ATR-77(7523-520)-6

22.5

[redacted]

THE AEROSPACE CORPORATION
El Segundo, California 90245

Aerospace Report No.
ATR-77(7523-20)-6

EVALUATIONS OF 10 MW PILOT PLANT DESIGNS

1 July 1977

Prepared by
THE AEROSPACE CORPORATION
Energy Systems Group
El Segundo, California 90245

FOREWORD

This report is written as a partial account of work performed for the Energy Research and Development Administration, on the Central Receiver Program, under continuation of Contract Number EY76-C-03-1101.

TABLE OF CONTENTS

APPENDICES

A. Collector Subsystem

B. Receiver Subsystem

C. Storage Subsystem

D. EPGS Subsystem

E. Control Subsystems

F. Cost Analyses

G. Total System

1. Introduction

The United States Energy Research and Development Administration (ERDA) is mandated by its organizational charter to foster the development of alternate sources of energy on a broad technological front. One of the more immediately promising approaches is the first generation Solar Thermal Central Receiver which is based on the reception and focusing of the sun's radiance to generate steam for conversion of heat into electrical power. In support of that approach, ERDA has funded four parallel system conceptual studies over the past two years, and shortly will be funding the construction of a Pilot Plant the design of which is derived from those studies.

The synthesis of a preferred configuration for the Pilot Plant from the data provided by the study phase is an interesting but demanding process. Not only must the performance be thoroughly understood, and in some cases spot-checked by independent analysis, but the cost-effectiveness or value of a superior technical approach must be validated before its adoption. Sandia Laboratories, Livermore, technical manager of the study contracts, has been charged with this responsibility by ERDA. In a series of actions begun earlier this year Sandia is evaluating the proposed approaches and will recommend to ERDA one or two "best" configurations for the Pilot Plant.

The Aerospace Corporation, as part of its current efforts in support of ERDA, is assisting in the evaluation process by directly supporting the Sandia review teams. That assistance includes the assignment of eight technical personnel, representing various technical disciplines, to the Sandia working panels to analyze the specifc technical areas as identified by the Sandia chairperson.

This Report is a compilation of material provided to Sandia Laboratories by The Aerospace Corporation. The Report is not an independent evaluation of the Pilot Plant designs. The Report was requested by ERDA as, and is intended to be, a record of The Aerospace Corporation contributions to the Pilot Plant configuration selection process.

At the time of this submittal, the selection process is not complete. Several more weeks of significant activity by the working groups is expected with continued participation by Aerospace. If appropriate, an addendum to this Report will be transmitted at a later date.

2. Summary of Evaluation

The Appendices are the core of this report. They present in an objective way the results of specific analyses or inquiries undertaken for the Sandia working panels. This section summarizes the essential points of those findings, and in addition discusses more subjectively some of the interesting aspects of the Pilot Plant design.

Collector Subsystem

Appendix A1 contains the results of very thorough computer analyses of the four collector field designs presented by Martin, MDAC, and Boeing (2). (A similar analysis of Honeywell's configuration requires modifications to the Aerospace computer program which could not be completed in time for this first report.) The performance simulations included the losses due to atmospheric extinction in the heliostat to receiver space; the expected hourly variation in clear-day insolation levels at an Inyokern site, which can be compared to Barstow performance; and reasonable and uniform tracking and mirror waviness errors. In addition to studying the applicable "design points" the total energy delivered by the fields for approximately 15% of the year's available sunshine hours was calculated.

Based on the quasi-yearly output (510 hours), which is considered to be reasonably representative of the full year, the McDonnell-Douglas overall design was found to be the most efficient, on the basis of total energy received per unit of collector area. It edged the Martin design by about 9% and surpassed the Boeing design by exactly the amount of loss introduced by the Tedlar dome.

Looking closely at the Martin and MDAC losses it appears that though Martin has a better average field cosine (83 vs 78%) over the 510 hours, a fact which supports their contention that the north field is intrinsically more efficient, MDAC has lower average spillage (1.2 vs 2.7%), lower average blocking (0.2 vs 7.2%), and lower average atmospheric losses (1.2 vs 2.0%). These factors apparently more than compensate for the average Martin cosine and shading loss (4.2 vs 7.6%) advantages.

The above results, however, must be put in perspective. What is seen principally is an indication of the effectiveness of a field layout as opposed to the effectiveness of a particular heliostat design. One may note that the north field because of the greater distances of its farthest heliostats intrinsically causes more spillage, that it complicates a layout to prevent blockage, and that it suffers more atmospheric losses. However, a better layout of the Martin field may be possible, and the best heliostat itself cannot be chosen on the basis of these results.

The Boeing performances, for operations in either a surround or north field, were quite good indicating that in spite of the Tedlar loss (and its concomitant requirements of either larger or more heliostats) a satisfactory field layout can be designed. The considerations on Boeing, then, narrow to the individual heliostat design aspects only, i.e., cost and reliability.

The computer analyses produced some other interesting results. Using an Aerospace model of atmospheric extinction the maximum expected losses of the fields due to slant range effects were found to be: MDAC 3.4%; Martin 5.6%; Boeing surround field 3.2%; Boeing north field 5.8%.

In comparing the results of the Aerospace simulations to those of the Contractors at their respective design points, it was found that overall the comparison to MDAC was nearly exact but that the comparison to Martin was not. In this latter case the principal area of disagreement was in shading and blocking, where Aerospace's analysis of Martin's field showed 5.6% loss compared to Martin's estimated 2.0%.

Relative to the need for variable focusing and/or canting of the mirrors Aerospace's computer analyses indicated that such measures are probably not cost effective, reducing spillage from 1.1 to 0.2% for MDAC in going from the worst to best design and from 3.8 to 2.7% for Martin. Spillage due to mirror waviness, however, is a very sensitive function, increasing from 1.1 to 3.0% for MDAC and from 2.7 to 8.2% for Martin as the specification is varied from 1.0 to 2.0 mrad.

The above discussion focussed on the results of computer analyses of the field layouts. The following paragraphs address evaluations of the particular heliostat designs themselves as gleaned from the PDR documentation and as recorded in detail in Appendix A2.

The Boeing design represents a significant and potentially attractive departure from the more massive designs proposed by the other contractors. It intuitively appears to be less expensive to build and maintain principally because the wind protection should result in a lighter structure and less costly drive mechanism.

There are two major questions, however, that are not resolved by the existing Boeing documentation. It is very difficult to come to any conclusion relative to the long term maintenance of optical performance, mainly due to the Tedlar dome. Further, the intuitive feeling that the design is less expensive, particularly over a thirty year period, has not been convincingly demonstrated. These two questions are of course related since any appreciable optical degradation of the dome could affect the cost effectiveness of the design.

In spite of the above reservations the Boeing heliostat deserves continued serious consideration, particularly for the Pilot Plant. It is the only one of the four heliostat designs that is fundamentally different from the others in materials and in the fabrication process. From the point of view of maximizing information return from the limited Pilot Plant operations this approach has to be ranked very high.

The Martin design together with that of MDAC must be characterized as the baseline or non-innovative approach. The Martin design itself does not appear to offer significant advantages over other proposed designs, and in fact has several features which are considered to be potentially troublesome. The yolk mount appears to be mechanically inferior to the MDAC design because of the moments exerted on the azimuth drive and consequently bearing wear. The bonding of glass directly to the steel face sheets is also a major issue receiving considerable attention.

Once again referring to the idea of maximization of information return from the Pilot Plant phase, the Martin design probably should be ranked the lowest. This is chiefly because a similar Martin design is already incorporated in the STTF, where it can generate some desired data on its operational performance and problem areas.

Of the three glass reflector proposals the MDAC design appears to be the best balance between performance, reliability, and cost. The location of the azimuth drive is good and the focusing scheme seems to be the cheapest. It is an overall design similar to Martin's STTF unit, however, and from the information return viewpoint this might be counted against it.

Honeywell's heliostat design, judged strictly on its own merits, fares poorly. The mirror modules are massive and complicated; its larger main members increase the magnitude of thermal effects; and the overall design is judged to be expensive. Because of its tilt-tilt mechanism, however, and the fact that it is built lower to the ground than the other glass units (thus decreasing wind resistance) the Honeywell design might under some circumstances return interesting information from operations in the Pilot Plant.

Receiver Subsystem

(to be provided)

Storage Subsystem

In an overall sense the range of storage subsystem choices offered is considered to be narrow and somewhat unappealing. All three employ oil as the basic medium; two of the three employ Hitec salt for superheating; all are based on sensible heat designs for both the bulk and superheat units.

From a technical point of view the most promising configuration appears to be that offered by Honeywell, which is their paper study (without benefit of experimental data) amalgam of the better aspects of the other contractor approaches. This configuration features the MDAC-like oil-plus-rock bulk storage design augmented by the Martin-like Hitec salt superheater. The exact details of their PDR presentation were not totally satisfying but this basic configuration appears best (see Appendix C1).

This choice could be modified by the results of the Sandia cost effectiveness studies, wherein the additional cost of providing superheat to the storage discharge is weighed against the benefits of the increased cycle efficiency and the associated reduction in the required number of heliostats. If superheat is shown not to be cost-effective, then the MDAC design is indicated.

Electrical Power Generation Subsystem

Until very recently the choice of the EPGS appeared to be an academic exercise, with only the same General Electric turbogenerator unit being proposed by all contractors, and the cooling approach being defined by a stated requirement. In the last week, however, Brown-Boveri of Switzerland has emerged as an exciting and viable contender and other manufacturers have indicated serious interest in receiving the RFQ from Southern California Edison (see Appendix D1).

The Brown-Boveri approach differs from the G. E. in that they propose a high-speed turbine, 9000 rpm vs 3600 rpm, followed by a gear-box unit to allow matching to the requirements of the generator. The high-speed approach is said to have a beneficial cascading effect on the turbine design (smaller unit resulting in the ability to provide higher efficiency blades) such that some 4% greater cycle efficiency is obtained. The addition of the gear-box reduces this number, but the net effect is still appreciably positive.

Investigations in this area by the EPGS panel continues. Aerospace will continue to support the work of the group as required.

Control Subsystems

The term "Control Subsystems" is used here to cover a wide ranging set of Pilot Plant design considerations. To be sure, it refers principally to the Master Control Subsystem (MCS) which is a singular concept and a discrete grouping of hardware items. However, it also covers all the other subsystems controls, in themselves and in connection with the MCS; the interfacing of the major subsystems; the designs of the major subsystems as those designs impinge on control philosophy; operations, safety, and reliability issues; and the acquisition of data from the Pilot Plant that will allow extrapolation of performance and costs to the commercial plant end objectives. In fact, although the direct costs of "controls" are relatively low the concern over these control-related issues and their definition and organization are (and will be) disproportionately high.

Ironically, the Control Subsystems issues are perhaps the least advanced area of the just-completed contracts studies. For this reason, the evaluation Panel on Controls, in many cases has had to concern themselves with first principals: What is the prime objective of the Pilot Plant? Are all the subsystem operating modes and design requirements necessary? How much R&D data is to be extracted from the subsystems? What is the reliability of the existing SCE facilities at Barstow? What is the Public Relations role of the Plant? Because the contractor progress in Control Systems was not so advanced at the end of the study, and because the first principals questions are still in the process of being developed (and answered), the evaluations of Control Systems can not proceed as did evaluations of the other major subsystems. Instead of ranking the contractors as a whole, here the good parts of each design will be adopted and expanded as necessary.

The wide-ranging extent of the Control Systems evaluation and study process is suggested by the number and variety of the subjects reported on in Appendix E. Some of the highlights of these special studies and the key findings of the review of the PDR documentation are summarized below...

- None of the contractor's MCS designs was adequate but MDAC's came closest to desired capabilities.
- Honeywell's MCS capabilities essentially matched MDAC's.
- Martin's MCS was judged to be non-competitive.
- The state of dependency of "Data Acquisition" and "plant control" in the MCS is not yet able to be defined.
- The MCS displays should be designed to satisfy the requirements of public relations.
- From a controls viewpoint the Honeywell heliostat design is inefficient, highly redundant structurally, and difficult to control. The Martin heliostat design, to a lesser extent, is also overweight and mechanically inefficient. The Boeing mechanical design and control features are good. The MDAC design was the best of the glass heliostats.

- The Honeywell-proposed heliostat calibration technique, a tower-mounted array of sensors, is the recommended design (with the addition of inexpensive sensors).

- The MDAC heliostat closed-loop control system design is contraindicated.

- No single-point failures can lead to catastrophic receiver failure.

- The receiver, storage, and EPGS subsystems will use conventional controls techniques. However, their control will be more complex because of the transient nature of the plant.

The reader is referred to the Appendices for a more detailed exposition of these and other aspects of the Control Subsystems.

Cost Analyses

In support of the Cost Panel activities the Aerospace Corporation was specifically requested to analyze the Contractor's inputs in the area of EPGS and Balance of Plant (Structures, Electrical Plant Equipment, Miscellaneous Plant Equipment, etc.). Costs were submitted by the Contractors both for the Commercial Plant and the Pilot Plant, and the details of the Aerospace analyses and responses are recorded in Appendices F1 and F2.

Relative to the Commercial Plant estimates a comparison of the submitted costs to the costs for coal and nuclear plants indicated...

- The contractors' estimates for structures and improvements all fell within the range of historical costs. Honeywell's costs for "Yardwork" were very high.

- The Solar turbogenerator and turbine plant costs are likely to be 2 1/2 times the normal utility cost for these subsystems.

- The contractors' estimates for electrical plant equipment costs appears to be consistent with experience. Honeywell once again showed unusually large costs for switchgear and computer.

- The Solar plant would operate at about 1/3 the operating and maintenance costs of current fossil fuel plants.

Relative to the Pilot Plant the contractors' total estimates of the cost per kW of installed capacity are quite consistent, ranging from $7.0 thousand for Martin through $7.1 for MDAC to $7.8 for Honeywell. The estimated costs of the two-year test program are substantially different, however, with Martin at $3.3, MDAC at $4.2, and Honeywell at $6.6 million. The big difference here occurs in the operation and maintenance category, with the sum of the categories of Technical Support and Spare Parts being reasonably consistent.

Total System

The participation of the Aerospace Corporation in the Sandia System Panel, wherein the technical findings of the other subsystem panels are integrated with the findings of the Costing Group to determine the most cost effective approach, has been minimal. To date, the only occasion for support has been a very early attempt at ranking various Pilot Plant configurations as defined by Sandia. That ranking is shown in Appendix G1. One would conclude from the small spread in the ratings that significant differences in the contractors' designs are not apparent, and thus considerably subjective selections are appropriate. This conclusion, of course, could be modified by the application of the costs, which were not available at the time of the ranking.

APPENDIX A

COLLECTOR SUBSYSTEM

APPENDIX A1

COLLECTOR FIELD PERFORMANCE ANALYSES

Aerospace Participant: C. L. Laurence

Central Receiver - Pilot Plant
Examination of Optical Performance

1.0 Introduction

The design concepts from the pilot plant PDR's of McDonnell-Douglas (MDAC), Martin-Marietta, (MMC) and Boeing have been examined for optical system performance. Four designs are included since Boeing has field layouts compatible with both the MDAC and MMC receivers. The design work of Honeywell will be considered in a later paper.

2.0 Definition of Terms

Certain phrases will be used in this report for specific design concepts Those phrases are concerned mostly with focusing techniques.

2.1 Focusing Techniques

The term mirror will refer to the entire reflective surface of a heliostat. If a heliostat is physically divided into independently movable segments these are referred to as facets. MDAC sometimes calls them segments. For faceted heliostats two modes of energy focusing are possible. The first mode is by tilting of the facets to achieve focusing. This is referred to as canting. The second mode is by shaping the facets to further focus the energy. This is usually done by spherical curvature and is simply referred to as focusing.

There are several conventions for canting or focusing which might be adopted for a plant. The term range will be used to indicate that each heliostat in the field is canted or focused to the slant range of the heliostat from the receiver. The term constant means that the canting or focusing of all heliostats in the field is the same. If the canting or focusing focal length is not specified the focal length is taken to be the slant range of the farthest heliostat directly north of the receiver tower. This has been found to be close to the optimum focal length to use for constant canting or constant focusing. The optimum is actually about 10 to 20% shorter than this and results in some short focusing with most heliostats focused behind the receiver. Focusing long at these long ranges results is only a slight increase in image size over range focusing.

The term zoned refers to the use of a specified focal length to be the same for all heliostats whose slant ranges fall within specified ranges. It is thus an intermediate measure between range focusing and constant focusing.

2.2 Heliostat Configuration

The mutual arrangement of heliostats in the field is referred to as configuration or packing. The contractors have proposed packing techniques which are the same as or closely similar to the following types. The first is north-south, east-west (NS-EW) packing where the heliostats are arranged in north to south rows and east to west columns. The second is radial-stagger (R-S) packing where the heliostats are arranged in radial "rows" and lateral "columns" and alternate intersections of rows and columns are empty. Radial refers to the line from heliostat to receiver tower and lateral is tangential to this line.

3.0 Basis for the Optical Simulation

3.1 Simulation Computer Program

The simulation program divides the heliostats in the field into 121 elements and assumes that each element appears to be a point source from the receiver. The processing is Monte-Carlo cone tracing. A heliostat in the field is randomly selected as well as an element on the heliostat. The location, distance and orientation of the element determine it's contribution to a limb-darkened image of the sun at the receiver. The power density at the receiver is in the form of a 21 x 21 matrix.

The effects of mirror waviness and tracking errors are handled by perturbing the element's orientation in a normal distribution whose one standard deviation angle is specified as an input parameter.

Shading and blocking are handled geometrically by determining whether or not the center of an element falls within the shadow or blocking projection of any one of eight possible neighbors.

Atmospheric absorption is handled by multiplying the power density from an element by $\exp(-\gamma s)$ where s is the slant range and γ is the absorption coefficient.

The program converges by monitoring the relative error in power density at the point of maximum power density in the 21 x 21 matrix. It has been found that 20,000 trials usually produce relative errors of about 0.05.

Data on the field layout is handled in the form of 121 cells in an 11 x 11 matrix. The matrix is fit to the contractor's field design and the radial and lateral spacings of heliostats are calculated for each cell and are input to the program. Trim matrices are also input to the program to indicate if a cell is full partly occuped or empty and if partly occupied where the rows and columns are within the cell.

The program determines plant performance at one selected time of the year. Performance over a period of time is determined by selecting representative times of the year and the number of hours of operation within the year that each point represents. For example, annual performance might be represented by 44 points in time; the 21st day of 7 months; each day in hourly increments from noon to sunset. The entire 12 months, and all day light hours are represented because of the symmetry of the fields with respect to the position of the sun.

Due to the excessively long computer execution times the annual performance was not determined by 44 cases. Ten cases were chosen for each field to represent 510 hours of operation out of approximately 4020 hours annually available.

3.2 Simulation Input Parameter Specifications

The basic input parameters and design specifications used in the simulation for each contractor are given in Table 1. All parameters closely follow contractor specifications except the following items which require explanation.

Item 6. Martins field is divided in configuration. The lower portion is NS-EW packed. In the upper portion the heliostats lie on radial lines and laterals which are east to west rather than tangential. This configuration can be very closely represented by R-S packing.

Item 13. The same reflectivity has been chosen for all contractors using float glass. The value 0.87 was measured in Honeywell SRE tests. If higher reflectivities are achieved the value also represents a realistic degradation of reflectivity due to contamination. The reflectivity given for Boeing is based on Boeing's measurement of the total efficiency for two passes through the dome and one reflection from the mylar surface.

Item 14 and 15. Mirror waviness and tracking errors strongly affect losses due to spillage at the receiver. Many recent measurements show that 2.0 milliradians is a reasonable value to represent tracking errors in the presently designed gimbals. Little or no data is available on mirror waviness. The value 1.0 milliradian has been chosen as a rough estimate. Some data on spillage as a function of mirror waviness will be given. In fairness to the contractors all simulations were done with the same values of mirror waviness and tracking error.

Item 16. MDAC specifies aiming at three evenly distributed points along the length of the receiver.

Item 17. The expected atmospheric losses are based on a study by Dr. C.M. Randall of the Aerospace Corporation (ATM 77(7523-20)-2). The value 5.1×10^{-5} 1/m is taken as a minimum likely loss on a clear day and 1.5×10^{-4} 1/m is taken as a maximum likely loss before shutdown might be required due to weather conditions.

Item 18. Insolation levels are computed from a curve fits of actual insolation data. The data used in this simulation is the best fit of Inyokern data.

The site latitude is taken as 35 degrees north.

4.0 Optical Performance at Ten Selected Times of the Year

The performance at summer solstice, equinox, and winter solstice from noon to sunset in two hour intervals is shown in Tables 2 through 5. Performance at the design point is also shown.

McDonnell-Douglas - Table 2

As specified by MDAC the heliostats are constant canted without facet focusing. Note that the spillage is nearly constant, indicating that the system suffers little from aberration effects, although the effects can be seen as the spillage increases in the later hours. As expected blocking is only a very weak function of solar position and for this design is very nearly eliminated at all times as a source of loss.

Martin-Marietta - Table 3

The Martin simulation is based on range canting, assuming that each heliostat will have its facets tilted on site. The facet focusing is in five zones with slant ranges to 364 m focused at 322 m, from 364 m to 449 m focused to 407 m, from 449 m to 534m focused to 491m, from 534 m to 618m focused to 576m and beyond 618m focused to 661 m.

Again, the spillage is fairly constant in time. The spillage is greater than MDAC's because of the longer average slant ranges involved. The north field is more sensitive to mirror waviness and tracking errors. The blockage is from three to four percent higher than that predicted by Martin. It is likely that minor variations in the field layout could considerably improve the blocking situation.

Boeing (Open Cylinder Receiver) - Table 4

The focusing for this simulation is based on Boeing's equation for the gravity warping of the stretched mylar mirror. The focal length is given by

$$f = 376.5 / \sin \psi$$

where ψ is the elevation of the reflector normal. This focusing works quite well, as is shown by the spillage factors in Table 4. The spillage does show some sensitivity to aberration effects as evidenced by the increases for later hours. Some additional focusing could be beneficial here.

In comparison to MDAC (Table 2) the shading is comparable and slightly better, but the blocking is considerably worse. This illustrates the benefits of additional field optimization. The blocking can be eliminated without appreciably increasing shading. The shading and blocking factors computed here do not include the effects of the domes; thus, in reality will be somewhat greater than the values shown. Boeing has used a larger heliostat size to make up for the lower optical efficiency of the heliostats due to the domes. The cost for this increase will be either more shading and blocking or the decreased efficiency of a larger field.

Boeing (Cavity Receiver) - Table 5

The performance of this field is vary competitive with respect to shading and blocking (again neglecting dome effects) but it has more spillage. The increased spillage is due to the larger number of heliostats located at longer slant ranges from the receiver. The large values of spillage indicate that for this size field some additional focusing mechanism is needed or, perhaps, a larger receiver aperture.

It should be noted that the increased reflector area required to make up for optical efficiency of the domes will have to be greater than that simply required to make up the optical efficiency difference. Whether the increased area is accomplished by larger heliostats or more heliostats the result will be additional shading and blocking due to the larger heliostats or additional spillage due to more distant heliostats.

5.0 Summary of Performance Representing 510 Hours of Operation

The total energy received and lost as well as time weighted averages of the performance factors are given in Table 6. These offer an easier comparison of the fields over a period of time and could serve as a rough approximation to annual performance.

The fourth line in the table is the total received energy divided by the total collector area. The MDAC design make the most efficient use of the collector area. The field could have been even more efficient with fewer heliostats. Too many heliostats have been added to allow for outages. Boeing's overall efficiency is lower primarily because of the optical efficiency of their heliostats.

Spillage and atmospheric losses will always be worse for the north field because of the increased average slant ranges. The Boeing north field has consideraly larger losses due to spillage.

The shading and blocking performance of the MDAC field is superior even though more heliostats are used than in Boeing's open cylinder field. The Martin field is the worst in this area primarily due to excessive blocking. The Boeing cavity receiver field performs well but only because the field is excessively large.

The open cylinder (surround) type fields have the worse average cosine factors but this more than compensated for in other areas of optical performance.

6.0 Atmospheric Absorption

The minimum and maximum expected atmospheric losses for each field are given in Table 7. Due to the longer average slant ranges the north field is more sensitive to this loss. However, it appears that the clear weather losses will not be more than one or two percent.

7.0 Design Point Efficiencies

The simulation generated efficiencies and received power levels at the design points are compared for MDAC and MMC in Tables 8 and 9.

In Table 8 it was felt that MDAC under estimated heliostat utilization and over estimated spillage but no significant differences are apparent.

In Table 9 the calculation of total potentially available power did not agree with the figure given by Martin. The difference is not significant and is very sensitive to estimated heliostat area.

The most significant differences for Martin is in the blocking losses. The simulation shows 3.6% more blocking than estimated by Martin. After a great deal of experience with the use of the simulation program on many field layouts there is no reason to doubt the blocking factors generated by the program. Blocking in certain heliostats was checked by hand calculations. The use of R-S packing to represent the packing of the outer portion of the Martin field would not signicantly affect blocking since the only approximation is in the location of laterally placed neighbors.

8.0 Special Parametric Studies

8.1 Dependence of Loss on Focusing Techniques

Tables 10 and 11 present the losses due to spillage at the receiver for various focusing techniques. Table 10 shows that 0.6% is gained if the facets are slant range canted. About .3% to .4% is gained if the facets are curved. Such improvements are not likely to be cost effective.

Martin advocates the use of range canting with zone focusing. Table 11 shows that very little is gained from this technique over less costly methods. One of the least costly methods is constant canting with constant focused facets. This will only degrade performance by about 0.4%.

8.2 Sensitivity to Mirror Waviness

Tables 12 and 13 shows that spillage is very sensitive to mirror waviness and that the north field is much more sensitive to this effect. All of the spillage values are for 2.0mr tracking errors, each axis.

8.3 Effect of Facet Curvature on Receiver Spillage

Since facet flatness is sensitive to ambient temperature several runs were made on the MDAC design for various facet curvatures. These runs assume that all facets in the field are curved the same. The results are shown in Table 14. The temperatures are computed from data supplied from B. Delameter of Sandia Corporation, Livermore, California. The focal length temperature relationship is based on the assumption the facet is formed flat at 70°F. If it is formed at another temperature the temperatures are shifted accordingly.

The data shows that large variations in curvature from slightly negative curvature (convex surface) up to curvatures focusing as short as 200m will not significantly affect performance. The corresponding temperature range is from 60°F to 120°F. Some curvature is beneficial. The optimum focal length is about 300 meters.

9.0 Conclusions

In order of optical performance the field designs should be ranked in the following order

A) McDonnell-Douglas
B) Martin-Marietta
C) Boeing with MDAC Receiver
D) Boeing with MMC Receiver

In terms of the number of heliostats, size of the field, and shading and blocking efficiency the MDAC field is superior. From an optical standpoint it is most efficient to be able to surround the receiver when northern located heliostats are less efficient because of their range. Thus, the surround field is more efficient than the north field (This statement only applies to the 10 MW field). For a final selection the efficiency of the receivers must be included in the comparison. If the open receiver is more thermally lossy it could offset its optical advantage.

Of interest is the use of the Boeing heliostat in a fully optimized field layout. Assume the heliostats are 25% less efficient than MDAC's. As pointed out previously, the field will require more than 25% more heliostats to produce the same energy levels. The additional heliostats are less effective because they have to be farther away from the receiver. If the heliostats are larger there will be additional shading and blocking.

Table No. 1

PILOT PLANT DESIGN SPECIFICATIONS USED FOR OPTICAL SIMULATION

	McDonnell Douglas	Martin Marietta	Boeing (Cylindrical Receiver)	Boeing (Cavity Receiver)
1) Field Size (m) N-S, E-W	568 x 703	618 x 660	600 x 600	800 x 800
2) Tower Location (m) (from north edge)	368	618	400	800
3) Receiver Height on Tower (m)	80	90	80	90
4) Receiver Type	open cylinder	cavity	open cylinder	cavity
5) Receiver Dimensions (m)	7 dia. x 12.5	aper. 7.50 x 7.50	7 dia x 12.5	7.50 x 7.50
6) Heliostat Configuration	radial-stagger	mixed	N-S, E-W	N-S, E-W
7) Heliostat Type	6 facet invertable	9 facet dished	Mylar with dome	Mylar with dome
8) Heliostat Area (m^2)	37.9	41.0	48.5	48.5
9) Number of Heliostats	1760	1554	1643	1893
10) Total Collection Area (m^2)	66,704	63,714	79,721	91,851
11) Focusing Method	flat facets same cant	dished facets zoned radii range canted	gravity focused	gravity focused
12) Canting Focal Range (m)	351	slant range	N/A	N/A
13) Mirror Reflective Efficiency	0.87	0.87	0.68	0.68
14) Mirror Waviness (mr)	1.0	1.0	1.0	1.0
15) Tracking Error (mr)	2.0	2.0	2.0	2.0
16) Aim Strategy	3 points 0, +/- 1/3 height	centered	3 points	centered
17) Atmospheric Losses (1/m)	5.1×10^{-5}	5.1×10^{-5}	5.1×10^{-5}	5.1×10^{-5}
18) Insolation Levels	curve fit of Inyokern data			

Table No. 2

Ten Performance Points within the Year

Contractor: McDonnell Douglas

Specifications: Constant Canting
Flat Facets
1760 heliostats*

DAY and TIME	Insolation (W/m^2)	Power Received (MW)	Power Lost (MW)	Spillage %	Shading %	Blocking %	Average cosine
JUNE 21 Noon	1042	50.35	0.56	1.1	0.0	0.02	0.8474
JUNE 21 2 pm	1015	47.60	0.59	1.2	0.0	0.18	0.8252
JUNE 21 4 pm	903	38.95	0.49	1.2	0.56	0.27	0.7611
JUNE 21 6 pm	483	13.81	0.21	1.5	21.56	0.24	0.6699
SEPT 21 Noon	1022	49.24	0.62	1.2	0.0	0.14	0.8464
SEPT 21 2 pm	980	45.95	0.59	1.3	0.05	0.10	0.8234
SEPT 21 4 pm	780	31.17	0.38	1.2	6.00	0.20	0.7507
DEC 21 Noon	917	42.21	0.42	1.0	1.52	0.14	0.8159
DEC 21 2 pm	830	35.64	0.44	1.2	4.85	0.19	0.7990
DEC 21 4 pm	325	9.00	0.13	1.4	31.26	0.18	0.7376
Design Point	950	40.90	0.47	1.1	4.72	0.23	0.7960

*Losses due to heliostat outages, sensor posts, and tower shadowing not included

Table No. 3

Ten Performance Points within the Year

Contractor: Martin Marietta

Specifications: Range Canting
Zoned Facet Focusing
1554 heliostats*

DAY and TIME	Insolation (W/m^2)	Power Received (MW)	Power Lost (MW)	Spillage %	Shading %	Blocking %	Average cosine
JUNE 21 Noon	1042	42.90	1.16	2.6	0.0	5.80	0.8496
JUNE 21 2 pm	1015	40.33	1.19	2.9	0.03	5.67	0.8245
JUNE 21 4 pm	903	30.99	0.92	2.9	2.10	6.16	0.7390
JUNE 21 6 pm	483	11.15	0.48	4.1	11.88	5.21	0.6090
SEPT 21 Noon	1022	43.79	1.17	2.6	0.0	8.26	0.9254
SEPT 21 2 pm	980	41.21	1.04	2.5	0.01	8.09	0.8968
SEPT 21 4 pm	780	26.78	0.32	1.2	4.52	8.09	0.8148
DEC 21 Noon	917	39.78	1.05	2.6	0.0	9.88	0.9661
DEC 21 2 pm	830	34.61	0.88	2.5	0.93	9.34	0.9409
DEC 21 4 pm	325	9.86	0.26	2.6	16.63	6.14	0.8715
Design Point	950	37.85	1.06	2.7	0.02	5.62	0.8205

*Losses due to heliostat outages, sensor posts, and tower shadowing not included

Table No. 4

Ten Performance Points within the Year

Contractor: Boeing (Open Cylindrical Receiver)
Specifications: Gravity Focus, 1643 heliostats*

DAY and TIME	Insolation (W/m^2)	Power Received (MW)	Power Lost (MW)	Spillage %	Shading %	Blocking %	Average cosine
JUNE 21 Noon	1042	46.64	0.51	1.09	0.0	1.24	0.8557
JUNE 21 2 pm	1015	44.07	0.50	1.13	0.0	1.53	0.8287
JUNE 21 4 pm	903	34.36	0.63	1.81	3.5	1.79	0.7717
JUNE 21 6 pm	483	12.70	0.43	3.24	19.99	1.80	0.6817
SEPT 21 Noon	1022	44.89	0.70	1.53	0.0	2.39	0.8550
SEPT 21 2 pm	980	41.71	0.73	1.73	0.0	2.56	0.8286
SEPT 21 4 pm	780	27.39	0.78	2.78	8.10	2.03	0.7604
DEC 21 Noon	917	35.14	0.86	2.39	7.88	2.60	0.8337
DEC 21 2 pm	830	32.61	0.92	2.73	2.98	2.80	0.8045
DEC 21 4 pm	325	8.74	0.42	4.54	23.63	2.16	0.7350
Design Point	950	37.47	1.10	2.85	2.84	2.62	0.7992

* Losses due to heliostat outages, sensor posts, and tower shadowing not included.

Table No. 3
Ten Performance Points within the Year

Contractor: Boeing (Cavity Receiver)

Specifications: Gravity Focus, 1893 heliostats*

DAY and TIME	Insolation (W/m^2)	Power Received (MW)	Power Lost (MW)	Spillage %	Shading %	Blocking %	Average cosine
JUNE 21 Noon	1042	50.84	1.78	3.38	0.0	2.66	0.8480
JUNE 21 2 pm	1015	47.90	1.66	3.36	0.0	2.66	0.8193
JUNE 21 4 pm	903	36.69	1.60	4.18	3.42	2.13	0.7352
JUNE 21 6 pm	483	13.67	0.88	6.08	15.73	1.33	0.6082
SEPT 21 Noon	1022	53.04	1.94	3.53	0.0	3.79	0.9151
SEPT 21 2 pm	980	49.18	2.01	3.93	0.0	3.70	0.8846
SEPT 21 4 pm	780	32.78	1.78	5.20	6.73	2.62	0.8079
DEC 21 Noon	917	45.61	2.61	5.41	5.00	4.13	0.9500
DEC 21 2 pm	830	41.31	2.60	5.92	2.06	4.00	0.9263
DEC 21 4 pm	325	12.20	1.10	8.28	18.22	2.96	0.8525
Design Point	950	44.55	1.61	3.49	0.0	2.94	0.8215

* Losses due to heliostat outages, sensor posts, and tower shadowing not included.

Table No. 6

SUMMARY OF THE TEN PERFORMANCE POINTS REPRESENTING 510 HOURS OF OPERATION

	McDonnell Douglas	Martin Marietta	Boeing (Cylindrical) Receiver	Boeing (Cavity) Receiver
Total Insolation (MW - Hr/m^2)	0.4083	0.4083	0.4083	0.4083
Total Received Energy (MW-Hr)	17581	15490	15895	18490
Total Lost Energy (MW-Hr)	220	437	327	888
Total Energy Received per Unit Collector Area (MW-Hr/m^2)	0.264	0.243	0.199	0.201
Spillage (%)	1.24	2.70	2.00	4.60
Average Shading (%)	7.64	4.23	7.31*	5.73*
Average Blocking (%)	0.16	7.15	2.09*	2.91*
Average Cosine	0.7790	0.8314	0.7862	0.8224
Minimum Atmospheric Losses (%)	1.2	2.0	1.1	2.0

* These numbers do not include the effects of shading and blocking by the domes

Table No. 7

ENERGY LOSSES DUE TO ATMOSPHERIC ABSORPTION

Minimum absorption is based on $\gamma = 5.1 \times 10^{-5}$ 1/m *
Maximum absorption is based on $\gamma = 1.5 \times 10^{-4}$ 1/m

	ENERGY LOSSES (%)	
	Min.	Max.
McDonnell Douglas	1.2	3.4
Martin Marietta	2.0	5.6
Boeing-Open Cylinder	1.1	3.2
Boeing-Cavity	2.0	5.8

* $T = e^{-\gamma L}$

T = transmittance

L = path length

Table No. 8

McDONNELL DOUGLAS - DESIGN POINT EFFICIENCIES

WINTER SOLSTICE 2 P.M., 950 W/m^2 INSOLATION

	Aerospace Simulation		McDonnell Douglas	
	Power Level	Efficiency	Efficiency	Power Level (MW)
Incident Power Available	63.4 MW			63.4
Heliostat Utilization		0.974	0.969	
Effective Cosine		0.796	0.801	
Heliostat Reflectivity		0.870	0.880	
Shading and Blocking		0.951	0.950	
Sensor Post and Tower Losses*		0.974	0.974	
Atmospheric Attenuation		0.988	0.980	
Spillage (mirror waviness and tracking)		0.989	0.977	
Incident Power on Receiver	38.8 MW			38.3

*Not independently estimated

Table No. 9

MARTIN MARIETTA - DESIGN POINT EFFICIENCIES

SUMMER SOLSTICE, 2 P.M., 950 W/m^2 INSOLATION

	Aerospace		Martin-Marietta	
	Simulation Power Levels	Average Efficiencies	Efficiency	Power Level (MW)
Incident Power Available	60.51 MW[1]			60.48
Heliostat Utilization		0.997[2]	0.997	
Effective Cosine		0.821	0.807	
Heliostat Reflectivity		0.870	0.900	
Shading & Blocking Losses		0.944	0.980[3]	
Tower Shadow and Sway		1.000[2]	1.000	
Atmospheric Attenuation		0.980	0.962	
Spillage (optical and tracking losses)		0.973	0.961	
Incident Power on Receiver	37.74 MW			39.69

1. (Number of heliostats) x (heliostat area) x insolation
2. Not independently estimated
3. Not included in Martin's efficiency chart, used from other Martin data

TABLE NO. 10

Effect of Focusing Method on Receiver Spillage

(McDonnell-Douglas)

(Mirror Waviness = 1.0 mr)

(Tracking Error = 2.0 mr, each axis)

(Winter Solstice, 2 pm)

Focusing Technique	Spillage %
Constant Canting, Flat Facets	1.12
Constant Canting, Constant Focused Facets	0.68
Slant Range Canting, Flat Facets	0.56
Slant Range Canting, Constant Focused Facets	0.20

TABLE NO. 11

Effect of Focusing Method on Receiver Spillage

(Martin-Marietta)
(Mirror Wariness = 1.0 mr)
(Tracking Error = 2.0 mr, each axis)
(Summer Solstice, 2 pm)

Focusing Technique	Spillage %
Constant Canting, Flat Facets	3.8
Constant Canting, Constant Focused Facets	3.1
Constant Canting, Zone Focused Facets	3.0
Constant Canting, Range Focused Facets	3.1
Zoned Canting, Zone Focused Facets	2.8
Zoned Canting, Constant Focused Facets	2.8
Range Canting, Flat Facets	3.3
Range Canting, Constant Focused Facets	3.0
Range Canting, Zone Focused Facets	2.7
Range Canting, Range Focused Facets	2.8

Table No. 12

EFFECT OF MIRROR WAVINESS ON RECEIVER SPILLAGE (McDONNELL DOUGLAS)

(WINTER SOLSTICE 2 P.M.)

Mirror Waviness (mr)	Spillage (%)
1.0	1.1
1.5	1.8
2.0	3.1

Table No. 13

EFFECT OF MIRROR WAVINESS ON RECEIVER SPILLAGE (MARTIN MARIETTA) (SUMMER SOLSTICE 2 P.M.)

Mirror Waviness (mr)	Spillage (%)
1.0	2.7
1.5	4.9
2.0	8.2

Table No. 14

EFFECT OF FACET CURVATURE (TEMPERATURE) ON RECEIVER SPILLAGE (McDONNELL DOUGLAS)

(WINTER SOLSTICE 2 P.M., CONSTANT CANTING, CONSTANT FOCUSED FACETS)

Facet Focal Length (m)	Corresponding Temperature (°F)	Spillage %
-250	28.4	5.8
-350	40.3	3.7
-500	49.2	2.6
-1000	59.6	1.8
flat	70.0	1.1
351	99.6	0.7
301	104.6	0.6
251	111.5	0.6
201	121.8	0.8
151	139.0	1.4

APPENDIX A2

REVIEW OF COLLECTOR PDR DOCUMENTATION

Aerospace Participant: D. W. Warren

REVIEW OF COLLECTOR PDR DOCUMENTATION

1. Boeing

The Boeing design represents a significantly different philosophy for the central receiver heliostat. The optical characteristics of the dome-protected membrane, while different from those of the other designs, pose no special problems for evaluation. What are difficult to assess are the magnitudes of the risks inherent in the more fragile structure. In particular, long term maintenance of optical performance is a major concern. The comments that follow address the performance of the heliostats and generally assume that the performance will remain relatively unchanged with time.

The Dome

Many of the advantages and disadvantages of the Boeing design are due to the presence of the dome. The main disadvantage is the reduced transmittance, approximately 75% for two passes. A second major drawback is the anticipated need to replace the dome after 15 years. In this connection, some thought should be given to whether it would be practical to fabricate the replacement domes together with those to be used immediately, and then store the replacements until needed.

The main advantage of the dome lies in the protection provided from weather -- particularly wind. In addition to making possible the lighter reflector structure, it appears to permit normal operation of the system during wind conditions which would impair or curtail the operation of the exposed designs. Boeing's capability to assess the aerodynamic characteristics of their structures appears excellent, as might be expected. In addition, they seem to have been the only one of the contractors to wind tunnel model a partial field as well as an isolated unit.

Field Layout

The Boeing heliostat is compatible with either the Martin or MDAC field layouts, and could be substituted (with minor field layout changes due to shading and blocking by the dome) for either of the other Az-El designs. The larger reflecting area of the Boeing design almost compensates for the dome transmission losses, and the few percent reflectivity advantage of aluminized mylar over second-surface glass makes the Boeing and MDAC heliostats comparable in total reflected energy. A single Boeing heliostat is still at a disadvantage compared to a Martin, however, and more units would be required, resulting in an extension of the already large field.

Boeing's design calls for 110 (6%) fewer heliostats than MDAC's. The difference lies in the allowance for heliostat outages: Boeing makes none and MDAC's appears conservative (excessive).

Focusing

The gravity focusing inherent in the stretched membrane design has the advantage of being partially compensating for heliostat range. For a given sun altitude, more distant heliostats tend to have their surfaces more nearly vertical, resulting automatically in a longer focal length. That the compensation is only partial is shown in Figure I, where focal length is plotted against range for heliostats, receiver and sun, all in a N-S plane. The heliostats are seen to focus long except for the extremities of the Martin field in summer. It appears (see Appendix A-1) that if a constant focal length is to be used throughout the field, it should be picked to be somewhat less than the maximum slant range. This implies that the membrane tension (focal length) should be decreased somewhat from the 750 psi used to generate Figure I, provided surface quality could be maintained. W. Delameter (Sandia) has pointed out that the membrane tension will decrease with increasing temperature. Since the temperature inside the bubbles is likely to be higher than that outside due to greenhouse effect, the membrane tension should be set sufficiently high so that surface quality does not deteriorate at the highest operating temperature.

Therefore, before the membrane tension is set, the minimum tension for acceptable surface quality should be established. A modeling of yearly energy spillage versus focal length (tension) would also be useful, perhaps using daily temperature data.

Finally, if the reflectors are to be individually tested for surface tension, a scheme could be devised for routing the tautest membranes to the outer parts of the field, improving the effectiveness of the gravity focusing.

<u>Specific Comments</u> (page numbers refer to Volume III of the PDR)

p.22 Theoretical models made using the optical constants of evaporated aluminum do not exhibit an increase in reflectivity with angle of incidence such as is shown in Figure 3.3.1-1. Although theoretical predictions of thin-film behavior are always suspect, in this case the model is qualitatively substantiated by experimental measurements.[1] It could be that there is something unique to the manufacture of aluminized mylar which produces this behavior.

p.23 The maximum absorptivity of the receiver coating should more properly be in the range 0.90 - 0.95.

---

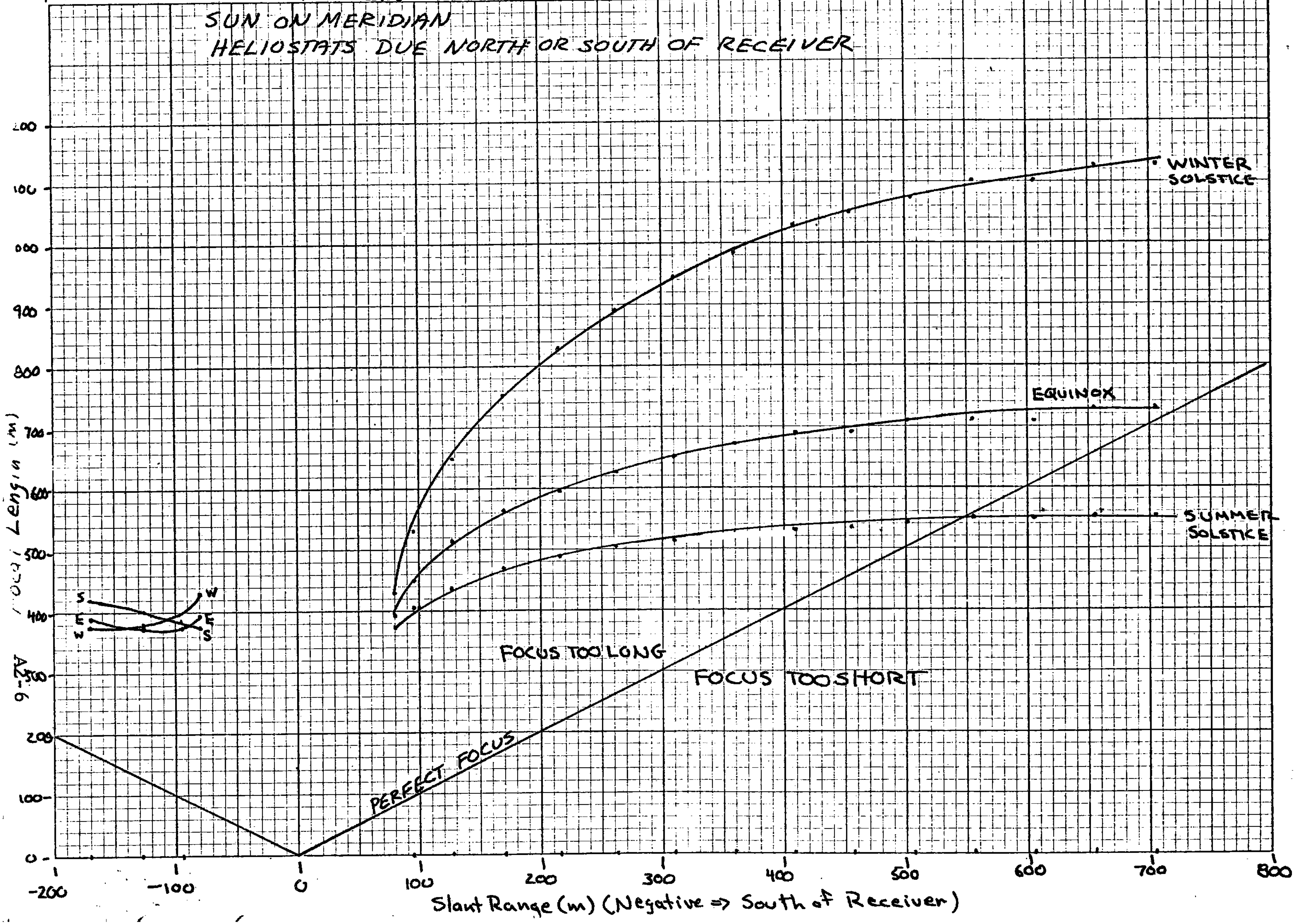
[1] F. Benford, W.A. Ruggles, "Some Characteristics of Metal Mirrors and a New Gonioreflectometer", JOSA, <u>32</u>, 174 (1942)

p. 42	Figure 3.3.2.2-8 appears to verify MDAC's conclusion that the heliostats will reach an equilibrium with the dirt such that reflected energy remaining fairly stable with time.
p. 62	A crude analysis of Figure 3.3.3.1-9 indicates that approximately 8% of the energy lies outside the perfect image boundary. Some of this energy is due to scattering, but the rest must come from surface errors. This implies an upper limit of ~2.7mr (1σ) error in the surface normals. The true value could be considerably less.
p. 65	Does the calculation of spilled energy take into account the decrease in receiver absorptivity beyond 60 degree angle of incidence? The effective width of that portion of the MDAC receiver with angle of incidence less than 60° is ~19.9 feet. The result would be more than 4% loss in winter.
p. 66	More testing is needed on the acoustic coupling of the dome to the reflector membrane.
1. 102	It should be demonstrated that reducing the indicated tolerances does indeed bring the aiming error within acceptable limits.

Conclusion

The Boeing design provides an attractive alternative to the more massive heliostats proposed by the other contractors. The tradeoff that has been made appears to have been one of performance vs cost. The Boeing heliostats are significantly less efficient than the exposed, glass-faceted designs, but seem intuitively as if they ought to be significantly cheaper as well. The chief omission of the PDR is a convincing demonstration of this premise. For the design to merit further attention, it should be shown that the reduced efficiency is at least offset by the reduced costs, including those projected for maintenance over the life of the system.

FIGURE I - FOCUS OF BOEING HELIOSTATS VS. RANGE AND SEASON (750 psi membrane tension)



2. Martin-Marietta

The Martin-Marietta (MM) design is characterized by a field of Az-El heliostats lying entirely north of a cavity receiver. The heliostats are similar to MDAC's, consisting of a mount supporting a faceted reflector. The following comments do not consider the effects of the all north field except as they apply to the performance of a single heliostat. Implications of the all-north field for overall collector efficiency are discussed in Appendix A-1.

Field Layout

The most striking feature of the all-north field is its size. The maximum slant range is almost twice that of the MDAC and Honeywell designs, and nearly half the MM heliostats lie outside the maximum dimensions of the other fields. Since the increase in atmospheric transmission losses is presumably exponential with slant range, doubling the range effectively squares the transmission loss factor, i.e., a transmittance of 0.98 at 350m becomes $0.98^2 =$ 0.96 at 700m. The longer slant ranges also impose more stringent tolerances on tracking and mirror surface accuracies, since the distance over which the errors act is up to twice as long.

One advantage of the all-north field is the elimination of azimuth drive singularities, which only occur in the south field (for sites north of 23 1/2°N. latitude).

Focusing

The MM design calls for focusing the mirror facets to one of five ranges, depending on the position to be occupied in the field, and canting of the individual facets to superimpose the images.

It is clear that flat (uncanted unfocused) heliostats are not practical for the pilot plant, resulting in too much spillage. As indicated on page I-9 of the collector volume, a major reduction in image size can be achieved by canting alone. Since adjustments should be provided on the mirror facets to reduce manufacturing tolerances, the same adjustments can be used for canting. MM proposes to adjust the canting of each heliostat individually, which seems a reasonable idea. The time at which the canting should be performed to reduce overall aberrations, vernal equinox noon, is consistent with Honeywell's conclusion regarding the toeing-in of their larger reflecting modules.

Focusing of the individual facets if of more questionable value. Curving the facets makes an additional (≈. 6%) improvement over canting, but it is not clear that the gain in efficiency would not be offset by the additional cost of fabricating and handling the curved facets. MM claims that curved facets are no more difficult or expensive than flat ones.

Specific Comments (page numbers refer to Volume III of the PDR)

I-10 The yolk mount would appear to be mechanically inferior to the MDAC design because of the large moments which could be exerted on the yolk arms. Immediate consequences might be more wind flexure and longer periods could see increased bearing wear in the azimuth drive.

IV-28 Is a gaussian really a proper representation of the image flux distribution?

IV-36 1σ pointing errors of .298 and .274 mr in azimuth and elevation appear unrealistically small, even considering the SRE results (IV-40).

IV-43 The bonding of glass directly to the steel face sheets is a major issue which needs to be settled.

IV-54 If R = radius of curvature

r = radial distance in the plane of the surface

d = sagitta of reflector

Then $$\frac{\partial R}{\partial d} \approx -\frac{2R^2}{r^2}$$

For $r = 1.5\text{m}$ and $\partial d/\partial T = 0.242\text{mm}/^{\circ}\text{K}$. The change in focal length for a difference of 1°K between the front and back of the mirror is:

Fl	ΔFl/°K	ΔT to shorten fl by 1/3
322m	-45m	2.4°K
407	-71	1.9
492	-104	1.6
576	-143	1.3
660	-187	1.2

It appears as if spillage does not become a problem until a mirror focuses short by a factor of about 1/3. The ΔT's required to produce these changes in focus are shown in column 3. This indicates that the sensitivity to thermal defocus is greatest in the outer parts of the field, where blocking and hence backlighting induced gradients might be more of a problem. This condition and ways (such as white painting) to avoid it should be looked at more carefully.

V-1 In general, the SRE results were the most thoroughly documented and carefully analyzed of all the reports.

V-83 Results of the two surface contamination measurements are generally in line with MDAC's. Measurements taken on a daily basis might have shown the same self-cleaning behavior as MDAC's.

Conclusions

The MM design does not appear to offer significant advantages over the other proposals, in particular that of MDAC, which it most closely resembles. Instead, there are several features of the design which seem somewhat arbitrary and which which could lead to poorer performance and maintenance troubles.

3. McDonnell-Douglas

The McDonnell Douglas (MDAC) design features a field of A3-El, faceted heliostats, laid out in a "radial stagger" pattern about an external cylindrical receiver. The critical difference between the MDAC design and the others is this external receiver. The following comments assume the viability of the receiver design.

Field Layout

MDAC has presented the most well-conceived field layout. The optimization and analysis capabilities of the University of Houston are the best available.

Focusing

MDAC is proposing to use 6 flat facets on each heliostat, canted with shims to a nominal focal length equal to the longest slant range in the field. This appears to be the cheapest way of achieving acceptable image quality.

It seems, however, as if the mechanical tolerances on the reflector support could be eased by providing adjusting screws on the facets, in which case the heliostats could be individually canted for their working range at little additional cost. If a single focusing range is used, it appears as if it should be somewhat less than the maximum slant range for best efficiency.

Tracking

It is hoped that MDAC will soon decide in favor of open-loop tracking, in which case harmonic drives should be selected over orbi-drives.

Reflective Coating

MDAC contends that stress on the silver film, such as might be caused by repeated thermal cycling, tends to crystalize it and decrease the reflectivity. This does not sound implausible, although the exact mechanism is not clear. It could be that there is an increase in scattering resulting in a loss of specular reflectivity. Models run using the optical constants for mono-crystaline silver in the range .64 - .75 μm show a slightly higher reflectivity than for a chemically deposited film, which is presumably poly-crystaline.

Specific Comments (page numbers refer to Volume III of the PDR)

1-28 Research into first-surface, overcoated silver mirrors should definitely continue.

1-29 The thermal stress due to in-plane temperature differentials in a sheet of glass is roughly $S=M\alpha$ where M is Young's modulus (7.8×10^6 lbs/in^2 for glass) and α is the temperature coefficient of expansion. For MDAC's measured α of $3.9 \times 10^{-6}/^\circ F$, $S \approx 30$ lbs/in$^2/^\circ F$ and ΔT should be kept below 16°F if the 500 psi stress limit is not to be exceeded.

3-13 The ambient air temperature range of 32-104°F seems too narrow. Temperatures shown in Figure 3.1.2-5 are mean temperatures. What are the extremes?

3-20 An observer could see more than one-sun irradiance if all of the mirror surfaces were not accurately parallel.

3-44 Of the four contractors, MDAC seems to have given the most thought to manufacturing and assembly of the heliostats.

4-24 Vertical storage appears to maintain the best specularity.

4-31 Spillage increases rapidly as the mirrors become convex. To prevent an excessive amount of spillage from cool facets, it might prove necessary to bond the flat facets at temperatures of from 40-50°F. The impact on production cost and capacity of having to maintain this lower temperature could prove significant. Pre-curved facets should then be investigated.

4-83 The big error item for open-loop tracking appears to be "command". Aren't there any ways of reducing this contribution?

4-136 MDAC is advocating alignment schemes similar to MM (digital radiometer), Honeywell (cal array), or Boeing (laser spherodolite).

4-230 The rough calculation of the value of increased reflectivity vs the cost of washing appears to justify frequent washing.

6-122 For the glass facing the sun, the ΔT between glass and steel (glass higher?) seems higher than might be expected. Would ΔT be reduced with low-iron float? The effect of ΔT between glass and steel would be opposed by that of ΔT between ambient and bonding temperatures as long as the ambient temperature were above the bonding temperature. If not, the two effects would add.

The data for steel facing the sun suggests a potentially serious backlighting problem. The increase in ΔT appears to be caused almost entirely by the temperature increase in the steel. Is this grounds for white-painting?

Conclusions

Of the three glass reflector proposals, MDAC's seems the best balance between performance, reliability and cost.

4. Honeywell

Honeywell was the only contractor to develop the tilt-tilt principle for its heliostats. The result reflects a different design philosophy as well as the differences inherent in the tilt-tilt concept.

Field Layout

Honeywell's field layout procedures are excellent, and they are a close second to MDAC in this area. The design is essentially a radial stagger, with a different angular spacing of the heliostats (as seen from the receiver) for each circular arc. In this sense, the layout is more sophisticated than MDAC's, where the angular separations are the same within one of 6 radial zones.

Honeywell's receiver is considerably taller than the others. Although necessary primarily because of the internal cavity configuration, the extra height also reduces shading, blocking, and cosine losses. Poorer field efficiency would be expected with the other receivers unless they were raised to a comparable height.

Design

The Honeywell design concept is very appealing, incorporating cradle-type, two-bearing support instead of large cantilevers. This sort of design is often used where accuracy is of prime concern (cf. the 80-inch heliostat telescope at Kitt Peak). In such cases, however, only a small number of units are built, and cost is not a major consideration. It is not clear how much of the complexity of Honeywell's design results from providing two bearings/axis. Certainly the extra stiffness of the mirror modules is required in part because the load is supported at only two points.

Modules

Honeywell's mirror modules are massive and complicated, and are built up from a large number of components. Their thickness would seem to promise the greatest resistance to flexure, although the problem is compounded by their extra weight. Analysis of the SRE measurements (see SRE collector test report 277-14333, 18 February 1977) shows surface normal deviations of

~0.37 mrad (1σ cone half-angle) under simulated static wind loading. The reflected error would then be ~ 0.74 mrad.

The plan to go to two large glass facets per module increases the likelihood of trouble with glass quality and thermal effects.

Specific Comments (page numbers refer to Volume III of the PDR)

p. 2-2	Two foundations give more resistance to overturning moments. What are the consequences of the relatively large thermal deformations of the main beams?
p. 2-4	Access to heliostats has not been thoroughly investigated. Mirrors should be focused somewhat shorter than maximum slant range.
p. 2-7	The cal array appears to be a good idea. One cal array, which could be locked into one of eight accurately determined orientations, would be sufficient. The grid spacing analysis (see p. 4-93) justifies a 1-foot grid spacing.
p. 4-4	A factor of two difference in the thermal expansions of steel and glass is not "a reasonably close match" from the standpoint of thermally induced stresses. The bonding of the glass to the support structure is a potential trouble area, as in the other designs.
p. 4-20	Honeywell has larger main members than the other contractors, increasing the magnitude of thermal effects and probably necessitating the white painting.
p. 4-64	Could thermal deflections be partially compensated for in control software?

Conclusion

Honeywell apparently set out with the intention of designing the sturdiest and best-performing heliostat. Depending on the interpretation of the contractors' test data, it appears as if Honeywell missed its objective, or succeeded only marginally. What it certainly did do, however, was come up with the most massive, complex, and expensive design. Such detriments are excusable only if they buy a significant improvement in performance, and it is not at all clear that they have done so in Honeywell's case.

APPENDIX B

RECEIVER SUBSYSTEM

APPENDIX B1

INITIAL ATTEMPTS TO EVALUATE RECEIVER CONVECTIVE LOSSES

Aerospace Participant: W.D. Fischer

(Edited Copy of W.D. Fischer Trip Report)

The receiver meeting was held at Sandia Laboratories at 0800 hrs, 9 May 1977. . . . . .Aerospace was asked to assist in determining the best method for evaluating the convective losses and to plan a wind tunnel test of the forced convection losses. After the meeting, M. Abrams of Sandia and W. Fischer of Aerospace began designing a low velocity wind tunnel test of a 1/10 scale model of the receiver. As a result of the analysis, it was determined that free convection effects are very important not only in a wind tunnel but also in the actual receiver configuration. The chairman was notified that testing of a 1/10 receiver in a low velocity wind tunnel would not simulate the free and forced convection effects properly. Aerospace was asked to try and find during the following week some technical papers describing combined free and forced convection.

APPENDIX B2

INVESTIGATION OF MDAC RECEIVER COATING

Aerospace Participant: W. D. Fischer

(To be provided)

APPENDIX C

STORAGE SUBSYSTEM

Appendix C1

REVIEW OF STORAGE PDR DOCUMENTATION

Aerospace Participant: W. D. Fischer

(Edited Copy of W.D. Fischer Internal Memo)

The thermal storage subsystems presented by the three participating contractors in the PDR do not provide a wide choice of concepts. Each of the designs uses a sensible heat storage system with caloria HT43 as the main storage medium. Both Martin Marietta (MMC) and Honeywell (HW) provide a eutectic salt second stage to allow better steam inlet conditions to the turbine. None of the contractors could justify using other substances for sensible heat storage. According to McDonnell Douglas (MDAC) Therminol 55 was as likely a candidate as caloria HT43. It was not chosen because tests showed a high rate of decomposition. Phase change, an alternative approach to thermal storage suggested by HW, was discontinued because of funding and technical risk.

Originally, single stage salt systems were eliminated by all the contractors because of the high initial cost to provide the same storage capability, and because of possible phase change in the salt at low temperature operation. Some important physical properties of the present storage media are given in Table 1.

The decomposition rate of caloria, which will greatly influence the cost of the storage subsystem, is not known. Currently, the contractors are using a 12-13% decomposition rate per year. Use of this fluid at large rates for commercial applications will not be cost effective as oil availability decreases, nor would it be proper utilization of a valuable natural resource. Yet, until other methods of energy storage become practical, and for the limited use envisioned in the near future for solar energy, this medium will be effective to demonstrate storage feasibility.

Table 1

Physical Properties of Storage Materials

HITEC:	
Chemical Composition:	53% KNO_3
	7% $NaNO_3$
	40% $NaNO_2$
Freezing Point:	142°C
Max Operating Temperature:	455°C
Specific Heat	$0.433 \frac{wh}{kg}\,{}^{o}K$
Caloria HT43 (Exxon Corp)	
Alephatic Oil	
Max Operating Temperature:	316°C
Specific Heat	$0.689 \frac{wh}{kg}\,{}^{o}K$
Granite Rock	
Specific Heat:	$0.227 \frac{wh}{kg}\,{}^{o}K$

As expected, review of the individual storage systems reveal advantages and disadvantages of each system. Martin Marietta proposes an all liquid system. The commercial plant requires seven storage tanks of caloria at 45,270 m^3 each and 2 tanks of HITEC at 4150 m^3 each. This requires 184% more caloria than MDAC and 213% more caloria than HW. The amount of HITEC required by MMC is 45% greater than HW. Some of these differences are due to the fact that Martin proposes a 150 MW plant as opposed to 100 MW for the others.

Six heat exchangers are proposed by MMC for both the commercial and pilot plant installations with 24,120 m^2 of heat transfer area required in the commercial plant and 2496 m^2 in the pilot plant. These are large units and contain more combined heat transfer area than those heat exchangers proposed by the other contractors. Some capital cost savings will be achieved by using larger heat exchangers, however, the larger amount of heat transfer area specified by MMC will reduce this advantage slightly. Similarily the repair and maintenance of the heat exchangers will not allow one unit to be off line and still operate the plant at reduced capacity. The flow rates and storage capacity of the MMC design are adequate to provide the thermal storage requirements specified in the PDR document.

The MDAC storage unit is perhaps the simplest in the amount of material handled. The thermocline principle used to store and extract heat from the same tank is slightly more advanced than the MMC concept and has been proven by MDAC to be a feasible solution by their SRE experiment. MDAC proposes to use four storage tanks of rock and caloria in the commercial plant and one tank in the pilot plant. MDAC has done a better job in estimating the void fraction of the caloria in their design than has Honeywell. MDAC proposes to use a 25% void fraction of coarse granite and sand in the ratio of 2:1 granite to sand. The dual size of rock will more adequately provide the void fraction estimated than will a single size rock. Of course care must be exercised in laying this porous bed so that there are no voids which would cause a maldistribution of flow which could destroy the thermocline.

Another problem associated with a rock and oil tank is the maintenance of the tank. The manifold is designed to be relatively free of plugging by sand, dirt, or sludge. Small leaks in the manifold will be forgotten and only if there is a detectable maldistribution of flow will the manifold require maintenance. The tank cool down rate and removal of the rock will cause a lengthy down period for the pilot plant and a reduced capacity for the commercial plant. In this respect the MMC design is far simpler and more serviceable.

Both MDAC and MMC have underestimated the insulation thickness in their SRE experiments. The contractors claim that penetrations and compaction of the insulation during fabrication caused the increased heat loss. Both MMC and MDAC have either increased insulation thickness or increased the insulation conductivity values for the proposed commercial and pilot power plant designs based on their SRE experience. Insulation heat loss for these larger tanks will be more closely aligned to the calculated values because penetration will be a smaller percentage of the total heat loss.

The major problem associated with the MDAC storage design is the discharge steam conditions from the single storage medium. The steam conditions are 2720 KPa and 299° C compared to 3620 KPa, 390° C and 3000 KPa, 428° C for HW and MMC. Obviously the lower temperature and pressure affect the cycle thermal efficiency considerably. The gross cycle efficiency for MDAC is 4 to 5% below the two stage systems.

Another indication of the impaired performance of the MDAC design is a simple calculation of the turbine performance based on storage discharge conditions, maximum steam flow rate, and the quality of the steam leaving the turbine at condenser pressure. The HW and MMC steam quality is above 97% while the MDAC steam quality is about 91%. Thus, the MDAC storage concept is pushing the design limits of the turbine to a much larger degree.

The Honeywell (HW) storage system has the advantage of synthesizing the best features of both storage systems proposed by MDAC and MMC. Using the caloria and rock concept developed by MDAC for the low temperature storage stage and the HITEC high temperature storage stage similar in concept to MMC, HW is able to offer a best compromise design.

The design appears to be more conceptual in nature since it is not based on an SRE design or even the most popular HW concept. All the features for the storage system are present and several trades were offered, but there appears to be something missing in this design. For example, HW ran an apparent trade study on the size of rock which would best provide the 74% of the low temperature storage capacity. They chose 12.7 mm rock. According to MDAC and Sandia, void fractions as low as 26% are difficult to achieve with one size rock. Certainly, the rock size is easily adjusted to accommodate the void fractions required. Another example is the heat exchanger selection by Honeywell. HW has selected 28 heat exchangers for the commercial power plant and six for the pilot plant application. HW, like MDAC suggests that parallel heat exchangers will provide ample heat transfer area, permit a larger variety of flow rates, and finally allow units to be out of service for maintenance and repair with the plant still able to operate at reduced capacity. Yet, HW did not provide any optimization of the number of parallel heat exchangers. There certainly should be a cost compromise between the size and number of heat exchangers. MDAC was able to provide one.

The HITEC tanks supplied by HW will be buried in a concrete container and will not be insulated. Instead a concrete barrier between the containers will be insulated along with the cover over the salt tanks. There are some advantages to this system. In case of an accident the HITEC will be confined to an enclosed space. Yet upon cooling after a spill the solid HITEC will be difficult to remove from the enclosed space. In addition, HW has not provided an estimate of the air temperature inside the concrete enclosure. Even with the top removed the temperature of the enclosed space will be high and perhaps too uncomfortable for maintenance and repair.

CONCLUSIONS

The thermal storage system provides an interesting dilemma. All storage concepts are quite similar. They all use sensible heat with caloria HT-43 as the main storage medium. The contractor with perhaps the least storage experience, Honeywell, has proposed to best storage concept. Yet proof of this statement awaits two important investigations under study at Sandia. Sandia is making a cost/efficiency study to determine if the addition of a second thermal storage stage will be cost effective with respect to the increase in thermal efficiency. The other important factor which must be evaluated is the degradation rate of caloria HT-43. A large replacement rate for caloria will damage the MMC design the most.

APPENDIX D

EPGS SUBSYSTEM

APPENDIX D1

RECORD OF MEETINGS WITH TURBINE SUPPLIERS

Aerospace Participant: P. K. Chang

(Edited Copy of P. K. Chang Internal Memo)

INTRODUCTION

The evaluation team for the Pilot Plant Electrical Power Generation Subsystem (EPGS) has met with various turbine suppliers in two series of meetings initiated by SCE and held at Rosemead, California. In the first, only SCE met with Elliot, English Electric, Turbodyne and Allis Chamers on June 8-10. On June 15-17 the team met with General Electric (GE), Westinghouse, Delaval, and Brown Boveri Corporation (BBC). The purpose of the meetings was to acquaint the turbine suppliers with the characteristics of the 10 MW pilot plant and its turbine design requirement. The team also solicited industrial experiences and comments which can be incorporated into SCE's specification for the turbine procurement.

SUMMARY

The preliminary responses from the turbine suppliers were good. However, it is too early to tell how many will be bidding for the 10 MW turbine. In general, they favor a down-exhaust arrangement, and a concrete pedestal is preferred over steel. The lead times for the turbines are 20 and 24 months for the 10 MW and 100 MW, respectively. The following table summarizes the current manufacturing status for each supplier.

Supplier	10 MW	100 MW
Elliot	No	No
English Electric	Yes	Yes
Allis Chamers	No	No
Turbodyne	Yes	No
General Electric	Yes	Yes
Westinghouse	No	No
De Laval	Yes	No
Brown Boveri Corp.	Yes	Yes

DISCUSSION

Because of other commitments, the writer was not able to participate in the first series of meetings. Therefore, the following paragraphs address only the second series.

Westinghouse Westinghouse has not built a 10 MW turbine in the last twenty years. It is not likely Westinghouse will respond to the RFP unless the development cost of the turbine is paid for. Currently, their turbines are 235 MW or larger.

DeLaval DeLaval can offer a 10 MW dual admission turbine, but their largest turbine is rated about 65 MW. DeLaval is definitely interested in reviewing the RFP.

Brown Boveri Corporation (BBC) Three months ago, BBC proposed to Black and Veatch (B&V) a high speed (9000 RPM) dual admission turbine for the pilot plant. Probably because of time constraints Honeywell/B&V

did not address this design in their PDR. In this design, there is a reduction gear box between the turbine's shaft and the electrical generator. The generator can be either 1800 RPM or 3600 RPM. Basically, a high speed turbine offers the following advantages...

- higher cycle efficiency
- lower cost due to less metal and smaller foundation
- short start up time
- lesser thermal shock problems.

Two obvious disadvantages are cost and the loss in efficiency due to the gear box. However, these are evidently offset by the advantages one can gain. According to BBC, a 10 MW turbine running at 9000 RPM is a common practice in Europe where fuel cost is much higher than in the U.S.

General Electric (GE) Three ERDA contractors (MDAC, MMC, and Honeywell) proposed GE's low speed (3600 RPM) dual admission turbines as the baseline design for the pilot plant. Because of this GE was considered to be a prime candidate for the 10 MW turbine design. This first GE meeting was more than just fact finding. Questions pertaining to the PDR turbine presentations were forwarded to GE by the EPGS team in advance. Unfortunately, the GE sales representatives were not able to answer those specific questions. Since a high speed machine is becoming more attractive for the pilot plant application, the EPGS team wants GE to investigate their availability. But since high speed turbines fall into a different GE division, the series of questions had to be forwarded there for responses.

APPENDIX E

CONTROL SUBSYSTEMS

APPENDIX E1

INITIAL EVALUATION OF MCS PDR DOCUMENTATION

Aerospace Participant: R. C. Rountree

(Edited copy of R. C. Rountree Internal Memo)

The attached material pertaining to MCS PDR evaluation is to be presented at the 18 May PDR Review Team meeting. Each item is in response to M. Soderstrand's data requests received 13 May. . . . The material was reviewed with Carman Winarski of SCE and Dave Darsey of Sandia-Albuquerque.

COMPARISON OF BASIC MCS CONCEPTS

CONCEPT	HONEYWELL	MARTIN MARIETTA	MC DONNELL DOUGLAS
• IMPLEMENTATION (Including Master and Subsystem Interfacing)	Coordinated master control via DDC (or analog) is highest level in control hierarchy; primarily automatic operations with provisions for normal commercial manual operator strategy, monitoring, commands, and interventions; DDC requires A/D, D/A except with collector computer	Hardwired hybrid control logic with emphasis on manual operator and autonomous subsystem control; PCS & DHS are digital as is collector control; DHS & collector are computers; written procedures provided for operators	Strong emphasis on centralized minicomputer control of subsystems via data bus to collector and individual wires to others; considerable A/D, D/A used; provisions for fully manual, full automatic, and combined manual/automatic operations
• CONTROLLABILITY (Including Mode Capability, Response Characteristics, Stability)	Incorporates adequate but less power production modes than MM or MDAC; transient studies via simulation of startup, clouds, load demand, and failure effects indicate controllability; stability at subsystem only; control logic developed; emphasis on various operating strategies & enhancement but no specific research test modes identified	Incorporates RFP required power production modes, mode transitions; MCS level responses not addressed (subsystem view only); stability via subsystem view; RFP required research testing modes not addressed although growth capability is implied	Incorporates 1 less power production mode than MM and many additional system level modes; stability margins & transient responses treated mainly by linearized models/techniques, and preliminary nonlinear via hybrid simulation; control laws/methodology developed (prelim); emphasis on provisions for MCS enhancement and research testing but no specific modes identified
• OBSERVABILITY (Including State Identification, Instrumentation, Data Acquisition, Analysis Techniques)	Provisions to collect, display, and record plant operating parameters for both operational monitoring and experimental objectives; parameters, instrumentation, and DAS identified including heliostat TV monitoring	Operator monitoring displays provided but observable states & related instrumentation not addressed; DHS is independent except when used as a backup - then no data obtained. Analysis techniques not addressed	Data displays, record, & storage provided for continuous & discrete signals; parameters & instrumentation lists identified for operation & for evaluation (prelim); analysis techniques not identified except for implied use of hybrid simulator

COMPARISON OF BASIC MCS CONCEPTS (Contd)

CONCEPT	HONEYWELL	MARTIN MARIETTA	MC DONNELL DOUGLAS
• EMERGENCY CAPABILITY	Automatic protective interlock system for plant equipment & personnel in event of major disturbance events (e.g., subsystem trips) or equipment failures; system uses relay type logic and station battery power; DDC & DAS to be independent to ensure data acquisition	Provision to detect, alarm, and respond to emergencies is mainly at subsystem level; PCS primarily coordinates subsystem controls, automatically implements certain actions, and provides operators with system level response capability	Primarily via emergency shutdown capability by complete manual or automatic control; also subsystem monitoring, fail-safe concept (computer & components), system self-check capabilities
• DESIGN/OPERATIONAL FLEXIBILITY AND COST	Flexibility emphasized in operating strategy to match varying solar conditions and to adjust to 1st-of-a-kind learning; DDC selected for diverse conditions and software accommodations of control strategy changes; probably middle capital cost between MM & MDAC with changes cost to be moderate via software	Limited flexibility due to hardwiring and independent DHS; subsystem performance cannot be reconstructed; probably lowest capital costs but changes cost to be high via hardware modifications	Flexibility emphasized; modular architecture to permit scaling to commercial plant; operationally via manual/automatic/combined modes, and changes accommodated via software; probably highest capital costs with changes cost to be moderate via software

See Also

["DAS AS AN INDEPENDENT MCS ELEMENT?"]

PROPOSED PILOT PLANT MCS APPROACH

ELEMENT	HONEYWELL	MARTIN MARIETTA	MC DONNELL DOUGLAS
• MCS CONCEPT	Coordinated master control via DDC; digital collector & other subsystem-analog; operator interaction	Hardwired hybrid control logic for manual operation; DHS & collector-digital computers; other subsystems analog	Centralized minicomputer control of all subsystems; automatic, manual, combined operations
• EQUIPMENT	Computers - 3 (DDC, DAS, CS) Annunciation (Visual, Recording) Field Mounted Instrumentation (Operational & Experimental) Control Room Design	Computers - 2 (DHS, CS) PCS Console & Elements Hardwire Logic Elements	Computers - 1 (DDC) Analog Controllers Instrumentation (Operational & Experimental) Annunciation (Visual, Recording) Multi-peripherals Interface (Patch Panel, Relays) Control Room Design
• SOFTWARE	MCS not addressed Except as control law Collector Software Defined	Defined for DHS: Real time & per operator demand; batch processing	Development, real time executive, application, maintenance, integration & test; simplified language
• OPERATIONAL MODES	Startup, Shutdown, RS-EPGS, RS & TS-EPGS, RS-TS, TS-EPGS Protection Mode Transition	Similar to HW plus RS-EPGS & TS, RS-TS-EPGS, RS-EPGS & TS-EPGS Emergency Detection & Response Mode Transition (56)	Similar to MM less RS-EPGS & TS-EPGS Emergency Shutdown Mode Transition
• DATA ACQUISITION & PROCESSING	Collect, display, record for operational monitoring & experimental objectives; 3546 process inputs, 120 control outputs, 6+ operator interfaces	Process, store, retrieve, and output data for plant elements except when used as collector backup; 2070 logged parameters, 181 output log parameters	Multi-capabilities including off-line for system enhancement & performance analysis; 506 process inputs, 154 control outputs (including contingencies)
• DYNAMIC SIMULATION	Developed & exercised computerized time dependent math models to simulate plant startup, cloud transients, load demand changes, and failure effects Avg. plant output = 5.4 MW_e, max = 10.5 MW_e	Not addressed at system level except qualitatively	Linear & hybrid nonlinear; hybrid only partially complete and 1 set of typical results presented (inconclusive)
• PRELIMINARY PHASE II TEST PLANNING	Not addressed	Not addressed	MCS computer due March '80; MCS integration tests during remainder of '80; research testing modes in '81

NON-TYPICAL CONTROL TECHNIQUES (PILOT PLANT)

HONEYWELL	MARTIN MARIETTA	MC DONNELL DOUGLAS
• MULTI-MODES & MODE TRANSITION CAPABILITY	• MULTI-MODES & MODE TRANSITION CAPABILITY	• MULTI-MODES & MODE TRANSITION CAPABILITY
• DIGITAL HELIOSTAT COMPUTER	• HELIOSTAT COMPUTER CONTROL WITH BACKUP BY DHS	• CENTRALIZED DDC CONTROL OF SYSTEM/SUBSYSTEMS VIA AUTOMATED PROCESS CONTROL TECHNIQUES (TO SATISFY DEVELOPMENT, OPERATION, AND DEMONSTRATION FUNCTIONS)
• DDC & MONITORING DISPLAYS IN MASTER CONTROL (TO HANDLE DIVERSE CONDITIONS AND ACCOMMODATE CHANGES IN CONTROL STRATEGY)	• DHS MINICOMPUTER AND PERIPHERALS FOR EVALUATION (SUBSYSTEM OUTPUT ONLY)	
• DATA SYSTEM COMPUTER & PERIPHERALS (TO MAINTAIN DATA COLLECTION/RECORDING DURING PLANT OPERATION)		• MAXIMUM FLEXIBILITY TO OPERATOR OR TEST ENGINEERS VIA FULL COMPLEMENT OF MANUAL & COMPUTER-AIDED CONTROLS
• SPECIAL INSTRUMENTATION FOR EXPERIMENTAL DATA ACQUISITION/EVALUATION		• OPTIMUM PATH FOLLOWING SOURCE VARIATIONS
• DESIGN/OPERATIONAL FLEXIBILITY FOR 1ST-OF-A-KIND LEARNING		• ON-LINE SYSTEM ENHANCEMENT CAPABILITY
• CONTROL HIERARCHY DICTATED VIA MAXIMUM ENERGY OUTPUT		• SIMPLIFIED SOFTWARE LANGUAGE FOR NON-SPECIALIST USER
		• SELF TEST AND FAIL SAFE BUILT-IN
		• SPECIAL INSTRUMENTATION FOR EXPERIMENTAL DATA ACQUISITION/EVALUATION

KEY ISSUES EFFECTING CONTROL SELECTION

1 - HONEYWELL:

- COST-EFFECTIVE
- SIMPLICITY
- PROVIDES CONTROLLABILITY & OBSERVABILITY
- NEAR CONVENTIONAL APPROACH
- FLEXIBILITY
- VERIFIED VIA DYNAMIC SIMULATION

2 - MC DONNELL DOUGLAS:

- MATCHES HONEYWELL CAPABILITY
- HIGH COST
- SOPHISTICATED APPROACH
- HYBRID SIMULATION IN DEVELOPMENT

3 - MARTIN MARIETTA

- MINIMUM CAPABILITY
- LIMITED FLEXIBILITY & OBSERVABILITY
- SIMPLIFIED APPROACH
- SYSTEM SIMULATION OMITTED

PDR EVALUATION STATUS/NEEDS

STATUS:

- 1ST "GUESTIMATE" DONE VIA REVIEW OF MCS SECTION MATERIAL ONLY
- COMPLETE ITEMS 1 - 3 PER SODERSTRAND REQUEST

NEED:

- COMPARISON OF CONTRACTOR APPROACHES VS. RFP & CLARIFICATION REQUIREMENTS
- FACTOR IN PILOT PLANT PHILOSOPHY DEFINITION
- FACTOR IN CONTRACTOR ACTION-ITEM RESPONSES REGARDING NON-TYPICAL CONTROLS
- CLARIFY CONTRACTOR SIGNAL PATHS (E. G., SUBSYSTEM TO DDC TO DAS OR STRAIGHT TO DAS)

DAS AS AN INDEPENDENT MCS ELEMENT?

INDEPENDENT	INTEGRATED
• REDUNDANCY	• COMMON DESIGN & COMPUTERS
• SLIGHTLY HIGHER COSTS	• MINIMUM INTERFACE PROBLEMS
• BACKUP MODE SHUTS DOWN DATA ACQUISITION MODE (MM)	• SOME ECONOMY OBTAINED
• CONTAINS OWN SOFTWARE & TIMING	• SAME LOOPS & TIMING FOR OPERATION AND EVALUATION
• PERMITS OFF-LINE SYSTEM ENHANCEMENT	• OVERLOAD OF SAME INSTRUMENTS
• SEPARATE INPUT SENSORS (∴ DIFFERENT READINGS AND COST INCREMENTS)	• POSSIBLY MORE FLEXIBLE

4.2 Technical Review After PDR Presentations

b. Which MCS Subsystems Are in Competitive Range

	Collector	Receiver	Storage	EPGS	System
HWI					Yes
MMC					No
MDAC					Yes
Boeing					

← DID NOT INVESTIGATE →

Rational:

HWI:

MMC:

MDAC:

Boeing:

SEE VUGRAPHS

DETAIL SYSTEM CONTROL EVALUATION

Criteria	Possible	HWI	MMC	MDAC
I. Commercial Plant System Controls				
117. Steady State Function	95	20	30	25
118. Mode Change Accommodation	40	20	30	25
119. Effect on other Subsystems	33	25	10	30
120. Use of Meteorological Data	20	10	5	15
121. Reliability	15	10	10	10
122. Simplicity	15	5	10	5
123. Low Technical Risk	15	10	10	10
124. Operations & Maintenance	50	40	20	45
125. Capital Cost	50	40	45	35
126. Totals	333	180	170	200
II. Pilot Plant System Controls				
127. Interface Requirements	33	15	10	20
128. Data Applicable to CP	50	45	15	40
129. Operational Flexibility	84	70	40	75
130. Design Flexibility	50	40	25	40
131. Mode Change Accommodation	34	20	30	25
132. Economic Data Applicable to CP	~~50~~	-	-	-
133. Reliability	33	20	20	20
134. Simplicity	33	25	30	15
135. Low Technical Risks	33	30	30	25
136. Operations & Maintenance	50	30	30	30
137. Capital Cost	50	40	45	35
138. Totals	~~500~~ 450	335	275	325

DETAIL SYSTEM CONTROL EVALUATION

Criteria	Possible	HWI	MMC	MDAC
III. Confidence in System Control Design				
139. Experience of Contractor	10	10	5	5
140. Recognition of Problems	32	30	10	25
141. Understanding Problems	25	20	10	20
142. Supporting Technical Analysis	25	20	5	15
143. Supporting Technical Data	25	20	5	20
144. Supporting Cost Analysis	25	15	0	20
145. Supporting Cost Data	25	15	0	20
146. Totals	167	130	35	125
Overall Totals	950	645	480	650

APPENDIX E2

INITIAL EVALUATION OF COLLECTOR CONTROL SYSTEMS

Aerospace Participant: R.R. Sheahan

(Edited Copy of R. R. Sheahan Internal Memo)

The attached five sheets were prepared in support of the MCS and Collector Evaluation Committee meetings at Sandia on 18 May. The total assignment is to support the MCS Committee on the four subsystems of the Central Receiver. The attached concentrates on the Collector. These sheets were given to C. Mavis and M. Soderstrand, Chairmen of the Collector and MCS Committees, respectively.

SUGGESTED HELIOSTAT CONFIGURATION

COMPONENTS	ALTERATIONS	RISK AREAS
Boeing Heliostat	None	Material Lifetime Fogging
or MDAC Heliostat	Integral Pedestal in Pre-Cast Foundation Non-Invertible "Open-Loop"	Reflector Panel Life and Distortion Dynamic Wind Load Effects
Boeing Control	Absolute Encoders on Gimbals $(2^{10}/2^{13}$ on Boeing) $(2^{13}$ on MDAC)	None
Honeywell Cal Array	Embed Sensors (or Fiber Optics) in Outer Wall of Receiver	None

COLLECTOR SUGGESTIONS

DO

Use Cal Array to Back Out Tilt & Alignment Errors

Use "Open Loop" Control (No Sensor Post)

Close Control Loops About Absolute Gimbal Encoders

Provide Return Loop on Data Bus

Use Pre-Cast Foundations With Integral Post

Use Complete Digital Control

Stow Vertical or Face Up (Hi-Wind)

Fence the Outer & Inner Perimeters

Provide for Temperature Changes on Panels

Stow by Defocusing

Generate Gimbal Angles at Central Controller

Provide for Cal Array Service From Inside Receiver Structure

Use Cal Array to Detect Back-Lash, Tilt, Thermal & Wind Deflections, Atmospheric Attenuation, Cleaning Requirements, etc.

Compensate for Biases & Deflections from Cal Array in Gimbal Angle Calculations

Use Heliostat Controller to Perform Diagnostics/Error Checking, and Report to Central Control

Provide Mechanical Adjust on Each Reflector Panel

Use Several Rack Mounted Mini-computers (Plus Spare) for Control

Provide for Reload of Diagnostic/Error Check Routines Over Command Lines

Provide Compatible Data Tapes for Off-Site Analysis

DON'T

Don't Shim During Assembly

Don't Use Sensor Posts

Don't Provide Face-Down Stow Capability

Don't Provide Battery Backup

Don't Provide Diesel Generator Backup

Don't Use DC Motors

Don't Use Mechanical Relays

Don't Stow Flat on Power or Command Loss

Don't Use Initialization Hardware on Heliostat (For Incremental Encoders)

Don't use ROM's at Heliostat to Generate Gimbal Angles

Don't Use "Soft" Adhesive to Soak up Thermal Expansion

Don't Send Personnel into Field Until Problem has been Identified at Central Control

Don't Hang Cal Array Panels Out Away from Receiver

Don't Use Honeywell Heliostats

Don't Count on Low-Iron Glass for Pilot Plant

	BOEING	HONEYWELL	MMC	MDAC
FIELD				
RECEIVER HEIGHT (M)	80	129	90	80
NUMBER OF HELIOSTATS	1643 (MDAC)	1598	1554 (1325)	1760
SLANT RANGE (M) MIN.	94	140	110	101
MAX.	446	418	703	377
TOTAL MIRROR AREA (M^2)	79,488	63,920	63,668	65,613
COLLECTOR AREA (ACRES)	69	56	83	75
HELIOSTAT				
FACETS/PANEL	1	2	1	1
PANELS/HELIOSTAT	1	4	9	6
PANEL SIZE (M)	7.85 DIAM.	3.05 x 3.28	2.13 x 2.13	2.90 x 2.16
AREA (M^2)	48.38	10	4.54	6.26 (6.12)
THICKNESS (IN.)	0.002	9	~2 1/2	~2 1/4
WEIGHT (LBS.)	188	650	194	200 (195)
SUPPORT	EDGE	2 TRUNIONS	3 POINT	4 POINT
FOCAL LENGTH (M)	400 (FACE UP) 2,200 (10° OFF V.)	418	322, 407, 492 576, 660	∞
HELIOSTAT FOCAL LENGTH (M)	"	418	"	376
REFLECTOR AREA (M^2)	48.38	40	40.97	37.28
FOCUSING TECHNIQUE	GRAVITY (VARIABLE)	FACET TILT MECH. ADJ.	FACET TILT MECH. ADJ.	FACET TILT FIXED SHIM
HELIOSTAT STRUCTURE				
DRIVE	AZ-EL	TILT-TILT	AZ-EL	AZ-EL
HEIGHT, MAX. (FT.)	26.5 (27.6)		23.66	22.5
WIDTH, MAX. (FT.)	25.75 (28)		23	21.3
HEIGHT, FLAT (FT)	13.6 (27.6)		13.5	12
GIMBALED WT. (LBS)	~300	7600	~4645	~2735
TOTAL WT. (LBS.) (LESS CONCRETE)	1106	8010	5200	3514
FOUNDATION				
DEPTH BELOW GRADE	18"	12"	15'	45"
CROSS SECTION	18" DIAM.	6' x 10'	24"-36" DIAM. CAST-IN-PLACE	32"-96" DIAM. PRECAST CONC.
WEIGHT (LBS)	350	5800	4840	9750

		BOEING	HONEYWELL	MMC	MDAC
ONTROL BUS TO HELIOSTATS					
	POINTING DATA FROM MCS	SPECIFIC GIMBAL ANGLES	1 OR 15 MOTOR STEP COMMANDS	EPHEMERIS	NONE (EPHEMERIS PROPOSED)
	FREQUENCY	5 SECONDS	1 SECOND	1 SECOND	
	DIAGNOSTICS/ ERROR CHECKS	YES	NO	YES	YES
	OTHER DOWNLINK	EPHEMERIS, TIME, ETC.	INITIALIZE	MODES, DATA REQUESTS, ETC.	DIRECT POSITION, MODE, ETC.
	UPLINK	STATUS, ANGLES, ERRORS, ETC.	NONE	MODE, ERRORS ETC.	STATUS, ERRORS ETC.
	DATA BUS	SHIELDED PAIR DAISEY - CHAIN	TWISTED/SHIELD. PAIR	TWISTED/SHIELD. PAIR	TWISTED/SHIELD. PAIR
	REDUNDANT BUS	YES	YES	NO	NO
CONTROLLER	AT MCS	4 MINI'S + SPARE	2 CPU'S + SPARE	1 MINI + DATA HANDLER AS SPARE	1 CPU
	BUS STRUCTURE	4 BUSSES/MINI (128 HELIO/BUS)	1 MEGABUS 18 LOCAL BUSSES (82-104 HELIO/BUS)	4 MAIN BUSSES TO 13 RMD'S 4 LOCAL BUSSES PER RMD (24 HELIO'S/BUS)	8 MAIN BUSSES TO 8 F.C. GROUPS (9 F.C.) 74 LOCAL BUSSES FROM F.C. TO 24 HELIO'S EACH
	ALIGNMENT ANGLE OFFSETS	IN MINI'S	IN CPU	IN RAM AT HELIO.	IN RAM AT FIELD CONTROL.
CONTROL LOOP	TYPE	CLOSED	CLOSED	CLOSED	CLOSED
	CLOSED ABOUT	INCREMENTAL ENCODERS (ABSOLUTES PROPOSED)	INCREMENTAL ENCODERS	13 BIT ABSOLUTE ENCODERS	SENSOR [illegible] (INCREMENTAL ENCODERS PROPOSED)
	LOCATION	GIMBALS	MOTOR SHAFTS	GIMBALS	(MOTOR SHAFT PROPOSED)
UE RANGE			75° TOWARD TOWER 20° AWAY (OUTER) 360° (INNER)	± 110° AZ 180° EL	± 270° AZ 0°-180° EL

		BOEING	HONEYWELL	MMC	MDAC
DRIVE					
	MOTORS	2	2 OUTER AXIS 1 INNER AXIS	2 OUTER AXIS 2 INNER AXIS	2
	TYPE	200 STEP/REV. STEPPING	SERVO	STEPPING (TRACK) INDUCTION (SLEW)	AC TORQUE
	VOLTAGE	±10VDC	24VDC	115V 1Φ	230V 3Φ
MECHANISM	OUTER AXIS	DIRECT ?	WORM/BALL SCREW	WORM/BULLGEAR	ORBIDRIVE (HARMONIC)
	INNER AXIS	"	2 STAGE HELICAL TO SPUR GEAR	"	"
RATIO	OUTER AXIS	1:1 ?	11,000~18,000:1	90:1 (SLEW) ? (TRACK)	45:1 TO 361:1 (242:1)
	INNER AXIS	"	1600:1 TO 10.1:1	"	"
CALIBRATION	TARGET	SPHERATHEODOLITE + (12' RADIUS BOOM)	8 PANELS 20'x20'	1 PANEL 20' x 20'	PANEL(S) SIZE ?
	LOCATION	TOWER MODULE 360° TRAVEL	TOWER FIXED	TOWER GIMBELED	TOWER
	LIGHT SOURCE	LASER (SOLAR)	SOLAR	LASER	SOLAR
	LOCATION	TOWER MODULE (SKY)	SKY	TOWER GIMBLED	SKY
	USE	DAY/NITE (DAY)	DAY	NITE	DAY?
	SENSOR	SPHEROTHEODOLITE (24 SOLAR CELLS)	224 SOLAR CELLS	TV	TV
	LOCATION	TOWER MODULE	TOWER PANELS	AT HELIOSTAT	FIELD ?
	AUTO/MANUAL	AUTO. (AUTO.)	AUTO.	MANUAL	?
	TYPE OF CALIBRATION.	GIMBAL UPDATE (PATTERN)	GIMBAL UPDATE & PATTERN	TILT FOCUS & GIMBAL UPDATE	GIMBAL UPDATE? PATTERN ?
FIELD POWER					
	VOLTAGE	120V 1Φ	115V 1Φ	120V 1Φ	240V 3Φ
	REDUNDANT PATH	YES	NO	NO	NO

APPENDIX E3

COOLWATER POWER PLANT RELIABILITY

Aerospace Participant: R.R. Sheahan

Coolwater (SCE) Power Plant Reliability

This memo describes the equipment and operating reliability at the SCE Coolwater power plant, located near the proposed site of the 10 MWe Pilot Plant. The data was supplied by Carmen Winarski of SCE.

Coolwater has been operational since 1960, and presently consists of 2 each 80 MWe gas turbine-generators designated Units 1 and 2. Units 3 and 4 are now being installed at Coolwater and will become operational this Fall. Units 3 and 4, with a combined capacity of 450 MWe, will be combined-cycle designs consisting of 4 gas turbine-generators exhausting into waste heat boilers which, in turn, drive 2 steam turbine-generators. Thus a total of 8 generators will be available at Coolwater, starting this Fall, to support the Pilot Plant.

There has never been a simultaneous loss of both Units 1 and 2 since 1960. On 2 occasions, however, the Coolwater plant did separate from the 220-500 KV transmission-line grid. Separation can be caused by a transformer failure, or a failure in the switch gear or protective devices. The exact nature of the 2 Coolwater events has not yet been determined because both occurred more than 5 years ago and a detailed explanation requires searching through old station records. This search will be encouraged if the information would be useful to Sandia.

Separation of the Coolwater plant from the grid does not imply failure of the grid itself. In addition to Coolwater, the grid is supplied by 2 each 800 MWe units at Mojave, another 800 MWe from Four Corners, and a variety of other units in the SCE system.

Preliminary discussions at SCE have centered around supplying the Pilot Plant site with a 15 KV line directly from Coolwater during construction. It may be less expensive to maintain this line permanently, rather than install a diesel generator at the Pilot Plant.

If a permanent Coolwater tie is installed, the Pilot Plant's power reliability will be a function only of the reliability of Coolwater itself, and of the interconnecting power line. The high voltage transmission grid and its coolwater switch gear will not be an issue. Given the zero-failure record of the 2 Coolwater generators over the past 17 years, the likelihood of a total failure of the new 8 generator configuration would appear to be negligible. The anticipated reliability of the transmission line should be investigated.

APPENDIX E4

ARGUMENTS FOR/AGAINST CLOSED-LOOP CONTROL AND INVERTED STOW OF PILOT PLANT HELIOSTATS

Aerospace Participant: R.R. Sheahan

SUBJECT: "CLOSED LOOP" CONTROL FOR PILOT PLANT HELIOSTATS

ARGUMENTS FOR:

- Automatically compensates for heliostat shifting and settling.
- Reduces MCS computations.
- Reduces data rates from MCS to heliostats.
- Simplifies heliostat control complexity.
- Higher drive backlash permitted.

ARGUMENTS AGAINST:

- Cannot compensate for sensor post shifting/settling.
- Sensor post obstructs field access.
- Sensor/sensor post require additional maintenance.
- Boeing & Honeywell never considered "closed-loop".
- MMC considered, then rejected, "closed loop".
- MDAC considered, is close to rejecting, "closed loop".
- Calibration array can compensate for heliostat shifting/settling, and detect control biases, dirt build-up, panel deterioration, etc.
- All "open-loop" designs actually closed-loop about encoders.
- "Closed loop" requires "open loop" synthetic track capability for start-up, cloud transients, defocus, stow.
- MCS complicated; must coordinate "closed-loop" and synthetic track modes during cloud transients.
- Receiver output reduced without coordination.
- MCS computational capability not reduced.
- MCS-heliostat data rate capability not reduced.
- Heliostat control complicated, not simplified.
- "Closed-loop" dependent on alignment between sensor mirror and mirror panels.
- Less MCS visibility into "closed loop" performance; more difficult to monitor.

RISKS WITHOUT "CLOSED-LOOP":

- Tighter drive backlash requirements may be needed

BENEFITS WITHOUT "CLOSED-LOOP":

- Less complex field layout, easier access
- Simplified heliostat control
- Heliostats constantly under positive, more visible, gimbal encoder control
- Lower lifetime costs

CONCLUSIONS:

- "Closed-loop" more complex
- No gain, possible loss, in receiver performance
- Lifetime costs higher
- No net benefits apparent

RECOMMENDATIONS:

- Specifically exclude "closed-loop" control for pilot plant
- Specify closed-loop control about absolute gimbal encoders for pilot plant

SUBJECT: FACE-DOWN (INVERTED) STOW CAPABILITY FOR PILOT PLANT HELIOSTATS

ARGUMENTS FOR:

- Dirt build-up may be less rapid when stowed face-down.
- Insufficient time remains before spec. preparation to validate the face-down requirement.
- The pilot plant heliostat field would be a good proving ground to evaluate dirt build-up.
- Face-down poses less safety problem than face-up.
- Face-down provides hail protection.
- Considerable sentiment exists for face-down stow.

ARGUMENTS AGAINST:

- No firm requirement has been established.
- Counter-evidence suggests vertical stow (rather than face-down) minimizes dirt build-up.
- 9 - 11% "dead" area required in reflector
- Significant cost/complexity penalties accompany face-down stow.
- 1500 heliostats should not be required to assess dirt built-up.
- Face-down stow may increase sand damage.
- Face-up stow (with tight control) poses little more safety problem than sun reflecting off a lake.
- All panels can withstand hail requirement face-up.
- Face-down stow increases drive unit wear and energy consumption.
- Face-up stow faster to achieve in rising wind.

RISKS WITHOUT FACE-DOWN:

- May need more frequent washing, more cost

BENEFITS WITHOUT FACE-DOWN (a or b or c):

(a)
- Maintain panel size, panel spacing
  - Less complex drive, lower cost

(b)
- Maintain panel size, close up panel spacing
  - Smaller (9% MMC, 11% MDAC) heliostat, lower cost
  - Less complex drive, lower cost
  - Maintain heliostat spacing
    - Less shading/blocking
    - Fewer heliostats, lower cost
  - Close up heliostat spacing
    - Same shading/blocking
    - Smaller field size, lower cost

(c)
- Fill "dead" space with larger panels
  - Less complex drive, lower cost
  - Mirror area increased (9% MMC, 11% MDAC)
    - Fewer heliostats, lower cost
    - Smaller field, lower cost

CONCLUSIONS:

- Arguments for face-down stow are vague
- Face-down stow significantly (9 - 11%) reduces performance, increases cost and complexity
- Risk and costs for face-down stow are disproportionately high compared to possible benefits

RECOMMENDATIONS:

- Specifically exclude face-down stow for the pilot plant
- Add only if short-term testing can validate same
    - Sandia should run dirt build-up tests before spec. preparation
    - If short-term test cannot validate requirement, then effects are too insignificant to drive pilot plant design

APPENDIX E5

HELIOSTAT/RECEIVER REDUNDANCY ANALYSIS CHARTS, BY CONTRACTOR

Aerospace Participant: R. R. Sheahan

Heliostat/Receiver Redundancy Analysis Charts,

By Contractor

A set of charts are attached, illustrating the redundancy provided by each contractor's receiver and heliostat designs. Figure 1 is an unaltered version. Figures 2 - 4 are marked up to reflect the Honeywell, MMC and MDAC designs. Figures 5 - 7 are marked up to reflect the Boeing collector in combination with each of the 3 receivers.

Three assumptions precede use of the charts. First, assume that the tower can tolerate a solar defocus. Second, assume that a wet receiver can tolerate a solar defocus. Third, assume that one of two problems exists: either the receiver flow has been disturbed; or a high wind condition exists.

Given these assumptions, the charts can be used to identify the likelihood of a catastrophic failure involving the receiver or heliostats. For a catastrophic failure to succeed, two conditions are needed: either the receiver flow fails completely (top half of the chart) or a high wind condition exists and, simultaneously, either the heliostat command authority or power separates completely (bottom half of the chart).

The results in Figures 2 - 7 are summarized in Figure 8, which lists the number of possible single-point failures and the degree of redundancy in each design. Note that the number of single-point failures range from 1 for Boeing and Honeywell, to 2 for MMC and 6 for MDAC.

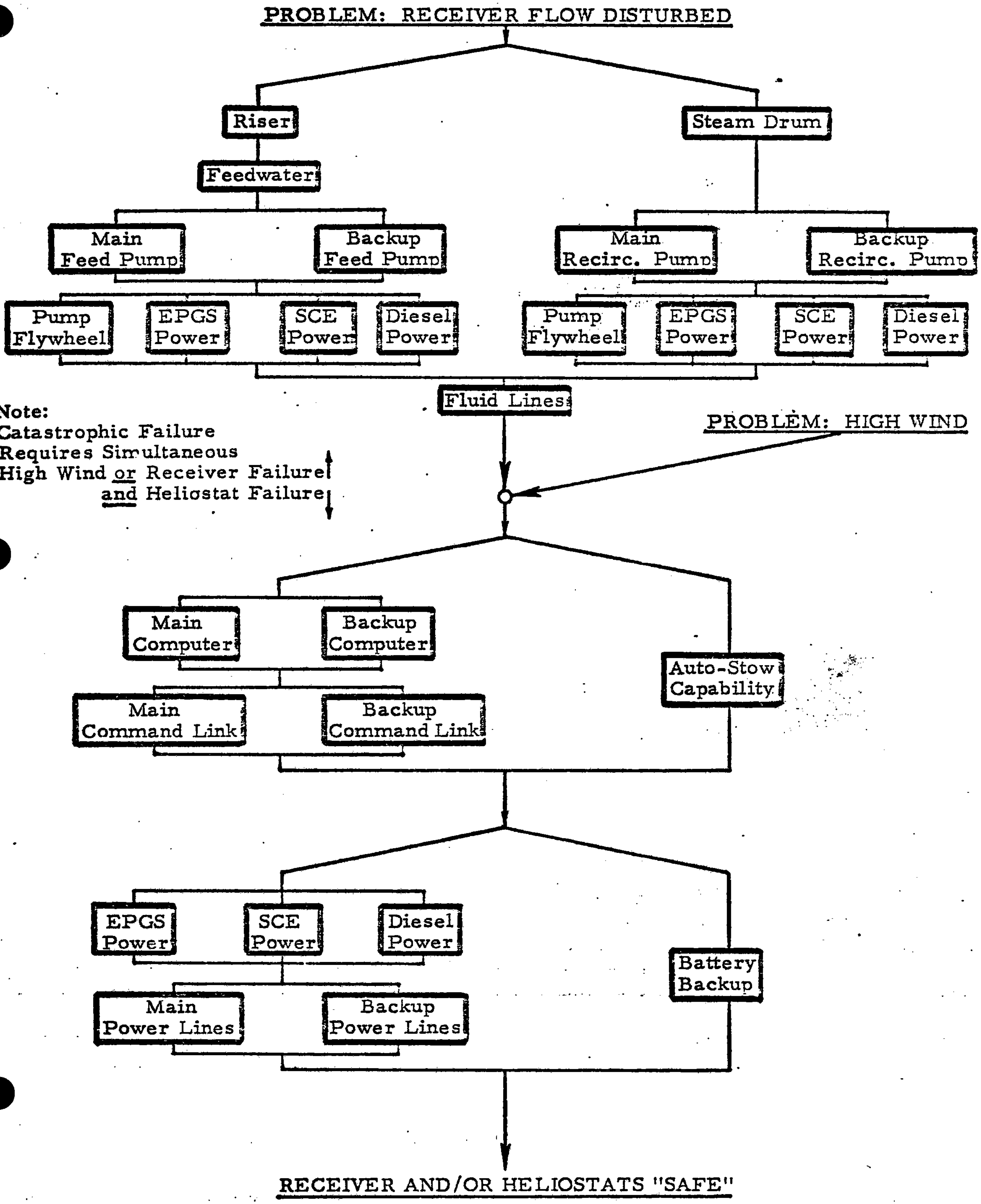
Figure 9 illustrates the suggested degree of redundancy which is thought to be desirable. In the receiver, some type of steam drum or water reservoir should back up the riser loop. Recirculation pumps are not advisable because of their added cost and complexity, and because receiver flow then becomes dependent of the power lines up the tower. Diesel backup or flywheels on the feedwater pumps are not recommended because they provide an excessive amount of redundancy.

In the heliostat subsystem, the inclusion of auto-stow, batteries or diesel backup is not recommended. The diesel provides an expensive and unnecessary degree of redundancy. Batteries are expensive and require maintenance. The auto-stow capability provides no functional redundancy to the control system. It simply acts as a "fuse" in the control loop, and displaces the control authority away from the MCS where I feel it should remain.

Receiver: GENERAL

Heliostat: ____________

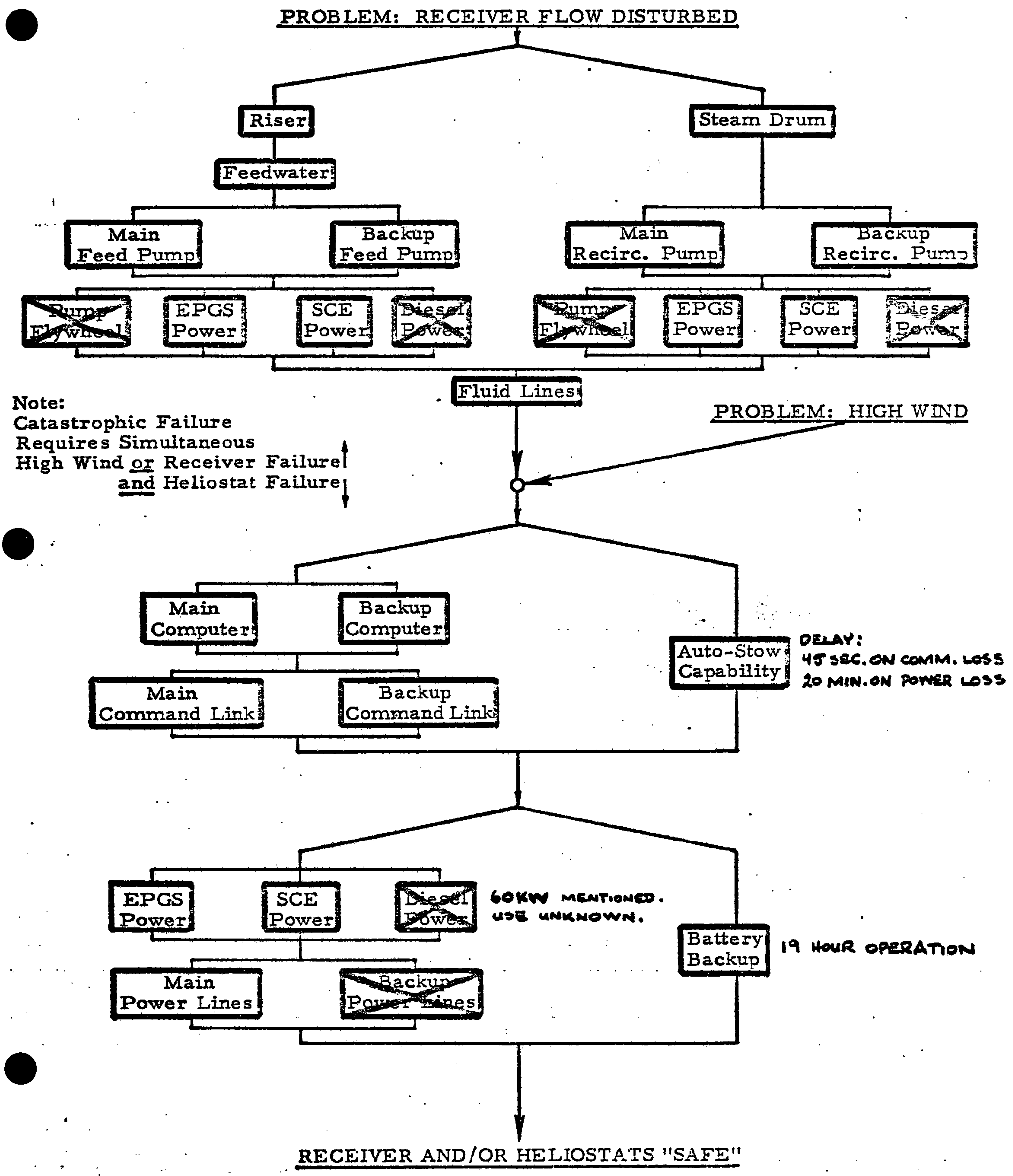
Figure 1 : Subsystem Redundancy



Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

Receiver: HONEYWELL
Heliostat: HONEYWELL

Figure 2: Subsystem Redundancy



Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

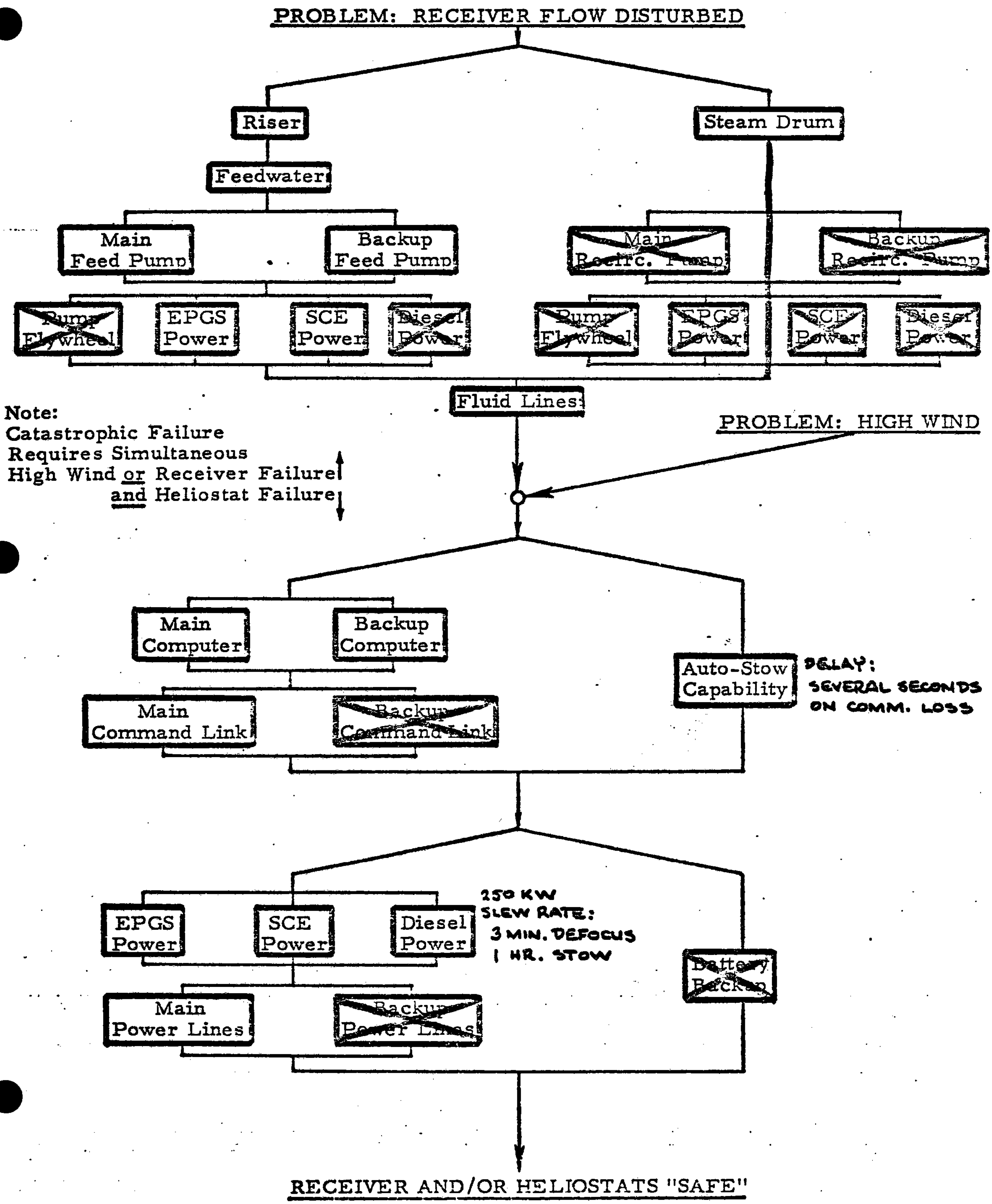
DELAY:
45 SEC. ON COMM. LOSS
20 MIN. ON POWER LOSS

60KW MENTIONED.
USE UNKNOWN.

19 HOUR OPERATION

Receiver: MMC
Heliostat: MMC

Figure 3: Subsystem Redundancy



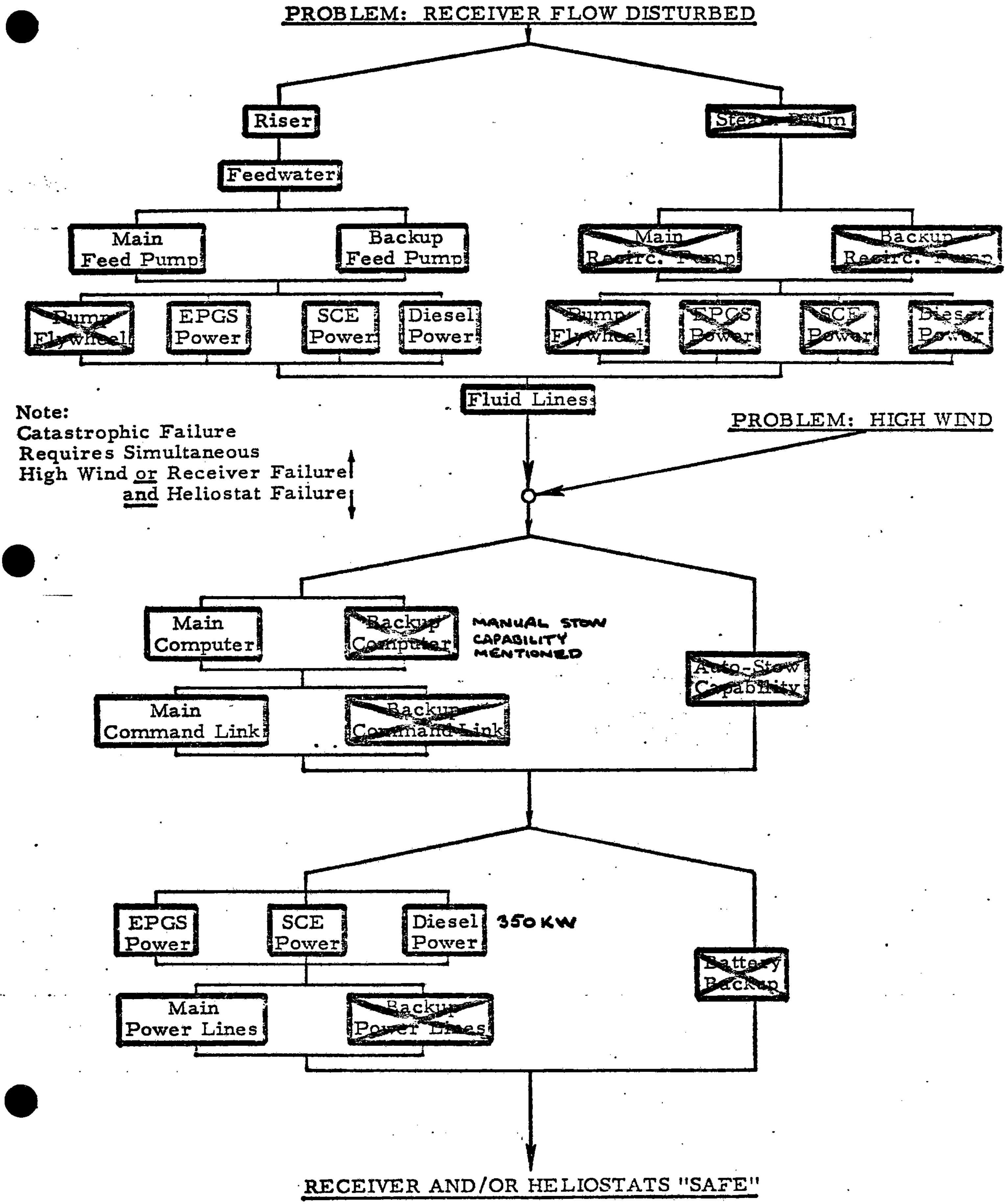
Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

DELAY:
SEVERAL SECONDS
ON COMM. LOSS

250 KW
SLEW RATE:
3 MIN. DEFOCUS
1 HR. STOW

Receiver: MDAC
Heliostat: MDAC

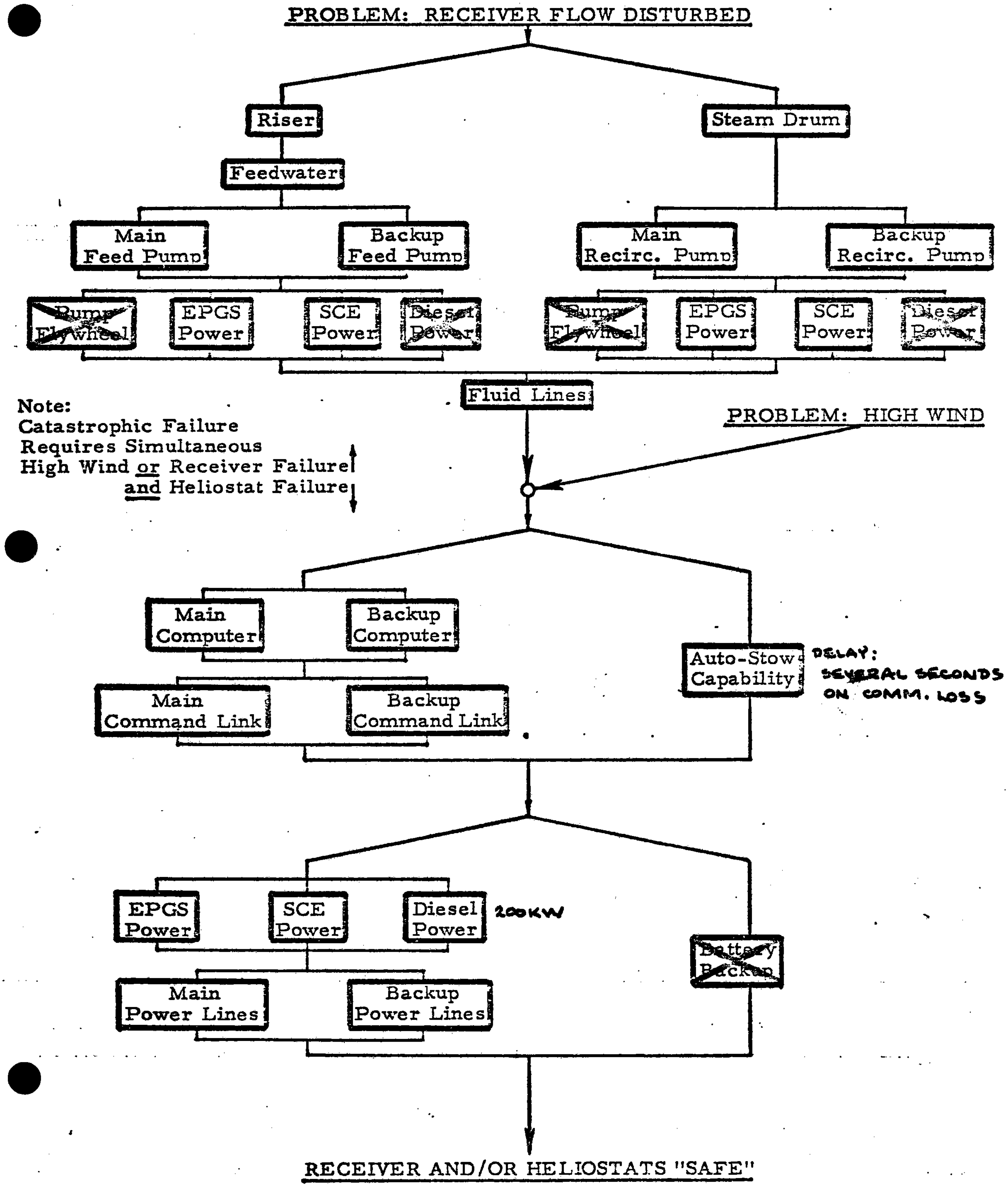
Figure 4: Subsystem Redundancy



Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

Receiver: HONEYWELL
Heliostat: BOEING

Figure 5: Subsystem Redundancy

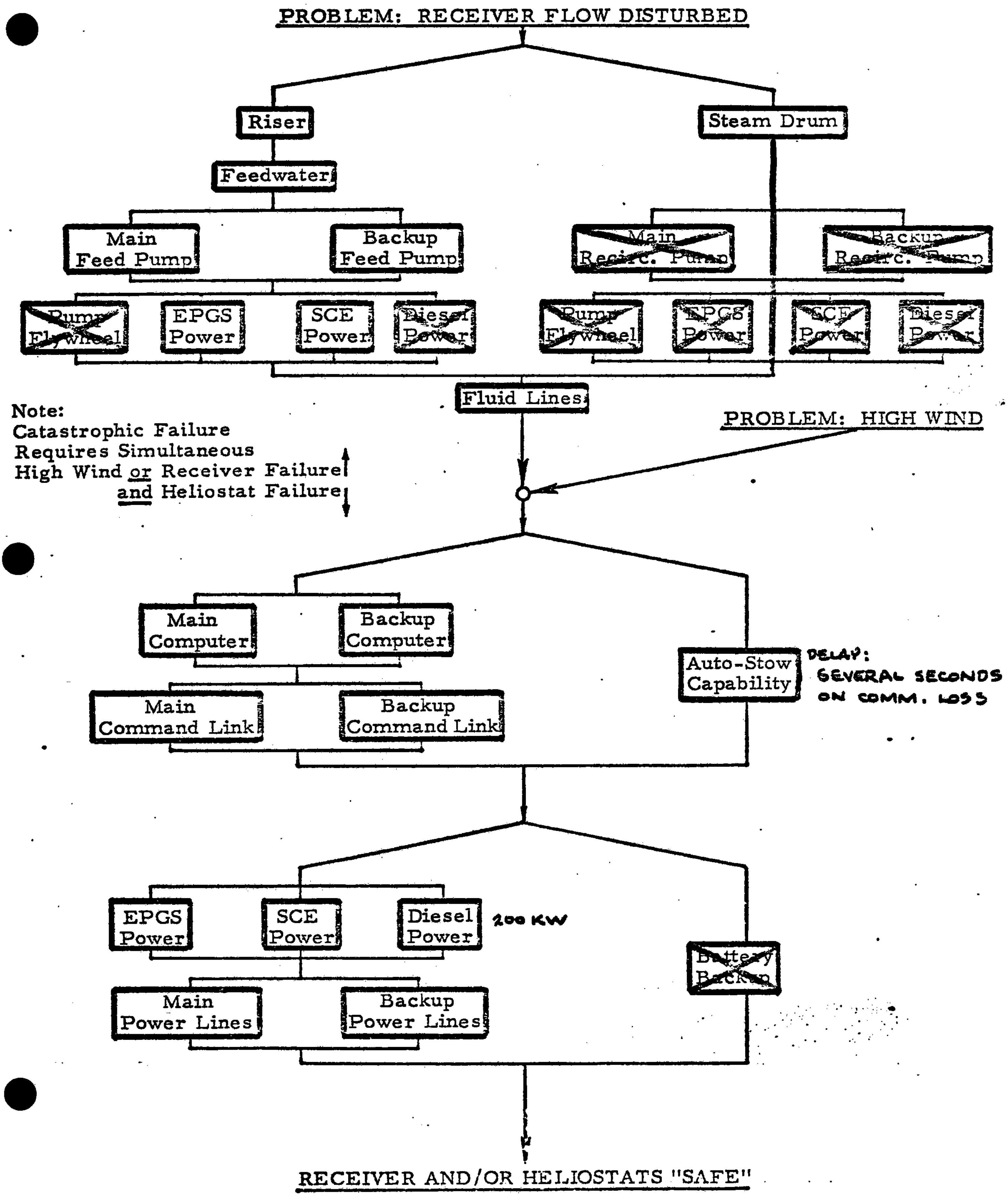


Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

Receiver: MMC

Heliostat: BOEING

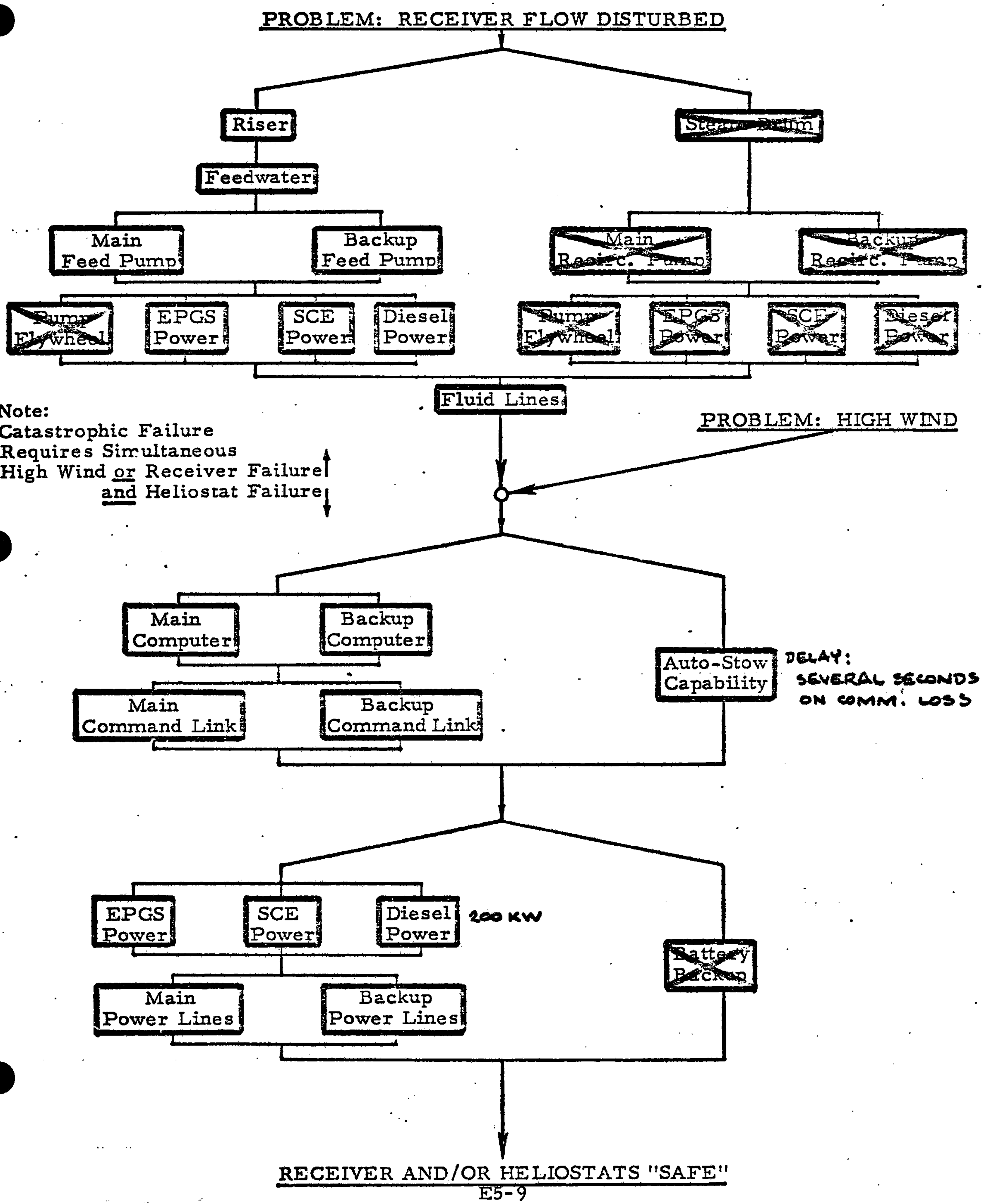
Figure 6: Subsystem Redundancy



Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

Receiver: MDAC
Heliostat: BOEING

Figure 7: Subsystem Redundancy



Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

DELAY: SEVERAL SECONDS ON COMM. LOSS

200 KW

Figure 8a. Possible Single-Point Failures

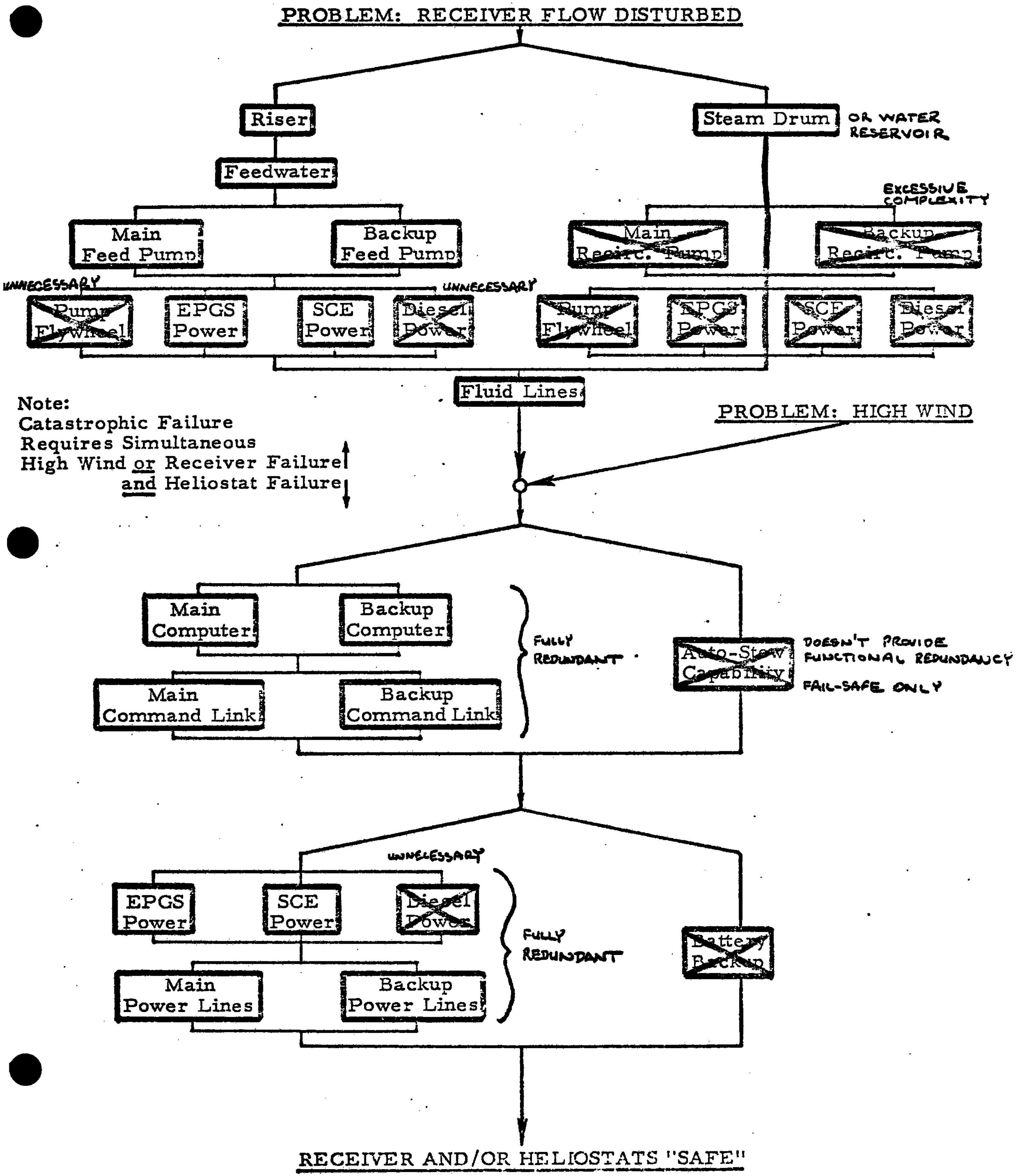
	Boeing	Honeywell	MMC	MDAC
Receiver Flow	-	1 Fluid Lines	1 Fluid Lines	3 Fluid Lines Riser Feedwater
Heliostat Control	0	0	0	2 Computer Comm. Link
Heliostat Power	0	0	1 Power Lines	1 Power Lines

Figure 8b. Degree of Redundancy

Receiver Flow		-	None	None	None
Heliostat Control	Control	Triple	Triple	Triple	None
	Lines	Triple	Triple	Double	None
Heliostat Power	Bus	Triple	Triple	Triple	Triple
	Lines	Double	Double	None	None

Receiver: SUGGESTED CONCEPT
Heliostat:

Figure 9 : Subsystem Redundancy

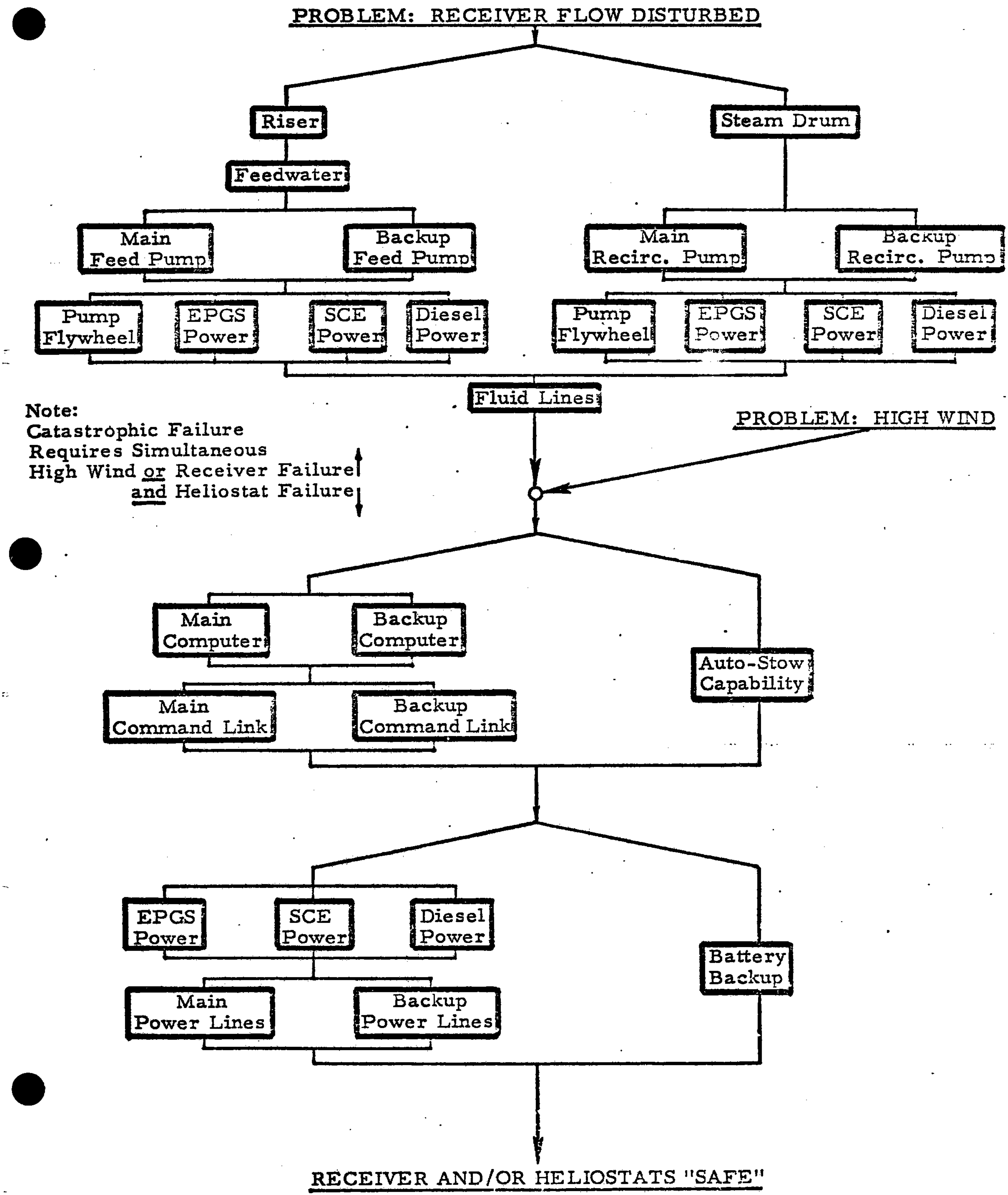


Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

Receiver:____________________

Heliostat:____________________

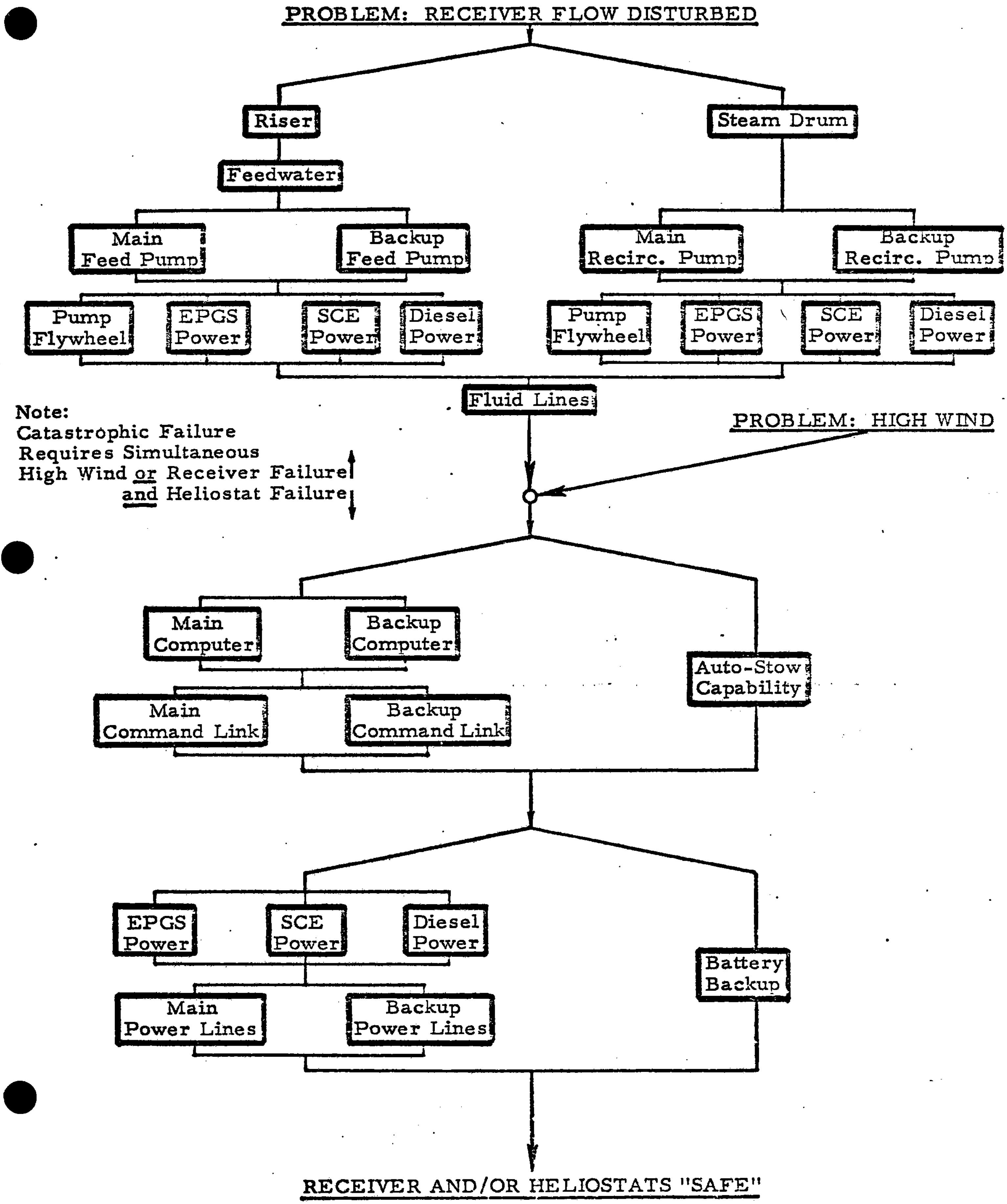
Figure : Subsystem Redundancy



Receiver: ____________________

Heliostat: ____________________

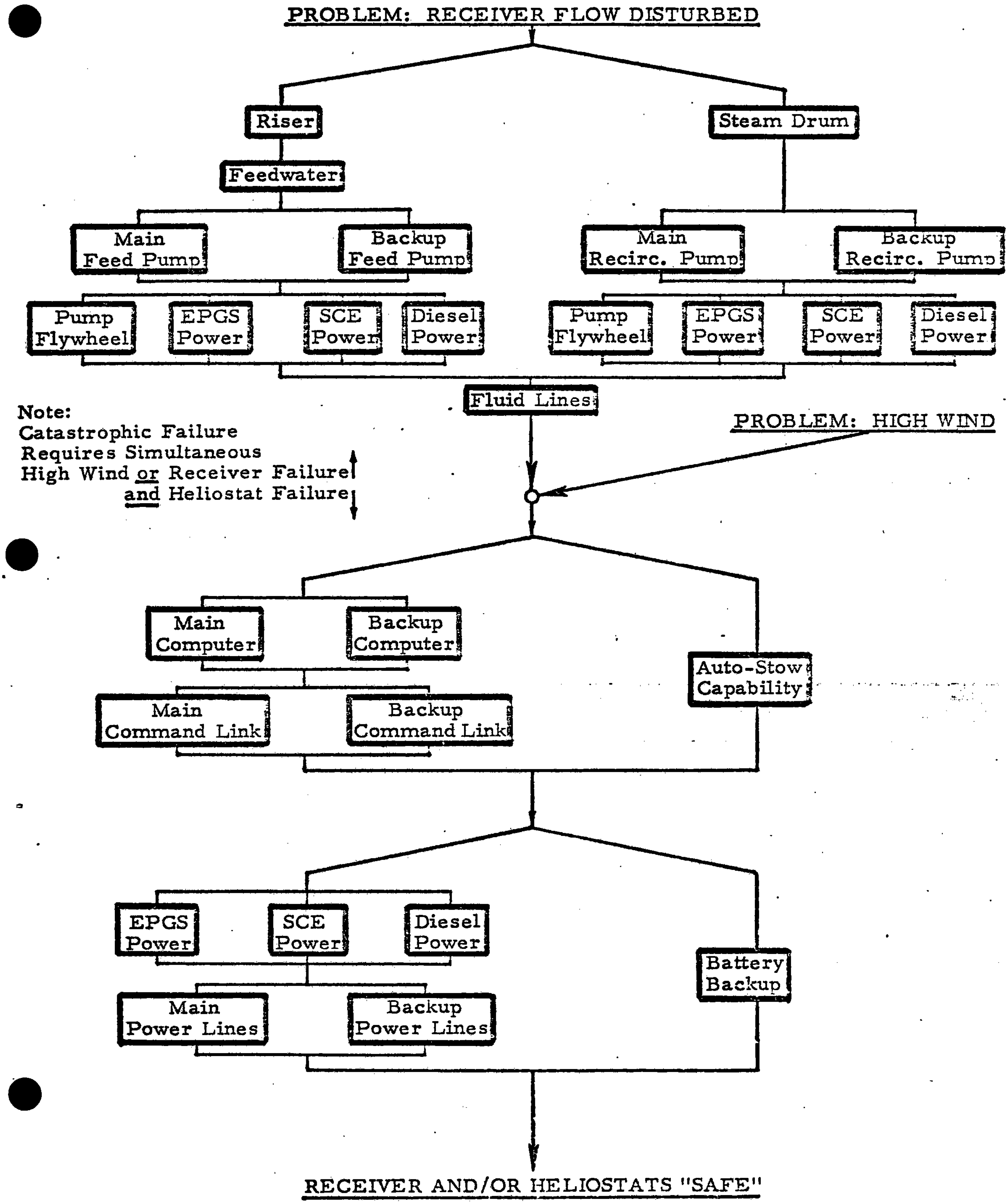
Figure : Subsystem Redundancy



Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

Receiver: ____________________
Heliostat: ____________________

Figure : Subsystem Redundancy



Note:
Catastrophic Failure
Requires Simultaneous
High Wind or Receiver Failure
and Heliostat Failure

APPENDIX E6

CRITICAL CENTRAL RECEIVER PROBLEMS AND CONSEQUENCES

Aerospace Participant: R. R. Sheahan

Generalized Logic Chains Illustrating Critical Central Receiver Problems and Consequences

Several types of subsystem-level control problems, common to all central receiver designs, threaten the safety of the receiver and/or heliostats. A series of figures were prepared for your consideration to illustrate these problems and the plant conditions which dictate either the catastrophic or benign consequences of the problems.

The 4 main problems of interest are illustrated in Figure 1, which flows from left to right. These problems are:

Total Power Loss - complete loss of electrical power to the heliostat motors

Total Command Loss - complete loss of all command authority over the heliostat drives

Receiver Flow Disturbed - anomaly in the water or steam flow in the receiver

High Wind - winds quickly rising to velocities requiring heliostat stow

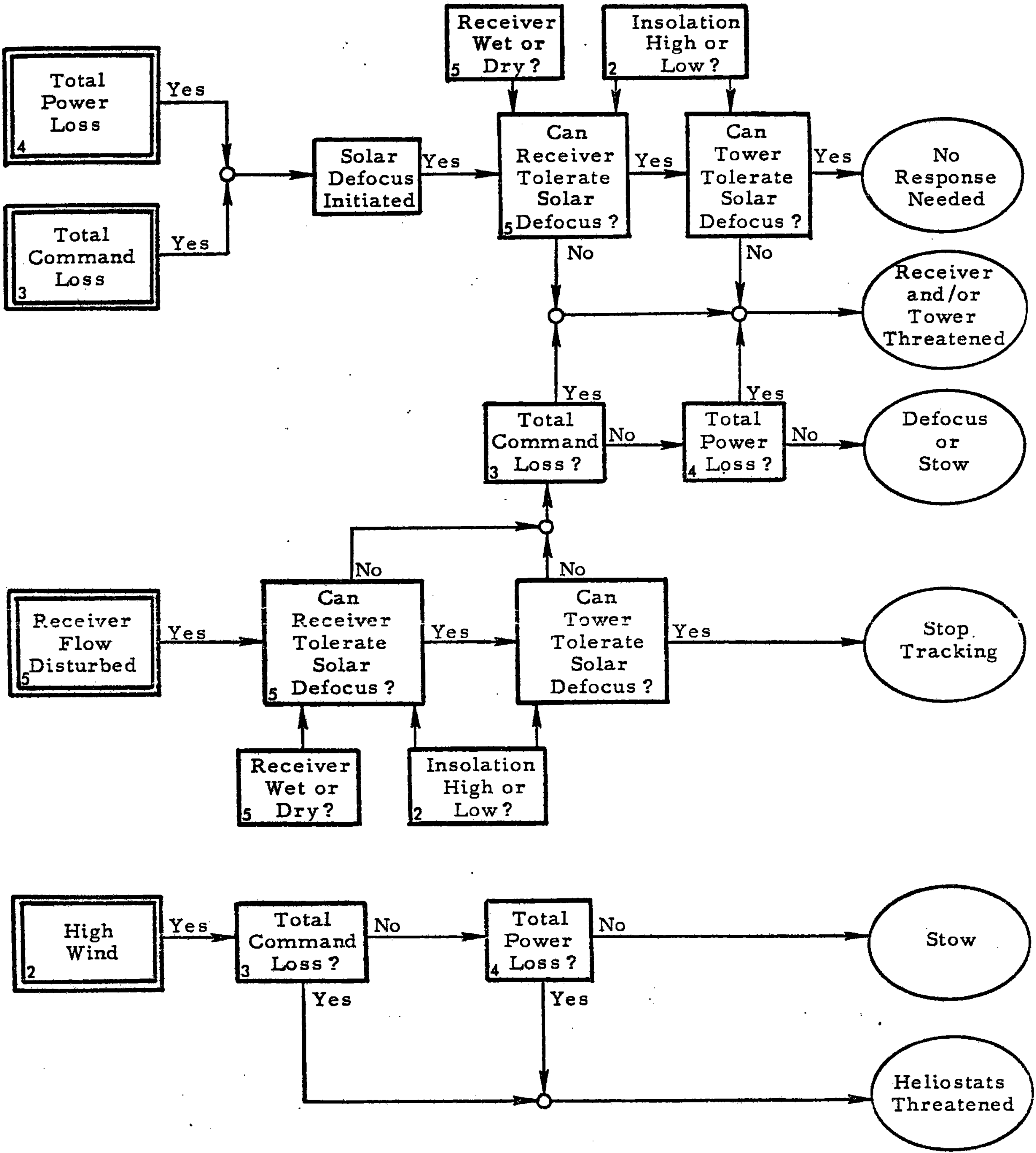
Given one of these problems, Figure 1 is entered at the left. The problem leads to a series of questions related to other subsystems. The answers to these questions dictate the path through the logic chain, leading ultimately to one of the consequences or actions arrayed on the right.

Figure 1 illustrates the interdependence of the heliostats and the receiver/tower. In particular, it demonstrates that the receiver/tower can be decoupled from the heliostats if both the receiver and tower can tolerate solar defocusing of the heliostats. The tolerance of the tower (the structure around the receiver cavity) is dictated by design and cannot be controlled. The tolerance of a dry receiver is also design dependent. However, since receiver flow is controllable, receiver tolerance can be insured if a minimal rate of water/steam flow can be maintained.

Two desirable design objectives follow from Figure 1. The tower should be designed to tolerate solar defocusing and; some flow redundancy should be provided the receiver. These 2 objectives, if met, would tend to isolate heliostat control failures from receiver failures and vice versa.

Similar logic chains in Figures 2 through 5, which read from top to bottom, complement Figure 1 by illustrating the plant conditions needed to cause the problems shown in Figure 1. The conditions of concern in square outline at the bottom of Figures 2 - 5 should be carried forward to Figure 1. Normal or benign conditions which are not cause for concern are presented in elliptical outline. Figures 3, 4, and 5 are useful in reviewing the redundancy provisions in the various control, power and receiver flow designs.

Figure 1: Critical Problems & Their Consequences



Note: 2 3 4 5 identify appropriate reference figures

Figure 2: Heliostat Status

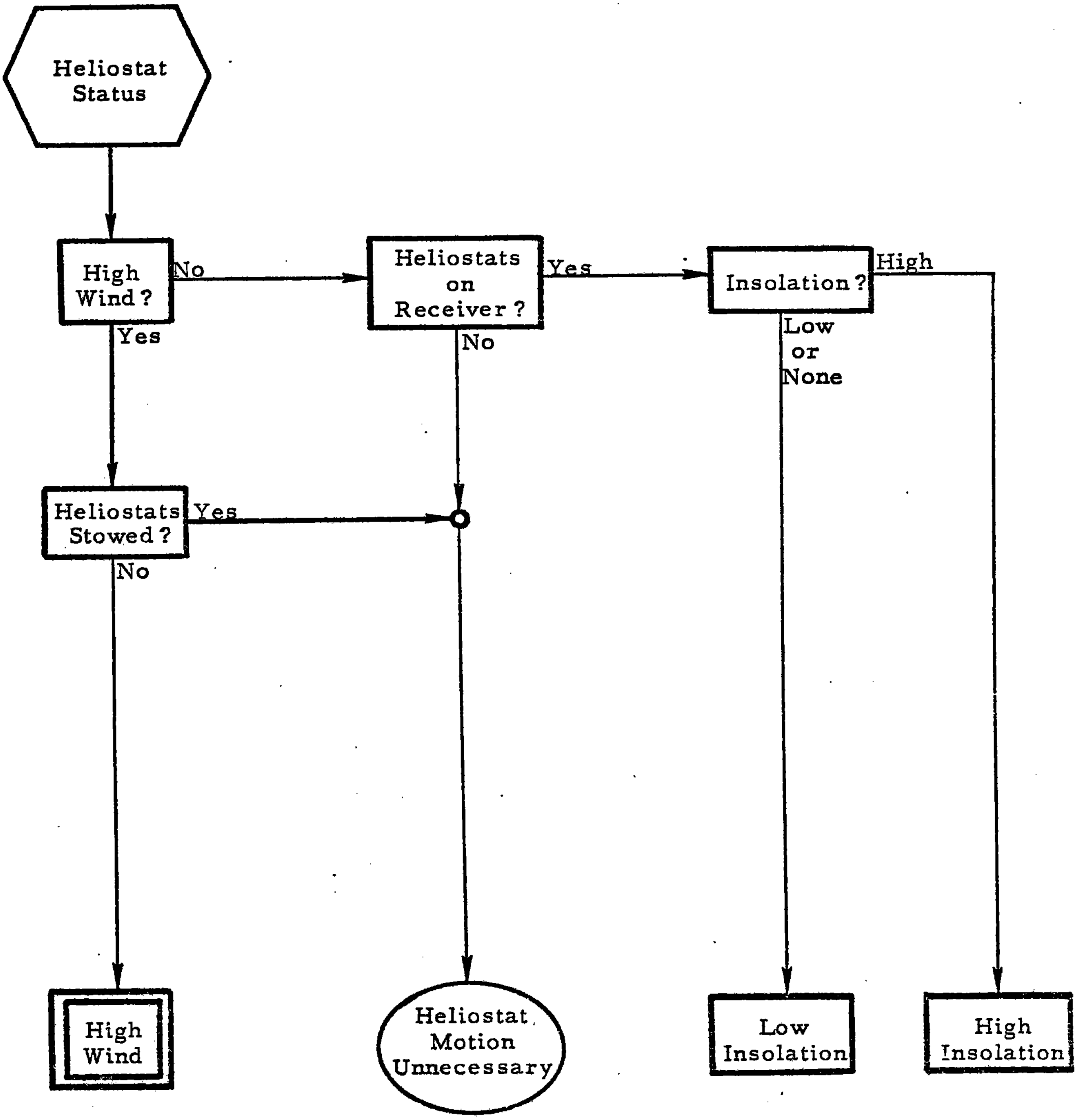


Figure 3: Command Status

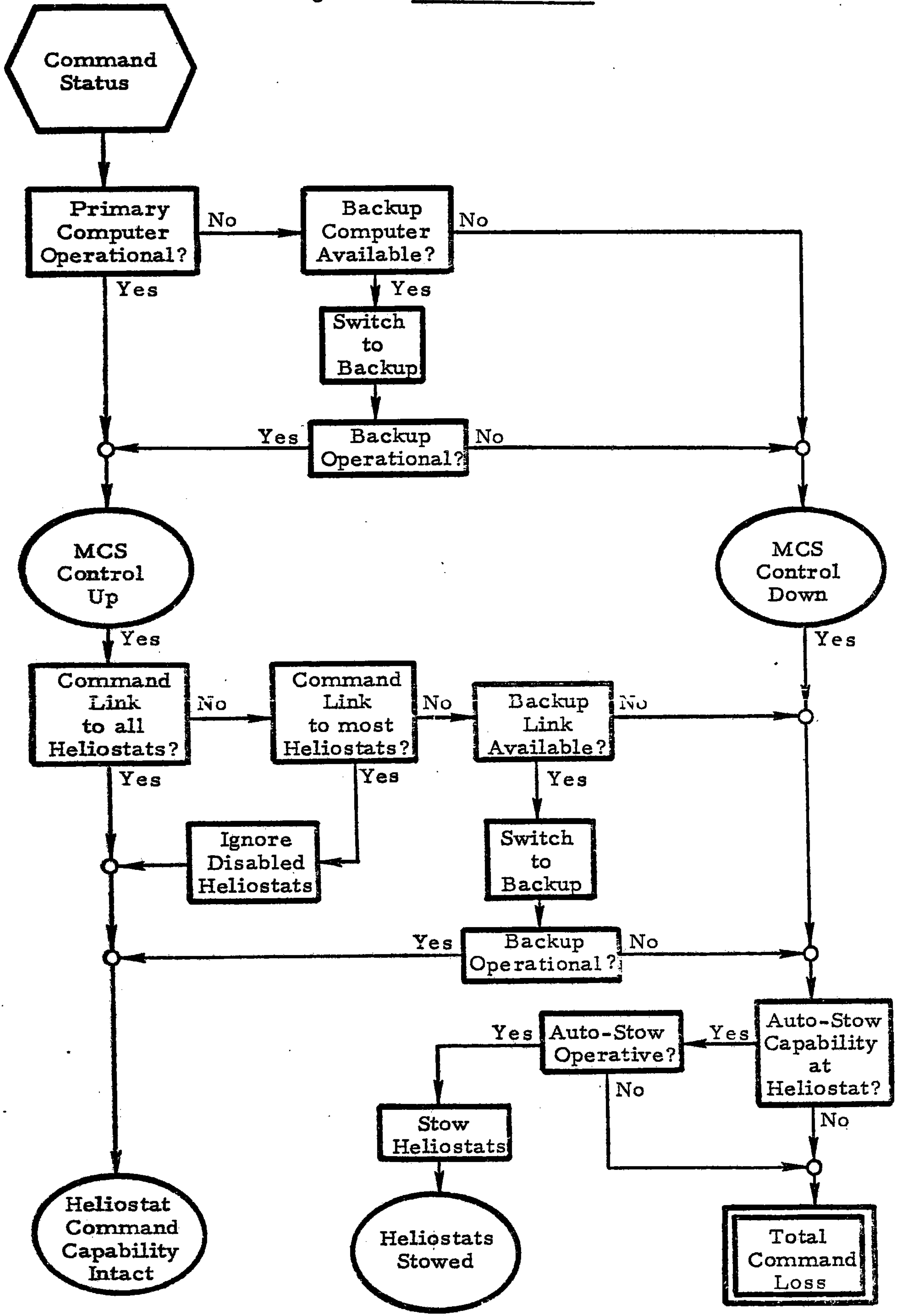


Figure 4: Power Status

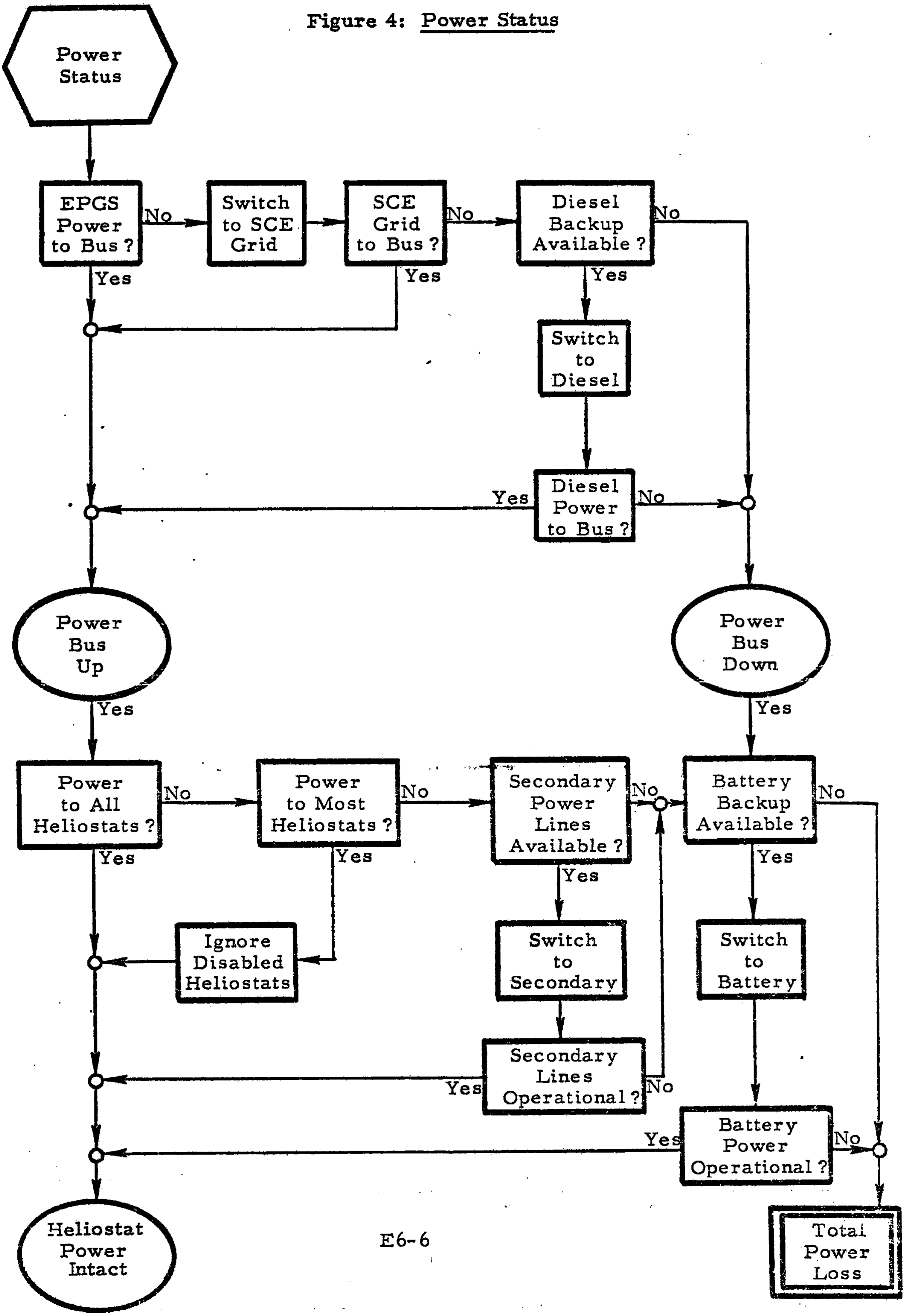
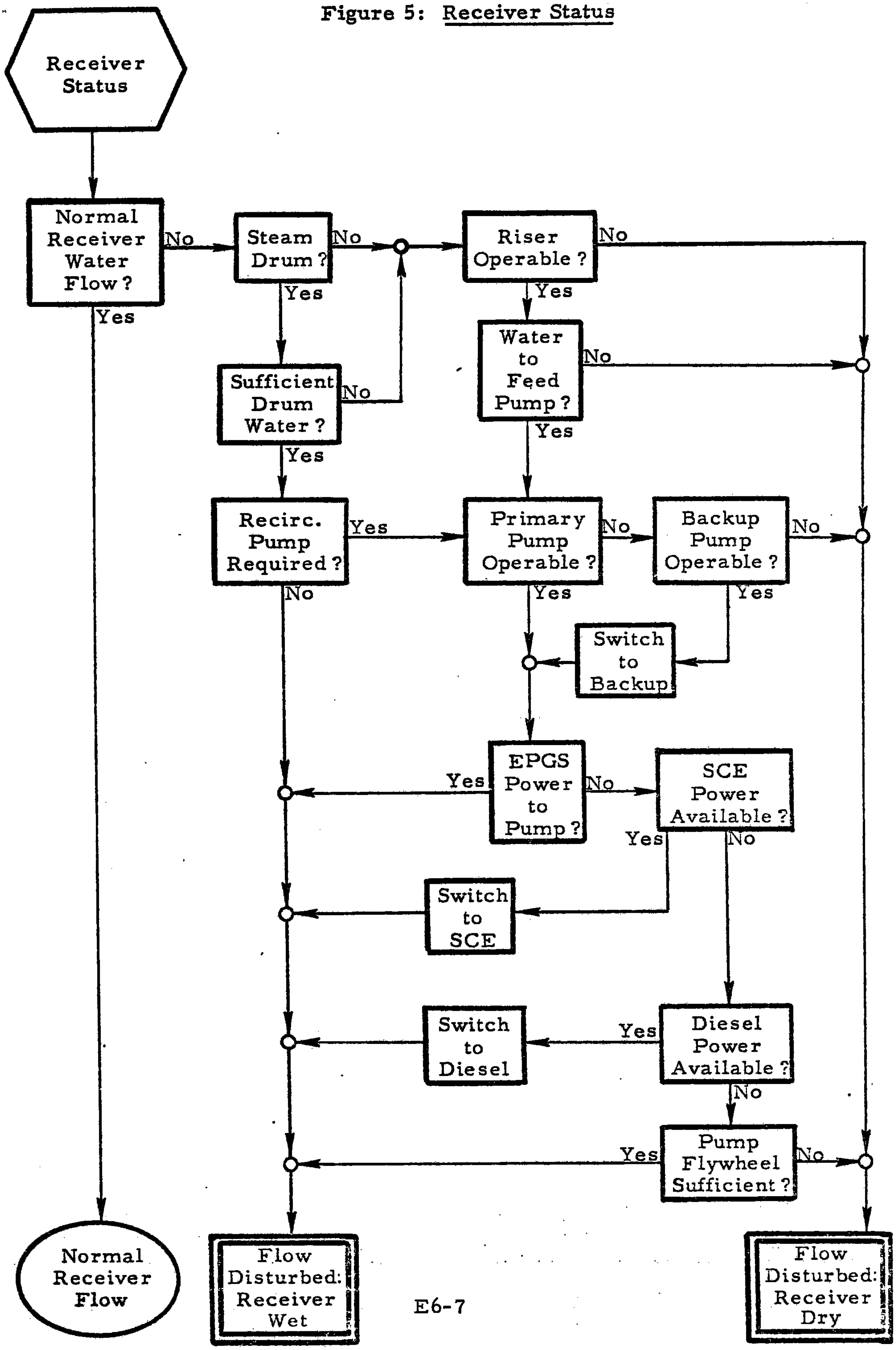


Figure 5: Receiver Status



APPENDIX E7

EVALUATIONS OF SUBSYSTEM CONTROLS

Aerospace Participant: R. C. Rountree

(Edited Copy of R. C. Rountree Internal Memo)

The attached material was submitted to Mike Soderstrand of Sandia at the 13 June MCS Evaluation Team Meeting... Included are the point evaluation sheets and a summary vugraph for each subsystem controls.

COLLECTOR CONTROL EVALUATION

- EDGE TO BOEING OVER MDAC
- EVALUATION POINT SHEETS ATTACHED
- BOE : - OFFERS HIGH CONFIDENCE CONTROL DESIGN (≈ STTF)
  - GOOD PERFORMANCE, GROWTH, AND OBSERVABILITY
  - SHELTERED EQUIPMENT, WITHOUT SINGLE POINT FAILURE
- HW : - FEATURES GOOD FLEXIBILITY, REDUNDANCY, AND OBSERVABILITY
  - LACKS ACCURACY AND UPLINK OPERATIONAL DIAGNOSTICS
  - SIMULATION VERIFICATION AS A PLANT INTEGRATED SUBSYSTEM
- MM : - PROVIDES BEST ACCURACY VIA ABSOLUTE ENCODER
  - GOOD DEFINITION OF SPECIFIC CONTROLS, BUT UNVERIFIED
  - LACKS OBSERVABILITY, FLEXIBILITY, AND REDUNDANCY
- MDAC: - CLOSE TO BOE EXCEPT FAILURE/REDUNDANCY CAPABILITY
  - GOOD PERFORMANCE AND OBSERVABILITY
  - PROBABLE SHIFT TO UNPROVEN OPEN LOOP APPROACH

DETAIL COLLECTOR CONTROL EVALUATION

Criteria	Possible	Boeing	HWI	MMC	MDAC
I. Commercial Plant Collector Controls					
1. Steady state Function	115	75	50	60	75
2. Mode change ~~Transient~~ Accomodation	40	20	25	30	25
3. Effect on other Subsystems	33	20	20	15	10
4. Reliability	15	10	10	5	5
5. Simplicity	15	10	5	10	5
6. Low Technical Risk	15	10	5	10	10
7. Operations & Maintenance	50	40	20	25	35
8. Capital Cost	50	--	--	--	--
9. Totals	283 ~~333~~	185	135	155	165
II. Pilot Plant Collector Controls					
10. Interface Requirements	33	25	20	15	20
11. Data Applicable to CP	50	35	35	15	30
12. Operational Flexibility	84	60	60	40	55
13. Design Flexibility	50	40	35	25	40
14. Mode Change Accommodation	34	15	20	25	20
15. Economic Data Applicable to CP	50	--	--	--	--
16. Reliability	33	20	20	15	10
17. Simplicity	33	20	10	20	10
18. Low Technical Risks	33	20	10	20	20
19. Operations & Maintenance	50	40	20	25	35
20. Capital Cost	50	--	--	--	--
21. Totals	450 ~~500~~	275	230	200	240

DETAIL COLLECTOR CONTROL EVALUATION

Criteria	Possible	Boeing	HWI	MMC	MDAC
III. Confidence in Collector Control Design					
22. Experience of Contractor	10	5	5	5	5
23. Recognition of Problems	32	25	25	15	25
24. Understanding Problems	25	20	15	10	20
25. Supporting Technical Analysis	25	15	15	15	15
26. Supporting Technical Data	25	20	10	10	20
27. Supporting Cost Analysis	25	--	--	--	--
28. Supporting Cost Data	25	--	--	--	--
29. Totals	117 ~~167~~	85	70	55	85
Overall Total	850	545	435	410	490

RECEIVER CONTROL EVALUATION

- EDGE TO HW; NO GROSS DIFFERENCES IN EVALUATION POINTS WITH MDAC
- EVALUATION POINT SHEETS ATTACHED
- HW :
  - B&V EXPERIENCE IS BENEFICIAL, HIGH OBSERVABILITY
  - LOSS OF MCS COMPUTER IS CRITICAL
  - BEST REDUNDANCY FOR RECEIVER FLOW AND HIGH WIND PROBLEM
- MM :
  - OFFERS LEAST COMPLEXITY
  - LACKS OBSERVABILITY (DATA FOR CP) AND FLEXIBILITY
  - MEDIUM REDUNDANCY FOR RECEIVER/WIND PROBLEM
- MDAC:
  - CLOSE TO HW, POSSIBLE BEST IN LONG TERM
  - MOST COMPLEX, PROBABLE HIGHEST CAPITAL COST
  - WORST REDUNDANCY FOR RECEIVER/WIND PROBLEM

DETAIL RECEIVER CONTROL EVALUATION

Criteria	Possible	HWI	MMC	MDAC
I. Commercial Plant Receiver Controls				
30. Steady state Function	115	50	30	45
31. Mode change ~~Transient~~ Accomodation	40	30	30	30
32. Effect on other Subsystems	33	15	25	20
33. Reliability	15	5	15	10
34. Simplicity	15	10	15	5
35. Low Technical Risk	15	10	10	10
36. Operations & Maintenance	50	30	30	35
37. Capital Cost	50	40	45	35
38. Totals	333	190	200	190
II. Pilot Plant Receiver Controls				
39. Interface Requirements	33	20	15	15
40. Data Applicable to CP	50	40	15	35
41. Operational Flexibility	84	60	40	55
42. Design Flexibility	50	40	30	40
43. Mode Change Accommodation	34	20	20	20
44. Economic Data Applicable to CP	50	--	--	--
45. Reliability	33	10	20	25
46. Simplicity	33	30	30	20
47. Low Technical Risks	33	30	30	25
48. Operations & Maintenance	50	30	30	35
49. Capital Cost	50	40	45	35
50. Totals	450 ~~500~~	320	275	305

DETAIL RECEIVER CONTROL EVALUATION

	Criteria	Possible	HWI	MMC	MDAC
III.	Confidence in Receiver Control Design				
	51. Experience of Contractor	10	10	5	5
	52. Recognition of Problems	32	30	15	25
	53. Understanding Problems	25	20	10	15
	54. Supporting Technical Analysis	25	15	15	15
	55. Supporting Technical Data	25	15	10	15
	56. Supporting Cost Analysis	25	--	--	--
	57. Supporting Cost Data	25	--	--	--
	58. Totals	117 ~~167~~	90	55	75
	Overall Total	900	600	530	570

EPGS CONTROL EVALUATION

- EDGE TO HW USING PARTIAL CRITERIA (DUE TO CONTRACTOR TURBINE/CONTROLS SIMILARITY)
- REVIEW EMPHASIS ON SIMULATION VERIFICATION AND OPERATIONAL FLEXIBILITY
- EVALUATION POINT SHEETS ATTACHED; LIMITED REVIEW TIME DEVOTED (HENCE LOWER POINT TOTALS TO DE-WEIGHT RESULTS)
- HW :
  - HIGH DEGREE OF FLEXIBILITY
  - INTEGRATED PERFORMANCE VERIFIED VIA SIMULATION
  - OBSERVABLE I/O VIA MCS
- MM :
  - SUPPORTS COMPLETE MODE/TRANSITIONS
  - LACKS OBSERVABILITY AND FLEXIBILITY
- MDAC:
  - ADDRESSES FUNCTIONAL AND PHYSICAL INTERFACES WITH MCS
  - DESCRIBES ELECTRICAL CONTROL INTERACTIONS WITH SUBSYSTEMS

STORAGE CONTROL EVALUATION

- EDGE TO MDAC; NO GROSS DIFFERENCES IN EVALUATION POINTS WITH HW
- EVALUATION POINT SHEETS ATTACHED; LIMITED REVIEW TIME DEVOTED (HENCE LOWER POINT TOTALS TO DE-WEIGHT RESULTS)
- HW : - B&V EXPERIENCE IS BENEFICIAL, HIGH OBSERVABILITY AND DEVELOPED CONTROL LOOP/LAW
  - CONTROL LOOP TIED TO MCS
  - LACKS FABRICATION AND TEST VERIFICATION
- MM : - OFFERS LIMITED COMPLEXITY BUT ALSO LEAST DESIGN INFORMATION
  - LACKS OBSERVABILITY (DATA FOR CP) AND FLEXIBILITY
  - BASIS IS SRE
- MDAC: - SIMPLEST DESIGN (MINIMUM LOOPS) AND MOST DESIGN INFORMATION
  - DESIGN/OPERATIONAL FLEXIBILITY FOR CONVERSION TO CP
  - BASIS IS SRE, AND AVOIDS HITEC CONTROL PROBLEM

DETAIL STORAGE CONTROL EVALUATION

Criteria	Possible	HWI	MMC	MDAC
I. Commercial Plant Storage Controls				
59. Steady state Function	115	50	40	30
60. Mode change ~~Transient~~ Accomodation	40	25	25	25
61. Effect on other Subsystems	33	15	25	20
62. Reliability	15	10	5	10
63. Simplicity	15	5	5	10
64. Low Technical Risk	15	5	5	10
65. Operations & Maintenance	50	20	20	25
66. Capital Cost	50	25	30	25
67. Totals	333	155	155	155
II. Pilot Plant Storage Controls				
68. Interface Requirements	33	20	15	20
69. Data Applicable to CP	50	40	15	40
70. Operational Flexibility	84	45	45	45
71. Design Flexibility	50	30	30	30
72. Mode Change Accommodation	34	20	25	20
73. Economic Data Applicable to CP	50	--	--	--
74. Reliability	33	20	10	20
75. Simplicity	33	10	10	20
76. Low Technical Risks	33	10	10	20
77. Operations & Maintenance	50	20	20	25
78. Capital Cost	50	25	30	25
79. Totals	450 ~~500~~	240	210	265

DETAIL STORAGE CONTROL EVALUATION

	Criteria	Possible	HWI	MMC	MDAC
III.	Confidence in Storage Control Design				
	80. Experience of Contractor	10	10	5	5
	81. Recognition of Problems	32	20	15	20
	82. Understanding Problems	25	20	10	15
	83. Supporting Technical Analysis	25	10	10	10
	84. Supporting Technical Data	25	15	10	15
	85. Supporting Cost Analysis	25	--	--	--
	86. Supporting Cost Data	25	--	--	--
	87. Totals	117 ~~167~~	75	50	65
	Overall Total	900	470	415	485

DETAIL EPGS CONTROL EVALUATION

Criteria	Possible	HWI	MMC	MDAC
I. Commercial Plant EPGS Controls				
88. Steady state Function	115	40	30	30
89. ~~Transient~~ Mode change Accomodation	40	25	25	20
90. Effect on other Subsystems	33	20	15	15
91. Reliability	15			
92. Simplicity	15			
93. Low Technical Risk	15		≈ SAME	
94. Operations & Maintenance	50			
95. Capital Cost	50			
96. Totals	188 ~~333~~	85	70	65
II. Pilot Plant EPGS Controls				
97. Interface Requirements	33	20	15	20
98. Data Applicable to CP	50	25	15	25
99. Operational Flexibility	84	45	35	35
100. Design Flexibility	50	--	--	--
101. Mode Change Accommodation	34	20	20	15
102. Economic Data Applicable to CP	50	--	--	--
103. Reliability	33			
104. Simplicity	33			
105. Low Technical Risks	33		≈ SAME	
106. Operations & Maintenance	50			
107. Capital Cost	50	25	30	30
108. Totals	201 ~~500~~	135	115	125

DETAIL EPGS CONTROL EVALUATION

Criteria	Possible	HWI	MMC	MDAC
III. Confidence in EPGS Control Design				
109. Experience of Contractor	10	5	5	5
110. Recognition of Problems	32	20	10	15
111. Understanding Problems	25	15	5	10
112. Supporting Technical Analysis	25	15	5	10
113. Supporting Technical Data	25	--	--	--
114. Supporting Cost Analysis	25	--	--	--
115. Supporting Cost Data	25	--	--	--
116. Totals	92 ~~167~~	55	25	40
Overall Total	481	275	210	230

APPENDIX E8

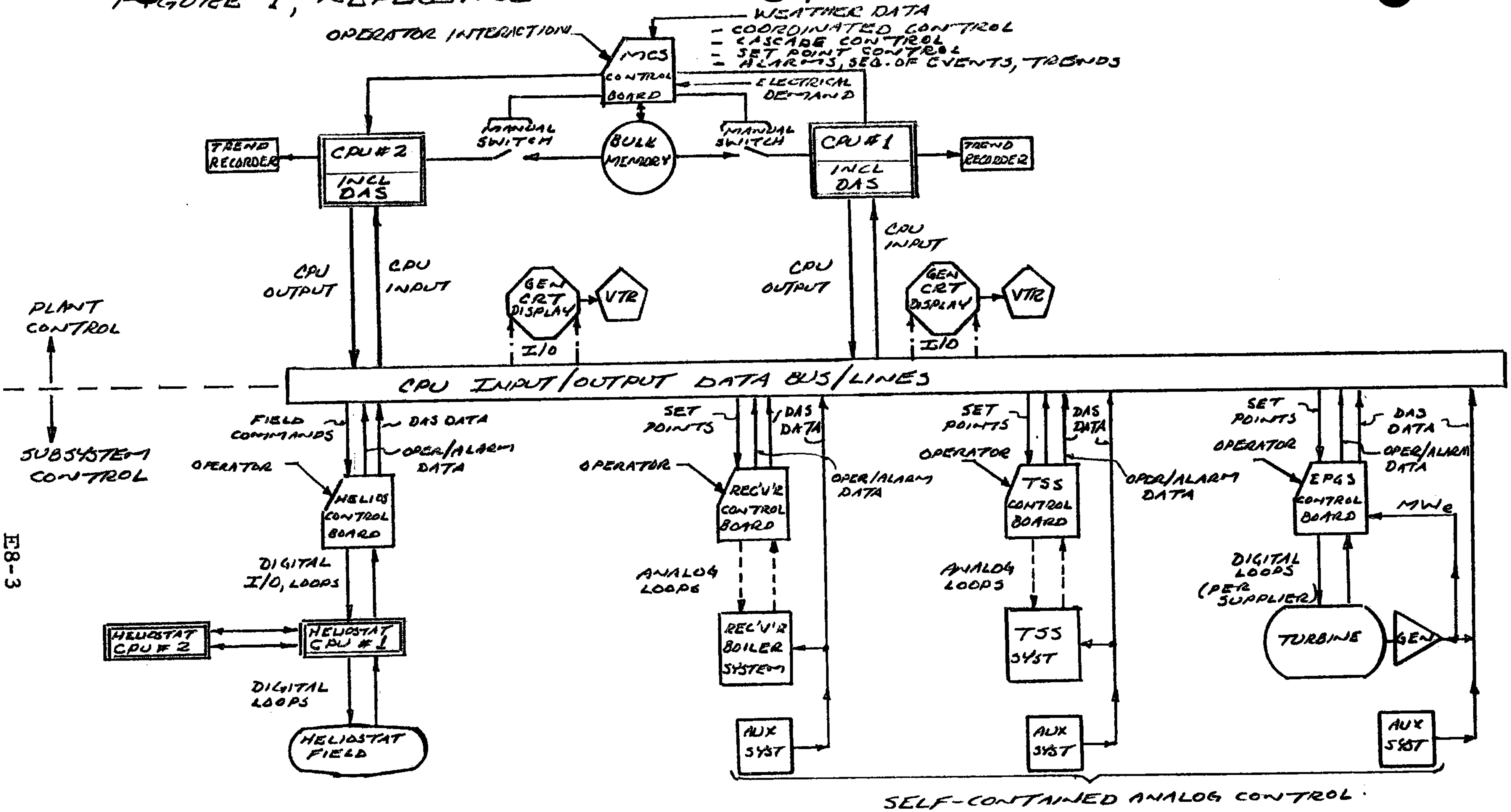
BLOCK DIAGRAMS OF POTENTIAL MCS CONFIGURATIONS

Aerospace Participant: R. C. Rountree

(Copy of R. C. Rountree Internal Memo)

The attached four figures are block diagrams for a reference and three alternative possible configurations for the pilot plant MCS. The reference was provided by Carman Winarski of SCE at the 13 June 1977 MCS Evaluation Team meeting at SLL. The three alternates are variations primarily in the number and role of the CPU's involved, and were generally discussed with Winarski prior to their generation. They were provided at his request to invite further discussion by team members regarding advantages and disadvantages of each and to yield a selection (i.e., one or a combination of these). Each configuration provides basic elements at the plant level and subsystem levels and each alternate configuration lists its variation to the reference.

FIGURE 1, REFERENCE* 4 CPU MCS/SS CONTROLS CONFIGURATION



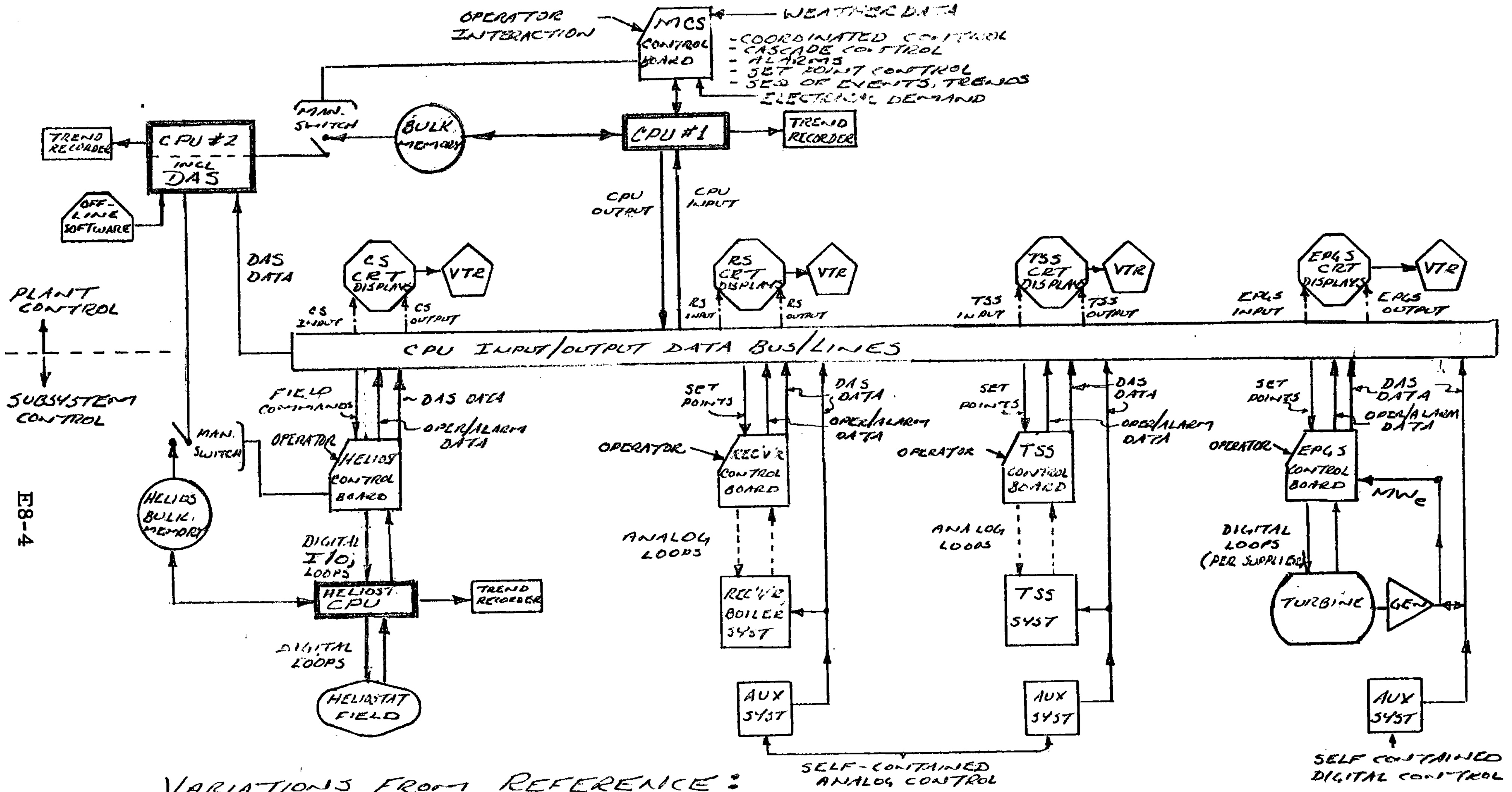
FEATURES OF REF:

- 4 CPU'S (REDUNDANT MCS, CS)
- DAS SHARING OF MCS CPU'S
- OPERATOR/AUTOMATIC CONTROL
- INDEPENDENT SS CONTROL LOOPS
- TREND RECORDERS, CRT'S, VTR'S

---

*FIG 1 IS AN INTERPRETATION OF C. WINARSKI (SCE) VERSION DATED 6-13-77

[illegible]URE 2, ALTERNATE* 3 CP[illegible] MICS/SS CONTROLS CONFIGURA[illegible]ON



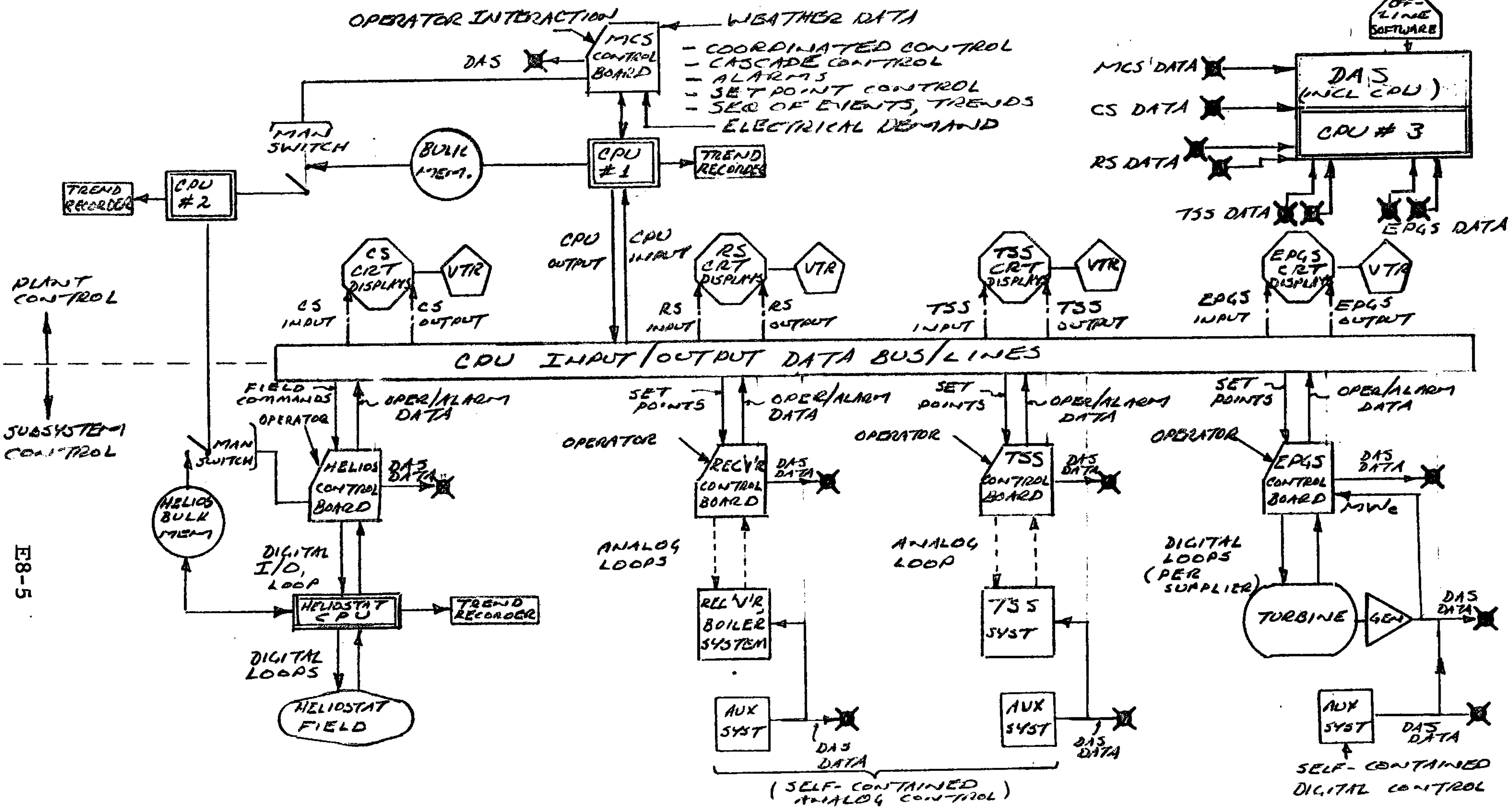
VARIATIONS FROM REFERENCE:

- 3 CPU'S (VS 4)
- CPU #2 AS BACKUP TO CPU#1 OR HELIOSTAT CPU
- DAS INTEGRATED W/CPU# 2
- COMPLEX CPU#2 SOFTWARE/SHARING
- TRICKY MEMORY TRANSFER (MAINTAINING DAS)
- EMERGENCY PLANT LEVEL HELIOSTAT CONTROL
- 1-CRT/VTR PER SUBSYSTEM
- TREND RECORDER W/HELIOSTAT CPU
- GENERATOR OUTPUT TO EPGS CONTROL BOARD & DAS
- DIGITAL AUX EPGS SYSTEM
- PART-TIME OFF-LINE SOFTWARE VERIFICATION

---

*REF IS C. WINARSKI VERSION OF 6-13-77, SEE FIGURE 1

IGURE 3, ALTERNATE* 4 CPU MCS/SS CONTROLS CONFIGURAT



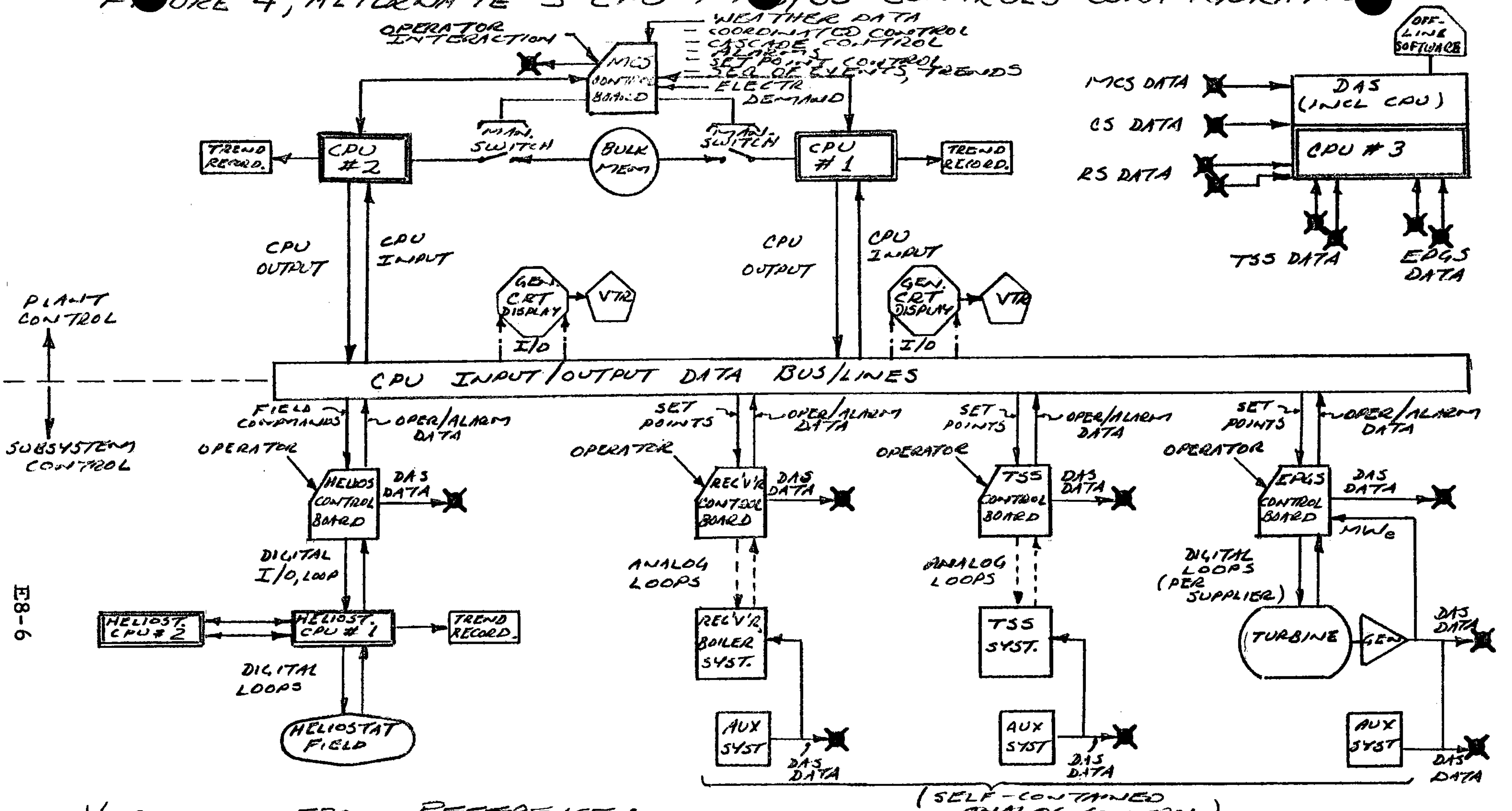
VARIATIONS FROM REFERENCE:

- 4 CPU'S (1 INDEP IN DAS)
- CPU #2 AS BACKUP TO CPU #1 OR HELIOSTAT CPU
- DAS INDEPENDENT (SOFTWARE, TIMING)
- OFF-LINE USAGE OF CPU #3
- EMERGENCY PLANT LEVEL HELIOSTAT CONTROL
- 1-CRT/VTR PER SUBSYSTEM
- TREND RECORDER W/HELIOSTAT CPU
- GENERATOR OUTPUT TO EPGS CONTROL BOARD & DAS
- DIGITAL AUX EPGS SYSTEM

---

*REF IS C. KLIMARSKI VERSION OF 6-13-77, SEE FIGURE 1

F[illegible]URE 4, ALTERNATE* 5 CPU M[illegible]S/SS CONTROLS CONFIGURATI[illegible]



VARIATIONS FROM REFERENCE:

- 5 CPU'S (1 MORE THAN REF)
- DAS INDEPENDENT (SOFTWARE, TIMING)
- OFF-LINE USAGE OF CPU # 3
- TREND RECORDER w/ HELIOSTAT CPU
- GENERATOR OUTPUT TO EPGS CONTROL BOARD & DAS

---

* REF IS C. WINARSKI VERSION OF 6-13-77, SEE FIGURE 1

APPENDIX F

COST ANALYSES

APPENDIX F1

COMMERCIAL PLANT COST ANALYSES

Aerospace Participant: J.A. Neiss

(Edited copy of letter to Joan Brune)

In accordance with your letter of 11 May, the following commercial plant analysis and comments are submitted.

. . .

Construction Cost Analysis

A summary comparison of each of the contractors' construction costs, by major system element, with that of the average cost for three coal plants and 62 nuclear plants is shown in Table 1. Table 2 provides comparative construction costs of coal and nuclear plants by major system and subsystem.

Since many utilitites already own land for future plant sites, the cost of land and land rights is generally low. However, as shown in Table 2, land and land rights has run as high as $80/kW although the average is about $4/kW.

The contractors' estimates for structures and improvements all fall within the range of historical costs. Martin's program apparently calls for both considerably less buildings and building size and complexity. Honeywell's cost for yardwork is difficult to reconcile.

While utilities are able to install turbine generators for coal plants at from $15-40/kW, the solar plant turbine generator for the first commercial is likely to be at least 2.5 times costlier. Overall turbine plant equipment costs are also likely to be 2.5 times as costly. These costs can only be reduced if the manufacturer can be assured of a moderate market, or system requirements for various subsystems can be reduced.

The contractors' costs for electrical plant equipment appear to be consistent with that being experienced for both coal and nuclear plants. Honeywell has unusually large costs for the switchgear and computer.

While the contractors' costs for miscellaneous plant equipment are considerably higher than current industry costs, some or all of this difference may be due to classification of costs. It should be noted that utilities generally contract for individual items of construction and that the allocations made to various systems are not uniform.

Overall, the solar thermal plant appears to cost from 5 to 10 times that of either a coal or nuclear plant in 1977 dollars. Projected new fossil fuel and nuclear plant costs by year of commercial operation are shown in Figure 1.

Operating Cost Analysis

In order to evaluate the contractors' operating and maintenance costs, an analysis was made of the 1974 operating and maintenance costs reported by utilities operating plants with an installed generating capacity of from 7 to 329 MWe. This analysis covered some 31 utilities operating 55 steam plants. All costs were escalated to a 1977 cost base.

A comparison of the total annual operating and maintenance costs, including fuel, of each utility is shown in Figure 2 along with that of the Douglas and Martin estimates. The solar thermal plant would operate at approximately one-third of the operating and maintenance costs of current fossil fuel plants due to the savings in fuel cost.

Figures 3-5 compare the operating economics of fossil fuel plants with the solar thermal plant excluding fuel costs. Figure 3 shows the cost per kWh of the Douglas and Martin estimates to be considerably higher than current fossil fuel plants. Approximately 11-15% of the solar plants operating and maintenance cost is for the periodic cleaning of the heliostats.

Figure 4 shows the cost per kWh as a function of installed capacity which eliminates the impact of the hours of plant operation. Figure 5 shows the cost per kW of installed capacity as a function of installed capacity. Similar results can be seen from Figures 4 and 5.

Levelized busbar energy costs have not been computed. Should you desire these costs along with annual financial statements, we will be happy to run these for you.

Table 1

SUMMARY COMPARISON
SOLAR THERMAL vs FOSSIL AND NUCLEAR PLANT COSTS
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

				Average Plant Cost	
Plant Size (MW_e)	100	150	100	293	1015
Number of Plants	1	1	1	3	62
Description	McDonnell(1) Douglas	Martin(1) Marietta	Honeywell(1)	Coal(2) Plants	Nuclear(3) Plants
Land & Land Rights		8	12	--	4
Structures & Improvements	71	45	140	68	146
Solar, Boiler, Reactor Plant Equip.	1792	2684	4896	308	202
Turbine Plant Equipment	257	199	268	80	120
Electrical Plant Equipment	57	57	80	59	61
Miscellaneous Plant Equipment	36	26	33	2	18
TOTAL PLANT COST	2213(4)	3019	5429	517	551

(1) Excludes transmission plant costs

(2) Extrapolated from costs provided by Pacific Power & Light, Dairyland Power Cooperative, City of Colorado Springs

(3) Extrapolated from Quarterly Report on Status of Nuclear Construction, June 1975, ERDA Form HQ-254

(4) No contingency costs shown

Table 2

COMMERCIAL PLANT ANALYSIS
SOLAR THERMAL POWER SYSTEM
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

Description	McDonnell Douglas	Martin Marietta	Honeywell	Comparative Construction Costs	
				(3) Coal Plants	(62) Nuclear Plants
Plant Size (MW_e)	100	150	100	200-350	475-1288
Land & Land Rights	—	6.87	10.72	0	0-80
Structures & Improvements					
Yardwork	15.30	22.47	100.48	19	
Turbine Building	21.60	5.33	15.98		
Admin & Control Building	11.00	5.33	8.88		
Circ & Sea Water Pumphouse	.10				
Maintenance/Warehouse Building	8.60	2.53	2.15		
Water Treatment Building	3.20		2.73	4	
Thermal Storage Structure	3.20				
Auxiliary Gen Building	.40				
Fire Pumphouse		.20		.30	
Condensate Pumphouse		.13			
Gate House		.07			
Total Structures & Improvements	63.40	36.06	130.22	28-133(1)	22-351
Solar Plant Equipment	1582.20	2147.40	4555.08	220-280(6)	82-482(7)

COMMERCIAL PLANT ANALYSIS
SOLAR THERMAL POWER SYSTEM
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

Description	McDonnell Douglas	Martin Marietta	Honeywell	Comparative Construction Costs	
				(3) Coal Plants	(62) Nuclear Plants
Turbine Plant Equipment					
Turbine Generators	141.50	110.20	137.03	15-40	
Heat Rejection System	38.30	33.67	70.66		
Condensing System	3.20	1.93	6.80		
Feedheating System	21.60	10.13	18.14		
Water Circ/Treatment Equip	23.80	4.20	16.28		
Auxiliary Boiler		.94			
Total Turbine Plant Equipment	228.40	161.07	248.91	40-95	43-274
Electrical Plant Equipment					
Switchgear	8.40	7.13	17.41		
Station Service Equipment	17.60	2.00	7.47		
Switchboards		.20	1.11		
Protective Equipment	2.30	3.20	7.58		
Electrical Structures & Wiring	2.70	16.73	9.67		
Power Wiring	1.70	2.80	9.91		
Total Electrical Plant Equipment	32.70	32.06	53.15	46-51	11-133
Plant Master Control Equipment					
Computer	.40	.40	9.54	Included in Electrical Plant Equipment	
Peripheral Equipment	.40	.27	.65		
Control Panel and Boards	.50	3.33	2.55		
Interface Equipment	3.40	1.07	4.05		
Software Design & Development		2.00	(2)		

COMMERCIAL PLANT ANALYSIS
SOLAR THERMAL POWER SYSTEM
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

Description	McDonnell Douglas	Martin Marietta	Honeywell	Comparative Construction Costs	
				(3) Coal Plants	(62) Nuclear Plants
Software/Hardware Test	2.10	1.07	(2)		
Hardware Design		.93	(2)		
Control Wiring	9.00	2.33	4.62		
Field Installation & Checkout	2.00				
Project Management		2.33			
Total Plant Master Control	17.80	13.73	21.41	---	---
Miscellaneous Plant Equipment					
Transportation & Lifting Equip	21.80	8.27	4.32		
Air & Water Service Systems	4.50	10.27	16.79		
Communications Equipment	.10	1.07	4.63		
Furnishings & Fixtures	5.70	1.53	5.15		
Total Misc Plant Equipment	32.10	21.14	30.89	1-2	1-295
Transmission Plant	.20	3.00	7.71	1	
Quality Assurance			21.16		
Distributables					
Contractor Field Office	9.10	6.07			
Insurance (Project)	7.20	1.33			
Insurance (Equipment)		.13			
Temporary Construction	6.10	16.27			

COMMERCIAL PLANT ANALYSIS
SOLAR THERMAL POWER SYSTEM
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

Description	McDonnell Douglas	Martin Marietta	Honeywell	Comparative Construction Costs	
				(3) Coal Plants	(62) Nuclear Plants
Construction Equipment	16.90	22.80			
Construction Services	9.70	33.33			
Spare Parts	32.00	13.67			
Taxes - State, Sales, Use				8	
Total Distributables	81.00	93.60		38(4)	
Indirects					
A&E Services	54.00	67.40	188.46		
Construction Management	86.80				
Solar Subsystem Integ Cont	12.50	23.87			
Plant Start-Up Costs	21.70	21.60	5.20		
Total Indirects	175.00	112.87	193.66	54(5)	
Contingency	---(3)	394.20	163.44	21	
Total Plant Cost	2212.80	3022.00	5436.35	435-615	184-1038

(1) Includes all foundation, substructures, superstructure and railroad access costs
(2) Included in indirect costs, A&E services
(3) Not estimated
(4) Excludes spare parts
(5) Excludes A&E services
(6) Boiler plant equipment
(7) Reactor plant equipment (some costs in current dollars)

Figure 1

PROJECTED NEW FOSSIL AND NUCLEAR PLANT COSTS

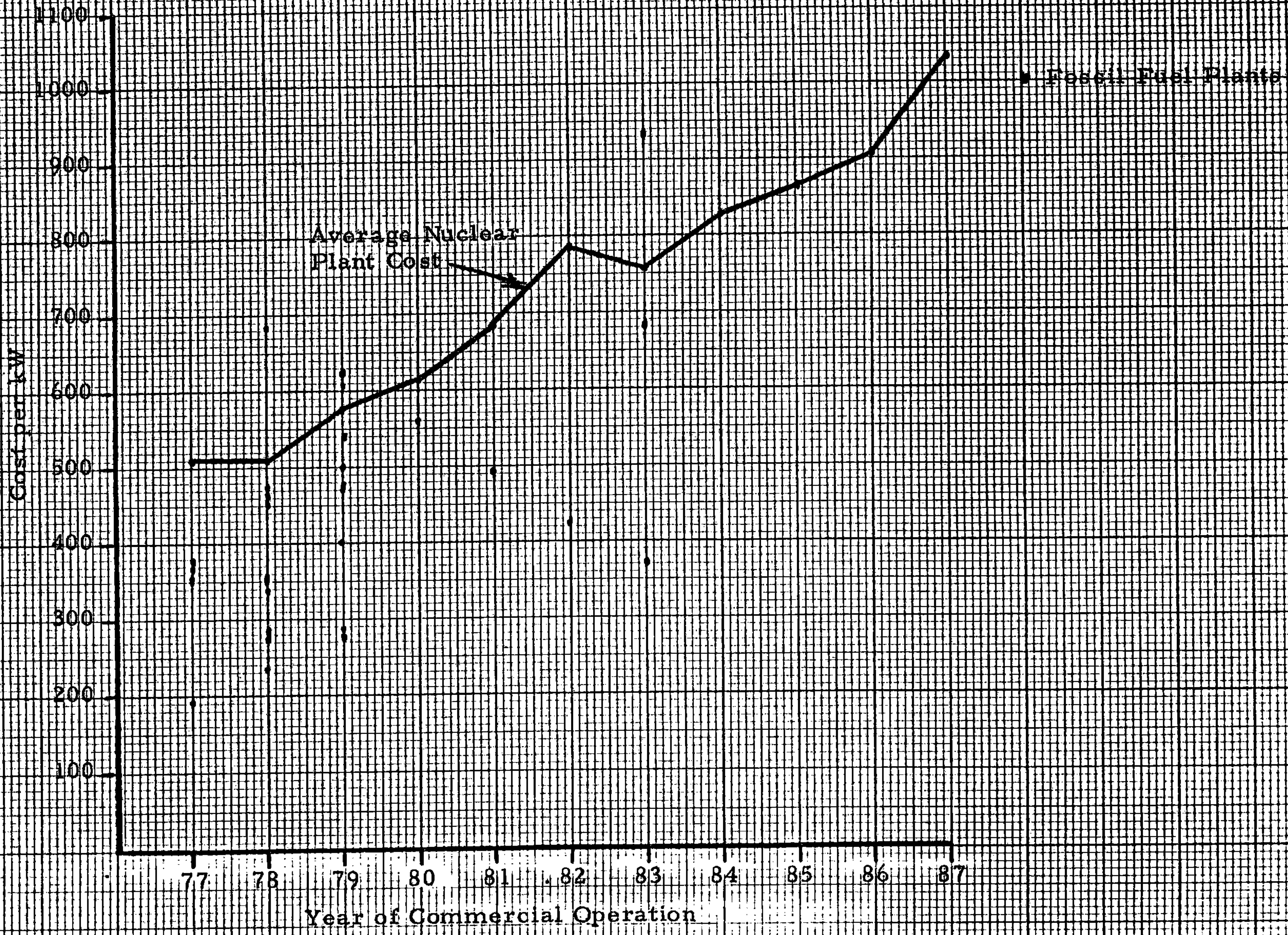


Figure 2

COMPARISON OF TOTAL ANNUAL OPERATING & MAINTENANCE COSTS
31 UTILITIES, 55 PLANTS INCLUDING FUEL
1977 COST BASE

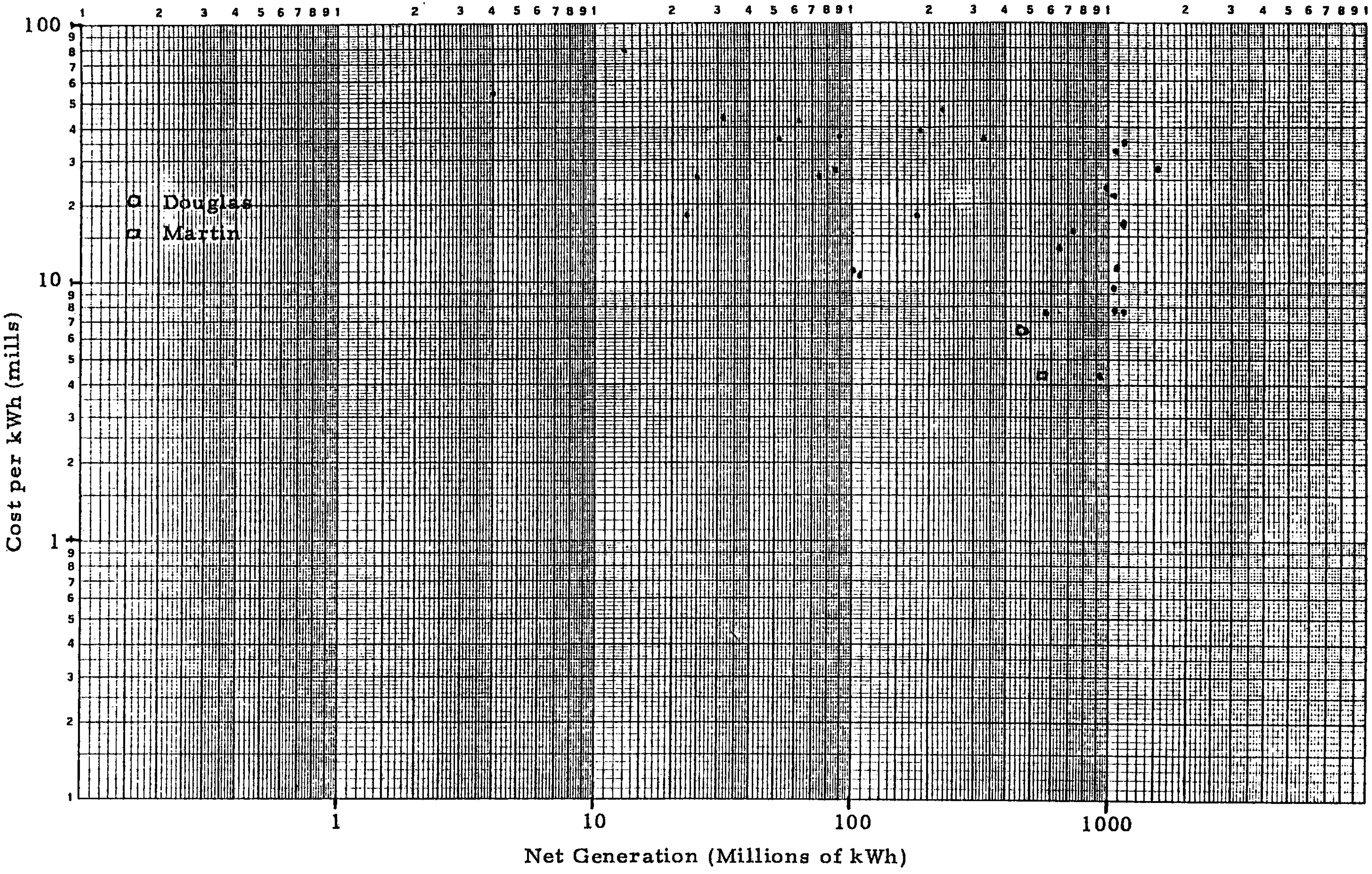


Figure 3

COMPARISON OF ANNUAL OPERATING & MAINTENANCE COSTS
31 UTILITIES, 55 PLANTS EXCLUDING FUEL
1977 COST BASE

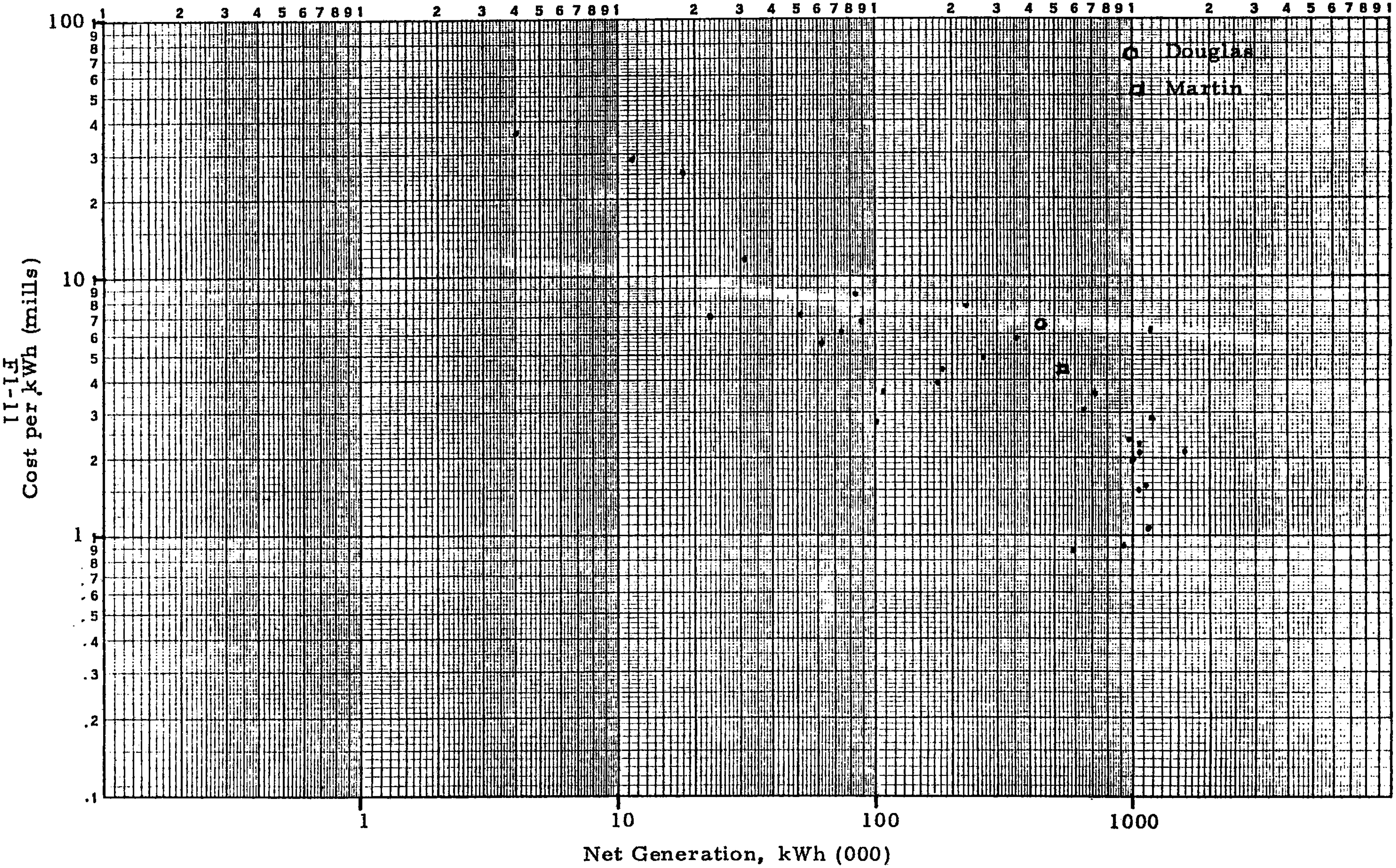


Figure 4

COMPARISON OF ANNUAL OPERATING & MAINTENANCE COSTS
31 UTILITIES, 55 PLANTS EXCLUDING FUEL
1977 COST BASE

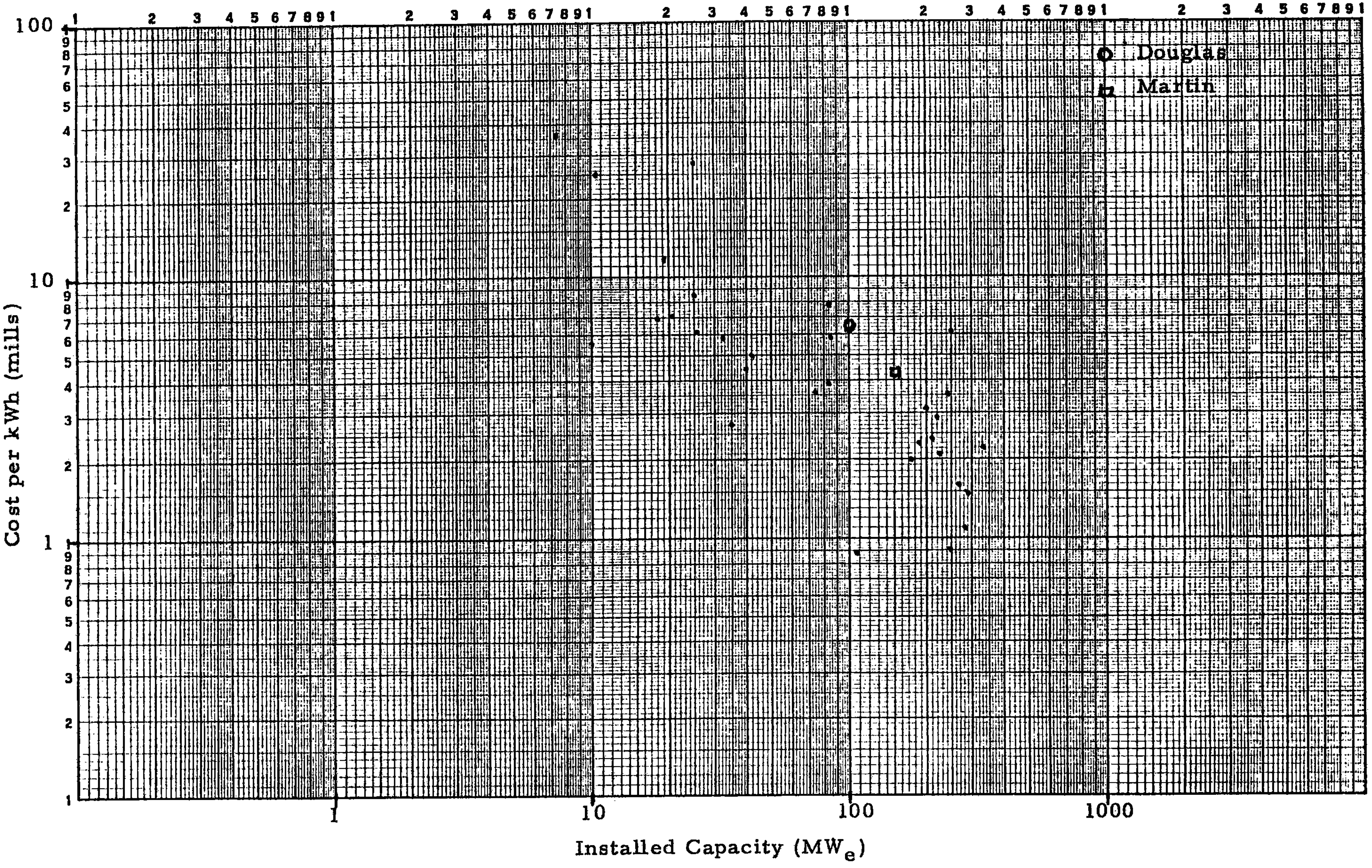
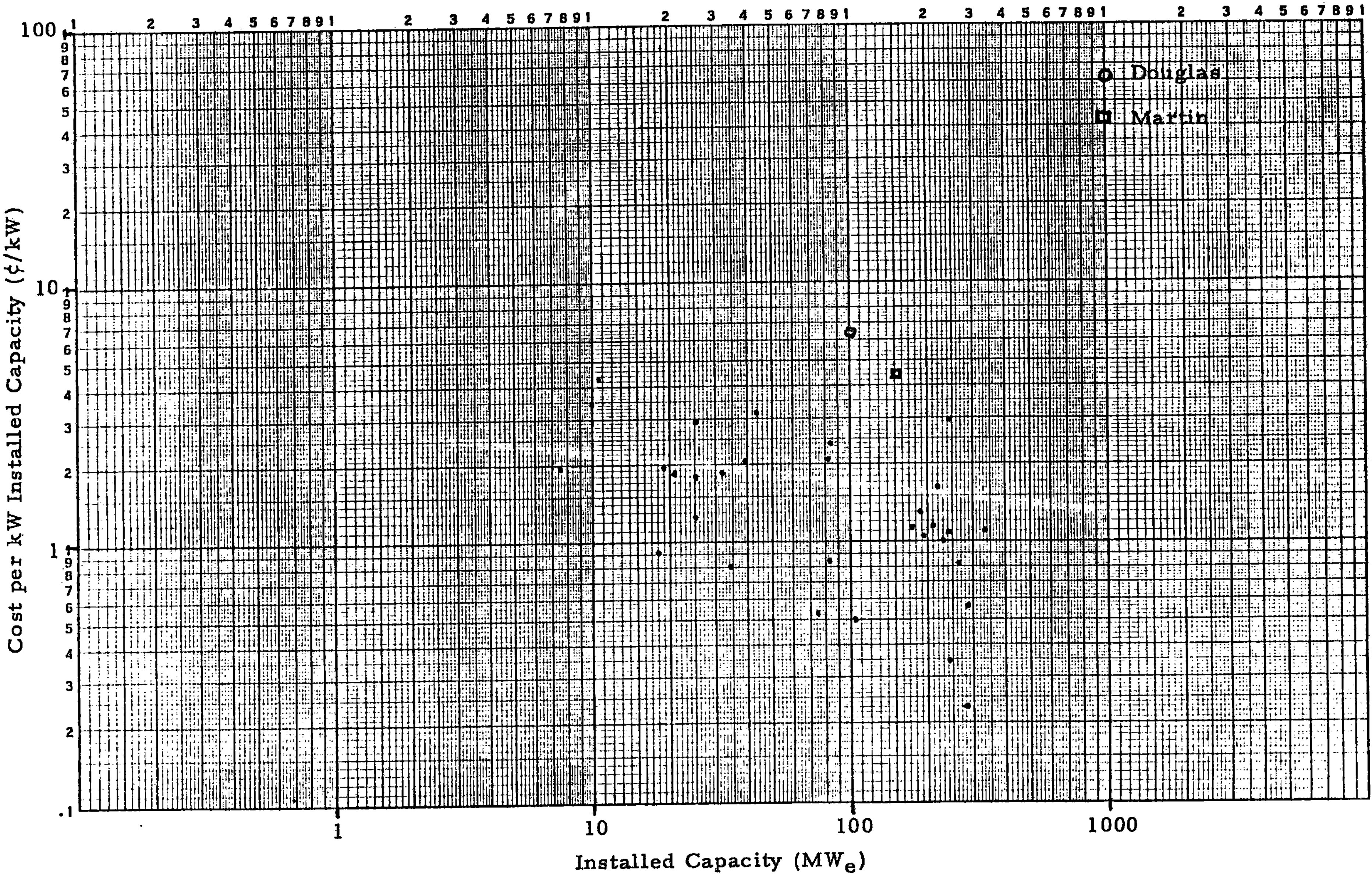


Figure 5

COMPARISON OF ANNUAL OPERATING & MAINTENANCE COSTS
31 UTILITIES, 55 PLANTS EXCLUDING FUEL
1977 COST BASE



Appendix F2

PILOT PLANT COST ANALYSES

Aerospace Participant: J. A. Neiss

(Copy of Letter to Joan Brune)

The following pilot plant analysis and comments are submitted:

A cost summary showing the cost per kW of installed capacity of the McDonnell, Martin Marietta, and Honeywell plant designs, and the SCE/DWP proposal of partnership estimates of September 15, 1976, is shown in Table 1.

The SCE/DWP land and land rights cost appears to be a "value" of land estimate and not a land acquisition cost. Other SCE/DWP estimates for the remaining system elements are approximations since their costs do not follow the WBS being utilized in your evaluation. The contractors' estimates for structures and improvements all are somewhat higher than the SCE/DWP estimate. The McDonnell Douglas and Honeywell estimates for turbine plant equipment are close to the SCE/DWP estimate with Martin Marietta somewhat lower.

The contractors' estimates for electrical plant equipment are close to the SCE/DWP estimate with the exception of plant master control equipment. The SCE/DWP estimates for both master control and miscellaneous plant equipment are unclear.

The contractors show significant differences in indirect costs. McDonnell Douglas and Honeywell contingency percentage on total costs was 9% while Martin Marietta applied a 15% contingency factor.

The cost per kW of installed capacity for each major WBS system and subsystem element is shown in Table 2.

1. Structures & Improvements

   Yardwork

   Honeywell's costs reflect considerably more site preparation, roadway, fencing, and lighting costs than either McDonnell or Martin.

Turbine & Warehouse Buildings

The McDonnell Douglas turbine building costs reflect a 12,000 sq ft structure at a cost of $59.50/sq ft. Their warehouse is a 5700 sq ft building costed at $9.47/sq ft.

2. Turbine Plant Equipment

The overall McDonnell Douglas and Honeywell costs are within 11% of each other while Martin Marietta's cost is considerably lower. Martin Marietta's costs for turbine generator and accessories and heat rejection system are somewhat lower than either McDonnell Douglas or Honeywell.

3. Electrical Plant Equipment

All contractors' estimates are relatively close to each other but appear to be lower than the SCE/DWP estimate.

4. Plant Master Control Equipment

McDonnell Douglas and Martin Marietta show identical costs. Honeywell's costs are 22% lower.

5. Miscellaneous Plant Equipment

The McDonnell Douglas costs are significantly higher than either Martin Marietta or Honeywell in areas of cranes, collector maintenance, and water systems.

6. Distributables & Indirect

The McDonnell Douglas combined distributable and indirect costs are 47% higher than Martin Marietta and 61% higher than Honeywell, primarily because of differences in construction management and solar systems integrating contractor costs

7. Contingency

The Martin Marietta 15% contingency appears to be high for this type of an estimate unless the uncertainties are large.

Two-Year Test Program

A comparison of the contractors' estimates for the two-year test program are shown in Table 3. Operating and maintenance staffing appear to range from 11 to 84 personnel per year. In addition, technical support staffing ranges from about 25-38 personnel per year.

The McDonnell Douglas estimate for spare parts is about 2.2% of total material cost while the Martin Marietta estimate is 1.3%.

Table 1
10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
Cost Summary
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell	SCE/DWP Proposal
Land & Land Rights	-	-	-	27.02
Structures & Improvements	311.00	175.70	207.44	154.58
Solar Plant Equipment				
Collector Equipment	2,197.00	1,939.00	3,113.18	
Receiver & Tower System	1,065.00	1,020.30	1,244.48	
Thermal Storage Equipment	432.00	1,030.00	569.67	
Thermal Storage Material	38.00	87.60	81.01	
Total Solar Plant	3,732.00	4,076.90	5,008.04	
Turbine Plant Equipment	507.00	418.90	565.43	521.04
Electrical Plant Equipment	107.00	140.60	143.36	174.04
Plant Master Control Equipment	211.00	211.30	165.21	
Miscellaneous Plant Equipment	268.00	87.40	160.42	
Distributables	284.00	333.90	-	
Indirects	1,117.00	620.80	870.01	
Contingency	590.00	909.80	631.85	
Total Solar Thermal Plant	7,127.00	6,975.30	7,751.76	

Table 2
10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Land & Land Rights	-	-	-
Structures & Improvements	311.00	175.70	207.44
Yardwork	66.10	51.70	108.21
Grading, Gen. Excav. Landscp.	37.00	4.00	13.81
Roadways, Fencing & Lighting	17.00	45.10	84.41
Roads	6.00	25.70	56.13
Sidewalks		1.00	(a)
Parking		1.80	(b)
Retaining Walls, Bridges	1.00	1.00	NR
Fences & Gateways	10.00	8.30	15.94
Yard Lighting		7.30	12.34
Sanitary Sewer System	11.00	2.60	1.01
Connection Existing Syst.		2.60	
Septic Tank			.11
Tile Field			.34
Piping, Conduits, Manholes			.56
Yard Drainage & Storm Sewer	1.00	(c)	8.98
Turbine Building	119.00	39.60	51.19
Substructure	36.00	5.40	7.86
Superstructure	33.00	22.60	26.38

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Building Mechanical	24.00	3.00	5.95
Lighting & Building Service	24.00	7.60	9.20
Painting	2.00	1.00	1.80
Administration Building	44.00	70.20	NR
Substructure	13.00	5.60	
Superstructure	12.00	35.10	
Building Mechanical	9.00	16.30	
Lighting & Building Service	9.00	10.90	
Painting	1.00	2.30	
Circulating & Service Water Pumphouse	1.00		NR
Warehouse	54.00	(d)	NR
Maintenance Building	6.00	11.20	12.12
Water Treatment Equip. Building	8.00		4.60
Thermal Storage Structure	13.00		NR
Fire Pump House		1.00	
Condensate Pump House		.90	
Gate House		1.10	
Control Building		(e)	31.32

10 MWe PILOT PLANT ANALYSIS
SOLAR THERMAL POWER SYSTEM
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

Description	McDonnell Douglas	Martin Marietta	Honeywell
Solar Plant Equipment	3,732.00	4,076.90	5,008.34
Collector Equipment	2,197.00	1,939.00	3,113.18
Reflective Unit	643.00	752.30	1290.92
Reflective Surface	380.00	67.10	44.61
Mirror Backing Structure	166.00	456.00	843.23
Heliostat Support Structure	97.00	229.20	403.08
Protective Enclosure			NR
Drive Unit	619.00	628.10	707.31
Azimuth Drive Assembly	228.00	267.80	346.26
Elevation Drive Assembly	210.00	239.40	200.81
Motors	81.00	42.10	107.84
Position & Limit Indicators	58.00	50.70	29.75
Emergency Power Supply		(f)	13.70
Power Distribution Equipment	42.00	28.10	8.91
Sensor/Calibration Equipment	115.00	15.10	56.06
Sensor Unit	31.00		19.26
Sensor Tower	68.00		20.54
Calibration Equipment		15.10	16.27
Wiring	16.00		

10 MWe PILOT PLANT ANALYSIS
SOLAR THERMAL POWER SYSTEM
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

Description	McDonnell Douglas	Martin Marietta	Honeywell
Control/Instrumentation Equipment	190.00	187.50	327.32
Field Control Electronics	121.00	171.20	244.16
Computer Hardware	12.00	6.60	47.43
Signal Distribution Equipment	57.00	9.70	35.73
Foundation & Site Preparation	72.00	58.80	50.71
Heliostat	66.00	57.00	50.71
Site Preparation	6.00	1.80	
Design & Engineering	343.00	162.20	423.04
Systems			64.65
Reflective Unit	13.00	12.30	55.28
Drive Unit	19.00	5.20	22.65
Sensor/Calibration Equipment	19.00	9.20	24.02
Control Equipment	66.00	33.40	80.17
Foundation & Site Prep.		7.00	7.24
Eng. Support	162.00	95.10	169.03
Pre-Prod. Unit	16.00		
Site Plant Activity	48.00		
Pacific Containers & Transportation	7.00		15.33
Containers	6.00		1.80
Transportation	1.00		13.53

10 MWe PILOT PLANT ANALYSIS
SOLAR THERMAL POWER SYSTEM
COST PER kW OF INSTALLED CAPACITY
1977 COST BASE

Description	McDonnell Douglas		Martin Marietta		Honeywell	
Field Assembly, Install. & Checkout		208.00		106.70		232.07
Heliostat Field Assembly	185.00		58.10		183.35	
Installation Checkout			45.80		48.67	
Sensor/Calibration Field Assm.	23.00		.80		.05	
Installation & Checkout			1.20			
Calibration			.80			
Lightning Protection			6.60		10.42	
Project Management			21.70			
Receiver & Tower System		1,065.00		1020.30		1,244.48
Receiver Unit	760.00		442.80		686.37	
Absorber	557.00		63.30		104.41	
Drum			9.30		10.25	
Door, Housing, Lining	3.00		26.50		16.92	
Piping	80.00		19.10		45.12	
Support Structure	16.00		45.70		268.82	
Instrumentation & Control	32.00		11.60		19.60	
Packing & Transportation	12.00		6.00		10.66	
Field Erection & Installation	60.00		261.30		210.59	
Riser & Horiz. Piping (Receiver)		7.00		7.20		98.42
From Turbine	4.00		(5.80)		(79.78)	
Piping			2.70			
Hangars, Valves, Supports			1.80		61.99	

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas		Martin Marietta		Honeywell	
Insulation			1.30		4.37	
from Thermal Storage	3.00		(1.40)		(18.63)	
Piping			.60		12.12	
Hangars, Valves, Supports			.50		2.92	
Insulation			.30		3.59	
Downcomer & Horiz Piping (Receiver)		12.00		52.60		110.80
from Turbine Generator	10.00		(43.70)		(69.23)	
Piping			25.10		35.94	
Hangars, Valves, Supports			15.80		26.62	
Insulation			2.80		6.67	
from Thermal Storage	2.00		(8.90)		(41.37)	
Piping			3.20		17.51	
Hangars, Valves, Supports			5.30		20.89	
Insulation			.40		2.97	
Tower & Platform		41.00		239.70		191.62
Tower	24.00		198.00		(h)	
Platforms	7.00		(g)		(h)	
Elevator	8.00		30.60		(h)	
Lighting	1.00		3.90		(h)	
Lightning Protection	1.00		1.40		(h)	
Blowdown & Drain Lines			5.80			

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Tower Foundation	21.00	59.70	70.05
Foundation	19.00	54.80	68.14
Excavation	2.00	4.90	1.91
Design	224.00	192.90	87.42
Receiver	212.00	109.30	87.42
Tower & Foundation	9.00	70.80	
Riser, Downcomer Piping	3.00	12.80	(i)
Project Management		25.40	
Thermal Storage Equipment	432.00	1030.00	569.67
Thermal Storage Unit	95.00	317.70	218.59
Storage Tanks & Heaters	79.00	290.60	88.62
Insulation	9.00	24.90	11.83
Ullage Maintenance Equip.	4.00	2.20	6.14
Fluid Maintenance Equip.	3.00		112.00
Circulation Equipment	53.00	203.90	95.06
Piping & Support	17.00	100.90	27.18
Valves, Strainers	8.00	49.30	51.06
Pumps	7.00	12.40	12.06
Insulation	3.00	21.90	2.89
Steam Drums	1.00	11.50	.50
Water/Steam Piping	2.00	7.90	1.37
Field Erection	15.00		

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Heat Exchangers	86.00	217.30	34.29
Desuperheaters	1.00	1.10	2.22
Steam Generator	52.00	81.20	12.90
Thermal Storage Heater	27.00	112.30	16.95
Insulation	5.00	9.00	2.22
Support Structures	1.00	13.70	NR
Instrumentation & Control	39.00	9.90	41.76
Foundation & Site Preparation	29.00	14.50	46.27
Tank Foundations	1.00	.30	11.98
Other Foundations	1.00	6.30	7.41
Dikes or Emergency Cont.	23.00	.30	10.66
Site Preparation	1.00	1.40	.90
Safety Protection Equip.	3.00	6.20	15.72
Design	130.00	233.10	133.30
Project Management		33.60	
Thermal Storage Material	38.00	87.60	81.01
Inorganic Material	6.00	16.40	38.49
Organic Material	19.00	55.50	36.13
Delivery	4.00	11.40	6.39
Handling at Site	9.00	4.30	

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Turbine Plant Equipment	507.00	418.90	565.43
Turbine Generators	256.00	232.60	315.33
Turbine Generator & Accessories	244.00	222.00	303.09
Foundations	10.00	9.30	6.96
Lubricating System	2.00	(j)	2.25
Gas Systems			3.03
Seal Steam Lines		1.30	
Heat Rejection System	97.00	82.10	121.46
Heat Rejection Equipment	33.00	56.80	51.86
Installation	6.00	25.30	15.60
Exhaust Duct	12.00		32.33
Evaporation Pond	46.00		21.67
Condensing Systems	33.00	15.30	27.84
Pumps, Drives & Controls	9.00	1.30	3.70
Condensate Storage Tanks	14.00	.90	3.93
Piping, Valves & Fittings		5.00	17.62
Insulation	3.00	1.00	.79
Foundations, Supports	7.00	3.10	1.80
Turbine Bypass System		4.00	(j)
Feed-Heating System	106.00	66.00	48.83
Regenerative Heat Exchangers	11.00	12.50	12.01
Closed Heaters	10.00	9.70	3.93

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Open Heater		2.20	6.96
Insulation		.40	1.12
Foundations	1.00	.20	(k)
Pumps	91.00	21.40	17.51
Mainfeed Pumps	66.00	10.10	10.21
Aux Feed Pumps	7.00	10.10	6.51
Drains, Pumps & Drives	1.00	.40	(l)
Insulation	17.00	.20	.79
Foundations		.60	(k)
Piping and Tanks	4.00	32.10	19.31
Feed Piping		20.90	7.41
Extracting, Drain & Vent		1.40	8.08
Insulation		3.50	2.81
Hangars, Supports & Inserts		6.30	1.01
Water Circulation/Treat. Equip.	15.00	22.90	51.97
Make-up Treatment	8.00	6.00	4.38
Ion Exchange		2.60	NR
Piping, Valves, Fitings		1.80	
Storage Tanks		.60	3.93
Hangars, Foundations, Support		1.00	.45
Chemical Treatment	7.00	16.90	47.60
Chemical Storage		(m)	1.80
Condensate Demineralization		6.80	29.52

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Boiler Blowdown		1.50	16.28
Piping, Valves, Fittings		2.80	
Insulation		.60	
Hangars, Foundations		1.80	
Aux. Boiler		3.40	
Electrical Plant Equipment	107.00	140.60	143.36
Switchgear	29.00	32.80	31.21
Generator Circuits	13.00	2.50	6.06
Generator Switchgear	3.00	2.50	2.36
Neutral Grounding Equip.		(n)	1.01
Current & Potential Transf.	1.00	(n)	1.68
Surge Arrestors	8.00	(n)	1.01
Excitation Switchgear	2.00	(n)	(o)
Station Service	17.00	30.30	25.15
Station Switchgear	15.00	23.40	23.12
Motor Control Centers	2.00	6.90	2.02
Station Service Equipment	38.00	20.90	26.38
Station Service & Startup	27.00	14.60	4.83
Station Service Transf.	15.00	13.00	4.49
Startup Transformers	5.00	(p)	(p)
Foundations, Walls	2.00	1.60	.34

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Low Voltage Units	1.00		
Power Sources	15.00	6.30	21.55
Battery Systems	2.00		7.30
Aux. Generators	13.00		
Motor Generator Sets			14.25
Switchboards			4.38
Protective Equipment	7.00	6.90	44.57
Ground Conductors & Conv.	7.00	4.20	35.25
Ground Wells, Mats, & Rods		1.60	9.32
Fire Protection Equipment		1.10	(j)
Electrical Structure & Wiring Cont.	9.00	56.00	17.29
Concrete Tunnels	1.00	.50	(q)
Cable Trays & Supports	8.00	12.60	2.92
Conduit		35.60	14.37
Other Structures		7.30	NR
Power Wiring	24.00	24.00	19.53
Generator Circuit		1.20	5.84
Station Service	24.00	22.80	13.69

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas		Martin Marietta		Honeywell	
Plant Master Control Equipment		211.00		211.35		165.25
Computer	3.00		3.70		79.70	
Peripheral Equipment	3.00		2.80		4.27	
Control Panels & Boards	3.00		18.00		21.22	
Interface Equipment	25.00		4.50		17.96	
Software Design & Develop.	22.00		23.50		(i)	
Software/Hardware Test	14.00		12.20		(i)	
Hardware Design	85.00		10.50		(i)	
Control Wiring	36.00		13.60		15.04	
Special Test Program Inst.	3.00		100.00		27.02	
Project Management			22.50			
Field Installation	17.00					
Miscellaneous Plant Equipment		268.00		87.40		160.42
Transportation & Lifting	146.00		44.70		38.17	
Cranes, Hoists, Monorails	39.00		6.30		25.93	
Turbine Building Crane	9.00				25.03	
Other Cranes	30.00				.90	
Roadway			3.50		3.48	
Receiver Maintenance	36.00				(h)	
Collector Maintenance	71.00		31.90		8.76	
Air & Water Service Systems		100.00		32.30		70.27
Compression Air	12.00		4.20		24.14	
Water Supply Pump	14.00					
Fire Pumps, Drives	3.00		3.10		3.37	

10 MWe Pilot Plant Analysis

Solar Thermal Power System

Cost Per kW of Installed Capacity

1977 Cost Base

Description	McDonnell Douglas		Martin Marietta		Honeywell	
Water Conditioning System	24.00				.34	
Storage Tanks, Reservoirs	3.00		8.00		2.24	
Station Service Pumps					4.60	
Domestic Water Treatment	1.00					
Domestic Water Pumps	2.00					
Water Heating Equipment	3.00				2.47	
Water Distribution System	38.00		17.00		33.11	
Communications Equipment	-		9.90		22.90	
Local Communication Systems			7.10		.45	
Signal Systems			2.80		22.45	
Furnishings & Fixtures	22.00		3.50		29.08	
Safety Equipment	2.00		1.10		2.47	
Shop, Lab & Test Equipment	18.00		.30		9.21	
Office Equipment	1.00		1.10		3.37	
Env. Monitoring Equip.			.90		13.47	
Dining Facilities					.56	
Cleaning Equipment			.10			
Distributables		284.00		333.90		(c)
Contractor Field Office	36.00		54.50			
Other Construction Items	29.00		3.30			
Insurance, Injuries	29.00		3.00			
Insurance, Const. Equip.			.30			
Temporary Construction	24.00		91.30			

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas			Martin Marietta		Honeywell	
Site Access & Improvements	2.00			1.50			
Buildings & Structures	19.00			73.50			
Electricity & Water				16.30			
Communications Equipment	3.00						
Construction Equipment		66.00		44.90			
Construction Services		57.00		87.70			
Purchased Utilities				13.30			
Security, Watchmen	16.00			2.90			
Education & Testing Programs	25.00			2.00			
Materials Receiving	12.00			14.10			
Inspection & Test Const. Mat.	2.00			.20			
Site Cleanup	2.00			25.40			
O & M Const. Facilities				23.80			
Storm Protection				6.00			
Spare Parts		72.00		52.20			
Turbine Plant	1.00			10.40			
Electrical Plant	1.00			3.70			
Collector Equipment	20.00			26.80			
Receiver	42.00			1.30			
Thermal Storage	8.00			10.00			
Indirects			1,117.00		620.80		870.01
A & E Services		123.00		144.00		258.44	
Preliminary Design	38.00			32.90		(i)	

10 MWe Pilot Plant Analysis
Solar Thermal Power System
Cost Per kW of Installed Capacity
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Detailed Design Services	85.00	82.40	(i)
Eng. Support During Const		28.70	(i)
Construction Management	338.00		(i)
Solar Subsystem/Integ. Contractor	520.00	336.50	611.57
Compatibility Analysis		102.60	
Program Planning		13.50	
Program Control		90.10	
Subsystem Design Verification		11.50	
Solar System Checkout		38.00	
Program Management		58.80	
Industrial & Systems Safety		22.00	
Plant Startup	136.00	140.30	(i)
Contingency	590.00	909.80	631.85
Total Solar Thermal Plant	7127.00	6975.30	7751.76

Note: Items Included in the Following

(a) Yard drainage and storm sewer system

(b) Roads

(c) Grading, gen excavation

(d) Maintenance building

(e) Administration building

(f) Auxiliary power sources

(g) Tower

(h) Tower and platform

(i) A&E services

(j) Turbine generator

(k) Turbine building

(l) Riser and horizontal feedwater piping

(m) Condensate demineralizer

(n) Generator switchgear

(o) Generator circuits

(p) Station service transformers

(q) Yard drainage and storm sewer

Table 3

10 MW_e Pilot Plant Analysis
Solar Thermal Power System
Two-Year Test Program
Cost Summary (000)
1977 Cost Base

Description	McDonnell Douglas	Martin Marietta	Honeywell
Two-Year Test Program			
Operation & Maintenance	2,050	560	4,170
Test Program Technical Support	1,520	2,296	2,188
Spare Parts	640	474	241
Total Test Program	4,210	3,330	6,599

APPENDIX G

TOTAL SYSTEM

APPENDIX G1

INITIAL PILOT PLANT CONFIGURATION RANKING

Aerospace Participant: T. J. Connor

The attached preliminary ranking was prepared at the request of C. Yokomizo, Chairman of the Systems Panel. It followed the procedures and used the scoring weights documented by Sandia, and was accomplished by the author after (a) attending the PDR's, (b) reading the PDR System Description Volumes, and (c) discussing each subsystem with the Aerospace evaluation-panel support personnel. It was submitted on 25 May.

Preliminary Pilot Plant Configuration Ranking

Configuration	Score*
5	267
2	264
6	261
4, 10	259
3, 7, 11	256
8	254
9	251
1	242

*Max Score = 287 (Capacity Displacement and Collector Annual Energy Not Yet Rated)

Configuration Definitions

	Collector	Receiver	Storage
# 1	H	H	H
2	MD	MD	MD
3	MM	MM	MM
4	MD	MM	H
5	MD	MM	MD
6	MM	MD	MD
7	MD	MD	MM
8	B	MM	H
9	B	MD	H
10	MD	MM	MM
11	MD	MD	H

H = Honeywell
MD = McDonnell-Douglas
MM = Martin Marietta
B = Boeing