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WORKER HEALTH AND SAFETY IN SOLAR THERMAL POWER SYSTEMS

IV. Routine Failure Hazards

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September 1979

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Environmental Science and Engineering
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ABSTRACT

Routine failure events in selected solar thermal power system designs are examined, and their rates of occurrence estimated. The results are used to compare and rank the systems considered. Modules of 1 to 100 MWe are developed based on reference or other near-term designs. Technologies used include parabolic trough, parabolic dish, and central tower focusing; central and distributed power generation; and proximate and independent siting of power modules. Component counts and failure rates estimated include heat transfer system leaks, sensor failures, and mechanical and electrical component failures, such as pumps, motors, and wire and cable. Depending on the technology chosen, leak rates can approach 1000 per year per 100 MWe system capacity, while component failure rates can be several times that level. Within categories of failures, the various technologies can have rates differing by a factor of 1000 or more. A uniform weighting for the consequences of the various failure types is proposed. Under this weighting, central tower systems are most favored, followed by parabolic trough, parabolic dishes with dispersed power generation, and parabolic dishes with central power generation. This weighting does not account for possible variations in the technologies. A sensitivity analysis is used to bound the relative hazards of the various failure events required to invert one or more of the system rankings.

TABLE OF CONTENTS

	Page
1. Introduction	1
2. Data Base on Component Failure Rates	6
3. Technology Options	11
4. Parabolic Dish Systems with Central Steam Rankine Cycle Power Generation	12
4.1 Common Collector Field Requirements for Parabolic Dish Systems	12
4.2 System Description of the 100 MWe Module Parabolic Dish System	14
4.2.1 Piping for the 100 MWe Module	14
4.2.2 Linear Expansion Compensators for the 100 MWe Module	16
4.2.3 Valves for the 100 MWe Module	17
4.2.4 Wiring for the 100 MWe Module	18
4.2.5 Additional Features for the 100 MWe Module	19
4.3 System Description of the 10 MWe Module Parabolic Dish System	19
4.3.1 Piping for the 10 MWe Module	20
4.3.2 Linear Expansion Compensators for the 10 MWe Module	22
4.3.3 Valves for the 10 MWe Module	22
4.3.4 Wiring for the 10 MWe Module	23
4.3.5 Additional Features for the 10 MWe Module	23
4.4 System Description of the 1 MWe Parabolic Dish System	24
4.4.1 Piping for the 1 MWe Module	24
4.4.2 Linear Expansion Compensators for the 1 MWe Module	26
4.4.3 Valves for the 1 MWe Module	26
4.4.4 Wiring for the 1 MWe Module	27
4.4.5 Additional Features for the 1 MWe Module	27
4.5 Comparison of Parabolic Dish Systems	28
4.6 Failure Rate Estimates for the Parabolic Dish Systems	31
4.6.1 Leak Rates of Parabolic Dish Components	31
4.6.2 Mechanical and Electrical Equipment Failures	31
4.6.3 Failure to Isolate Leaks	34
4.6.4 Power Generation Subsystem Failures	35
4.6.5 Other Components	35
4.6.6 Summary of Failure Rates for Parabolic Dish Systems	35
5. Parabolic Trough System with Central Steam Rankine Cycle Power Generation	38

TABLE OF CONTENTS, (Continued)

	Page
5.1 Parabolic Trough Collector Field Layout for the 100 MWe Module	38
5.2 System Description of the 100 MWe Parabolic Trough Module	39
5.2.1 Piping for the Parabolic Trough System	39
5.2.2 Linear Expansion Compensators for the Parabolic Trough System	42
5.2.3 Valves for the Parabolic Trough System	42
5.2.4 Wiring for the Parabolic Trough System	43
5.2.5 Additional Features for the Parabolic Trough System	44
5.3 Failure Rate Estimates for the Parabolic Trough System	45
5.3.1 Leak Rates of Parabolic Trough Components	45
5.3.2 Mechanical and Electrical Equipment Failures	45
5.3.3 Sensor Failures	45
5.3.4 Failure to Isolate Leaks and Major Leak Potential	45
5.3.5 Power Generation and Thermal Storage Subsystem Failures	50
6. 100 MWe Central Tower Steam Receiver Design	53
6.1 Common Design Requirements of the McDonnell Douglas Central Tower 100 MWe Systems	53
6.2 Description of the 510 MWe Tower Design	54
6.2.1 Piping	54
6.2.2 Valves	56
6.2.3 Additional Tower Components	56
6.2.4 Heliostat Drive Motors	56
6.2.5 Heliostat Wiring	56
6.3 Description of the 170 MWe Tower Design	58
6.3.1 Piping	58
6.3.2 Valves	59
6.3.3 Additional Tower Components	59
6.3.4 Heliostat Drive Motors	59
6.3.5 Interconnecting Components	60
6.4 Description of the 51 MWt Tower Design	60
6.4.1 Piping	60
6.4.2 Valves	61
6.4.3 Additional Tower Components	61
6.4.4 Heliostat Drive Motors	61
6.4.5 Heliostat Wiring	61
6.4.6 Interconnecting Components	62
6.5 Electric Power Generation Subsystems for the 100 MWe Central Tower Plants	62
6.6 Thermal Storage Subsystem for the 100 MWe Central Tower Plant	63
6.7 Summary of Components of 100 MWe Central Tower Systems	63
6.8 Failure Rate Estimates for Central Tower Systems	66
6.8.1 Leak Rates of Central Tower Components	66

TABLE OF CONTENTS, (Continued)

	Page
6.8.2 Mechanical and Electrical Equipment Failures	66
6.8.3 Sensor Failures	66
6.8.4 Electrical Power Generation Subsystem	66
6.8.5 Summary of Failure Rate Results for Central Tower Systems	66
 7. Parabolic Dish System with Stirling Cycle Dispersed Electric Power Generation	
7.1 System Description of the 1 MWe Parabolic Dish Module with Dispersed Electric Power Generation	
7.2 Component Description of the 1 MWe Dish/Stirling System Receiver	74
7.2.1 Receiver and TES Components	74
7.2.2 Field Components	77
7.3 Summary of Component Counts for a 100 MWe Dish/Stirling System	77
7.4 Failure Rate Estimates for the Dish/Stirling System	82
7.4.1 Leak Rates of Dish/Stirling Components	82
7.4.2 Mechanical and Electrical Equipment Failures	82
7.4.3 Sensor Failures	82
7.4.4 Summary of Failure Rate Results for the Dish/Stirling System	82
 8. Comparison of 100 MWe STPS Failure Rates	88
8.1 Hazard Rankings	89
8.1.1 Hazard Ranking Sensitivity Analysis	89
8.1.2 Central Tower Hazard Ranking Sensitivity Analysis	93
8.1.3 Parabolic Dish Hazard Ranking Sensitivity Analysis	95
8.1.4 Other Ranking Sensitivity Analyses	95
8.2 Discussion of Category Rankings	96
8.2.1 Total Leaks	96
8.2.2 Major Leaks	97
8.2.3 Motor Failures	97
8.2.4 Valve Failures	98
8.2.5 Pump Failures	98
8.2.6 Wire and Cable Failures	98
8.3 Economic Consideration in the Improvement of Failure Rates	99
 9. Operations and Maintenance Impact of Routine Failures in STPS	100
9.1 Strategy of Failure Repair	101
 References	102

LIST OF TABLES

Number	Title	Page
1	Component Failure Rates	8
2	Components of the Parabolic Dish Systems with 100 MWe Capacity	29
3	Leak Rates in the 100 MWe Parabolic Dish Systems	32
4	Mechanical and Electrical Component Failure Rates in 100 MWe Parabolic Dish Systems	33
5	Components of the 100 MWe Parabolic Trough Module	46
6	Leak Rate in 100 MWe Parabolic Trough System	48
7	Mechanical and Electrical Component Failure Rates in 100 MWe Parabolic Trough System	49
8	100 MWe Central Tower Steam System Components	68
9	Leak Rates in 100 MWe Central Tower Systems	69
10	Mechanical and Electrical Equipment Failure Rates in 100 MWe Central Tower Systems	70
11	Component Count for a Dish/Stirling Unit	78
12	Component Count for a Dish/Stirling Field	81
13	Component Count for a 100 MWe Dish/Stirling System	83
14	Leak Rates in a 100 MWe Dish/Stirling System	85
15	Mechanical and Electrical Equipment Failure Rates in a 100 MWe Dish/Stirling System	86
16	Aggregate Failure Rates and Rankings of Alternative 100 MWe STPS	90

LIST OF FIGURES

Number	Title	Page
1	Component Failure Rates	10
2	Parabolic Dish 100 MWe Module Plant	13
3	Collector Placement in 100 MWe Parabolic Dish Design	15
4	10 MWe Module	21
5	1 MWe Module Collector Field Schematic	25
6	Components of Parabolic Dish 100 MWe Systems	30
7	Expected Failure Events in a 100 MWe Parabolic Dish System	36
8	Parabolic Trough Collector Field Layout	40
9	Parabolic Trough Field: Branch Schematic	41
10	Components of Parabolic Trough 100 MWe System	47
11	Expected Failure Events in a 100 MWe Parabolic Trough System	52
12	Components of Central Tower 100 MWe Systems	67
13	Expected Failure Events in 100 MWe Central Tower Systems	72
14	1 MWe Dish/Stirling Field Diagram	75
15	1 MWe Dish/Stirling Piping Diagram	79
16	1 MWe Dish/Stirling Wiring Diagram	80
17	Component Count for a 100 MWe Parabolic Dish-Stirling Cycle Dispersed Generation System	84
18	Expected Failure Events in a 100 MWe Dish/Stirling System	87
19	Category Rankings as a Function of Overall Rankings	91
20	Domain for the Inversion of Rank Ordering Among the Central Tower Systems	94
21	Worker Hazards for the Location of a Pipe Failure	101

1. INTRODUCTION

Environmental safety and health (ES&H) effects of solar thermal power systems (STPS) provides one of several inputs to the technical assessment of the various STPS options. Both the impacts on the ecology and on the population exposed to the effects of the power plant are contained within the broad category of ES&H. The impacts on exposed populations can result from several types of processes, each of which must be addressed in an appropriate way if this assessment is to be performed.

When nuclear power plants are to be licensed, a key step in the safety assessment is to establish a design basis accident (DBA). In accordance with the current philosophy, the DBA is the most severe accident which is not prohibited by physical principles. After extensive analysis, a DBA is now associated with the loss of coolant accident (LOCA). A further nuance to this attempt to identify the DBA, is that any precautionary and design measures that will be used to cope with the DBA will also ameliorate the smaller problems and off-normal events.

Without debating the merit of this approach for nuclear power plants, we assert that such an approach must be rejected for STPS in the absence of supporting evidence. Fundamentally, we do not yet know that accident sequences will lead to substantial ES&H hazards, and subsequently, what set of precautionary measures are required. A fortiori, we must reject the DBA approach. We have no assurance that we can identify the full range of hazards from routine events of minor consequence to rare and potentially life-threatening ones, which exhibit sufficient commonality in origin, behavior, and systems requirements to be accounted for within an analytical scheme. Even within the nuclear context, we note that it is unclear whether

rare but infrequent events will dominate the aggregate hazard. In fact frequent minor events may in the end contribute more substantially to ES&H hazards.

Further dissimilarities between STPS and nuclear power industry safety practice should be noted for comparison. In the nuclear industry, a philosophy of "defense in depth" is adopted, in which redundancy becomes an essential aspect of system design and the assurance of safe operation. This redundancy has several origins, not the least of which is the large potential hazard from the release of the radioactive materials inventory of a nuclear power plant. Rationally, however, we must also acknowledge that the measures adopted to provide for enhanced safety of any system will be a result of negotiations within a technical-political sphere. These negotiations may have, as one aspect, some balancing of perceived risks and benefits. If a technology is burdened with so many constraints that it is unable to compete economically, then of course its potential benefits are unavailable to society. The establishment of stringent safety standards in the nuclear power industry reflects both a need for safety and, then, an ability of that technology to compete with options such as coal in spite of demands for replication of some major and costly subsystems. We would question that STPS will be able to compete on this basis. While no hazard comparable to the radioactive material inventory exists in an STPS, the economics of this technology appears to be sufficiently vulnerable that a demand for "safety at any cost" would, in our opinion, simply make STPS non-competitive for the foreseeable future.

Where, then, does this leave us in the assessment of ES&H questions about STPS technologies? Basically, while we can in part examine the

potential hazards based on hypothetical systems designs, we cannot as yet determine what type of event will be most significant in determining the overall hazard level. Consequently, we have attempted to examine the nature of potential ES&H hazards of all severities and expected frequencies of occurrence, rather than constructing one or more DBAs and assessing their frequency of occurrence and severity. This report deals with routine events, principally fluid release due to component failure. This type of event is expected to have only a small hazard per occurrence, but the frequency of occurrence must be evaluated before a reasonable assessment of aggregate hazard is developed. If the events posited seem at first to be inconsequential and trivial, it is hoped that the reader will withhold this judgment until the implications for substantial application of STPS are developed.

Further justification for concern over apparently minor events arises from the scope of this project, which focuses on worker health and safety in STPS plant operations. We have noted [1] that one may assess the nature and magnitude of hazards to workers by comparative examination of worker activities in several industrial activities. A priori, we cannot predict the amount of worker exposure to in-plant hazards. Therefore, part of this study has been directed towards developing some sense of the level and nature of routine maintenance.

A particular interest is the assessment of fluid release hazards of receiver and collector systems as an integral part of various alternative solar thermal power systems. To provide a reasonably uniform basis, various alternative 100 MWe capacity designs are described or hypothesized using both central and distributed receivers. The capacity is provided by one or more modules. Utilizing relevant aspects of these designs,

failure modes and rates are described, and where possible, quantitatively analyzed. Having deduced the failure modes and rates, various hazards and personnel exposure from those hazards are discussed, with preliminary conclusions regarding safety identified. The analysis, excludes thermal storage subsystems and electric conversion equipment due to the wide variability in these subsystems. Therefore, the conclusions are indicative of worker hazards, rather than predictive in detail, and reflect the preliminary state of STPS system designs.

A further ramification of the preliminary, and selectively detailed, stage of development of the various technology options, is the need to engage in speculation concerning the design of commercial systems. A comparative safety analysis must consider comparable systems, so we are forced to generate these designs in part by ourselves. To avoid setting up "straw men", a conservative approach has been adopted. The designs considered are directly extrapolated and scaled from extant pilot and commercial plant designs.

It is fair to question whether such speculative work can provide insight into worker health and safety, hazards from STPS technologies. We would assert that reasoned speculation does provide insight, not to predict what will happen, but rather, to elucidate what would happen if current technical trends are pursued uncritically. If results of this study show some ES&H aspect to be insupportable, the strongest conclusion one could draw within these constraints is that some aspect of the technology must be modified. Conversely, the STPS options examined cannot be taken as mature designs; in fact, it is hoped that this type of analysis will help in developing designs that will have better ES&H characteristics.

The approach has been taken suitable for commercial generation of

electric power to establish a characteristic scale for an STPS plant. Other alternatives include small-scale and captive (total-energy) generation. Certain technology options, such as central power towers, lend themselves only to moderately large applications, often 100 MWe capacity or greater in a single location. In principle, modules based on distributed collectors, such as parabolic troughs, could be made small, since even at the diminutive scale of 1 MWe per module, multiple collectors are used in each module.

Economics will, in the final analysis, mandate the size of viable STPS plants. Some subsystems will exhibit economies of scale (e.g., turbines, pumps, thermal energy storage systems) and thus favor large plants. Other components or factors may exhibit diseconomies of scale (e.g., piping networks, thermal losses, electrical distribution losses), and favor small plants. The selection of a capacity which balances these costs will minimize the costs of power production. At this early stage in development, we do not know what this value would be. Because the designs of the commercial designs generated in conjunction with those for the Barstow, CA, 10 MWe pilot plant assumed 100 MWe as the nominal size, we have adopted that size as the benchmark scale. This size though may be too small for central tower designs, which may optimize at 500 MWe [3]. We also question the soundness of the benchmark scale for distributed systems, since monolithic units of this size may prove uneconomic. We have therefore examined 100 MWe distributed designs with submodules of 1 and 10 MWe capacity.

2. DATA BASE ON COMPONENT FAILURE RATES

The assessment of failure rates and ES&H hazards of STPS requires both a knowledge of individual component failure rates and a detailed design of the STPS. There is, in addition, the need to evaluate the occurrence of rare events resulting from multiple failures or complex interactions of components. These situations are addressed in a separate report [2].

Failure rates for individual components have become the subject of substantial interest in diverse fields. The concern for reliability in components may be paramount in the space program, where NASA's "Operation Zero Defects" had an enormous impact in the perception of the degree of reliability possible. The information generated in such efforts is, we believe, not strictly relevant to STPS activities, since the costliness of such extreme reliability would likely not be warranted.

Reliability is also of great concern in the nuclear power industry, and this experience may be of greater applicability to STPS designs. The need for overall system reliability is far greater in a nuclear power plant than one might expect for an STPS. Nuclear power system reliability is obtained primarily by redundancy in components, and secondarily by the development of specialized techniques for enhanced reliability of individual components. Data bases developed for nuclear power systems reliability analyses might therefore be expected to have direct applicability to STPS. Several such data bases are available [4-8], the most quoted of which [4] is the "Reactor Safety Study" by Rasmussen (aka WASH 1400). This report has been the primary source of failure rate data for this study.

Some major system components can be identified, and the failure rates for these components were obtained from the cited references. Table 1 is a brief compendium of such rates for components and conditions applicable to STPS

activities. This table presents median expected rates, and upper bound (90th percentile) and lower bound (10th percentile) rates. The data is shown graphically in Figure 1. The data points are shown with error bars; typically the range of uncertainty will extend over one to three orders of magnitude. This considerable variability in failure rate makes any prediction of system failure rates semiquantitative at best.

Table 1

Component Failure Rates

Component	Failure	Failure Rate			Units	Notes
		Lower Bound	Median	Upper Bound		
Pumps	Failure to start	3×10^{-4}	1×10^{-3}	3×10^{-3}	demand ⁻¹	
	Failure to run--normal environment	3×10^{-6}	3×10^{-5}	3×10^{-4}	hour ⁻¹	
Pipes	Rupture	1×10^{-9}	3×10^{-8}	1×10^{-6}	hour ⁻¹ km ⁻¹	(a,b)
Pressure Vessels	Minor leak	3×10^{-8}	1×10^{-6}	3×10^{-5}	hour ⁻¹ km ⁻¹	(a,b,c)
	Failure	3×10^{-8}	3×10^{-7}	3×10^{-6}	hour ⁻¹	
Gaskets	Leak	1×10^{-7}	3×10^{-6}	1×10^{-4}	hour ⁻¹	
Flanges & Elbows	Leak or rupture	1×10^{-8}	3×10^{-7}	1×10^{-5}	hour ⁻¹	
Expansion Joints	Leak	1×10^{-8}	3×10^{-7}	1×10^{-5}	hour ⁻¹	
Flexible Joints	Leak	1×10^{-7}	3×10^{-6}	1×10^{-4}	hour ⁻¹	(d)
Welds	Leak	1×10^{-10}	3×10^{-9}	1×10^{-7}	hour ⁻¹	
Valves	Failure to operate	3×10^{-4}	1×10^{-3}	3×10^{-3}	demand ⁻¹	(e)
	External leak or rupture	1×10^{-9}	1×10^{-8}	1×10^{-7}	hour ⁻¹	(f)
Cables	Open circuit failure	3×10^{-7}	3×10^{-6}	3×10^{-5}	hour ⁻¹ km ⁻¹	(g,h)
Sensors	Failure	3×10^{-7}	3×10^{-6}	3×10^{-5}	hour ⁻¹	
Electric Motors	Failure to start	1×10^{-4}	3×10^{-4}	1×10^{-3}	demand ⁻¹	
	Failure to run	3×10^{-6}	1×10^{-5}	3×10^{-5}	hour ⁻¹	(i)

(a) Geometric mean of values from Ref. [4] for small and large pipes.

(b) Assumes 1 section of pipe ~ 10 m

(c) Assumes that minor leaks are $\sim 20 \approx 3 \times 10^1$ times as frequent as major leaks (ruptures), in accord with values in Ref. [1].

(d) Assumed value 1×10^1 times as great as that for expansion joints, due to greater length and larger degree of flexibility required.

(e) Values apply to motor- and solenoid-operated valves. Air-operated valves have failure rates $\sim 3 \times 10^{-1}$ times as large, but are unlikely to be used due to extended nature of STPS sites.

(f) Motor-, solenoid-, or air-operated valves.

(g) Derived from comparison of Refs. [1] and [4].

Table 1 (continued)

- (h) Applies to underground cables. Above ground wires may have failure rates $\sim 3 \times 10^{-1}$ times as large.
- (i) Assumes normal environmental conditions. Under extreme environmental conditions the failure rate may be $\sim 1 \times 10^2$ times as large.

Figure 1

Component Failure Rates

3. TECHNOLOGY OPTIONS

Four distinct types of systems have been considered, three classified as distributed systems and one as a central tower system. These are

- 1) parabolic dish collector with central steam and power generation
- 2) parabolic trough collector with central steam and power generation
- 3) parabolic dish with integral power generation
- 4) central tower with once-through steam generation

By no means are these all the possible choices, but rather these options were selected such as to span distinctively different principles of design and operation. Within their respective types, all four systems are near- to medium-term candidates for application. These systems will be described in detail in the subsequent sections.

4. PARABOLIC DISH SYSTEMS WITH CENTRAL STEAM RANKINE CYCLE POWER GENERATION

A parabolic dish collector-receiver system has been conceptualized based on the General Electric Shenandoah Large Scale Experiment [9]. Utilizing the same collector-receiver concept, three hypothetical 100 MWe system configurations were designed, consisting of 1, 10, and 100 MWe modules. Common capabilities of the three systems include the ability to generate a peak of 510 MWt of steam at 510°C and 10.1 MPa, the design specifications for the McDonnell-Douglas central tower commercial system [10]. All systems use the same collectors, efficiency assumptions, and solar insolation values. The first system uses one collector field-power generation-thermal storage module.

In each of these systems, a heat transfer fluid is pumped to the collector-receivers located at the focus of a parabolic dish. There it flows through a coil of tubing located behind the focal plane of the parabolic dish, and is heated in the coil. The fluid returns to the power conversion area of the power plant, there, using a heat exchanger, steam is generated. The heat transfer fluid may also be stored in the thermal energy storage system. For simplicity, modules were designed with the power generation-thermal storage areas at one end of the module, and collector rows extending in only one direction away, as shown in Figure 2.

4.1 Common Collector Field Requirements of the Parabolic Dish System

These assumptions were used in the determination of the number of collectors required for the three systems are:

- 1) Size of collector: 7 m in diameter, 38.48 m^2 area
- 2) Collector-receiver efficiency: 60%
- 3) Collector field fluid heat transport efficiency: 90%
- 4) Steam generator heat exchanger efficiency: 100%
- 5) Solar insolation: 950 W/m^2

Figure 2

Parabolic Dish 100 MWe Module Plan

These values are in consentience with the Shenandoah design [9].

The number of collectors needed to generate 510 MWt of steam under these assumptions is then:

$$\frac{5.10 \times 10^8 \text{ W}}{(38.48 \text{ m}^2/\text{collector}) \times (950 \text{ W/m}^2) \times (0.60) \times (0.90)} = 25,800 \text{ collectors}$$

In the design of the collector fields, it was assumed, in accordance with the Shenandoah field design [9], that collectors would be spaced along north/south and east/west lines in repeated diamond shaped patterns. A north/south spacing of 8.9 m between collectors and an east/west spacing of 18.4 m between collectors is used. These values produce a relatively dense collector field. However, wider spacing will result in larger piping requirements and associated equipment requirements. Figure 3 illustrates the collector placements as well as field piping and valving designs.

4.2 System Description of the 100 MWe Module Parabolic Dish System

In this system a single array of approximately 25,800 collectors is connected by an extensive system of piping to a single power generation and thermal storage unit assumed to be identical to the corresponding subsystems in the McDonnell Douglas central tower design [10].

Twenty collector units are serviced by north-south running nested supply and return branch pipe line pairs. There are eight east-west running supply and return row pipeline pairs which service 161 branch line pairs each. The eight row line pairs are in turn serviced by a single pair of main pipe lines connected directly to the heat exchanger-steam generator section of the power generation area of the plant. The component requirements are analyzed below.

4.2.1 Piping for the 100 MWe Module: Since branch line pairs each service 20 collectors spaced 8.9 m apart, the supply and return branch lines will be $(19)(8.9 \text{ m}) = 169 \text{ m}$ in length. Since there are 161 branch line pairs

Branches service 20 collectors each. There are 161 such branches per row. Paired linear expansion compensators occur along each pair of branch pipes at every other collector.

- = pneumatic modulating control valve.
- = pneumatic shutoff valve.
- = manual isolation valve.
- = manual fluid fill or drain valve.
- = collectors
- = temperature sensors

Figure 3

Collector Placement in 100 MWe
Parabolic Dish Design

Parabolic Dish Dispersed Collector Subsystem.
Branch and Collector Detail Schematic Diagram.

per row and 8 rows of branches in the collector field, there will be

$$(161 \text{ pairs/row})(2)(8 \text{ rows})(169 \text{ m}) = 435 \text{ km}$$

of branch line tubing. An additional 7 m of piping will be needed to connect each collector to the paired branch lines, 3.5 m each to and from the branch supply lines. This is an additional 180 km of piping. All supply and return piping pairs are expected to be nested with surrounding insulation.

Since row line pairs will service 161 branch line pairs each 9.2 m apart, both supply and return row pipe lines will be $(160) \times (9.2 \text{ m}) = 1,470 \text{ m}$ in length. With 8 row pairs in the collector field, total row piping should be

$$(2 \text{ lines/pair})(8 \text{ row pairs})(1470 \text{ m}) = 23.5 \text{ km}$$

With a distance between adjacent row pairs of 178 m and a nominal 15 m to the steam generator, main line piping should be equal to

$$[(7)(178 \text{ m}) + 15 \text{ m}][2 \text{ lines/pair}] = 2.5 \text{ km}$$

The total piping is then 641 km. The receiver coil is 64 m in length and an additional 10 m is needed for connection to the base of the dish. This is an additional $(64 + 10 \text{ m})(25,800 \text{ dishes}) = 1909 \text{ km}$ of tubing. Piping connections will be necessary at intervals of $\sim 9 \text{ m}$, so that 71,200 will be required in the module. An additional 10 connectors are required for each dish piping, for a total of 330,000 connectors per module. The receiver coil will require at least 3 welds, for a total of 77,400 welds. Additional connectors and welds may be needed depending on assembly procedures.

4.2.2 Linear Expansion Compensators for the 100 MWe Module: To allow for expansion of piping and tubing, linear expansion compensators are expected to be placed along branch and row lines. Extreme temperature swings of 400°C ($\sim 700^{\circ}\text{F}$) are possible. The coefficient of thermal expansion of carbon steel

is $1.2 \times 10^{-5} \text{ K}^{-1}$, so 641 km of pipe can expand by 3.0 km. This must be provided for by the placement of compensators. For branch lines, a pair of these compensators will be placed along each branch line pair at every other collector (10 pairs/branch), thus amounting to 25,800 compensators. For row lines, a pair of linear expansion compensators will be placed along each row line pair at every other branch (80 pairs/row) for a total of

$$(2/\text{pair})(80 \text{ pairs/row})(8 \text{ rows}) = 1,280 \text{ compensators}$$

Total requirements for the field are 27,000 linear expansion compensators.

4.2.3 Valves for the 100 Mwe Module: For control of collector field fluid flow, valves are needed at the main line, row line, branch line, and collector levels, as shown in Figures 2 and 3.

For the main lines, 5 manual shutoff valves are required for both the supply and return lines. In addition, single manual valves are needed on both lines for fluid fill and drain purposes.

For the row lines, one modulating automatic fluid flow control valve is needed for each supply row line, making 8 in all. An automatic shutoff valve is also needed for each supply and return row line, making 16 in all. Additionally, 40 manual shutoff valves, one for every 4 branches, and one manual fluid fill and drain valve is needed for each supply and return row line. Therefore, 640 manual isolation valves and 16 fluid fill and drain valves are needed for the row lines.

One modulating automatic flow control valve, one automatic shutoff valve, 6 manual shutoff valves, and a fluid fill and drain valve will be incorporated in each branch line pair. Since there are 1290 such pairs, a total of 12,900 valves will be needed.

The collectors each require 2 manual isolation valves and 2 fluid fill and drain valves, for a total of 51,500 of each valve type. The total

system requirement is then 116,604 valves.

4.2.4 Wiring for the 100 MWe Module: The wiring for each dish is assumed to be independent, and to follow the same geometric pattern as the heat transfer fluid piping. The quantity of wiring required to provide one wire per dish may be calculated in the branch/row/main line pattern depicted in Figures 2 and 3.

There are 1288 branches, each with 20 dishes. Wiring will start at the row, and connect to 10 dishes in each direction. The spacing is 8.9 m between dishes, so the n th dish on a branch is $8.9n$ m from the row. The total wiring is thus

$$1288 \text{ branches} \times 2 \text{ sides/branch} \times \sum_{n=1}^{10} 8.9n = 1261 \text{ km}$$

Similarly, each of the 8 rows has 20 wires going to each branch, and the 161 branches per row are spaced 9.2 m apart. Thus the wiring length is

$$8 \text{ rows} \times 20 \text{ wires/branch} \times \sum_{n=1}^{161} 9.2n = 19,200 \text{ km}$$

Lastly, the rows are 178 m apart, and $20 \times 161 = 3220$ wires must go to each row. The connections are presumed to go to a point midway between the fourth and fifth rows. Therefore, there are rows at $1/2$, $3/2$, $5/2$, and $7/2$ of the row spacing of 178 m on each side. The wiring is therefore

$$3220 \text{ wires/row} \times 178 \text{ m} \times \left(\frac{1}{2} + \frac{3}{2} + \frac{5}{2} + \frac{7}{2}\right) \times 2 \text{ sides} = 9170 \text{ km}$$

The total wiring is thus 29,600 km for each wire per dish. A dish may require three reversible motors, each requiring two hot wires, plus a single common line, making seven wires. A two-axis position sensor may require six wires, and a thermal sensor two more. Thus a total of 15 wires may be required per dish. Additionally, the automatic valves require wiring, but there are comparatively few of these. Thus, approximately 444,000 km of wire will be required.

4.2.5 Additional Features for the 100 MWe Module: In addition to the above requirements for the collector field, flexible metallic hose connectors are required for each collector's supply and return lines. These connectors allow for movement of the collector-receiver as it tracks the sun. 51,500 flexible connectors are required. Additionally, as many as 50 pumps may be required to circulate the collector fluid through the field. Also, the collector field will require a collector fluid maintenance and make-up facility. Finally each collector may be provided with three motors for two-axis tracking and for rapid stowing of the collector, requiring 77,400 motors in all.

It has been assumed that, for the single module plant, the electric power generation and thermal storage subsystems of this system are identical with those of the McDonnell Douglas 100 MWe commercial steam system [10]. This uses a conventional steam Rankine cycle turbine generation power system and a sensible heat thermal storage subsystem. However, in this system it is expected that 5 modules of steam generator equipment will be needed to produce the required steam from the hot collector return fluid. Each module will consist of preheat, boiler, and superheater heat exchanges. Steam reheaters and additional turbines might be desired under some circumstances.

The thermal storage subsystem consists of 4 oil-rock storage tanks, a thermal storage heater, a steam generator, a desuperheater, an ullage maintenance unit and a fluid maintenance unit.

4.3 System Description of the 10 MWe Module Parabolic Dish System

The 10 MWe module would, to provide a system capacity of 100 MWe, require 10 collector fields of equal size. Accordingly, each collector field includes 2,580 collector-receiver units and the piping necessary for collector fluid flow from the steam generator to the collectors and back again.

The physical proximity of modules is unimportant, since independent operation is assumed.

In each module, a single pair of north-south running main pipe lines services 5 pairs of east-west running row pipe lines. Each pair of lines services 43 pairs of north-south running branch lines. In this system, the branch line pairs service 12 collector receiver units each. See Figure 4 for a field layout drawing of a module, and Figure 3 for branch collector field details.

4.3.1 Piping for the 10 MWe Module: Since branch line pairs connect 12 collectors per pair, both the supply and return branch lines will be $(11)(8.9 \text{ m}) = 98 \text{ m}$ in length. Total branch line piping for the module will then be:

$$(43 \text{ pairs/row})(2/\text{pair})(5 \text{ rows/module})(98 \text{ m}) = 42.1 \text{ km}$$

An additional 7 m of piping to connect collectors to the branch lines adds 18.0 km to this requirement.

Since row line pairs will service 43 branch line pairs each, both supply and return row pipe lines should be

$$(5 \text{ row line pairs/module})(2/\text{pair})(386 \text{ m}) = 3.86 \text{ km}$$

With a distance between row pairs of 107 m and a nominal 15 m to the steam generators, total main line piping is

$$[(4)(107 \text{ m}) + 15 \text{ m}][2 \text{ lines/pair}] = 0.85 \text{ km}$$

Total row and main line piping is then 4.7 km, and total piping, excluding receiver coils, is then 64.8 km.

As in Section 4.2.1, each receiver requires a total of 74 m of tubing, making a total of 1909 km. Assuming again 1 piping connector each 9 m, plus 10 connector per dish, and 3 welds per receiver, 33,000 connectors and 7740 welds will be required in the module.

Figure 4

10 MWe Module: Collector Field Schematic

4.3.2 Linear Expansion Compensators for the 10 MWe Module: To allow for expansion of piping and tubing, 6 pairs of linear expansion compensators will be placed along each branch line pair and 22 pairs along each row line pair in a fashion as discussed in Section 4.2.2. Requirements can then be calculated as follows:

branch line pairs: $(6 \text{ pairs/module})(2/\text{pair})(43 \text{ branches/row})(5 \text{ rows/module}) = 2580$

row line pairs: $(21 \text{ pairs/row})(2/\text{pair})(5 \text{ rows/module}) = 210$

The total is 2,790 for the module.

4.3.3 Valves for the 10 MWe Module: For control of fluid flow through the collector fields, valves are required at the main line, row line, branch line, and collector levels, as shown in Figures 3 and 4.

For the main lines, 3 manual shutoff and one manual fluid fill and drain valves are required for each of the two main lines.

For the row lines, modulating automatic flow control valves are required for each of the 5 supply row lines. Automatic shutoff valves are needed for each of the 5 return row lines. Additionally, 10 manual shutoff valves at a spacing of one per 4 branches, and one manual fluid fill and drain valve are needed for each supply and return row line are included. Therefore, 100 manual shutoff valves and 10 manual fluid fill and drain valves are required for this module.

For the branches, one modulating automatic flow control valve is needed for each of the 215 branch supply lines, and one automatic shutoff valve is required for each of the 215 branch return lines. Six manual shutoff valves are required per branch pair, making a total of 1,290, while 430 fluid fill and drain valves are required for the branch lines of the system.

The collectors themselves require a manual isolation valve and fluid fill and drain valves, making 2,580 of each in the module. Total valve

requirement for the module is then 12,598.

4.3.4 Wiring for the 10 MWe Module: The wiring of the 10 MWe module will be in accordance with the assumptions of Section 4.2.4 and the layout of Figures 2 and 4.

There are 215 branches, each with 6 collectors on each side of the row line on an 8.9 m spacing. The wiring requirement on the branches is

$$215 \text{ branches} \times 2 \text{ sides/branch} \times \sum_{n=1}^6 8.9n = 80.4 \text{ km}$$

The row wiring has 12 wires going to each of 43 branches with a spacing of 9.2 m between branches. The wiring required is

$$5 \text{ rows} \times 12 \text{ wires/branch} \times \sum_{n=1}^{43} 9.2n = 522.2 \text{ km}$$

The rows are spaced 107 m apart, so that pairs of rows are 107 and 214 m from the middle row. We assume that the generator is located there, so that 516 wires go from there to each exterior row. This requires wiring of length

$$516 \text{ wires/row} \times 2 \text{ sides} \times (107+214 \text{ m}) = 331.3 \text{ km}$$

The total is 934 km per wire to each dish. As described in Section 4.2.4, we assume 15 wires per dish, making a total of 14,010 km of wiring.

4.3.5 Additional Features of the 10 MWe Module: As described in Section 4.2.5, each collector requires 2 flexible metallic hose connectors and 3 drive motors, making 5,160 and 7,740 connectors and motors, respectively per module. As many as 5 pumps will be required for fluid circulation for this system, and each module will have an associated fluid maintenance and make-up facility.

It has been assumed that for each 10 MWe module, the electric power generation and thermal storage subsystems are similar to those of the McDonnell Douglas 10 MWe pilot plant [10]. This system incorporates a conventional steam rankine cycle turbine-based electric power generation subsystem. However, this system will also require a preheater, boiler, and superheater heat

exchangers to comprise the steam generators required for each module. The thermal storage subsystem consists of a sensible heat oil-rock storage tank, a thermal storage heater, a steam generator, a desuperheater, an ullage maintenance unit and a fluid maintenance unit.

4.4 System Description of the 1 MWe Module Parabolic Dish System

The 1 MWe module would, to provide a system capacity of 100 MWe, require 100 identical collector fields. Therefore, each collector field must include 258 collector-receiver units and the necessary piping connections to the steam generator. As for the 10 MWe module, physical proximity of modules is unimportant.

In each module, a single pair of row lines services 22 branch line pairs. The first 21 of the branch line pairs service 12 collectors each, while the last branch line pair services only 6 collectors. Figure 5 shows the module field layout.

4.4.1 Piping for the 1 MWe Module: The branch line pairs that connect 12 collectors per pair will be $(11)(8.9 \text{ m}) = 98 \text{ m}$ in length, whereas those that connect 6 collectors will be $(5)(8.9 \text{ m}) = 44 \text{ m}$ in length. Total branch line piping for this system will then be:

$$(21 \text{ pairs/row})(2/\text{pair})(98 \text{ m}) + (1 \text{ pair/row})(2/\text{pair})(44 \text{ m}) = 4.20 \text{ km}$$

An additional 7 m of tubing is required for connecting each collector to the branch lines, adding 1.80 km more piping:

Since each module has a row line pair to service 22 pairs of branch lines, both supply and return row pipe line requirements are, with a nominal 15 m to the steam generator for each row-pair added,

$$15 \text{ m} + (21)(9.2 \text{ m})(1 \text{ row line/module}) = 0.21 \text{ km}$$

for a total row line piping of 0.42 km. Total module piping is then about 6.42 km.

Figure 5

1 MWe Module: Collector Field Schematic

As described in Section 4.2.1, each receiver requires a total of 74 m of tubing, for a total of 19.09 km. Again assuming 1 piping connection for each 9 m and 10 connectors per dish, and 7 welds per receiver, 3300 connectors and 774 welds will be required in the module.

774 welds will be required in the module.

4.4.2 Linear Expansion Compensators for the 1 MWe Module: To allow for expansion of piping and tubing, 6 pairs of linear expansion compensators will be placed along each 12-collector branch line pair, and 3 will be placed along each 6-collector branch line pair. Eleven pairs will be placed along each row line pair as discussed in Section 4.4.2. Requirements are calculated as follows:

$$\begin{aligned} \text{branch line pairs: } & [(6 \text{ pairs}/12 \text{ branch})(21 \text{ branches/module}) + \\ & (3 \text{ pairs}/6 \text{ branch})(1 \text{ branch/module})] = 258 \end{aligned}$$

$$\text{row line pairs: } (11 \text{ pairs/row})(1 \text{ row/module})(2/\text{pair}) = 22$$

Total requirements are then 280.

4.4.3 Valves for the 1 MWe Module: For fluid flow control, valves are needed at the row line, branch line, and collector levels. Refer to Figure 3 for illustration.

For the row lines, 5 manual shutoff valves at a spacing of one for 4 branch lines, and one manual fill and drain valve are required for each row line, therefore, 10 manual shutoff valves and 2 manual fluid fill and drain valves are required in the module. In addition, one automatic modulating fluid control valve is needed for the supply row line, and one automatic shutoff valve is needed for the return row lines.

For the branches, one modulating automatic flow control valve is needed for each of 22 branch supply lines, and one automatic shutoff valve is also required for each of 22 branch return lines. Six manual shutoff valves are required per branch pair, making 132 in all. Finally, 44 fluid fill and drain valves are required for the 22 branch line pairs of the system.

The collectors themselves will again require manual isolation valves and 2 fluid fill and drain valves, or 510 of each kind in the module. Total valve requirements for the system are then 1,266.

4.4.4 Wiring for the 1 MWe Module: The wiring of the 1 MWe module will follow the row and branch structure of Figure 5.

Collectors are spaced 8.9 m apart on the branches, with 21 branches having 6 on each side, and a single branch having 3 on each side of the row. The wiring requirement on the branches for a single wire to each collector is

$$\begin{aligned}
 & 21 \text{ branches} \times 2 \text{ sides/branch} \times \sum_{n=1}^6 8.9n + \\
 & 1 \text{ branch} \times 2 \text{ sides/branch} \times \sum_{n=1}^3 8.9n = 7.96 \text{ km}
 \end{aligned}$$

The row wiring has 12 wires going to each of the first 21 branches, and 6 wires to the last. The branch spacing is 9.2 m, hence the wiring length is

$$12 \text{ wires/branch} \times \sum_{n=1}^{21} 9.2n + 6 \text{ wires/branch} \times 9.2 \times 22 = 26.72 \text{ km}$$

The total wiring is thus 24.68 km for each wire to collector. Assuming 15 wires per collector, as in Section 4.2.4, a module will require 520 km of wiring.

4.4.5 Additional Features of the 1 MWe Module: As indicated in Section 4.2.5, 2 flexible hose connectors and 3 drive motors per collector are required, making 516 connectors and 774 drive motors. It is expected that each module will require a single circulation pump in addition to a collector fluid maintenance and make-up facility.

It is assumed that for each 1 MWe module, an appropriately scale version of the McDonnell Douglas 10 Mwe pilot plant electric power generation and thermal storage subsystems [10] will be constructed. This system will then

employ a conventional steam Rankine cycle turbine-based electric power generation subsystem for each module. The steam generator for each module will also require a preheater, boiler, and superheater. Each thermal storage module is expected to have one sensible heat oil-rock storage tank, a thermal storage heater, a steam generator, a desuperheater, an ullage maintenance unit, and a fluid maintenance unit. It is expected that some components of the thermal storage system may experience a scaling down in number as well as size from the 10 MWe pilot system referred to above. Consideration of single module thermal storage heaters and steam generators, and single pumps for thermal storage charging and discharging loops would result in requiring 100 of each of these items for the entire system.

4.5 Comparison of Parabolic Dish Systems

Table 2 summarizes the major components of the parabolic dish systems of 100 MWe total capacity, based on the 1, 10, and 100 MWe modules described above. As the data from this table indicates, the number of modules has only minor an effect on most collector field component counts. A notable exception is wiring. The component counts are shown in Figure 6, with the three module sizes shown separately when differences of 5% or more exist.

Increasing the number of modules in the 100 MWe system naturally increases the number of power generation and thermal storage subsystems, but that may be mitigated by the fact that redundancy within modules can be sacrificed when larger numbers of smaller modules are employed. With larger numbers of small modules, control system complexity may be increased to some extent since more equipment operations must be monitored and controlled. Basic heat transfer fluid loop component counts (e.g., piping, valves) are seen to be quite similar even as the module size varies by a factor of 100.

Table 2

Components of the Parabolic Dish Systems
with 100 MWe Capacity

Systems	100 MWe Module (1 Module/System)	10 MWe Module (10 Modules/System)	1 MWe Module (100 Modules/System)
Collector Fields:			
Collectors	25,800	25,800	25,800
Heat Transfer Fluid Piping	641 km	648 km	642 km
Receiver Tubing	1909 km	1909 km	1909 km
Piping Connectors	330,000	330,000	330,000
Tubing Welds	77,400	77,400	77,400
Expansion Connectors	27,000	27,900	28,000
Valves	117,000	126,000	127,000
Flexible Connectors	51,600	51,600	51,600
Wiring	444,000 km	141,000 km	52,000 km
Drive Motors	77,400	77,400	77,400
Pumps	50	50	100
Fluid Maintenance Facilities	1	10 (or fewer)	100 (or fewer)
Power Generation Subsystem:			
Steam Generator Heat Exchangers	15	30	300
Turbine-Generator Complexes	1	10	100
Thermal Storage Subsystem:			
Thermal Storage Tanks	4	10	100
Hoater Heat Exchangers	5	20	100
Steam Generator Heat Exchangers	15	60	300
Charging Loop Pumps	5	20	100
Discharging Loop Pumps	5	20	100

Figure 6

Components of Parabolic Dish 100 MWe Systems

4.6 Failure Rate Estimates for the Parabolic Dish Systems

The failure rates for the components identified in the parabolic dish systems can be estimated using the data base of Table 1/Figure 1 and the component counts of Table 2/Figure 6. Several types of components and events are considered in the characterization of plant operation.

4.6.1 Leak Rates of Parabolic Dish Components: Sources of leaks in the parabolic dish systems will include piping, flanges, welds, valves, and expansion and flexible joints. The component counts are shown in Table 3, rounded to one significant figure. Also shown in this table is the mean component failure rates for leaks, from Table 1, and the mean expected failure frequency in a 100 MWe system operating at a 0.4 capacity factor (i.e. $0.4 \times 8760 = 3500$ hours per year). Total expected leak rates are 800 per year per 100 MWe system, of which 0.3 will be major pipe ruptures.

4.6.2 Mechanical and Electrical Equipment Failures: Routine and off-normal events may lead to failures of mechanical and electrical equipment. The failures can occur during continuous operation of equipment or, in the case of electric motors in particular, during start-up of equipment. Component counts and failure rates are shown in Table 4. Along with this data are listed the expected failure incidence per year, for continuous operations, or per demand, for intermittent component uses. Major routine failure rates include those for motors and for wires and cables.

Certain failure rates are important not because of large absolute magnitude, but due to the uncertainty of the consequences. For example, the failure of 8 motors per system demand may have serious consequences for worker health and safety if defocusing fails to occur during high winds and workers are exposed to hazardous conditions in making repairs.

Table 3

Leak Rates in 100 MWe Parabolic Dish Systems

Component	Number (100 MWe system)	Mean Failure Rate (hour ⁻¹)	Leaks per Year
Valves	1×10^5	1×10^{-8}	4
Connectors	3×10^5	3×10^{-7}	300
Welds	8×10^4	3×10^{-9}	0.8
Expansion Joints	3×10^4	3×10^{-7}	30
Flexible Joints	5×10^4	3×10^{-6}	500
Piping and Tubing	3×10^3 **	1×10^{-6} +	10
		3×10^{-8} †	0.3
TOTAL			800

* 1 year = 3500 hours at 0.4 availability

** km

+ minor leak rate (hour⁻¹ km⁻¹)

† major rupture rate (hour⁻¹ km⁻¹)

Table 4
Mechanical and Electrical Component Failure Rates
in 100 MWe Parabolic Dish Systems

Component	Number (100 MWe System)	Mean Failure Rate		Expected System Failure Rate	
		(hour ⁻¹)	(demand ⁻¹)	(year ⁻¹ +)	(demand ⁻¹)
Pumps	6 x 10 ¹ *	3 x 10 ⁻⁵	1 x 10 ⁻³	6	0.06
	9 x 10 ¹ **	3 x 10 ⁻⁵	1 x 10 ⁻³	9	0.09
	3 x 10 ² ***	3 x 10 ⁻⁵	1 x 10 ⁻³	30	0.3
Motors	8 x 10 ⁴	1 x 10 ⁻⁵	3 x 10 ⁻⁴	3000	8 #
	1 x 10 ⁵		1 x 10 ⁻³		100
Valves	4 x 10 ⁵ *	3 x 10 ⁻⁶ ‡		4000	
	1 x 10 ⁵ **	3 x 10 ⁻⁶ ‡		1000	
	5 x 10 ⁴ ***	3 x 10 ⁻⁶ ‡		500	

+ 1 year = 3500 hours at 0.4 availability

* 100 MWe module

** 10 MWe module

*** 1 MWe module

‡ hour⁻¹ km⁻¹

assuming one motor operated per demand

4.6.3 Failure to Isolate Leaks: About 95% of the valves, 98 to 99% of the pipe connections, and all of the flexible metallic hose connectors and the collectors are located on, or are serviced by, the branch lines. It is of concern if leaks within the branches cannot be isolated within the branches. Failure to isolate can result in greater fluid leakage losses, need to defocus more collectors, and greater fluid handling problems when making repairs.

Branch fluid supply can be cut off with an automatic modulation control valve and with 2 manual shutoff valves. From Table 3, we assume a total of ~1000 leaks per year within the branches. A failure to isolate the leak at the most local level will occur if a single valve fails to operate. This event will occur at a rate of

$$(10^3 \text{ leaks/year})(10^{-3} \text{ valve failures/demand}) = 1 \text{ primary isolation failure/year}$$

in a 100 MWe system. If a failure to isolate occurs, manual closure of valves would be necessary to isolate a leak within the branch lines. Failure of either of two manual valves will prevent isolation, and this will occur at a rate of

$$(1 \text{ primary isolation failure/year})(2 \times 10^{-3} \text{ failures/demand}) \\ = 2 \times 10^{-3} \text{ secondary isolation failures/year}$$

Depending on the size of the leak and the time required to isolate it with manual valve closure, other collector branches downstream from the leaking branch may experience a loss in fluid flow and may need to be defocused.

probability analysis could be done, using leak rates and valve failure/demand rates, to determine the rates for isolation of larger and larger portions of the piping network, with the corresponding collector defocusing requirements.

If an entire row had to be isolated for the single module plant, 1/8 of the total number of collectors would have to be defocused, or about 3200.

4.6.4 Power Generation Subsystem Failures: Fossil fuel-fired power plants experience 4×10^{-2} "leaks" per plant-year and 2×10^{-3} "major ruptures" per plant year (5.8). Whether power plant failure rates were dependent upon the size of the plants is unclear. If these rates apply to the entire power plant, the parabolic dish systems presented would have 0.04 to 4 leaks/year and 0.002 to 0.2 major ruptures per year, with the larger values for systems with more power plant modules.

4.6.5 Other Components: Among the most prevalent components will be flow and temperature sensors. On the order of 1×10^5 may be included in a 100 MWe parabolic dish system. Sensor failure rates may be on the order of 3×10^{-6} hour⁻¹, giving a yearly failure rate on the order of 1000. However, the course of action when a sensor fails is unknown, due to possible redundancy of instrumentation.

Other major components include oil to steam heat transfer equipment and oil purification equipment. Neither appears to offer major routine maintenance problems, but this is uncertain at this stage.

4.6.6 Summary of Failure Rate Results for Parabolic Dish Systems: The results presented in Tables 3 and 4, and the accompanying discussion, indicate failure rates which predict that hundreds of repairs may have to be performed per year in a 100 MWe system. Most of these events are of minor consequence, but the aggregate effect on worker health and safety may still be significant. To provide some comparative data the results cited are plotted in Figure 7 with assumed rates of 10 to 1000 times per year for events which result from a demand on the component. The lower rate of demand is about once per month, infrequent but certainly not insignificant in a

Figure 7

Expected Failure Events in a 100 MWe Parabolic Dish System

100 MWe system. The higher rate is somewhat more than twice per day, as might be expected for events demanded in start-up and shut-down. Only the lower rate is given for valves, since it would not be expected that all valves would be actuated with each demand.

The results depicted in Figure 7 indicate that several components will contribute significantly to overall failure rates and thereby impact worker health and safety. Routine maintenance, such as replacing or checking motors, will apparently be a fairly common matter.

We note that the occurrence of a component failure need not entail more than an economic penalty. Explicitly, we have not drawn any link between repairs and worker health and safety. However, the hazards of dealing with these systems have been addressed previously [1]. We claim simply that the large number of failures indicates a substantial level of worker activity within the STPS plant, and therefore substantial potential for exposure to high temperature materials, hazardous fluids, and other sources of injury to workers.

There is a substantial need to consider repairability in STPS designs of this type, and to consider in some cases the selection of premium components. This is a second aspect of the results of Figure 7. The economic, and health and safety trade-offs may substantially change the failure rate estimates presented.

5. PARABOLIC TROUGH SYSTEM WITH CENTRAL STEAM RANKINE CYCLE POWER GENERATION

A parabolic trough collector-receiver system has been conceptualized for the generation of 100 MWe. The technology is based on the Willard, New Mexico Shallow Well Pumping experiment [11]. In view of the relative insensitivity of the major failures of system components to the size of the independent modules, a single 100 MWe module has been designed and analyzed.

For the 100 MWe solar thermal power system using parabolic trough collectors, a system has been hypothesized that consists of a large array of parabolic trough collectors, an extensive network of collector fluid lines, and a single organic rankine cycle turbine-based power generation system with an adjacent thermal storage unit. Because the system is based on line-focusing collectors, rather than point-focusing ones as in parabolic dishes and central towers, lower working temperatures and somewhat lower efficiencies are expected. This system will be described and then analyzed for failure potential.

5.1 Parabolic Trough Collector Field Layout for the 100 MWe Module

To determine the number of collectors required for this system, the following assumptions were made:

- 1) Due to expected turbine operating temperature of approximately 300°C, a reduction in turbine efficiency to 22.5% from 30% in the higher temperature two-axis focusing systems is anticipated.
- 2) Size of collector: 2.7 m wide, 3.7 m long, 10.0 m² in area
- 3) Collector-receiver efficiency: 55%
- 4) Collector field fluid heat transport efficiency: 90%
- 5) Steam generator heat exchanger efficiency: 100%
- 6) Solar insolation: 950 W/m²

The required thermal power for the plant is set such as to provide the electric power equivalent of 510 MWt in the higher efficiency system. This requires $510 \times 0.03 / 0.225 = 680$ MWt at peak. The number of collectors required is

$$\frac{6.80 \times 10^8 \text{ W}}{(10.0 \text{ m}^2/\text{collector})(950 \text{ W/m}^2)(0.55)(0.90)} = 145,000 \text{ collectors.}$$

5.2 Systems Description of the 100 MWe Parabolic Trough Module

The layout for the Shenandoah Large Scale Experiment [12] collector field design for parabolic troughs was used as a model. Twelve collectors are ganged in series and connected together end to end to form a single flow loop with north-south orientation. Each of these ganged collector series, referred to as a branch, is supplied with heat transfer fluid from a supply line at one end and is emptied into a return line at the opposite end. The collector branches are lined up in rows which will run east-west. There are 38 such rows with 318 branches in each row. Figures 8 and 9 show a field and branch design diagram, respectively. It should be noted that this design represents a very densely packed collector field, having a 44% coverage with collectors. Wider spacing between collectors will result in more piping and associated equipment requirements.

5.2.1 Piping for the Parabolic Trough System: Each branch contains 12 collectors, with a total length of $(12)(3.7 \text{ m}) = 44.4 \text{ m}$. A receiver tube runs along the center of each branch. Receiver tubing for the system will total

$$(38 \text{ rows})(318 \text{ branches/row})(44.4 \text{ m/branch}) = 537 \text{ km}$$

To connect the branches to the row pipe lines, approximately 6 m of piping is required. For the system, connector pipes of length

$$(38)(318)(6 \text{ m/branch}) = 73 \text{ km}$$

are required. Nineteen supply row pipe lines and 20 return pipe lines are

Figure 8

Parabolic Trough Collector Field Schematic

△ = manual isolation valve

△⌋ = manual fluid fill and drain valves

△⊙ = automatic control valve

△⊙⊕ = automatic isolation valve

There are 38 rows of 318 branches (3816 collectors) each.

These rows are serviced by 19 supply lines and 20 return lines.

36 in. main lines service the row lines.

Arrows indicate directions of fluid flow.

Figure 9

Parabolic Trough Field: Branch Schematic

required to service the 38 rows of collector branches. Assuming a 5.7 m separation between branch lines, equivalent to an east-west collector separation of 3.0 m, row pipe lines will be

$$(39 \text{ row lines})(317 \text{ branches})(5.7 \text{ m/branch}) = 70.5 \text{ km}$$

Supply main lines to service the 19 row supply lines must be 1740 m in length, and return main lines to service the 20 row return lines must be 1830 m in length. Total heat transfer piping for the system is then 147 km. In addition there is 537 km of receiver tubing.

Each branch must be connected to the supply and return row lines, for a total of

$$(2 \text{ connections/branch})(318 \text{ branches/row})(38 \text{ rows}) = 24,108 \text{ connections}$$

between branches and rows. Each branch will have about 8 additional connections to valves and flexible joints, for an additional 96,672 connections. The total is 121,000 connections. Internal joints between trough segments will be welded. This will require 11 welds in each branch, for a total of 133,000 welds.

5.2.2 Linear Expansion Compensators for the Parabolic Trough System: At an assumed requirement of one for every 20 m of piping, 5,500 would be required for the system to allow for thermal expansion. This is in rough proportion to the heat transfer piping in the parabolic dish systems, and does not include provision for the expansion of the receiver tubing.

5.2.3 Valves for the Parabolic Trough System: Valves are required at the main line, row line, and branch line levels to control fluid flow through the collector field, as shown in Figures 8 and 9. The valving requirements are based on the design for the Shenandoah LSE [12].

Ten manual shutoff valves are required for each of the five supply and return main pipe lines. In addition, manual fluid fill and drain valves are required for each of the two main lines.

A modulating automatic fluid flow control valve is required for each supply row line, making 19 for the system. An automatic shutoff valve is required for each return row line, making 20 for the system. Additionally, one manual isolation valve for every 10 branch lines, and one manual fluid fill and drain valve for each row line is required. Since there are 12,084 branches, 1208 isolation and 39 fluid control valves are needed.

One modulating automatic control valve, one automatic shutoff valve, two manual isolation valves, and two manual fluid fill and drain valves are required for each branch line of the system. This makes a total of 72,504 valves. The total number of valves for the entire system is 73,795.

5.2.4 Wiring for the 100 MWe Parabolic Dish Module: The wiring for each trough will be presumed to be independent and to follow the same geometric pattern as the heat transfer fluid piping. The amount of wiring required to provide one wire per trough assembly (branch) may be calculated in the branch/row/main line pattern described in Figures 8 and 9. All wires will be assumed to terminate at the center of the branch; this is equivalent to assuming that wiring goes to a branch from only one side but that control functions are operated from both sides in a symmetric pattern.

The spacing between branches is 5.7 m, and the branch is 44.4 m long. Thus, a wire reaching from the main pipe line to the midpoint of the nth branch along a row has a length of $(5.7n + 22.2)$ m. Since there are 38 rows of 318 branches each, the total wiring is

$$38 \text{ rows} \times \sum_{n=1}^{318} (5.7n + 22.2) = 11,250 \text{ km}$$

Each row must then have 318 wires coming from the control room, assumed to be between rows 19 and 20, as in Figure 8. The branch spacing is 48 m, hence the distance from the control room to the nth row from the center is

$48(n - \frac{1}{2})$ m. Since there are two symmetric sides about the control room, the wiring length is

$$318 \text{ wires/row} \times 2 \text{ sides} \times \sum_{n=1}^{19} 48(n - \frac{1}{2}) = 5510 \text{ km}$$

Thus a total of 16,760 km of wiring is required to provide one wire per branch.

Each branch will have two reversible motors, requiring 4 hot plus a common power line. A single axis position sensor requires at least 4 wires. In addition, two sensors will require at least 4 additional wires, making a total of 13. Thus the total wiring requirement is 218,000 km.

5.2.5 Additional Features of the 100 MWe Parabolic Trough Module: It is expected that approximately 50 pumps will be required to circulate the collector fluid through the collector field. Each collector branch is expected to require 2 motors for the tracking motion of the branches of parabolic troughs, and two flexible connectors to allow for this motion. Thus 24,200 of each are required. It is anticipated that about 5 organic vapor generator modules will be required for heat transfer from the collector fluid to the turbine working fluid. Each module will probably consist of preheater, boiler, and superheater heat exchangers. Finally, there will be a collector fluid maintenance and makeup facility for the system.

The electric power generation subsystem of this single module plant will use an organic rankine cycle turbine to allow for greater efficiency at the lower operating temperatures ($\sim 300^{\circ}\text{C}$) anticipated. For the handling of the organic working fluid, quality maintenance equipment and additional special operating procedures and equipment may be necessary depending upon the stability, volatility, toxicity, and other properties of the fluid.

The thermal storage subsystem of this plant may be similar in both operating and equipment features to the McDonnell Douglas commercial sensible heat system [10].

5.3 Failure Rate Estimates for the Parabolic Trough System

The component counts of the previous sections are summarized in Table 5, and are depicted in Figure 10. From these results, failure rates may be estimated from the data base of Table 2 and Figure 6. The various sources of component failure are described below.

5.3.1 Leak Rates of Parabolic Trough Components: In analogy to Section 4.6.1, component counts, mean failure rates, and expected frequency of occurrence of leaks are listed in Table 6. The annual plant operations are assumed to have a 0.4 capacity factor, equivalent to 3500 hours per year operation. Aggregate leak rates are 300 per year for a 100 MWe system. These are principally from flexible connectors and other pipe connectors. Major failures of pipes amount to less than 0.1 per year.

5.3.2 Mechanical and Electrical Equipment Failures: In analogy to Section 4.6.2, routine and demand-dependent failure rates may be calculated for mechanical and electrical components. These failure rates are shown in Table 7. Major failures include those of the motors and of wires and cables.

5.3.3 Sensor Failures: In Section 5.2.4, wiring adequate for two sensors per branch was provided. In addition to this, 24,000 sensors, flow and other sensors may be needed on the heat transfer piping. If 50,000 sensors are used in all, data of Table 1 and Figure 1 predict 500 failures per year.

5.3.4 Failure to Isolate Leaks and Major Leak Potential: Connections are expected to cause most leaks in this system, and about 95% will be within the branches. Only if both the automatic control valves and manual isolation valves fail to operate, will any of the 300 leaks per year listed in Table 6

Table 5

Components of the 100 MWe Parabolic Trough Module

Collector Field

Collectors	145,000
Branches (12 collectors each)	12,100
Heat transfer piping	147 km
Receiver tubing	537 km
Piping connectors	121,000
Tubing welds	133,000
Expansion connectors	5,500
Valves	73,800
Flexible connectors	24,200
Wiring	218,000 km
Drive Motors	24,200
Pumps	50
Fluid Maintenance unit	1

Power Generation Subsystem

Vaporizer Heat Exchangers	15
Turbine Generator Complexes	1

Thermal Storage Subsystem

Thermal Storage Tanks	4
Heater Heat Exchangers	5
Vaporizer Heat Exchangers	15
Charging Loop Pumps	5
Discharging Loop Pumps	5

Figure 10

Components of Parabolic Trough 100 MWe System

Table 6
Leak Rate in 100 MWe Parabolic Trough System

Component	Number (100 MWe System)	Mean Failure Rate (hour ⁻¹)	Leaks per Year *
Valves	7×10^4	1×10^{-8}	2
Connectors	1×10^5	3×10^{-7}	100
Welds	1×10^5	3×10^{-9}	1
Expansion Joints	6×10^3	3×10^{-7}	6
Flexible Joints	2×10^4	3×10^{-6}	200
Piping & Tubing	7×10^2 **	1×10^{-6} +	2
		3×10^{-8} ‡	0.07
TOTAL			300

* 1 year = 3500 hours at 0.4 availability

** km

+ minor leak rate (hour⁻¹ km⁻¹)

‡ major rupture rate (hour⁻¹ km⁻¹)

Table 7

Mechanical and Electrical Component Failure Rates
in 100 MWe Parabolic Trough System

Component	Number (100 MWe System)	Mean Failure Rate		Expected System Failure Rate	
		(hour ⁻¹)	(demand ⁻¹)	(year ⁻¹ *)	(demand ⁻¹)
Pumps	6×10^1	3×10^{-5}	1×10^{-3}	6	0.06
Motors	2×10^4	1×10^{-5}	3×10^{-4}	700	20 6
Valves	7×10^4		1×10^{-3}		70
Wires and Cables (km)	2×10^5	3×10^{-6} +		2000	

* 1 year = 3500 hours at 0.4 availability

+ hour⁻¹ km⁻¹

not be isolated at the branch lines. If isolated, only a single branch of collectors would be defocused. Since valve failure rates are 1×10^{-3} demand⁻¹, it would be expected that in

$$(300 \text{ leaks/year})(10^{-3} \text{ valve failures/demand})^2 = 3 \times 10^{-4} \text{ events/year}$$

will branch leaks not be isolated at the branch level. However, in $(300)(10^{-3}) = 0.3$ events/year, manual closure of valves would be necessary to stop fluid flow.

For any branch leaks that cannot be isolated or for row line leaks, manual isolation valves are provided along the row lines to isolate as small a part of the collector field as possible. A probability analysis could be done using leak rates and valve failure/demand rates to determine the yearly probabilities needed isolating various portions of the piping network.

Since each supply row line services 2 rows of collector branches, shutdown of a full row supply line will mean isolation and defocusing for 2/38 (1/19) of the system. Any mainline leak shutdown would force the isolation of at least 4 rows, over 10% of the system. Pipe leaks are almost wholly a function of the number of connections, of which the main lines have about 400. A connector leak rate of 3×10^{-7} hour⁻¹ (Table 1) would give a mainline leak rate of 0.4 per year. These leaks would force isolation of at least 4 rows, and potentially the whole system, for shutoff of the leak and repair.

5.3.5 Power Generation and Thermal Storage Subsystem Failures: The use of the organic Rankine cycle, turbine-based, single module electric power generation subsystem, presents many new problems for analysis. The paucity of operating experience with these systems provides inadequate failure data. If similar "leak" and "major rupture" failure rates were to be the same as

for steam turbine systems, 4×10^{-2} leaks and 2×10^{-3} "major ruptures" could be expected per year. However, it is expected that the chemical and physical characteristics of the individual working fluid chosen will be important in the determination of failure potential and assessing the importance of this potential for worker safety.

Failure potential for the thermal storage subsystem will be similar to the McDonnell Douglas single module steam system.

5.3.6 Summary of the Failure Rate Results for the Parabolic Trough System:

In analogy to Section 4.3.6, a plot of expected failures, including both operating and demand-dependent failures, has been constructed. This is shown in Figure 11. As for the parabolic dish systems considered in Section 4, several failure modes contribute significantly to the aggregate failure rate. Comparison of Figures 7 and 11 show that the parabolic trough system tends to have a somewhat lower failure rate than the parabolic dish systems, but the difference is not very great. The cautionary comments of Section 4.6.6 apply to the interpretation of the significance of these failure rates.

Figure 11

Expected Failure Events in a 100 MWe Parabolic Trough System

6. 100 MWe Central Tower Steam Receiver Design

Central tower systems can vary greatly in design, depending upon the size of the receiver-collector field modules, choice of collector fluids, receiver temperature ranges, and type of thermodynamic conversion cycle used for power generation. The nearest-term designs generally employ a water/steam cooled receiver and conventional Rankine cycle electric power generation. In this section, the McDonnell Douglas 100 MWe design [10] will be described and analyzed for failure potential. This design was developed as part of the developmental work associated with the Solar 1 10 MWe pilot plant to be constructed at Barstow, California.

Ideally, one would wish to analyze designs covering a range of sizes, and design concepts. However, appropriate failure data does not exist for other more advanced concepts. Further, it is felt that the uncertainties in any of the calculations exceeds the differences to be expected between any closely related design options.

It is hoped that the analysis for the McDonnell Douglas steam system, which will be the first to be pilot-tested, can be usefully applied to other central receiver systems for the purposes of comparative safety analyses.

6.1 Common Design Requirements of the McDonnell Douglas Central Tower 100 MWe Systems

The McDonnell Douglas 100 MWe systems have been designed with options for 1, 3 or 10 independently operating control towers. All systems utilize a single power generation system fed from the single or several towers incorporated in the designs. Thus, as in the parabolic dish systems described in Section 4, modules can be used to compose the 100 MWe system. In contradistinction to the parabolic dish designs, however, these modules must be in close physical proximity. However, in so far as

hazards arise from components not used to link the towers to the electric power generators, this analysis may be interpreted as an exploration of scale effects on failure rates.

Common design requirements of the three systems include the ability to generate 510 MWt of steam at 510°C and 10.1 MPa, using the same heliostats and solar insolation value. All three systems utilize the same electric power generation and thermal storage subsystems. Similar master control subsystems are expected. The important distinguishing variables, then, are the sizes of towers, receivers, and collector fields, and the amounts of piping and other fluid control equipment. These aspects of the systems will be described first, then the common power generation and thermal storage subsystems will be discussed. Finally, an analysis of failure rate for the systems will be presented.

The 1, 3, and 10 tower designs have thermal outputs of 510, 170, and 51 MWt per tower, respectively. It will be by these thermal power ratings that the tower designs will be denoted.

The requirement of 510 MWt at a solar insolation of 950 W/m² dictates the number of heliostats. We assume 70 and 90% efficiencies of the heliostat and receiver surfaces, respectively, and the second-generation McDonnell Douglas heliostat design, for which the heliostat area is approximately 45 m². The systems therefore require

$$\frac{510 \text{ MWt}}{(950)(0.70)(0.90)(49) \text{ W/heliostat}} = 18,900 \text{ heliostats}$$

6.2 Description of the 510 MWt Tower Design

6.2.1 Piping: The receiver in the 510 MWt tower system is located on a 242 m tower. There, feedwater is heated to steam at 516°C and 11.1 MPa in 4 preheater and 20 boiler panels. Boiler panels are made up of 170 tubes per

panel, and the preheater panels contain 113 tubes. The tubes are longitudinally welded to each other, and are 27 m in length. Total length of tubing in the receiver is then

$$(170/\text{panel})(20 \text{ panels})(27 \text{ m}) = 92 \text{ km}$$

in the boiler panels, plus

$$(113/\text{panel})(4 \text{ panels})(27 \text{ m}) = 12 \text{ km}$$

in the preheater panels. The total receiver tubing is then 104 km. Additionally each panel has an inlet and an outlet manifold welded to the tubes.

A receiver startup flash tank is included. It is a cylindrical vessel, used during warmup operation, 2.13 m long by 1.22 m in diameter, with vapor and condensate lines connected to it.

Four pipes for water/steam transport connect the receiver with the electric power generation area of the plant. The tower riser brings feedwater to the receiver. The water is pumped by three half-capacity electric feedwater pumps. The tower downcomer transports steam down the tower to the power generation area of the plant. The other two pipes are the receiver startup flash tank vapor condensate lines, mentioned above. These four lines follow the same routing, and are each about 450 m in length, for a total of 2 km. Total piping within the tower is thus 106 km. Since there is only a single tower, piping to the turbine generator should be minimal.

Each water and steam line through the tower is estimated [10] to have 60 fittings, making a total of 240. Some additional connectors are expected, but should be relatively few in number. The receiver tubes are welded at each end to the manifolds and, due to their length of 27 m, may each have two additional welds. There are 3852 tubes, from the panel designs specified above, so there will be 15,400 welds.

6.2.2 Valves: Each of the 24 receiver panels has three valves, and each of the four steam/water risers and downcomers will have two manual isolation and two fill and drain valves. A total of 88 valves will be therefore needed in the tower.

6.2.3 Additional Tower Components: Several flow and temperature sensors may be included in each receiver panel, for a total of approximately 100. Two cyclone water separators will be included with each boiler panel, for a total of 40.

6.2.4 Heliostat Drive Motors: The 18,900 heliostats in the single field will each require three motors, two for positioning and one for emergency slewing. The system therefore requires 56,700 motors.

6.2.5 Heliostat Wiring: The heliostats must each be connected to a central control system for motor drive and position sensing. The heliostat placement is complex, with variable heliostat spacing, and with a non-circular field shape. For simplicity, a uniform circular field with 23% coverage will be presumed. It will be presumed that each quadrant of the field will be separately wired through a radial and axial wiring pattern. The tower and associated generation equipment will be assumed to occupy a 100 m diameter inner circular region.

The heliostats, which occupy 23% of the land area, must each cover a field of area

$$\frac{45 \text{ m}^2}{0.23} = 196 \text{ m}^2$$

This is a circular region of 15.8 m diameter. This diameter will be by the assumed heliostat radial spacing. The total field will be of area

$$18,900 \text{ heliostats} \times 196 \text{ m}^2/\text{heliostat} = 3.70 \text{ km}^2$$

An annular region of thickness 1035 m centered about the inner 100 m diameter tower region suffices for this region. The field may therefore be envisioned

as having 66 concentric heliostat rings. The n th ring is at a radial distance r_n , equal to $(15.8n + 50)$ m, from the control area. (50 m is the radius of the inner region.) The circumference of the ring, and hence the number of heliostats per ring, is proportional to the distance of the ring from the field center. To provide the correct number of heliostats, an axial spacing L is assumed, such that the total length of the 66 rings is the number of heliostats times L . The circumference of each ring is $2\pi r_n$, hence

$$18900L = \sum_{n=1}^{66} 2\pi(15.8n+50)$$

Solving this gives $L = 12.7$ m.

Each field quadrant will be presumed to have a wire going to the heliostats radially along the centerline of the quadrant and then axially along the ring. The number of heliostats in a ring is given by $[2\pi r_n/L]$, where $[x]$ is the largest integer no greater than x . One eighth of these, or $[\frac{1}{4} \pi r_n/L]$, will be on one side of each of the four quadrant centerlines. The m th heliostat from the centerline in the n th ring will therefore have a wire length requirement of $mL+r_n$. Since there are 8 identical half-quadrants, the total wiring requirement is found by summing these lengths over one half-quadrant. This may be written as

$$8 \sum_{n=1}^{66} \sum_{m=1}^{[1/4 \pi r_n/L]} (mL+r_n)$$

For simplicity, the quantity $\frac{1}{4} \pi r_n/L$ may be presumed to be an integer. The summation may be done directly, then, and gives a value of 19,500 km of wiring for the parameters specified. Wiring for three reversible motors will require 7 wires, and for a two-axis position sensor about 6, so approximately 13 wires will be required per heliostat. The total wiring requirement

will therefore be approximately 254,000 km. This value is only approximate, and will be significantly dependent on the field wiring pattern as well as the uniformity of heliostat placement. For the current purposes this estimate is believed to be sufficiently precise.

6.3 Description of the 170 MWt Tower Design

Each receiver in the three receiver tower 100 MWe system is located atop a tower expected to be about 150 m in height. The towers, each with a maximum thermal output of 170 MWt of steam at 510°C and 11.1 MPa, feed into a common turbine generator and thermal storage subsystem. The following sections describe first the components of a single tower, and then the interconnecting components.

6.3.1 Piping for the 170 MWt Tower Design: The receiver in the 170 MWt tower will have 24 external panels. Of these, there will be 20 boiler panels and 4 preheater panels, each 20 m long. Boiler panels will contain 120 tubes per panel and preheater panels will contain 90 tubes per panel. Tubes will be longitudinally welded together. Lengths of receiver tubing in the boiler panels will be

$$(120/\text{panel})(20 \text{ panels/tower})(20 \text{ m}) = 48 \text{ km}$$

and in the preheater panels

$$(90/\text{panel})(4 \text{ panels/tower})(20 \text{ m}) = 7 \text{ km}$$

Each receiver panel also has an inlet and an outlet manifold welded to the tubes.

Each receiver will include a receiver startup flash tank 2.0 m long and 0.90 m in diameter, with design pressure 2.51 MPa, with vapor and liquid lines connected to it. These lines, and the riser and downcomer lines, are about equal in length, and are in the same proportion to the tower height as those in the 510 MWt tower system described above. On this basis, each line is

279 m in length, for a total of 1.5 km. Total piping is then 57 km within the tower.

As in Section 6.2.1, we assume the presence of 240 fittings on the four lines running through the tower. The receiver tubes will be presumed to be welded at top and bottom, and to have one additional weld to form the tubes. There are 2760 tubes, with 8280 welds.

6.3.2 Valves: Valving is associated with each panel and with each riser and downcomer. Since the 510 and 170 MWt designs have the same number of each, the valve count cited in Section 6.2.2 of 88 valves per tower will apply to this design.

6.3.3 Additional Tower Components: Several flow and temperature sensors may be included in each receiver panel, for a total of approximately 100. Two cyclone water separators will be included with each boiler panel, for a total of 40.

6.3.4 Heliostat Drive Motors: Each of the 170 MWt tower modules must have one third of the total heliostats, or 6300. As in Section 6.2.4, three motors will be required per heliostat for a total of 18,900.

6.3.5 Heliostat Wiring: The assumptions cited in Section 6.2.5 will be used, with the exception that the tower and associated equipment will be assumed to occupy a 60 m diameter circular region, rather than the 100 m region in the 510 MWt tower design. This change maintains approximately the same azimuthal angle for the innermost heliostat in the two designs. The heliostats are again assumed to be arrayed in rings, with the n th ring a distance r_n from the control center, where r_n is given by $(15.8n+30)$ m (30 m is the radius of the inner region). To provide the appropriate area for 6300 heliostats, the annular region must have an area of 1.23 km^2 , equivalent to a ring of thickness 600 m. The field is then assumed to be comprised of

600/15.8 $\approx$ 38 concentric rings, with axial spacing of heliostat L, such that, analogously to Section 6.2.5,

$$6300L = \sum_{n=1}^{38} 2\pi r_n$$

Solving this equation gives L = 12.8 m. Then the wiring length for a single wire per heliostat is found, as in Section 6.2.5, as

$$8 \sum_{n=1}^{38} \left[\frac{1}{4} \pi r_n / L \right] (mL + r_n)$$

and is approximately 3840 km. For the 13 wires per heliostat cited in Section 6.2.5, 49,900 km of wiring will be required

6.3.6 Interconnecting Components: The McDonnell Douglas design [10] specifies a total of about 13 km of piping and 48 valves to connect all three towers to the central power generation area. Assuming that the maximum pipe length is 12.2 m (40 ft), 1070 pipe connections will be required. Additional components, including wiring, may be required, but these are expected to be relatively small additions to the component counts calculated above.

6.4 Description of the 51 MWt Tower Design

Receiver specifications for this system are based, in part, upon the design of the 10 MWe Solar 1 pilot plant [10] to be constructed at Barstow, California. Each receiver in this tower design is located atop a tower 67 m in height. Each tower will have a maximum thermal output of 51 MWe of steam at 510°C and 11.1 MPa, and will be surrounded by one tenth of the total number of heliostats, or 1890. Steam will be fed to a common turbine generator and thermal storage subsystem. The following sections describe first the components of a single tower, and then the interconnecting components.

6.4.1 Piping for the 51 MWe Tower Design: The receiver of the 51 MWt tower design will have 24 external receiver panels. Of these, 18 will be boiler

panels and 6 preheater panels per tower, both types of panels contain 70 tubes per panel, and the tubes are 13.9 m in length. Total length of tubing is then

$$(24 \text{ panels/tower})(70 \text{ tubes/panel})(13.9 \text{ m}) = 23 \text{ km}$$

Each receiver panel has an inlet and outlet manifold welded to the tubes.

The receiver will include a cylindrical receiver startup flash tank 1.82 m in length, and 0.60 m in diameter, with design pressure 2.51 MPa, and with vapor and condensate lines attached.

Riser, downcomer, flash tank vapor and flash tank condensate pipe lines are all assumed to be equal in length and in proportion to tower height based on the 510 MWt tower design. Therefore these pipes are each 121 m long, for a total of 0.5 km for the four lines. Total piping is then 24 km.

As in Section 6.2.1, 240 connections will be required for the four risers and downcomers. The receiver tubes, of which there are 1680, are each single pipe lengths. They will be welded at top and bottom for a total of 3360 welds.

6.4.2 Valves: As in Section 6.2.2, valve counts should be 88 for the receiver and the risers and downcomers.

6.4.3 Additional Tower Components: As in Section 6.2.3, 100 flow and temperatures are assumed to be incorporated in the receiver panels. Two cyclones will be included for each boiler panel, for a total of 36.

6.4.4 Heliostat Drive Motors: The 1890 heliostats will each, as in Section 6.2.4, require three motors, for a total of 5670 motors,

6.4.5 Heliostat Wiring: The tower and associated equipment will be assumed to occupy a region 40 m in diameter, with the n th concentric ring of heliostats located at a radial distance r_n of $(15.8n+20)$ m (20 m is the radius of the inner region). The 1890 heliostats will occupy an annular region of

area 0.37 km^2 , equivalent to a ring of thickness 320 m around the 40 m diameter tower region. The field will then be assumed to be composed of $320/15.8 \approx 20$ concentric rings spaced 15.8 m apart. The axial heliostat spacing, L , is set as in Section 6.2.5 to allow the correct number of heliostats. This requirement is given by the equation which equates the total heliostat spacing and ring circumference, given as

$$1890L = \sum_{n=1}^{20} 2\pi r_n$$

Solving this equation give $L = 12.4 \text{ m}$. In analog to Section 6.2.5, the wiring length for a single wire to each heliostat is given by

$$8 \sum_{n=1}^{20} \left[\frac{1}{4} \frac{\pi r_n}{L} \right] [mL + r_n]$$

and is approximately 370 km. Assuming 13 wires per heliostat, a total of 4810 km wiring will be required.

6.4.6 Interconnecting Components: The McDonnell Douglas design [10] specifies a total of about 35 km of piping and 100 valves to interconnect the towers to the central power generation areas. Assuming that the maximum pipe length is 12.2 m (40 ft), 2870 connections will be required. Additional components, including wiring, will be required, but these are expected to be relatively small additions to the component counts calculated above.

6.5 Electric Power Generation Subsystem for the 100 MWe Central Tower Plants

This subsystem incorporates a turbine which is rated at 112 MWe gross when running on steam at 510°C and 10.1 MPa from the receiver. When running on steam regenerated from the thermal storage subsystem, it is rated at 76.1 MWe gross. The subsystem design features conventional steam turbine power plant elements such as a condenser, wet cooling tower, a low pressure feed-water heater, three high pressure heaters, a deaerator, and water treatment

facilities. Special features for the solar thermal application include three receiver feedwater pumps, five thermal storage drain pumps, thermal storage feed pumps, and circulation lines to the thermal storage subsystem.

6.6 Thermal Storage Subsystem for the 100 MWe Central Tower Plant

The thermal storage subsystem of this plant consists of four vertical cylindrical tanks 27.6 m diameter and 18.3 m high, each of which contains 2×10^7 kg of crushed granite and coarse silica sand in a 2:1 mixture, and 2200 m^3 (538,000 gal) of Caloria HT43 heat transfer oil. Associated with the tanks are an ullage maintenance unit and a fluid maintenance unit. The thermal storage provides six identical heat exchangers in parallel for heating the thermal storage tanks, with hot steam. A desuperheater is provided to cool the steam to the desired temperature for heating the thermal storage fluid, 360°C , and to reduce thermal cracking of the oil. The safety of this system has been reviewed in detail as part of this report series [13].

For the generation of thermal storage steam, the thermal storage steam generator consists of five modules which consist of preheat, boiler, and superheater heat exchangers. Steam is produced at 299°C and 2.72 MPa.

To circulate thermal storage fluid through the heat exchanger loops, for either charging the thermal storage units or generating steam, each is provided with five pumps in parallel. The charging loop has 61 meters of 0.66 m (26 in) diameter piping and 122 m of 0.36 m (14 in) pipe. The extraction loop has 61 m of 0.66 m (26 in) diameter and 91 m of 0.36 m (14 in) diameter pipe.

6.7 Summary of Components of 100 MWe Central Tower Systems

The calculations of component counts for each tower size and for interconnections and common facilities can be used to prepare a summary of components in alternative 100 MWe central tower designs using 1, 3, or 10 towers.

This summary is shown in Table 8. Tower component counts generally increase significantly as the number of towers increases. Other component counts generally are insensitive to the number of towers, except for wiring, which decreases substantially as the number of towers increases. These component counts are shown graphically in Figure 12 for the three tower sizes.

6.8 Failure Rate Estimates for the Central Tower Systems

The component counts summarized in Table 8 and Figure 12 can be used to estimate annual failure rates by application of the data base of Table 1 and Figure 1. The various sources of failures are described below.

6.8.1 Leak Rates of Central Tower Components: In analogy to Section 4.6.1, component counts, mean failure rates, and expected frequency of occurrence of leaks are listed in Table 9. Principle leak sources include piping and connectors. The total leak rate and major leak rates are seen to increase quite sharply as the number of towers increases.

6.8.2 Mechanical and Electrical Equipment Failures: In analogy with Section 4.6.2, routine and demand-dependent failure rates may be calculated for mechanical and electrical components. These failures are shown in Table 10. Principle failures are of motors and wires.

6.8.3 Sensor Failure: The sensor failure rate of Table 1 and Figure 1 predicts failure rates of 1, 3, and 10 per year for the 1, 3, and 10 tower designs.

6.8.4 Electrical Power Generation Subsystem: As in Section 4.6.4, major and minor leak rates are expected to be 0.002 and 0.04 per year, respectively, in the electrical power generation subsystem.

6.8.5 Summary of Failure Rate Results for Central Tower Systems: The results summarized in Tables 9 and 10 may be combined, and thus depict the principle failures in the central tower designs considered. As in Section

Figure 12

Components of Central Tower 100 MWe Systems

Table 8

100 MWe Central Tower Steam System Components

	1 Tower (510 MW _t /tower)	3 Towers (170 MW _t /tower)	10 Towers (51 MW _t /tower)
<hr/>			
Tower Components			
Receiver and Tower Piping	106 km	171 km	240 km
Interconnecting Piping	—	13 km	35 km
Connectors	240	1790	5270
Welds	15,400	24,800	33,600
Valves	88	312	1040
Cyclone Separators	40	120	360
Startup Flash Tanks	1	3	10
Sensors	100	300	1000
Feedwater Pumps	3	9	30
Field Components			
Heliostat Motors	56,700	56,700	56,700
Wiring	254,000 km	150,000 km	48,000 km
Power Generation Subsystem			
Turbine Generator Complexes	1	1	1
Thermal Storage Subsystem			
Thermal Storage Tanks	4	4	4
Heater Heat Exchangers	5	5	5
Steam Generator Heat Exchangers	15	15	15
Charging Loop Pumps	5	5	5
Discharging Loop Pumps	5	5	5
Piping	2 km	2 km	2 km

Table 9
Leak Rates in 100 MWe Central Tower Systems

Component	Number (100 MWe System)			Mean Failure Rate (hour ⁻¹)	Leaks per Year*		
	1 tower	3 tower	10 tower		1 tower	3 tower	10 tower
Valves	88	312	1040	1×10^{-8}	0.003	0.01	0.04
Connec- tors	240	1790	5270	3×10^{-7}	0.3	2	6
Welds	15400	24800	33600	3×10^{-9}	0.2	0.3	0.4
Piping (km)	108	186	277	$1 \times 10^{-6+}$ $3 \times 10^{-8\ddagger}$	0.4	0.7	1
Pressure Vessels	41	123	370	3×10^{-7}	0.04	0.1	0.4
TOTAL					1	3	8
MAJOR LEAKS**					0.05	0.1	0.4

*1 year = 3500 hours at 0.4 availability.

+minor leak rate (hours⁻¹ km⁻¹)

‡major leak rate (hours⁻¹ km⁻¹)

**major pipe leaks and pressure vessel ruptures

Table 10
Mechanical and Electrical Equipment Failure Rates
in 100 MWe Central Tower Systems

Component	Number (100 MWe System)			Mean Failure Rate (hour ⁻¹ de- mand ⁻¹)	Expected Failure Rate		
	1 Tower	3 Tower	10 Tower		1 Tower (year ⁻¹ * demand ⁻¹)	3 Tower (year ⁻¹ * demand ⁻¹)	10 Tower (year ⁻¹ * demand ⁻¹)
Pumps	13	19	40	3x10 ⁻⁵	1	2	4
				1x10 ⁻³	0.01	0.02	0.04
Motors	56700	56700	56700	1x10 ⁻⁵	2000	2000	2000
				3x10 ⁻⁴	6 [‡]	6 [‡]	6 [‡]
Valves	88	312	1040	-	-	-	-
				1x10 ⁻³	0.09	0.3	1
Wire & Cable (km)	254000	150000	48000	3x10 ⁻⁶ +	3000	2000	500

*1 year = 3500 hours at 0.4 availability

+hour⁻¹ km⁻¹

‡assuming one motor operating per demand

4.6.6, demand rates of 10 to 1000 per year will be assumed, except for valves, where only the lower valve will be considered. These results are shown in Figure 13. Principle failures include those motors and in wire and cable.

Figure 13

Expected Failure Events in 100 MWe Central Tower Systems

7. PARABOLIC DISH SYSTEM WITH STIRLING CYCLE DISPERSED ELECTRIC POWER GENERATION

The utilization of solar thermal power systems for small-scale electric power production can be based on individual collector-receiver units with proximate conversion to electricity. One design, developed for the small STPS systems program at JPL, uses parabolic dish concentrator coupled directly to thermal storage and a Stirling cycle engine. The complete power conversion package, including cooling system, can be mounted in a narrow cylindrical region beyond the focal point of the dish and on the axis of symmetry.

The use of individual electric power conversion units on parabolic dishes will inherently make power available in relatively small units. Even a large parabolic dish cannot be much more than 20 to 30 m in diameter if major sections are to be subject to mass production and transportation to the STPS site. This limits thermal power to about 0.4 MWt per module, and electric power to about 0.15 MWe. There will be some economies associated with grouping these units, but probably these will be less significant than in parabolic dish thermal collectors such as are described in Section 4. The JPL designs tend to focus on ~16 m diameter dishes clustered into modules of about 1 MWe with a 40% capacity factor. Consequently, in this section the 100 MWe system to be analyzed will be composed of 100 equivalent and independent 1 MWe modules.

7.1 System Description of the 1 MWe Parabolic Dish Module with Dispersed Electric Power Generation

A 1 MWe module utilizing parabolic dish receiver/collectors with dispersed electric power generation has been designed [14-16] for use in community or small systems applications. With several variations in collector geometry and operational modes, the system consists of 23 independent para-

abolic dishes 16 m in diameter. The collector provides thermal energy to a Stirling cycle engine mounted behind the receiver focal plane and on the dish axis of symmetry. The collector can be designed to provide integral thermal energy storage (TES) by providing a TES media inside of capsules thermally coupled to the collector and to the engine by heat pipes. (Other designs provide no more than a TES buffer with storage provided by a battery system with rectifier and inverter.) A single dish provides ~50 kWe gross, with some reserve possible for storage and leveling. In addition to TES, a natural gas-fired auxiliary heater can be provided for hybrid operation. Engine cooling is provided by a water/ethylene glycol coolant system with a radiator mounted on the engine support structure. In that fashion, dry cooling is provided and the coolant system design does not have to allow for dish motion with respect to the ground. A proposed field layout is shown in Figure 14. The dish spacings are 31.8 and 60.1 m in the two coordinate directions. The field coverage is approximately 14%.

7.2 Component Description of the 1 MWe Dish/Stirling System Receiver

The 1 MWe system will be composed of 23 identical parabolic dish receiver / collectors with dish mounted Stirling cycle engines ("dish/Stirling"). The components of this system will be described in the following sections.

7.2.1 Receiver and TES Components: For the several designs considered [15], the receiver is composed of a thermal absorber for solar insolation cooled directly or through intermediate components by the working gas of the Stirling cycle engine. Since this gas is generally at high pressure (c. 10 MPa peak), the heat transfer elements to this gas will be composed either of an appropriately designed pressure vessel or tubing bundle. For specificity, we will model the system as having the former, although failure rates must be expected to be similar in the two cases.

■ UTILITY BUILDING

○ PARABOLIC DISH COLLECTOR

Figure 14.

1 MWe Dish/Stirling Field Diagram

The cooling of the receiver, if performed by heat pipes [16], will require 27 primary pipes 25.4 mm in diameter and 0.74 m long, and 196 secondary pipes 12.7 mm in diameter and 0.26 m long. In addition, engine heater head tubing will consist of 50 tubes 6.4 mm in diameter and 0.30 m long. Each of these tubes will be welded at both ends, either for enclosure of heat pipe fluid or for attachment to the engine head. Thus, for a single dish/Stirling unit 86.0 m of tubing and 546 welds will be required.

The Stirling cycle engine will be equipped with three temperature sensors, for receiver, engine, and coolant systems, and an accompanying sensor for the alternator frequency. The working gas pressure will be adjusted to control the operating speed of the engine. This will require a sensor for gas pressure, a pump for pressure control, and a gas cylinder or other vessel for gas transfer. The engine designed by United Stirling of Sweden (USS model P-40) requires four valves for cycle staging. The engine itself requires a starter motor.

The cooling system will have an engine-driven water pump. The coolant lines form a loop between engine and radiator along a 4 m engine strut and a 10.4 m dish support quadrupod, making a total of 28.8 m of water piping per dish/Stirling unit. The coolant lines will also be fitted with fill and drain valves, and will require 8 pipe joints.

A natural gas supply will run along the field and then up each dish structure to the receiver. In addition to the 4 and 10.4 m sections of pipe along the engine strut and dish quadrupod, a 12 m line up the dish support, making a total of 26.4 m per unit. In addition, 5 connectors and a flexible joint are included to allow for dish motion, and a shut-off valve will be provided.

Control of the orientation of the dish will be provided by three motors, two for tracking and one for emergency slewing.

The dish/Stirling unit component count is summarized in Table 11. Twenty-three such units compose a 1 MWe module.

7.2.2 Field Components: The field components for the 1 MWe dish/Stirling system consist of natural gas, electric power, and control networks.

The natural gas piping array is shown in Figure 15. The gas lines run along the three long rows of dishes, and across the utility building. Based on the dimensions of Figure 14, piping length will be 788 m. Assuming that pipes are available in lengths no greater than 12 m (40 ft), 3 connectors are required for each dish in the shorter (31.8 m) direction and 6 in the longer (60.1 m) direction. One connector is also required for attachment to each dish's piping, with three connectors at the intersection of the row lines. This makes a total of 101 connectors on the field. Three shut-off valves will be provided for the long row lines.

Wiring for each dish will be independent and will follow the same geometric pattern as the natural gas lines. The number of wires in each section is shown in Figure 16 for a single wire to each dish. The total wiring length on this basis is 4114 m. Each dish is expected to require approximately 36 wires, to operate the dish drive motors (7 wires), position sensors (6 wires), temperature, frequency, and pressure sensors (10 wires), engine valve controls (5 wires), working gas pump (2 wires), engine starter (2 wires), power output (2 wires), and natural gas igniter (2 wires). Thus total wiring length is 148 km.

Field component counts are summarized in Table 12.

7.3 Summary of Component Counts for a 100 MWe Dish/Stirling System

A 100 MWe system will be composed of 2300 dish/Stirling units located on 100 independent fields. The component counts can therefore be constructed

Table 11
Component Count for a Dish/Stirling Unit

	Component Count
Piping	
Coolant	28.8 m
Natural Gas	26.4 m
Receiver	86.0 m
Connectors	
Coolant	8
Natural Gas	5
Flexible Joints	1
Welds	546
Valves	
Engine	4
Coolant	2
Natural Gas	1
Motors	
Starter	1
Dish Drive	3
Pumps	
Coolant	1
Working Gas	1
Pressure Vessels	
Receiver	1
Working Gas	1
Sensors	
Engine	4
Alternator	1

- UTILITY BUILDING
- PARABOLIC DISH COLLECTOR

Figure 15

1 MWe Dish/Stirling Piping Diagram

UTILITY BUILDING

PARABOLIC DISH COLLECTOR

N

NUMBER OF WIRES

Figure 16

1 MWe Dish/Stirling Wiring Diagram

Table 12
Component Count for a Dish/Stirling Field

	<u>Field Component Count</u>
Natural Gas	
Piping	788 m
Connectors	101
Valves	3
Electric Power and Control	
Wire and Cable	148 km

from those listed in Tables 11 and 12. These counts are listed in Table 15, and are shown graphically in Figure 17.

7.4 Failure Rate Estimates for the Dish/Stirling System

The component counts summarized in Table 13 and Figure 17 can be used to estimate annual failure rates by application of the data base of Table 1 and Figure 1. The various sources of failures are described below.

7.4.1 Leak Rates of Dish/Stirling Components: In analogy to Section 4.6.1, component counts, mean failure rates, and expected frequency of occurrence of leaks are listed in Table 14. The several types of connectors and welds are predicted to be the dominant source of leaks.

7.4.2 Mechanical and Electrical Equipment Failures: In analogy to Section 4.6.2, routine and demand-dependent failure rates may be calculated for mechanical and electrical components. These failures are shown in Table 15.

7.4.3 Sensor Failures: The sensor failure rate is listed in Table 1, gives a predicted frequency of failure events of 100 per year.

7.4.4 Summary of Failure Rate Results for the Dish/Stirling System: The results presented in Tables 14 and 15 may be combined to provide an overview of system failures. As in Section 4.6.6, demands will be assumed to occur at rates of 10 to 1000 times per year. These combined results are shown in Figure 18. Major events include pump, valve, and motor failures.

Table 13

Component Count for a 100 MWe Dish/Stirling System

	Component Count for a 100 MWe System
Piping	404 km
Pipe Connectors	40,000
Welds	1,256,000
Flexible Joints	2300
Valves	16,400
Pumps	2300
Electric Motors	9200
Sensors	11,500
Pressure Vessels	4600
Wire and Cable	14,800 km

Figure 17

Component Counts for 100 MWe Parabolic Dish - Stirling Cycle Dispersed Generation System

Table 14

Leak Rates in 100 MWe Dish/Stirling System

Component	Number (100 MWe System)	Mean Failure Rate (hour ⁻¹)	Leaks per Year*
Valves	2×10^4	1×10^{-8}	0.7
Connectors	4×10^4	3×10^{-7}	40
Welds	1×10^6	3×10^{-9}	10
Flexible Joints	2×10^3	3×10^{-6}	20
Piping (km)	4×10^2	$1 \times 10^{-6+}$	1
		$3 \times 10^{-8\dagger}$	0.04
Pressure Vessels	5×10^3	3×10^{-7}	5
TOTAL			80
MAJOR LEAKS			5

*1 year = 3500 hours at 0.4 availability

+minor leak rate (hour⁻¹ km⁻¹)

†major leak rate (hour⁻¹ km⁻¹)

Table 15

Mechanical and Electrical Equipment Failure Rates
in a 100 MWe Dish/Stirling System

Component	Number (100 MWe System)	Mean Failure Rate (hour ⁻¹)	Failure Rate (demand ⁻¹)	Expected Failure Rate (year ⁻¹ *)	(demand ⁻¹)
Pumps	2x10 ³	3x10 ⁻⁵		200	
			1x10 ⁻³		2
Motors	9x10 ³	1x10 ⁻⁵		300	
			3x10 ⁻⁴		0.7 [‡]
Valves	2x10 ⁴	-			
			1x10 ⁻³		20
Wire and Cable (km)	1x10 ⁴	3x10 ⁻⁶ ⁺		100	
			-		

*1 year = 3500 hours at 0.4 availability

⁺hour⁻¹ km⁻¹

[‡]assuming one motor operating per demand

Figure 18

Expected Failure Events in a 100 MWe Dish/Stirling System

8. COMPARISON OF 100 MWe STPS FAILURE RATES

Eight alternative STPS designs producing 100 MWe at about a 0.4 capacity factor have been described and analyzed to predict expected failure rates.

The systems considered are:

1. Parabolic Dish receivers with central steam/electric generation
100 MWe Module: 1 module/system
2. Parabolic Dish receivers with central steam/electric generation
10 MWe Module: 10 modules/system
3. Parabolic Dish receivers with central steam/electric generation
1 MWe Module: 100 modules/system
4. Parabolic Trough receivers with central organic steam/electric generation
5. Central Tower water/steam receiver with common power conversion
510 MWt Tower: 1 tower/system
6. Central Tower water/steam receiver with common power conversion
170 MWt Tower: 3 towers/system
7. Central Tower water/steam receiver with common power conversion
51 MWt Tower: 10 towers/system
8. Parabolic Dish/Stirling Cycle Dispersed Power Generation
1 MWe Module: 100 modules/system

These systems may be compared on the basis of seven characteristic failure modes, each of which will impact worker health and safety as repairs are made. The categories considered are:

1. Minor pipe leaks
2. Major pipe and vessel leaks (ruptures)
3. Motor failures

4. Valve failures
5. Pump failures
6. Wire and cable failures
7. Sensor failures

In each case we presume that the activities associated with making repairs will have some associated hazard to workers. This assumption will be examined in Section 9 in detail.

8.1 Hazard Rankings

Estimated failure rates for these seven categories and eight systems will be found in Tables 3, 4, 6, 7, 9, 10, 14, and 15, and in Sections 4.6.5, 5.3.3, 6.8.3, and 7.4.3. The failure rates are collected in Table 16. The failure rates are ranked for each category on a scale of 1 to 8, with 1 being the lowest failure rate. In categories for which failure rates have yearly and demand-dependent rates, both rates are considered, and no discrepancies between rankings based on the two rates occur. For cases in which two or more systems have the same failure rates, the average ranking number is assigned to the several systems. The rank totals have been added, and the sums in turn ordered to provide an overall ranking.

The overall ranking arbitrarily is based on an equal weighting for each category ranking. There is no a priori reason why this equal weighting should be preferred over any other proposed pattern. In fact, the choice of equal weights reflects our ignorance, rather than knowledge, of the hazards involved when the preliminary designs are studied in this manner.

8.1.1 Hazard Ranking Sensitivity Analysis: To examine the significance of this weighting, one can correlate the category rankings with the overall rankings. Categories for which category and overall ranking are sensibly the same will have little effect on the overall ranking for any modest change in the relative weighting of the categories. In Figure 19 the overall ranking

Table 16

Aggregate Failure Rates and Rankings of Alternative 100 MWe STPS

	Central Towers			Parabolic Trough	Parabolic Dish/Distributed Generation	Parabolic Dish		
	1 Tower 510 MWe/ Tower	3 Towers 170 MWe/ Tower	10 Towers 51 MWe/ Tower			100 Modules 1 MWe/ Module	10 Modules 10 MWe/ Module	1 Module 100 MWe/ Module
Leaks (year ⁻¹) [Rank]	1 [1]	3 [2]	8 [3]	300 [5]	80 [4]	800 [7]	800 [7]	800 [7]
Major Leaks (year ⁻¹) [Rank]	0.05 [1]	0.1 [3]	0.4 [7]	0.07 [2]	5 [8]	0.3 [5]	0.3 [5]	0.3 [5]
Motor Failures (yr ⁻¹ demand ⁻¹) [Rank]	2000+6 [4]	2000+6 [4]	2000+6 [4]	700+6 [2]	300+0.7 [1]	3000+8 [7]	3000+8 [7]	3000+8 [7]
Valve Failures (demand ⁻¹) [Rank]	0.09 [1]	0.3 [2]	1 [3]	70 [5]	20 [4]	100 [7]	100 [7]	100 [7]
Pump Failures (yr ⁻¹ demand ⁻¹) [Rank]	1+0.01 [1]	2+0.02 [2]	4+0.04 [3]	6+0.06 [4]	200+2 [8]	30+0.3 [7]	9+0.09 [6]	6+0.06 [5]
Wire & Cable (year ⁻¹) [Rank]	3000 [7]	2000 [5.5]	500 [2.5]	2000 [5.5]	100 [1]	500 [2.5]	1000 [4]	4000 [8]
Sensors (yr ⁻¹) [Rank]	1 [1]	3 [2]	10 [3]	500 [5]	100 [4]	1000 [7]	1000 [7]	1000 [7]
Rank Totals [Overall Rank]	16 [1]	20.5 [2]	25.5 [3]	28.5 [4]	30 [5]	42.5 [6]	43 [7]	46 [8]

Figure 19
Category Rankings as a Function of Overall Rankings

is plotted against the seven category rankings. Category and overall rankings are sensibly the same for total leak rate, valve failures, and sensor failures (Figures 19(a), (b), and (g), respectively). With the exception of the dish/dispersed generation system and the inversion of order in the closely-matched parabolic dish systems, pump failures also exhibit this equality (Figure 19(e)). Thus, it is the weighting factors for major leaks, motor failures, and wire and cable failures (Figures 19(b), (c) and (f), respectively) which are most likely to affect the overall rankings. The extent to which these rankings may be affected can be considered in terms of systematic variations of the assumed weighting factors.

The rankings of Table 16 may be concatenated into a ranking for the four failure categories for which the category and overall rankings are sensibly the same (total leaks, and valve, pump, and sensor failures.) Unit weighting factors are assigned to each category, although it is only the sum of these factors which is important. We maintain independent rankings for the other three categories, major leaks, motor failures, and wire and cable failures, and assign weighting factors m_l , m_f , and w_c , respectively. For physical reasons, the weighting factors must be non-negative. The rank totals for each system may then be written as

$$R_1 = 4 + m_l + 4 m_f + 7 w_c$$

$$R_2 = 8 + 3 m_l + 4 m_f + 5.5 w_c$$

$$R_3 = 12 + 7 m_l + 4 m_f + 2.5 w_c$$

$$R_4 = 19 + 2 m_l + 2 m_f + 5.5 w_c$$

$$R_5 = 20 + 8 m_l + m_f + w_c$$

$$R_6 = 28 + 5 m_l + 7 m_f + 2.5 w_c$$

$$R_7 = 27 + 5 m_l + 7 m_f + 4 w_c$$

$$R_8 = 26 + 5 m_l + 7 m_f + 8 w_c$$

where R_i is the rank total of the i th system, order as

$i = 1$ central tower: 510 MWt/tower

$i = 2$ central tower: 170 MWt/tower

$i = 3$ central tower: 51 MWt/tower

$i = 4$ parabolic trough

$i = 5$ dish/dispersed

$i = 6$ parabolic dish: 1 MWe/module

$i = 7$ parabolic dish: 10 MWe/module

$i = 8$ parabolic dish: 100 MWe/module

The subscripts i are in the same order as the ranking desired when $m1 = mf - wc = 1$. This will be denoted as the base case. Thus, $R_i < R_j$ in the base case if $i < j$.

8.1.2 Central Tower Hazard Ranking Sensitivity Analysis: In the base case the rankings of the central tower systems deteriorate (i.e. the rank total increases) as the number of towers increases. We can examine the domain of weighting factors under which this ordering is reversed, that is where one or more of the inequalities

$$R_2 < R_1$$

$$R_3 < R_2$$

$$R_3 < R_1$$

is satisfied. These may be written in terms of weighting factors as:

$$R_2 < R_1: 4 m1 - 3 wc < -8$$

$$R_3 < R_2: 4 m1 - 3 wc < -4$$

$$R_3 < R_1: 4 m1 - 3 wc < -16/3$$

Note that the weighting factor for motor failures, mf , does not appear at all in these equations. The three domains described are plotted in Figure 20. As can be seen, the weighting factors must be chosen to be quite large for a complete inversion of rank order (domain III) among the central tower

Figure 20

Domain for the Inversion of Rank Ordering Among the Central Tower Systems

systems. We suspect, therefore, that the correct ordering for the central tower systems is as listed in Table 16, even if the relative weighting factors of the hazard categories is not as in the base case.

8.1.3 Parabolic Dish Hazard Ranking Sensitivity Analysis: A similar question may be posed with respect to the parabolic dish systems. In this case, however, examining the equations above for R_6 , R_7 , and R_8 shows that order inversion can occur only for $w_c < 1/4$. This is possible, but its validity is unclear. As before, we may not know the correct weighting factors, but in this case we must recognize that the closeness of the ranking leads to some uncertainty within the three parabolic dish options. The rankings with respect to other types of systems, however, seem defensible.

8.1.4 Other Ranking Sensitivity Analyses: Several other limited comparisons may be offered. For example, high weighting factors for motor and for wire and cable failures will tend to make the dish/dispersed systems more highly ranked, since its rankings in these two categories are both 1. If it is to rank as well as even the most poorly ranked central tower system (i.e. $R_5 \leq R_3$), then

$$6 \text{ mf} + 3 \text{ wc} \geq 16 + 2 \text{ ml}$$

Either mf, wc, or both must be a fairly large number, even if ml is close to zero. It does not seem likely that either motor or wire and cable failures should be extremely hazardous.

Lastly, for a parabolic trough system, and the equivalent 100 MWe module parabolic dish system to be inverted in rank, $R_8 < R_4$, which requires that

$$9 + 3 \text{ ml} + 5 \text{ mf} + 2.5 \text{ wc} < 0$$

Since the weighting factors are each ≥ 0 , this condition can never be met.

It appears that many relative rankings listed in Table 16 are justifiable even in the absence of incontrovertible knowledge of relative category hazards.

8.2 Discussion of Category Rankings

The ranking procedure has several potential shortcomings, since not all failure categories nor all system failures within each category are equivalent in their respective hazard to workers. Nevertheless, some sense of the relative level of hazard is demonstrated by the category and overall rankings. The significance, problems, and potential shortcomings are discussed in the following sections.

8.2.1 Total Leaks: The rankings of systems with respect to the total rate of occurrence of leaks in Table 16 shows that central tower systems have the lowest rates (lowest ranks). Except for the single 510 MWt tower design, pipe connector leaks dominate, with minor pipe leaks and weld failures following. These failures will, in general, be in the high pressure steam system associated with the receiver and turbine generator. Experience in the electrical services industry [1], which includes most conventional electric power generation utilities, indicates that burn hazards to workers is a significant factor in the aggregate worker injury rate. It would be expected that this would be the characteristic injury type for leaks in central tower designs. However, in receivers using coolants other than water/steam, additional injuries could be expected due to the use of potentially more hazardous materials.

Ranked behind the central tower systems is the parabolic dish/dispersed generation option. The major leak sources are the receiver coolant pipes and welds. This assessment is based on a preliminary design for an integral TES, and hence is subject to substantial uncertainty.

The parabolic trough and parabolic dish systems have large total expected leak rates due to the extensive heat transfer fluid piping networks used in these designs. The straight-line geometry of the parabolic trough provides some significant benefit compared to the complex piping arrangement of the parabolic dish system. The choice of fluid for heat transfer in the parabolic dish system also implicitly causes a relatively high failure rate, since the poor heat transfer capabilities of the silicone oil requires an abnormally large heat transfer area and hence a large quantity of tubing. Intrinsically, the piping networks are extensive, and therefore subject to many failures.

8.2.2 Major Leaks: The most poorly ranked systems, the dish/dispersed and the 10 tower central tower design, are so ranked principally due to the presence of a large number of pressure vessels--the engines and gas storage tanks in the former case, and steam system components in the latter. The remaining systems have major leaks principally due to pipe ruptures. In these cases, the rates and intrinsic hazards should depend on the nature of the fluids used for heat transfer.

8.2.3 Motor Failures: Motor failures usually are related to the size of the collection unit--the larger it is, the fewer such units, and hence motors are required. There are some additional considerations, such as system efficiency, pattern of use, and other uses for motors (e.g., starter motors in the dish/dispersed system). The direct hazard to workers may come from the need to change the failed motor. Other indirect hazards can exist, and need to be considered in a specific system analysis. For example, the possibility was cited in Section 6 that motor failure during the course of heliostat stowing in the wind might require workers to manually stow the heliostat under wind conditions exceeding structural limits. This will expose

workers to a mechanical hazard. Failure to stow a parabolic dish receiver in the event of a loss of coolant accident could lead to melting of the receiver [17] and various worker hazards associated with the event.

One should note that, of all the failure categories, it is in motor failures that the least variability is found. The lowest and highest ranked system differ by approximately a factor of 10 in failure rate. The significance, then, of this category in determining difference in hazard is relatively low.

8.2.4 Valve Failure: The hazards from a valve failure are expected to closely parallel those of pipe leaks. The rankings are seen to be identical, too. Note that leaks in valves are included not as valve failures, but as minor leaks. In either case, however, the replacement of the valve will subject workers to various potential hazards. Again, the question of what this hazard is and how it is controlled is discussed in Section 9.

8.2.5 Pump Failures: The most poorly ranked system in this category is the dish/dispersed system, for which independent coolant and working fluid pumps must be used in small (c. 50 kWe) units. The other systems are relatively more closely grouped than in most other categories, so the effects on worker health and safety may be similar.

8.2.6 Wire and Cable Failures: The number of such failures will be based principally on the size of collectors, as was true for motors, and on the complexity of control functions to be performed. A clear preference exists for small modular systems, as seen by the good rankings of the dish/dispersed and 1 MWe module parabolic dish systems. These systems are ranked well even though the control functions are relatively complex in both cases, demanding a large number of wires per collector.

The repair of faults in some of the larger systems defies imagination. We speculate that the costs of locating a fault in a 3 km line to a heliostat may exceed the economic value of that heliostat.

8.2.7 Sensor Failures: Sensor counts, and hence failure rates, are quite speculative, as is the question of whether failed sensors must be replaced.

8.3 Economic Consideration in the Improvement of Failure Rates

All of the foregoing calculations have used mean failure rates for the appropriate components. Components can, of course, be designed or selected to have lower failure rates, but an economic penalty is extracted in doing so. The choice of how much reliability to "buy" is based either on economic considerations of plant operation or on the economics of worker safety. Experience shows that the two choices may not coincide.

We note in passing that the economic costs of component improvement may differ substantially from system to system. For example, the small number of components other than heliostat drive motors in central tower designs may make them more tractable with respect to reductions in overall hazard level than the other systems considered. The fact that these components are large and specialized may have the opposite effect.

9. OPERATIONS AND MAINTENANCE IMPACT OF ROUTINE FAILURES IN STPS

The preceding sections have considered expected failure rates of major components in several STPS designs. Failure rates of components in the thermal transport systems, including piping, fitting, valves, sensors, and pumps, can amount to several thousand per year per 100 MWe capacity. Failure rates in the collector fields, including wiring and focusing motors, can also amount to several thousand per year per 100 MWe capacity. In some limited number of instances these failures immediately affect worker health and safety, such as if a high pressure steam line were to rupture in proximity to a normal work area. In perspective, however, most of the failures analyzed are minor and present no immediate danger to workers. For example, a minor pipe or flexible joint leak may, over time, cause some significant release of hazardous materials, and there is some hazard presented by the high temperatures at which these components will be. However, the predominant hazard is that the failure must be repaired, rather than some situation induced by the failure itself. During the repair it may be necessary to disassemble the components surrounding the failure, such as pipe insulation, and in fact it may be necessary to search over extended areas to locate the failed component.

The minor nature of the great majority of component failures identified may lead one to believe that the hazard posed to workers is also minor. In general we concur, at least with the proviso that by a minor hazard we mean one which is within our ability to handle failures on a routine and normal basis. Even routine events have their impact on worker health and safety, and minor technology changes may well have significant impact on overall worker injuries (1). In that sense, we would note that a

strategy of STPS design and operation may be developed specifically aimed at the control of worker hazards. For example, distributed collector system may require piping designs and configurations able to provide for ready and facile access to particular components in the event of failures. Maintenance procedures may also have to be modified such as to allow for detection and repair of minor failures.

9.1 Strategy of Failure Repair

Of particular concern in the category of minor or routine failures is the prevalence of minor piping component failures. Since some of the heat transfer fluids proposed for STPS use pose immediate and long term safety hazards, the number of such failures may lead to some substantial excess worker exposure. Both the failure and the attempt to repair the failure will contribute to worker hazards within the plant, and in many cases the operation of the proximate portion of the plant without repair may increase worker hazards.

This partitioning of the hazards into several sources may assist in the development of a strategy of hazard control. The hazard posed by a failure is expected to increase over time once the failure has occurred. For specificity, we consider that a small pipe leak may grow with time or that leaking fluid may accumulate within the insulation of the pipe. Either of these will cause the worker hazard to increase over time.

As a counterbalancing factor, we consider that merely locating the pipe leak will pose some hazard to workers. Since the leak location may not be readily apparent in the presence of extensive pipe insulation, the repair of the leak may require extensive removal of insulation and disassembly of other components. However, if approximately 2,000 failures are occurring

per year, the number of failures located during such a search procedure may be expected to increase as such searches become less frequent.

De facto, the hazard of locating a single failure decreases as searches are made less frequently. This situation is shown schematically in Figure 21. Depending on the way in which the various hazards change with time, a time τ may be selected, as shown in this figure, at which the total hazard of the failure is minimized. The identification of this time may prove difficult, and will depend on many system design characteristics. It is of significance, however, if worker hazard is to be controlled.

Figure 21

Worker Hazards for the Location of a Pipe Failure

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