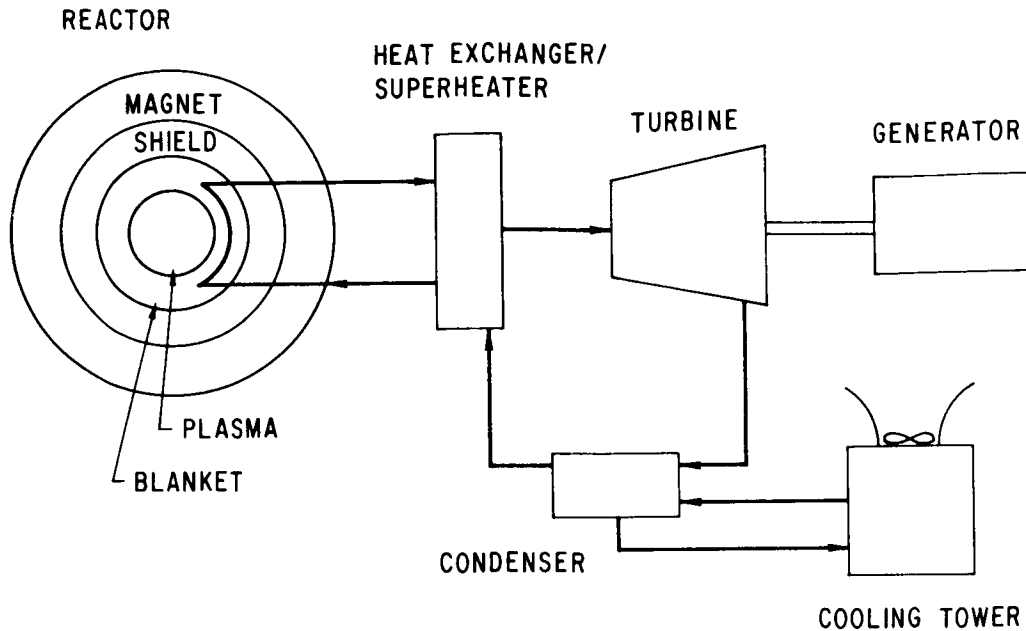
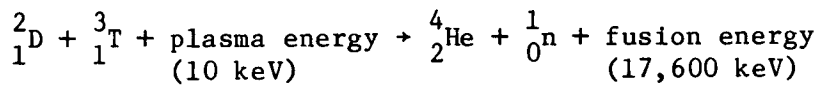
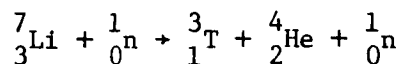
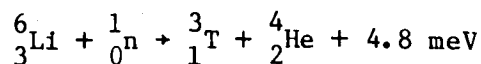


Fig. 3.9. Fusion Power System

A number of fusion reactions are possible, but the one that is most likely to be used in initial fusion reactor designs<sup>57</sup> is as follows:



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:



These reactions would take place within the reactor during normal operations, and since more tritium is produced than 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  $3 \times 10^5$  kg of lithium will be required per 1,000 MWe/year.<sup>57</sup>

### 3.5.2 Summary of Health and Safety Issues

The identified major health and safety issues are illustrated in Fig. 3.10 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.<sup>59</sup> This statement

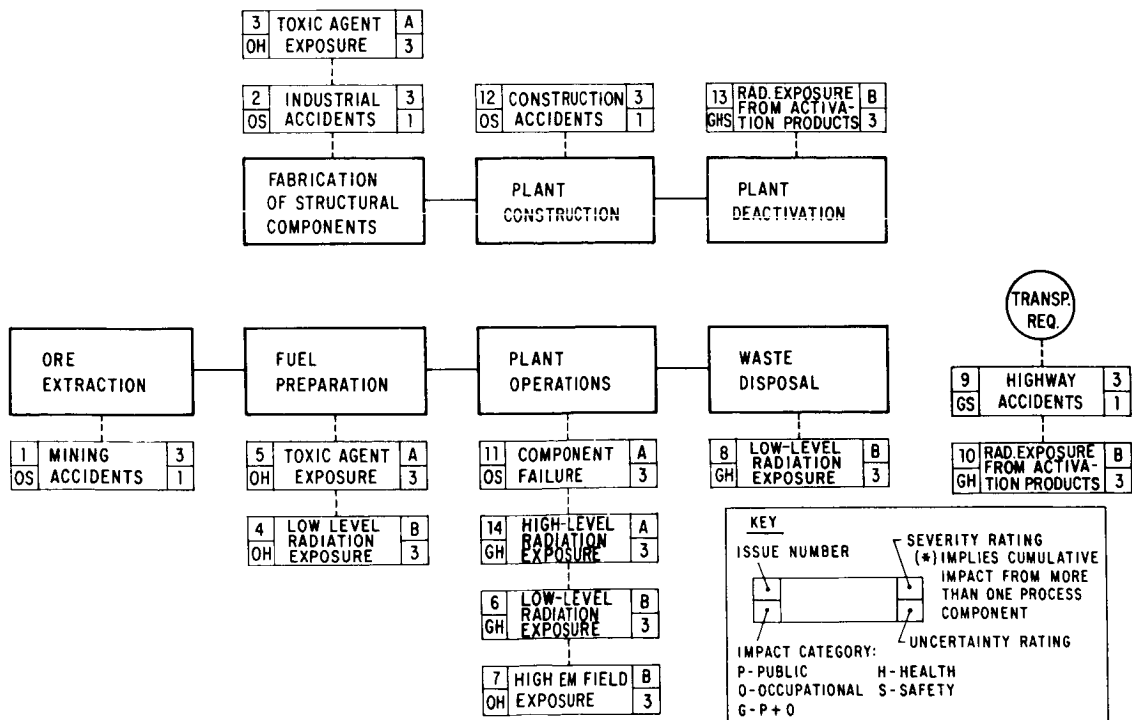


Fig. 3.10. Flow Diagram of the Health and Safety Issues of the Fusion Power System

Table 3.5. Issue Summary for the Fusion Power System

Issue	Process	Impact Category			Impact Quantification/ 1000 (W)	Severity Rating	Uncertainties	Uncertainty Rating
		Public	Occupational	Continuous				
1. <sup>a</sup> Safety of open pit and brine pumping operations.	Lithium ore extraction and processing (5% yield).	X	X	X	0.18 x 10 <sup>-3</sup> fatal accidents, 6.8 x 10 <sup>-3</sup> nonfatal accidents.	3	Injury and disease incidence rates of lithium ore extraction.	1
2. <sup>b</sup> General industrial safety.	Fabrication of structural components	X	X	X	~0.001 fatal accidents, ~0.01 nonfatal accidents.	3	Choice of system design and facility size will influence the quantity and identity of structural components.	1
3. <sup>c</sup> Toxic agent exposure.	Component fabrication	X	X	X	Threshold limit value (TLV) for Be: 0.002 mg/m <sup>3</sup> .	A	Satisfactory protection by workplace exposure standards.	3
4. <sup>d</sup> Low-level radiological hazards.	Fuel preparation, Tritium	X	X	X	Tritium required for plant startup only.	B	Size of tritium production facilities and worker exposure levels.	3
5. <sup>e</sup> Toxic agent exposure.	Fuel preparation, H <sub>2</sub> S exposure	X	X	X	TLV for H <sub>2</sub> S: 15 mg/m <sup>3</sup> .	A	H <sub>2</sub> S exposure specific to the Girdler process for deuterium extraction.	3
6. <sup>f</sup> Low-level radiation exposure.	Normal plant operations	X	X	X	Tritium; maximum dose downwind of plant: 1 rem/year.	B	Exposure level inside of plant.	3
7. <sup>g</sup> Exposure to high EI fields.	Plant operation	X	X	X	EI effects: data inconclusive.	B	EI field health effects.	3
8. <sup>h</sup> Exposure to activation products.	Waste disposal, damage repair.	X	X	X	First wall and blanket finite lifetime due to radiation damage, nonvolatile components.	B	Capability and migration potential of wastes.	3
9. <sup>i</sup> Highway safety.	Transportation of materials, fuel, and waste.	X	X	X	Truck transport 1.28 x 10 <sup>-4</sup> fatal accidents/yr, 1.1 x 10 <sup>-3</sup> nonfatal accidents/yr.	3	Amount and mode of required transportation.	1
10. <sup>j</sup> Low-level radiation exposure.	Transport of materials, fuel, and waste.	X	X	X	None currently available.	B	Amount and mode of required transportation.	3
11. <sup>k</sup> Component failure, plant safety, liquid metal fires and spills, pressure and thermal explosions, missile generation due to magnet or vacuum failure.	Operation and maintenance.	X	X	X	Similar to other industrial experience with high-energy material.	A	System reliability and likelihood of a fire or explosion.	3
12. <sup>l</sup> Construction site accidents.	Plant construction.	X	X	X	0.002-0.004 fatal accidents.	3	Materials and construction personnel requirements.	1
13. <sup>m</sup> Radiation exposure from activation products.	Plant deactivation.	X	X	X	Nonvolatile nature of activation products suggests a low level of impact for this issue.	B	Human response to low-level exposure uncertain. Exposure scenario of unknown probability.	3
14. <sup>n</sup> High-level radiation exposure.	Catastrophic event.	X	X	X	Unknown	A	Likelihood of exposure during such an event.	3

Sources: a8, 57; b8; c63, 64; d55; e57; f63; g59, 60; h62; i8, 66; j60, 63; k57; l8; m58, 60, 67; n57, 59, 60, 65.

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.<sup>63</sup> 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.

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.<sup>61</sup>

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.<sup>68,69</sup> 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.<sup>63</sup>

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.



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.<sup>59</sup> As such, a fusion system would not produce nuclear materials 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 byproduct of energy research with an indirect safety impact.

## 4 COMPARATIVE ENERGY SYSTEM ASSESSMENT

This section contains a comparison of the impacts of the five energy generation technologies. Table 4.1 provides, for each of the systems, the total quantifiable expected deaths per 1,000 MW/yr of power generation, and the deaths per year in each issue category. Also included is the number of unquantifiable issues for each system.

Table 4.1. Summary of Quantifiable Health and Safety Impacts and Number of Unquantifiable Issues for SPS and Four Alternative Technologies<sup>a</sup>

Category of Impact	Fission	Coal	Terrestrial Photovoltaic	SPS	Fusion
Total	0.65 A(3),B(1)	5.84 A(2),B(1)	1.46 A(2)	0.31 A(4),B(5)	0.004 A(4),B(6)
Public	0.55 A(3),B(1)	3.70 A(1),B(1)	0.03 A(2)	-- <sup>b</sup> A(4),B(1)	-- A(1),B(3)
Occupational	0.10 A(2),B(1)	2.14 A(1)	1.43 A(2)	0.31 A(1),B(4)	0.004 A(4),B(3)
Long Term	0.6459 A(1)	5.75 A(2),B(1)	1.33 A(1)	-- A(2),B(4)	0.0002 A(2),B(5)
Intermediate-Term <sup>c</sup>	-- B(1)	0.92	0.13 A(2)	0.31 A(2),B(2)	0.004 A(1),B(1)
Short Term (Catastrophic)	-- A(2)	--	--	-- A(1)	-- A(1)
Accidents	0.25 A(3),B(1)	4.30	1.43 A(1)	0.3 A(2),B(3)	0.004 A(1)
Disease	--	1.54 A(2),B(1)	0.03 A(2)	0.01 A(3),B(3)	-- A(1),B(1)
Radiation	0.39 <sup>d</sup> A(3),B(1)	0.0023 <sup>d</sup>	--	-- A(1),B(3) <sup>e</sup>	-- A(2),B(5) <sup>d</sup>

<sup>a</sup>Figures shown are expected deaths/year over 30-year plant lifetime, unless otherwise specified. Numbers in parentheses are numbers of issues identified in (A) and (B) severity categories.

<sup>b</sup>Ellipses indicate unquantified or negligible issues.

<sup>c</sup>Occurring during raw material extraction, processing, and fabrication for component production and system deactivation. Estimates are total per 1,000 MW generation.

<sup>d</sup>Ionizing radiation.

<sup>e</sup>Microwave radiation.

For the most direct comparison - total quantifiable deaths per year - systems in a more advanced stage of development generally exhibit higher impact or risk levels. Ranking strictly on the basis of quantifiable death risk may, however, lead to misleading conclusions because of unknown effects from poorly quantified or unquantified issues. The difficulty is illustrated in Fig. 4.1, which shows that there is more uncertainty about the quantified health and safety hazards of the terrestrial photovoltaic and satellite power systems than there is about the quantified hazards of the other three systems (see top half of figure). For example, the major quantified impacts of the terrestrial photovoltaic system are largely due to occupational hazards from construction and maintenance of the large arrays of solar collectors, and these estimates have no historical basis as far as manpower requirements are concerned.

Figure 4.1 also provides a perspective on the potential role of unquantified issues by illustrating the number of these issues for each technology. The SPS and fusion systems, which have the lowest level of quantifiable impacts, have the largest number of unquantifiable risks to health and safety.

On the basis of quantifiable effects on the public (nonoccupational) health and safety, a similar higher impact level is estimated for the more developed or near-term technologies, as shown in Fig. 4.2. According to these public hazards estimates, fusion and the satellite power system would appear to be the two least hazardous systems, but, as the bottom half of the figure shows, the numbers of unquantifiable public-impact issues are greatest for fusion and SPS and least for coal.

Figure 4.3 shows the impacts of component production and facility construction, averaged over a 30-year plant lifetime. In this comparison, the solar technologies have the greatest impact because their labor requirements are greater than those of the coal and light water reactor technologies.

As stated previously, in terms of the public perception of their significance, it may be unrealistic to evaluate catastrophic events on the basis of average risk of death per year of plant operation. A major factor in the determination of the future viability of a new technology may be the real or perceived potential for the occurrence of a catastrophic event independently from that of more-continuous low-risk events. For this reason, this assessment identifies the potential for catastrophic events as a separate

evaluation. For the systems considered, potential catastrophic events identified are:

Combined-cycle coal power system

- none identified

Fission power system

- Core meltdown, breach of containment
- Plutonium diversion, terrorist bomb

Terrestrial photovoltaic power system

- none identified

Satellite power system

- Space vehicle crash in urban area

Fusion power system

- Acute radiation exposure from explosive rupture of reactor vessel

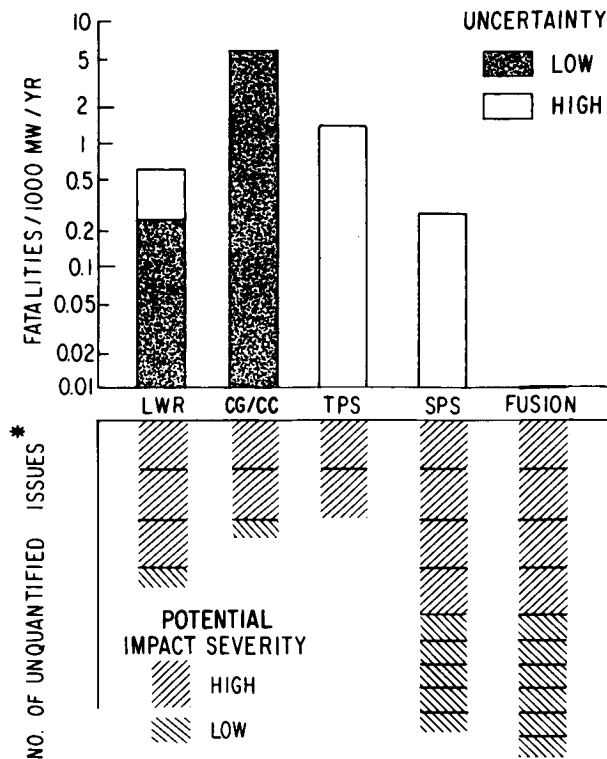


Fig. 4.1. Total Impacts (Public + Occupational) of the Five Energy Systems

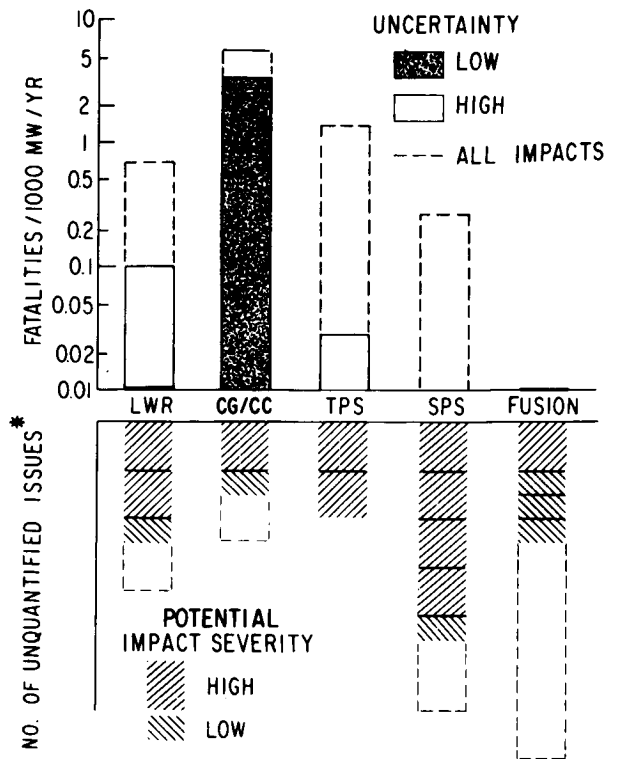


Fig. 4.2. Public Impacts of the Five Energy Systems

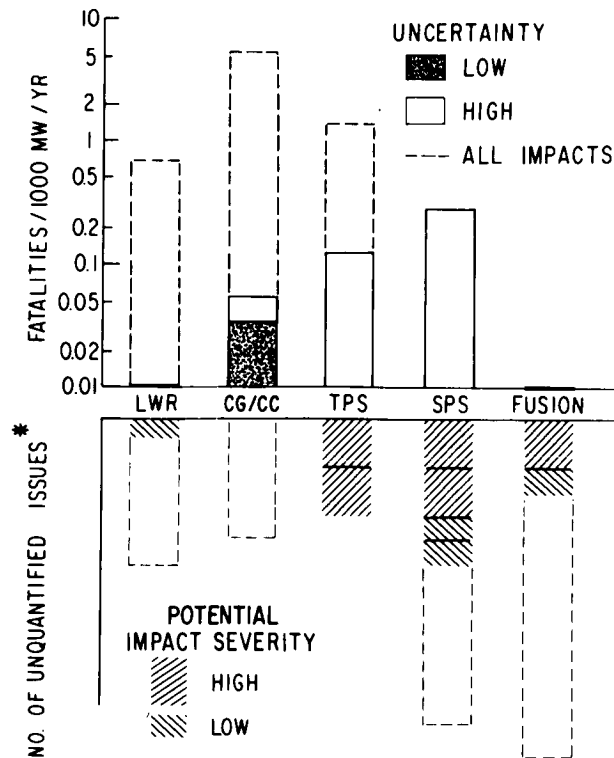


Fig. 4.3. Impacts of Component Production and Facility Construction of the Five Energy Systems

\*Included to qualitatively indicate importance of unquantifiable issues. Cannot be used for quantitative comparisons. Includes potential catastrophic events.

**APPENDIX A**

**FISSION: ISSUE IDENTIFICATION  
AND EVALUATION**

TECHNOLOGY: Light Water Reactor

ISSUE NO. 1

PROCESS: Uranium ore extraction and milling.

IMPACT CATEGORY: Accidental injuries resulting from workplace hazards, continuous risk during facility operation.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: Mine accidents occur regularly during the work year and result in a range of disabilities and dismembering injuries from falls, human error, machine failure, and unanticipated rock-fall hazards.

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.

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

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

TECHNOLOGY: Light Water Reactor

ISSUE NO. 2

PROCESS: Uranium ore extraction and milling.

IMPACT CATEGORY: Lung cancer from exposure to radon and other sources of low-level radiation by occupational population, continuous during plant operation.

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

HEALTH AND SAFETY IMPACT: Increased rates of lung cancer have been documented in underground uranium miners. Evidence supports the relationship between exposure to alpha-emitting radionuclides such as  $^{222}\text{Rn}$  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 plant.

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:  $0.3 \times 10^{-8} \mu\text{Ci}$  of  $^{222}\text{Rn}/\text{ml}$  of air, maximum permissible concentration. U.S. exposure limit, 4 months of occupational exposure per year ( $10^{-7} \mu\text{Ci}$  of  $^{222}\text{Rn}/\text{ml}$  of air).

SEVERITY RATING: 2

UNCERTAINTY RATING: 2

REFERENCE: 11



TECHNOLOGY: Light Water Reactor

ISSUE NO. 3

PROCESS:  $U_3O_8$  conversion,  $UF_6$  enrichment,  $UO_2$  fabrication.

IMPACT CATEGORY: Workplace accidental injury; continuous risk during plant operation.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: The occupational population is at risk of serious physical injury from chemical and thermal hazards. Initial conversion of  $U_3O_8$  to  $U(NO_3)_6$  can expose workers to an explosive hazard.

QUANTITATIVE IMPACT ESTIMATE: Occupational injury during uranium processing: 0.003-0.2 fatal and 0.568 nonfatal injuries associated with the fuel requirement of a 1,000-MWe plant with a 75% load factor.

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: 13

TECHNOLOGY: Light Water Reactor

ISSUE NO. 4

PROCESS: Fuel processing; conversion, enrichment, fabrication.

IMPACT CATEGORY: Public and occupational exposure to low-level radiation; continuous risk during plant operation.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: 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  $180 \times 10^{-6}$  cancer deaths per rem and  $150 \times 10^{-6}$  eventual genetic defects per rem exposure of the entire population. Estimated occupational impacts: 0.003 - 0.033 occupational fatality/yr; 0.0003 fatality/yr/1,000 MWe 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: 7, 14

TECHNOLOGY: Light Water Reactor

ISSUE NO. 5

PROCESS: Fuel processing; conversion, enrichment, fabrication; continuous risk during plant operations.

IMPACT CATEGORY: Public, occupational exposure to HF, F<sub>2</sub> and fluorides.

PROBLEM SOURCE: Increasing the <sup>235</sup>U content of fuel (enrichment) requires U<sub>3</sub>O<sub>8</sub> concentrate to be converted to UF<sub>6</sub>. This step is accomplished by hydrofluorination with HF and F<sub>2</sub>. Process emissions contain fluorides.

HEALTH AND SAFETY IMPACT: 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<sub>6</sub> 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<sub>6</sub>. Exposure to levels of HF exceeding 400 mg/m<sup>3</sup> for short time periods can cause death; 25 mg/m<sup>3</sup> can result in severe lung damage.

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<sup>3</sup> for fluorine, 2 mg/m<sup>3</sup> as a time-weighted average.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCE: 9

TECHNOLOGY: Light Water Reactor

ISSUE NO. 6

PROCESS: Transportation requirements.

IMPACT CATEGORY: Injury to the general public resulting from transport requirements of the fuel cycle; continuous risk during plant operation.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: 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: 13, 15-18

TECHNOLOGY: Light Water Reactor

ISSUE NO. 7, 7'

PROCESS: Reactor plant operations (7), Decommission (7').

IMPACT CATEGORY: General health impacts related to plant operations.

PROBLEM SOURCE: Routine operation of a power reactor requires a manpower level of about 0.18 employee/MWe (180 personnel per 1,000-MWe unit). 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.

HEALTH AND SAFETY IMPACT: The spectrum of workplace injury in the nuclear power station is assumed to be similar to that observed in oil- and gas-fired stations of equal size. Exposure to low-level radiation results from daily workplace activities.

QUANTITATIVE IMPACT ESTIMATE: Accident rates due to reactor operations activities are estimated at 0.024-0.117 fatal and 1.3 nonfatal injuries per annual operating requirements of a 1,000-MWe unit. Estimated public impact from routine emissions of radionuclides is on the order of 0.05 fatalities per MW year.

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: Operations 2                      Decommission B

UNCERTAINTY RATING: Operation 2                      Decommission 3

REFERENCES: 12, 17, 18

TECHNOLOGY: Light Water Reactor

ISSUE NO. 8

IMPACT CATEGORY: Public and occupational risk during reaction operation.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: 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 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: 17, 19

TECHNOLOGY: Light Water Reactor

ISSUE NO. 9

PROCESS: Fuel reprocessing.

IMPACT CATEGORY: Exposure to low-level radiation; continuous risk during plant operation.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: 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: 15

TECHNOLOGY: Light Water Reactor

ISSUE NO. 10

PROCESS: Radioactive waste disposal.

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

PROBLEM SOURCE: High-level wastes accumulate as a result of fuel 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.

HEALTH AND SAFETY IMPACT: 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 - 0.0009 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: 20



TECHNOLOGY: Light Water Reactor

ISSUE NO. 11

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

IMPACT CATEGORY: General population safety risk during plant operation.

PROBLEM SOURCE: 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 activity.

HEALTH AND SAFETY IMPACT: It is generally accepted that an explosive device fabricated from diverted nuclear materials would have sufficient power to destroy a city block. Insoluble  $\text{PuO}_2$  as a fine particulate aerosol can be deposited deep in the lungs and initiate bronchiogenic lung cancers.

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. A pound of plutonium released in a metropolitan center would typically result in 25 eventual cancer deaths.

MAJOR UNCERTAINTY REQUIRING R&D: There is no consensus 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

REFERENCE: 7

TECHNOLOGY: Light Water Reactor

ISSUE NO. 12

PROCESS: Raw material acquisition.

IMPACT CATEGORY: Occupational safety during plant operation.

PROBLEM SOURCE: Large amounts of concrete, steel, and other conventional materials are needed for construction of light water reactors. Workers involved in these activities are at relatively high accident risk compared to those in other occupations.

QUANTITATIVE IMPACT ESTIMATE: Fatalities from occupational accidents during raw material acquisition are estimated to be  $\sim 0.001/1,000$  MW.

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

SEVERITY RATING: 2

UNCERTAINTY RATING: 1

REFERENCE: 8

TECHNOLOGY: Light Water Reactor

ISSUE NO. 13

PROCESS: Plant construction.

IMPACT CATEGORY: Occupational safety.

PROBLEM SOURCE: Reactor system fabrication and plant assembly 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 1,000-MW nuclear power plant is estimated to result in 0.002-0.004 fatality as a result of industrial and construction activities, prorated over a 30-year plant lifetime.

MAJOR UNCERTAINTY REQUIRING R&D: The actual nature of heavy industrial operations for system fabrication and plant construction must be evaluated more precisely.

SEVERITY RATING: 2

UNCERTAINTY RATING: 1

REFERENCE: 8

**APPENDIX B**

**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 health: coal dust inhalation continuous during plant operation.

PROBLEM SOURCE: Airborne coal dust and cold, damp atmosphere in mines.

HEALTH AND SAFETY IMPACT: 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.<sup>26</sup> The cold, damp conditions in mines are also associated with high rates of chronic bronchitis and emphysema.

QUANTITATIVE IMPACT ESTIMATE: For the reference 1,000-MWe plant using  $3.30 \times 10^9$  kg of coal per year, it is estimated that there will be 0.36-0.72 death per year and 14.1-18.5 disabilities per year from pulmonary disease.<sup>24</sup>

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  $2 \text{ mg/m}^3$ . In 1969 the average dust concentration in U.S. mines was reported as  $7 \text{ mg/m}^3$ .<sup>25</sup>

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCES: 24-26

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
 ISSUE NO. 2

PROCESS: Underground and surface coal mining.

IMPACT CATEGORY: Occupational safety: mining accidents. Continuous risk during plant operation.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: Disabling or fatal injury, dismemberment, electrocution.

QUANTITATIVE IMPACT ESTIMATE: The following estimates were obtained from Ref. 24 for the reference 1,000-MWe plant using  $3.30 \times 10^9$  kg of coal per year:

Type of Incident	Number/Year	95% Confidence Interval
Underground Mining		
Deaths	1.31	1.19- 1.45
Injuries	100	86.4 -114
Surface Mining		
Deaths	0.36	0.33- 0.44
Injuries	18.9	16.3 - 21.8

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: 24

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUE NO. 3

PROCESS: Transportation of coal.

IMPACT CATEGORY: Public safety: railroad crossing accidents. Continuous risk during plant operation.

PROBLEM SOURCE: Over 60% of recorded deaths associated with railway freight haulage are caused by railroad crossing accidents.<sup>27</sup> The remaining 40% occur primarily during switching and yard operations, which can generally be avoided by coal-unit trains.

HEALTH AND SAFETY IMPACT: On the basis of national statistics, there are 2.5 deaths/ $10^9$  ton-miles.<sup>24</sup>

QUANTITATIVE IMPACT ESTIMATE: Assuming the above accident rates and an average coal transport distance of 300 miles,<sup>28</sup> the reference 1,000-MWe plant using  $3.30 \times 10^9$  kg of coal annually would have 2.7 deaths and 13 injuries per year associated with coal transport.

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.

REGULATORY STATUS: No regulations specific to coal transport.

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCES: 24, 27, 28

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUE NO. 4

PROCESS: General plant construction.

IMPACT CATEGORY: Occupational safety: construction accidents limited to plant construction phase.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: Deaths, disabling injuries, electrocution.

QUANTITATIVE IMPACT ESTIMATE: The direct manual field labor required for plant construction is estimated at 7 million hours.<sup>23</sup> Using 1975 data for all contract construction, estimates of impact for this field labor are 1.1 deaths and 550 injuries.<sup>28</sup> Averaged over a 30-year plant lifetime, the estimates are 0.036 death and 18 injuries/1,000 MW/yr.

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: 2

UNCERTAINTY RATING: 1

REFERENCES: 23, 28



TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUE NO. 5

PROCESS: Plant operation: coal preprocessing, gasification, gas cleanup, steam cycle.

IMPACT CATEGORY: Occupational health: inhalation and skin contact of toxic and carcinogenic substances; continuous risk during plant operation.

PROBLEM SOURCE: Potential inhalation of fugitive emissions of gases and particulates formed in these processes; 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

HEALTH AND SAFETY IMPACT: 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. 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 hydro-generation 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."<sup>33</sup>

It should be pointed out that the in-plant levels in this pilot plant may vary significantly from those existing in a modern gasification plant.

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<sub>2</sub>, CS<sub>2</sub>, Cr, H<sub>2</sub>S, phenol, and V. Additional standards are anticipated.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 30-35

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
 ISSUE NO. 6

PROCESS: Power plant operation.

IMPACT CATEGORY: Public health: atmospheric emissions (near field, non-radioactive) continuous during plant operation.

PROBLEM SOURCE: 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,  $\text{SO}_x$ ,  $\text{NO}_x$ , and particulates from ash have been the major focus of environmental control regulations, and for this issue analysis it is assumed that  $\text{SO}_x$  and  $\text{NO}_x$  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;<sup>36</sup> 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.

HEALTH AND SAFETY IMPACT: 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: For a reference 1,000-MWe plant located in the upper Ohio River Valley with  $\text{SO}_2$  emissions of  $.086 \text{ kg}/10^9 \text{ J}$  ( $0.2 \text{ lb}/10^6 \text{ Btu}$ ) input, the estimated mortality impact is approximately 0.35 excess death per  $10^6$  persons within an 80-km radius,<sup>24</sup> or 1.05 excess deaths/yr assuming a typical population of 3,000,000 within that radius. The 80% confidence interval is estimated as 0-17 deaths.<sup>24</sup> Latency effects and changing population age distribution may make it necessary to increase these estimates by 25% by the year 2,000.<sup>37</sup> Currently available long-range transport models indicate potential low-level exposure to a much larger population outside the 80-km radius, with an associated cumulative impact one to two orders of magnitude larger, if a linear dose-response function is assumed.

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 proposed new standards<sup>38</sup> requiring 90%  $\text{SO}_2$  control on a rolling monthly average basis for all fuels, with a maximum emission of  $0.52 \text{ kg}/10^9 \text{ J}$  ( $1.2 \text{ lb}/10^6 \text{ Btu}$ ), or 70%  $\text{SO}_2$  control, with a maximum emission of  $0.26 \text{ kg}/10^9 \text{ J}$  ( $0.6 \text{ lb}/10^6 \text{ Btu}$ ). The proposed particulate standard would limit emissions to  $0.013 \text{ kg}/10^9 \text{ J}$  ( $0.03 \text{ lb}/10^6 \text{ Btu}$ ) and

would require 99% reduction for solid fuels. EPA would also limit NO<sub>x</sub> emissions to 0.26 kg/10<sup>9</sup> J (0.6 lb/10<sup>6</sup> Btu) for bituminous coal and to 0.22 kg/10<sup>9</sup> J (0.5 lb/10<sup>6</sup> Btu) for gaseous fuel derived from coal.

SEVERITY RATING: 1

UNCERTAINTY RATING: 1

REFERENCES: 24, 36-38

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUE NO. 7

PROCESS: Coal extraction and processing, plant operation.

IMPACT CATEGORY: Public health: water pollutant effluents, solid waste leachates; continuous during plant operations.

PROBLEM SOURCE: 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.<sup>39</sup>

HEALTH AND SAFETY IMPACT: 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.<sup>30-32</sup>

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.<sup>39</sup> 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: 30-32, 39

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUE NO. 8

PROCESS: Generating-plant operation.

IMPACT CATEGORY: Public health: radioactive coal emissions continuous during plant operation.

PROBLEM SOURCE: Small quantities of  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{232}\text{Th}$ , 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.

HEALTH AND SAFETY IMPACT: 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. 47, the above levels of whole-body irradiation would imply 0.0023 excess cancer death per year and 0.002 genetic defect 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.

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: 14, 40, 41

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUE NO. 9

PROCESS: Material extraction, processing, and fabrication for process components.

IMPACT CATEGORY: Occupational health and safety: mining and industrial accidents and illness. Public health; industrial air emissions. Short-term--prior to and during plant construction.

PROBLEM SOURCE: Significant quantities of concrete, steel, and other metals and metal products are required for coal mining, transport, and processing and for plant construction.

HEALTH AND SAFETY IMPACT: 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: Ref. 42 estimates the combined-cycle coal resource requirement as  $69.7 \times 10^3$  kg of steel/MW capacity and  $67.4 \times 10^3$  kg of concrete/MW capacity, which includes steel and concrete requirements for the entire fuel cycle. Associated with this material acquisition, the estimated occupational health and safety effects are: 0.53 death per 1,000-MW plant, or 0.017 death per year averaged over a 30-year plant lifetime; 135 PDL per 1,000-MW plant due to illness, or 4.5 PDL per year averaged over a 30-year plant lifetime; and 4,275 PDL per 1,000-MW plant due to accidents, or 142 PDL per year averaged over a 30-year plant lifetime.

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: 2

REFERENCE: 42

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUE NO. 10

PROCESS: Power plant operation.

IMPACT CATEGORY: Public health: atmospheric emissions (long-range, non-radioactive), continuous during plant operation.

PROBLEM SOURCE: Atmospheric emission of residuals from the gasification and combustion of coal is discussed in Issue 6. This issue deals with the effect of those emissions on populations outside of the 80-km radius considered in Issue 6. Various studies have shown that wind patterns can transport air pollutants over hundreds of kilometers.<sup>43,44</sup> Furthermore, during the long periods of transport, much of the SO<sub>2</sub> is oxidized to sulfates and forms respirable particles 1-2 microns in diameter. These particles are considered to be more hazardous than SO<sub>2</sub> in the gaseous phase.

HEALTH AND SAFETY IMPACT: Health effects of air pollutants are discussed in Issue 6.

QUANTITATIVE IMPACT ESTIMATE: Due to the long-range transport, large populations may be exposed to low levels of pollutants from a single power plant. For example, a 1,000-MW combined-cycle coal facility with emissions of the reference design located along the Ohio river in southern Ohio is estimated to cause a sulfate exposure of 0.01 µg/cm<sup>3</sup> in the densely populated New York City area. Due to the uncertainty of the pollutant concentration estimates and the effects of low-level exposure, a severity rating of (A) is specified for this issue.

MAJOR UNCERTAINTIES REQUIRING R&D: Characteristics and dose response for specific pollutants emitted from combined-cycle plant; atmospheric transformation and long-range transport; effect of low-level exposures.

REGULATORY STATUS: See Issue 6.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 43, 44

TECHNOLOGY: Combined-Cycle Coal, Low-Btu Gasifier, Open-Cycle Gas Turbine  
ISSUES NO. 11 - 14

PROCESS: Coal transport (11), Coal processing (12), Plant operation and maintenance (13), Plant deactivation (14).

IMPACT CATEGORY: Occupational safety: accident risk continuous during plant operation.

PROBLEM SOURCE: These issues include all of the various occupational safety hazards typical of the processes required for the combined cycle technology, with the exception of mining hazards, which are included in Issue 2.

HEALTH AND SAFETY IMPACT: Accidents

QUANTITATIVE IMPACT ESTIMATE: Plant deactivation (14): No estimates available: assumed comparable to construction (.036 death/yr/1,000 MW). Coal processing (12):<sup>24</sup> 0.076 death and 4.7 disabling injuries/yr ( $3.63 \times 10^6$  tons). Plant operation and maintenance (13):<sup>44</sup> 0.1 death and 4.3 disabling injuries/yr. Coal transport (11): 0.024 death and 9.2 disabling injuries/100 workers/yr (1975 statistics for all transportation and public utilities).<sup>8</sup>

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

REGULATORY STATUS: OSHA safety standards.

SEVERITY RATING: 11: 2  
12: 2  
13: 1  
14: 2

UNCERTAINTY RATING: 11: 2  
12: 1  
13: 1  
14: 2

REFERENCES: 8, 24, 44



APPENDIX C

CENTRAL TERRESTRIAL PHOTOVOLTAIC SYSTEM:  
ISSUE IDENTIFICATION AND EVALUATION

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 1

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

IMPACT CATEGORY: Occupational health and safety.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: 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 <sup>a</sup>
U.S. -- All Industries	59
Lead and Zinc Mining	180
Nonferrous Primary Smelting	120
Nonferrous Secondary Smelting	117
Quartzite Mining	130

<sup>a</sup>Average values for accidents and injuries, 1975-1979.

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: 8, 29, 42, 45, 46

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 1A

PROCESS: Raw-material extraction and processing for photovoltaic cells

IMPACT CATEGORY: Public health.

PROBLEM SOURCE: 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  $\text{SO}_x$ . 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.

HEALTH AND SAFETY IMPACT: 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,  $\text{SO}_x$ ,  $\text{NO}_x$ , and HC

Aquatic effluents:  $\text{NH}_3$  phenols, As, TSS, Cd, Cu, Pb, Se,  
Zn, and oil

Solid wastes:  $\text{CdO}$ ,  $\text{ZnSO}_4$ , SiO, and  $\text{Al}_2\text{O}_3$

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: 8, 29, 42, 45-47

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 1B

PROCESS: Production of photovoltaic cells.

IMPACT CATEGORY: Occupational health.

PROBLEM SOURCE: 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,  $\text{SnO}_x$ ,  $\text{HFNO}_3$ , Cd/S, and GaAlAs, as well as acids and degreasing solvents.

HEALTH AND SAFETY IMPACT: 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: 45, 47

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 1C

PROCESS: Production of photovoltaic cells.

IMPACT CATEGORY: Public health.

PROBLEM SOURCE: Production of photovoltaic cells involves toxic substances including silicon dust,  $\text{SnO}_x$ ,  $\text{HFNO}_3$ , Cd, As, and Ga.

HEALTH AND SAFETY IMPACT: Release of 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: 45, 47

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 2

PROCESS: Extraction, material processing, fabrication, transportation of conventional products.

IMPACT CATEGORY: Occupational and public health and safety.

PROBLEM SOURCE: Substantial amounts of conventional materials, e.g., aluminum, glass, steel, and cement, are required by central 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. Each of these activities is associated with public health risk resulting from air, water, and solid waste residuals and transportation accidents and with occupational health risk from workplace exposure to toxic substances and accidents.

HEALTH AND SAFETY IMPACT: Production of conventional materials for use in photovoltaic central power systems will require significant numbers of workers in high-risk occupations such as mineral mining and primary and secondary metal production. Environmental release of air, water, and solid waste residuals from these conventional processes will increase public health risk.

QUANTITATIVE IMPACT ESTIMATE: There are significant variations in estimates of both occupational and public health impacts. A composite of projections appears below:

Type of Impact	Material Aquisition <sup>a</sup>		Transportation	
	Occupational Health	Public Health	Occupational Health	Public Health
Deaths <sup>b</sup>	0.061-0.467	0.0275	3.2	0.7
Person Days Lost <sup>a</sup>				
Illness	60-111	20-140	-	-
Injury	1,400-3,810	-	2,900	1.5

<sup>a</sup>Includes extraction, processing, and fabrication.

<sup>b</sup>Per 1,000-MW output.

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: 1

UNCERTAINTY RATING: 2

REFERENCES: 42, 46

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 3

PROCESS: Construction of central system.

IMPACT CATEGORY: Occupational health and safety.

PROBLEM SOURCE: Construction of central photovoltaic power systems requires large amounts of manpower. Estimates vary significantly, ranging from 80,800 to 33,700,000 person hours/1,000 MW. Primary trades involved in construction include cement, electrical, roofing, sheet metal, and miscellaneous contracting.

HEALTH AND SAFETY IMPACT: Construction activities involve worker exposure to potential accident situations and toxic chemicals. Nature of risk varies with the trade involved:

Industry	Person Days Lost/ 100 Full-Time Employees <sup>a</sup>
Sheet Metal	106
Electrical	122
Cement	127
Roofing	90

<sup>a</sup>1975-77 average

QUANTITATIVE IMPACT ESTIMATE: Quantitative estimates of health impacts vary as radically as do estimates of manpower needs:

Type of Impact	Impact Estimates
Deaths	0.037 <sup>a</sup> -7.91 <sup>b</sup>
Person Days Lost <sup>c</sup>	
Illness	4.0 <sup>a</sup> -350 <sup>b</sup>
Accident	310 <sup>a</sup> -24,600 <sup>b</sup>

<sup>a</sup>Source: Ref. 42.

<sup>b</sup>Source: Ref. 46.

<sup>c</sup>Per 1,000-MW/year output.

MAJOR UNCERTAINTIES REQUIRING R&D: Refinement of manpower requirements during 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: 1

UNCERTAINTY RATING: 2

REFERENCES: 42, 46

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 4

PROCESS: Operation and maintenance of central photovoltaic power systems.

IMPACT CATEGORY: Occupational health and safety.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: 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: Quantitative impacts are tentative pending characterization of occupational conditions. The range of current estimates is shown below:

Type of Impact	Impact Estimates
Deaths <sup>a</sup>	0 <sup>b</sup> -1.22 <sup>c</sup>
Person Days Lost <sup>a</sup>	
Illness	0 <sup>b</sup> -0.16 <sup>c</sup>
Injury	0 <sup>b</sup> -3,800 <sup>c</sup>

<sup>a</sup>Per 1,000-MW/year output.

<sup>b</sup>Source: Ref. 42.

<sup>c</sup>Source: Ref. 46.

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

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

SEVERITY RATING: 1

UNCERTAINTY RATING: 2

REFERENCES: 11, 42, 45

TECHNOLOGY: Central Photovoltaic Power System

ISSUE NO. 5

PROCESS: Disposal recycling of spent photovoltaic cells.

IMPACT CATEGORY: Occupational and public health.

PROBLEM SOURCE: Photovoltaic central power stations are projected to have 30-year lifetimes. Photovoltaic cells are projected to have much shorter lifetimes: 10 years for silicon and GaAlAs cells, 5 years for Cd/S cells. 1,000 MW of GaAlAs cells will contain approximately  $1.27 \times 10^7$  kg of GaAlAs polycrystal. 1,000 MW of Cd/S cells will contain approximately  $9.8 \times 10^5$  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.

HEALTH AND SAFETY IMPACT: 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: 45, 47

APPENDIX D

SATELLITE POWER SYSTEM: ISSUE  
IDENTIFICATION AND EVALUATION

TECHNOLOGY: Satellite Power System

ISSUE NO. 1

PROCESS: Extraction, material processing, fabrication and construction, and transportation.

IMPACT CATEGORY: Occupational and public health.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: 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: Occupational injuries due to material acquisition, ground construction, and ground operation:  $\sim 1.854$  person-days lost/MW yr,  $\sim 0.0003$  fatality/MW yr.<sup>49</sup>

Occupational illness due to material acquisition, ground construction, and ground operation:  $0.605$  PDL/MW yr,  $\sim 0.00001$  fatality/MW yr.<sup>49</sup>

Health impact incidence rate of  $57$  PDL/100 man yr is  $7\%$  higher than national average (1975) for all industries. These impacts represent  $98\%$  of total manpower involved in SPS activity.

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: 29, 42, 48-50

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\* Assumes 450-GW SPS system with 30-yr life,  $0.92$  load factor ( $1.325 \times 10^7$  MW yr).

TECHNOLOGY: Satellite Power System

ISSUE NO. 2

PROCESS: Material processing/fabrication; photovoltaic cell production.

IMPACT CATEGORY: Occupational health and public health.

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: Atmospheric emissions of GaAlAs, arsenic-bearing particulates, and SO<sub>2</sub> 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<sub>x</sub> will be emitted during production of silicon for one MW of photovoltaic cells.<sup>45</sup> 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: 45, 47, 48

TECHNOLOGY: Satellite Power System

ISSUE NO. 3

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

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

PROBLEM SOURCE: 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.

HEALTH AND SAFETY IMPACT: Explosions and inflight system malfunctions pose risk of thermal and other physical trauma to populations located in flight pattern or near launch site.

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 zero probability for launch failure.

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

REGULATORY STATUS: No regulations currently applicable

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 48, 50-53

TECHNOLOGY: Satellite Power System

ISSUE NO. 4

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

IMPACT CATEGORY: Public health: Noise exposure, atmospheric emission effects during facility construction and facility operation and maintenance.

PROBLEM SOURCE: Potential that HLLV will exceed EPA noise-level guidelines. Creation of sonic booms from launch and reentry of HLLV.

Potentially harmful concentrations and dispersions of toxic emissions from HLLV ground cloud.

Potential upper-atmosphere changes resulting from column-cloud emissions from HLLV.

HEALTH AND SAFETY IMPACT: 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<sub>2</sub>, 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.<sup>51</sup>

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: 49, 50-52, 54



TECHNOLOGY: Satellite Power System

ISSUE NO. 5

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

IMPACT CATEGORY: Occupational, noise exposure, safety risks during facility construction and facility operation and maintenance.

PROBLEM SOURCE: There is a potential for exceeding OSHA noise guidelines during HLLV launch at launch site and for exposure to toxic components of fuels during spill episode and during launch.

There is a potential for explosion from fuel spillage and/or system malfunction at launch site.

There is a potential for system malfunction in transit.

HEALTH AND SAFETY IMPACT: 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: 49, 51, 53, 55

TECHNOLOGY: Satellite Power System

ISSUE NO. 6

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

IMPACT CATEGORY: Occupational health and safety.

PROBLEM SOURCE: 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 quantitative estimates are currently available. However, during the construction phase approximately 960 workers [740 in (low earth orbit) LEO, 200 in (geosynchronous earth orbit) GEO] will be required per 10 GW of capacity. 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 7). 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.

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

REGULATORY STATUS: No regulations currently applicable.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 48, 49, 51

TECHNOLOGY: Satellite Power System

ISSUE NO. 7

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

IMPACT CATEGORY: Occupational Health: Electromagnetic radiation exposure, safety considerations.

PROBLEM SOURCE: Diffraction and reflection of microwaves from transmission array and/or from leakage (e.g., structural failure, cracked waveguides) may expose workers to potentially dangerous levels of microwaves.

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).

HEALTH AND SAFETY IMPACT: Short-term exposure to excess microwave radiation may result in excess thermal stress as well as dysfunction of the central nervous system. The impact of exposure to low-level microwaves is uncertain but of potential significance. 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 6).

QUANTITATIVE IMPACT ESTIMATE: Accidental microwave exposure could approach a power density of  $2,500 \text{ mW/cm}^2$ . Although no quantitative estimate of the incidence of accidental exposure is available, the number of operation and maintenance personnel at risk will be approximately 13 (7 in LEO, 6 in GEO) per satellite. 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  $10 \text{ mW/cm}^2$  per 8-hr with no excursions  $> 25 \text{ mW/cm}^2$ .

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 49, 51, 56

TECHNOLOGY: Satellite Power System

ISSUE NO. 8

PROCESS: Operation and maintenance.

IMPACT CATEGORY: Public health-electromagnetic radiation.

PROBLEM SOURCE: Exposure of the public to electromagnetic radiation from low-level microwave exposure outside of rectenna exclusion zone.

HEALTH AND SAFETY IMPACT: Populations close to rectennae may be subject to low-level microwave exposure from grating lobes, reflection, and rectenna anomalies and to electromagnetic fields created by power transmission.

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

MAJOR UNCERTAINTIES REQUIRING R&D: Health effects of exposure to low-level microwaves. Siting patterns that may create nodes in grating lobe patterns that exceed the reference system projection of  $0.01 \text{ mW/cm}^2$ , maximum, outside of rectenna exclusion zone.

REGULATORY STATUS: No current regulations applicable.

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 48, 49, 51

TECHNOLOGY: Satellite Power System

ISSUE NO. 9

PROCESS: Operation and maintenance; ground station rectenna, microwave reception, power transmission.

IMPACT CATEGORY: Occupational health and safety.

PROBLEM SOURCE: 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, and from creation of a high-intensity, low-frequency electromagnetic field during electric power transmission.

HEALTH AND SAFETY IMPACT: Short-term exposure to excess amounts of low-level microwave radiation may result in excess thermal stress (the retina of the eye is especially susceptible to thermal damage) and changes in central nervous system functions. The impact of exposure to high-intensity, low-frequency electromagnetic fields is not thoroughly understood.

QUANTITATIVE IMPACT ESTIMATE: Accidental exposures (e.g., power beam reflection) could result in worker exposures to power beam densities of  $23 \text{ mW/cm}^2$ . Effect of long-term exposure to high-intensity, low-frequency electromagnetic fields is uncertain. The effect of low-level, long-term microwave exposure to levels  $< 1.0 \text{ mW/cm}^2$  is uncertain.

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

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

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 49, 51

TECHNOLOGY: Satellite Power System

ISSUE NO. 10

PROCESS: Operation and maintenance.

IMPACT CATEGORY: Public health and safety.

PROBLEM SOURCE: Excursion of power beam density beyond  $23 \text{ mW/cm}^2$  reference system limit. Inadvertent or surreptitious focusing of one or more beams outside of rectenna exclusion zone. It has been pointed out, however, that such redirection would be technically difficult according to the current reference design in which the power beam could only be focused toward the origin of a pilot beam.<sup>48</sup> 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.

HEALTH AND SAFETY IMPACT: Misdirection of power beam to center on populated areas would have significant psychological and potential physiological impact.

QUANTITATIVE IMPACT ESTIMATE: Limits on power beam densities ( $23 \text{ mW/cm}^2$ ) under the current reference system are based on theoretical atmospheric-heating constraints. OSHA standard (8-hr work day) is  $10 \text{ mW/cm}^2$  with no excursions beyond  $25 \text{ mW/cm}^2$ .<sup>56</sup> Thermal effects in humans are noticeable at  $\sim 100 \text{ mW/cm}^2$ . The surface area of the power beam is  $\sim 80 \text{ km}^2$ .

MAJOR UNCERTAINTIES REQUIRING R&D: Reliability of system for directing and shutting down the beam, susceptibility of directional controls to redirection, theoretical  $23 \text{ mW/cm}^2$  limit of power beam density. The reference system design has not been fully tested and thus its operational characteristics 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: 48, 51, 56

APPENDIX E

FUSION: ISSUE IDENTIFICATION  
AND EVALUATION

TECHNOLOGY: Fusion Power System

ISSUE NO. 1

PROCESS: Lithium ore extraction and processing.

IMPACT CATEGORY: Accidental injury as a result of mine operations and ore processing.

PROBLEM SOURCE: Accidental injury.

HEALTH AND SAFETY IMPACT: 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  $3 \times 10^5$  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 an operating 1,000-MWe fusion reactor.

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: 8, 57



TECHNOLOGY: Fusion Power System

ISSUE NO. 2

PROCESS: Fabrication of structural components.

IMPACT CATEGORY: Occupational safety: general industrial safety.

PROBLEM SOURCE: Workplace accidents and injuries.

HEALTH AND SAFETY IMPACT: 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.

QUANTITATIVE IMPACT ESTIMATE: General industrial accidental injury rates are reasonable estimates for the injury experience of industries that would be involved with fusion power. These rates predict 0.06 fatal and 0.32 nonfatal injuries per  $10^6$  person hours. On the basis of these rates an estimated 0.001 fatality and 0.01 nonfatal injury can be attributed to annual operation of a fusion facility.

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

REFERENCE: 8

TECHNOLOGY: Fusion Power System

ISSUE NO. 3

PROCESS: Component fabrication.

IMPACT CATEGORY: Occupational health: toxic agent exposure; metal aerosols.

PROBLEM SOURCE: Exposure to beryllium oxides as airborne particulates.

HEALTH AND SAFETY IMPACT: 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.

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)  $0.002 \text{ mg/m}^3$ .

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCES: 63, 64

TECHNOLOGY: Fusion Power System

ISSUE NO. 4

PROCESS: Fuel preparation and handling.

IMPACT CATEGORY: Occupational health: occupational exposure to tritium.

PROBLEM SOURCE: Low-level radiation exposure.

HEALTH AND SAFETY IMPACT: 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

REFERENCE: 65

TECHNOLOGY: Fusion Power System

ISSUE NO. 5

PROCESS: Fuel preparation.

IMPACT CATEGORY: Occupational exposure to hydrogen sulfide.

PROBLEM SOURCE: Toxic chemical exposure.

HEALTH AND SAFETY IMPACT: 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 =  $15 \text{ mg/m}^3$ .

SEVERITY RATING: A

UNCERTAINTY RATING: 3

REFERENCE: 57

TECHNOLOGY: Fusion Power System

ISSUE NO. 6

PROCESS: Normal plant operations.

PROBLEM SOURCE: Low-level radiation exposure.

HEALTH AND SAFETY IMPACT: Refer to Issue 4. The primary concern is over general population exposure to tritium.

QUANTITATIVE IMPACT ESTIMATE: Maximum ground-level dose downwind of the fusion plant: 1 rem/year.

MAJOR UNCERTAINTIES REQUIRING R&D: Further clarification of the dose term is needed.

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

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCE: 63

TECHNOLOGY: Fusion Power System

ISSUE NO. 7

PROCESS: Normal plant operations.

PROBLEM SOURCE: Occupational health: exposure to high-strength magnetic fields.

HEALTH AND SAFETY IMPACT: 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: No quantitative estimate of the impact of high magnetic fields can be made at this time.

MAJOR UNCERTAINTIES REQUIRING R&D: The biological effects of magnetic fields are being studied. No information relating to fusion power is available.

REGULATORY STATUS: None available.

SEVERITY RATING: B

UNCERTAINTY RATING: 3

REFERENCES: 59, 60

TECHNOLOGY: Fusion Power System

ISSUE NO. 8

PROCESS: Waste disposal, damage repair.

PROBLEM SOURCE: Health of general population: exposure to activation products.

HEALTH AND SAFETY IMPACT: 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: 62

TECHNOLOGY: Fusion Power System

ISSUE NO. 9

PROCESS: Transportation of materials, fuels, and waste.

PROBLEM SOURCE: General safety: highway accident injury.

HEALTH AND SAFETY IMPACT: 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  $1.28 \times 10^{-4}$  fatal and  $1.1 \times 10^{-3}$  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: 1

REFERENCES: 8, 66



TECHNOLOGY: Fusion Power System

ISSUE NO. 10

PROCESS: Transportation of waste materials.

PROBLEM SOURCE: General population health: low-level radiation exposure.

HEALTH AND SAFETY IMPACT: 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 radiological 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: 60, 63

TECHNOLOGY: Fusion Power System

ISSUE NO. 11

PROCESS: Operation and maintenance of reactor.

PROBLEM SOURCE: Occupational safety: Worker injury resulting from fire, explosion, and projectile formation due to component failure.

HEALTH AND SAFETY IMPACT: 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: 57

TECHNOLOGY: Fusion Power System

ISSUE NO. 12

PROCESS: Plant construction.

PROBLEM SOURCE: Occupational safety: construction site accidents.

HEALTH AND SAFETY IMPACT: Construction of a fusion plant is expected to require a commitment of effort and materials similar to that of a fission power plant. Workplace hazards associated with the fusion plant construction site are also expected to be similar and result in the same level of worker injury.

QUANTITATIVE IMPACT ESTIMATE: Assuming that standard construction industry accident rates will hold for a fusion plant work site, an anticipated worker injury rate of 0.002 - 0.004 fatal injury can be allocated to the operation of a plant over its assumed 30-year lifetime.

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: 1

REFERENCE: 8

TECHNOLOGY: Fusion Power System

ISSUE NO. 13

PROCESS: Plant deactivation.

PROBLEM SOURCE: General public health: low-level radiation exposure.

HEALTH AND SAFETY IMPACT: 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: 58, 60, 67

TECHNOLOGY: Fusion Power System

ISSUE NO. 14

PROCESS: Catastrophic event potential.

PROBLEM SOURCE: Acute radiation exposure and continuous contamination of water supplies by toxic agents.

HEALTH AND SAFETY IMPACT: 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.

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: 57, 59, 60, 65

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