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Development of a Mobile Heliostat Mirror Washing System

Foster-Miller Associates, Inc.

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DEVELOPMENT OF A MOBILE HELIOSTAT MIRROR WASHING SYSTEM

Contract Report Prepared
Under SNLL Contract 84-2240

Foster-Miller Associates, Inc.
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ABSTRACT

This report describes the development, design and fabrication of an experimental system for washing heliostats. The economics of heliostat cleaning, the design requirements and the design and testing of the wash system are discussed. The heliostat wash system was designed to wash the heliostats located at the 10 MWe Central Receiver Pilot Plant located near Barstow, California. The plant, called Solar One, is a cooperative activity between the Department of Energy and the Associates: Southern California Edison, the Los Angeles Department of Water and Power, and the California Energy Commission.

SOLAR THERMAL TECHNOLOGY
FOREWORD

The research and development described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from $100^{o}C$ in low-temperature troughs to over $1500^{o}C$ in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Component and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

This report describes the design and development of a heliostat wash truck. The truck has been used to wash heliostats at Solar One, the 10 MWe Solar Thermal Central Receiver Pilot Plant, near Barstow, California.

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1. INTRODUCTION

The power generated by a solar central power plant is directly related to the ability of the heliostats to redirect incident solar energy to the central tower receiver. In a natural environment, this ability is reduced by the deposition of airborne dust on the reflective surfaces. Since any degree of reflective surface degradation results in a plant performance and, therefore, cost penalty, some level of investment in a strategy for recovering lost energy can easily be justified on the basis of plant economics.

In April 1982, Sandia let a contract to Foster-Miller Incorporated (FMI) to design and fabricate a full scale experimental system for washing heliostat mirrors. The objective of this contract was to support the central receiver R&D effort by:

- Generating data on the cost, performance capabilities and requirements of heliostat mirror washing systems;
- developing a maintenance approach that would maintain heliostat field reflectivity and thereby minimize plant energy costs and enhance central receiver plant economic feasibility;
- stimulating broader industry participation in the DOE solar energy program.

1.1 Design Guidelines and Philosophy

The Sandia contract specified that the heliostat mirror washing system was to be mobile and capable of demonstrating water spray cleaning with and without a mechanical (contact) component. It was also to be designed for the Solar One heliostat. The design concepts, however, were to be generally compatible with a variety of heliostat designs. Early discussions between FMI and Sandia further established that the major design considerations should be cost-effectiveness, system flexibility and safety. Other characteristics required for the system included durability in a wet and dusty environment, and simplicity of design to insure ease of component adjustment/replacement.

1.1.1 Economics of Heliostat Mirror Cleaning

The design of a cost-effective heliostat mirror washing system requires consideration of the economics of solar plant operation as well as an understanding of heliostat soiling mechanisms and the effectiveness of alternate cleaning techniques.

A preliminary analysis of typical solar plant economics was conducted in order to identify the washing system parameters which have the greatest impact on overall cost-effectiveness. Based on this generic evaluation appropriate system concepts were developed.

The solar electric system revenue methodology developed for ERDA/EPRI evaluations of competing energy system designs (1) was used to compare the impact of various washing system parameters on plant economics. This technique uses levelized busbar energy cost, $\overline{BBEC}$, as a measure of cost-effectiveness. $\overline{BBEC}$ is defined as the ratio of annualized system-resultant cost, $\overline{AC}$, to the expected annual energy output, MWH_A.

$$\overline{BBEC} = \overline{AC}/MWH_A$$

The system cost includes annual charges for capital investment, operations, maintenance, and fuel for backup power. In the cost accounting structure of the model, a washing system contributes to both the cost of plant capital and maintenance. In order to simplify the analysis of washing system economics, it is desirable to express $\overline{AC}$ in terms of nonwashing and washing components:

$$\overline{AC} = P + aW + bw$$

where

P = annualized nonwashing plant cost, \$/year

W = capital investment for washing system, \$

w = recurring washing costs, \$/year

a,b = washing system coefficients.

Capital must be invested in the washing system to cover the cost of the washing vehicle (V), washing equipment (E), installation of equipment (I), and an initial inventory of spare parts (i). Thus,

$$W = V + E + I + i$$

The remaining washing expenditures occur on a per wash basis and include labor for operation (L_o), labor for maintenance (L_m), fuel for the washing vehicle (F), water usage (U), and water additives and/or treatment (T). Although the cost of replacing failed equipment and parts (M) is incurred at different intervals for different components, this expenditure is a function of duty cycle. Its net effect on washing economics was therefore also represented on a per wash basis. The proportion of each cost element is determined by labor and consumable rates, heliostat field size and cleaning strategy, while the absolute magnitude of w is directly proportional to the annual washing frequency (f). Therefore,

$$w = (L_o + L_m + F + U + T + M)f$$

The model coefficients a and b are functions of utility description data and general economic conditions. The same factors used to determine the annualized nonwashing plant cost, P, should be used to evaluate a and b. The nominal values for utility and economic parameters listed in Table 1-1 were assigned in order to establish the relative significance of initial versus recurring washing costs.

The influence of heliostat washing on the expected annual energy output, MWH_A, is somewhat more complicated as its value is affected by site weather patterns, an estimate of annual plant outage, and system operating limitations. A heliostat washing regime will impact the plant's operating efficiency by periodically restoring mirror reflectivity. In order to quantify this impact, it was assumed that the plant net annual output is proportional to the annual average reflectivity. Therefore as a first approximation,

$$MWH_A = K\dot{\overline{R}}$$

Table 1-1. Table of Nominal Values

Symbol	Name	Nominal Value
	Nominal Inputs	
	Utility Description Data	
N	System operating lifetime	30 years
β_1	Annual "other taxes" as a fraction of capital investment	0.02
β_2	Annual insurance premiums as a fraction of capital investment	0.0025
τ	Effective income tax rate	0.40
κ	Cost of capital to (and internal rate of return in) a "typical" utility	0.15
	General Economic Conditions	
g	Rate of general inflation	0.10
g_c	Escalation rate for capital costs	0.10
g_m	Escalation rate for maintenance costs	0.10
y_b	Base year for constant dollars	1980
y_{co}	Year of first commercial operation	1983
y_p	Price year of any expenditure	1981
y_t	Year of particular cash flow	Variable
	Nominal Intermediate Outputs	
$CRF_{k,N}$	Capital recovery factor (15%, 30 years)	0.1523
$\overline{FCR}$	"Typical" annualized fixed charge rate	0.2541
a	Coefficient for washing system capital investment	0.23
b	Coefficient for washing system recurring costs	3.0

The proportionality constant K is the ratio of nominal annual output to the nominal value of $\overline{R}$ assumed in determining that output.

Annual average reflectivity is defined as

$$\overline{R} = \frac{\int^{year} R_t dt}{\int dt}$$

where R_t is the field average reflectivity at time t.

At experimental stations such as CRTF, in Albuquerque, NM, where heliostat reflectivity has been monitored over a significant period of time, a value of $\overline{R}$ typical of the site and operating conditions can be determined from existing records. Ordinarily, however, similar data for a potential solar plant site are not available and values of $\overline{R}$ must be based on correlations relating degradation rates to site and heliostat specific characteristics.

By assigning values to various washing system and solar plant parameters, the relative significance of washing system cost components was determined and general design tradeoffs were anticipated. Table 1-2 lists nominal values used in the following preliminary cost review.

The solar plant average reflectivity of $\overline{R}$ = 0.85 and expected annual plant output of MWH_A = 35,000 MWh were chosen to reflect system conditions without washing. The associated proportionality constant K is then 4.12 x 10^4 MWh/R. If a conservative value for $\overline{BBEC}$ of 80.0 mills/kWh is assumed, a solar plant annualized cost of 2.8 million dollars is implied. A washing frequency of 12 washes per year was assumed to result in $\overline{R}$ = 0.90 for this analysis.

Based on the selected values, the following parameters and cost components were determined:

W = Estimate of capital investment for washing system
  = V + E + I + i
  = \$60,000 + \$35,000 + \$3,500 + \$1,500
  = \$100,000*

n = number of heliostats washed per truckload
  = $V_c/\phi A$
  = 2,000 gal/[(0.02 gal/ft^2) (508 ft^2/heliostat)]
  = 196 heliostats

*FMI's original estimate of production cost for washing system

Table 1-2. Nominal Parametric Values for Preliminary Evaluation

Symbol	Parameters	Nominal Value
	Solar Plant Parameters	
P	Annualized nonwashing plant cost	$2.80 x 10^6$
CAP	Plant capacity rating	10 MW_e
CF	Capacity factor	0.40
$\overline{R}$	Field average reflectivity	0.85
MWH_A	Expected annual plant output	35,000 MWh
N	Number of heliostats in field	1,818
A	Reflective surface area per heliostat	508 ft^2
R_o	Original heliostat reflectivity	0.92
	Washing System Capital Costs	
V	Washing vehicle	$60,000
E	Washing equipment	$35,000
I	Installation (10% of E)	$ 3,500
i	Initial inventory of spare parts (1.6% of V + E)	$ 1,500
	Washing System Parameters	
Z	Number of operators	2
r	Labor rate	$15/hr
m	Maintenance time/operating time	0.05
g	Cost of fuel	$1.25/gal
δ	Fuel usage rate	6 gal/hr
ω	Cost of water	$0.005/gal
ϕ	Water usage per unit area of heliostat	0.02 gal/ft^2
a	Cost of water additives	$6/gal
α	Volume of additive/volume of water	0.003
μ	Maintenance parts charge rate	$0.05/mi
v	Average vehicle speed	0.5 mi/hr
t_w	Time to wash per heliostat	2.5 min
t_{tr}	Time in transit from field to fill station	5 min
t_f	Time to fill truck	20 min
V_c	Vehicle water capacity	2,000 gal

t_c = time for one truck cycle

$= (nt_w + 2t_{tr} + t_f)/60$

$= (196 \cdot 2.5 \text{ min} + 2 \cdot 3 \text{ min} + 20 \text{ min})/60$

$= 8.6 \text{ hr}$

T = time for one complete wash cycle

$= Nt_c/n$

$= (1818 \cdot 8.6 \text{ hr})/196$

$= 80 \text{ hr}$

L_o = labor for operation

$= ZrT$

$= 2 \cdot \$15/\text{hr} \cdot 80 \text{ hr}$

$= \$2,400/\text{wash}$

L_m = labor for maintenance

$= mrT$

$= 0.05 \cdot \$15/\text{hr} \cdot 80 \text{ hr}$

$= \$60/\text{wash}$

F = fuel for the washing vehicle

$= g\delta T$

$= \$1.25/\text{gal} \cdot 6 \text{ gal/hr} \cdot 80 \text{ hr}$

$= \$600/\text{wash}$

U = water usage

$= \omega\phi AN$

$= \$0.005/\text{gal} \cdot 0.02 \text{ gal/ft}^2 \cdot 508 \text{ ft}^2 \cdot 1818$

$= \$92/\text{wash}$

T = water additives and/or treatment

$= a\alpha\phi AN$

$= \$6/\text{gal} \cdot 0.003 \cdot 0.02 \text{ gal/ft}^2 \cdot 508 \text{ ft}^2 \cdot 1818$

$= \$332/\text{wash}$

M = cost of replacing failed equipment and parts

$= \mu vT$

$= \$0.05/\text{mi} \cdot 0.5 \text{ mi/hr} \cdot 80 \text{ hr}$

$= \$2/\text{wash}$

From all of the above, the cost-effectiveness of the nominal washing scenario can be represented by

$$\overline{BBEC} = \frac{\$2.80 \times 10^6 + 0.23(\$100,000) + 3.0(\$3,486)(12)}{37,060 \text{ MWh}}$$

$$= 79.6 \text{ mills/kWh}$$

Even including capital and maintenance costs of cleaning equipment the resulting cost of power is lower than when cleaning is not utilized. Therefore, the investment and operation of the heliostat washing system is economically justified, in this example.

The results of this evaluation are strongly dependent upon site specific variables and washing system deployment strategy. If the unwashed field average reflectivity were 0.80 rather than the 0.85 assumed, the reference cost of power would be 85.0 mills/kWh instead of 80.0 and the reduction in $\overline{BBEC}$ due to washing would be 6.4 percent versus 0.5 percent, all else being equal. In addition different scheduling of the 12 cleaning cycles for the same site conditions would alter the annual average reflectivity and thus plant output as illustrated in Figure 1-1. When heliostats were assumed to be washed whenever the field reflectivity dropped below a limiting value rather than at regular intervals, the extrapolated average reflectivity increased significantly.

Heliostat washing economics also depend on the relationship between cleaning frequency and annual average reflectivity. Since beyond some site-dependent washing frequency there are diminishing returns in recovered reflectivity, the optimum frequency and associated power cost savings cannot be determined for a generic evaluation.

While a definite measure of washing system cost effectiveness cannot be projected due to the variability of site soiling conditions and meteorology and even due to seasonal and annual variations at a given site, design guidelines can be established to minimize washing system costs. Obviously optimum cost-effectiveness requires that system capital and operating costs be minimized without sacrificing

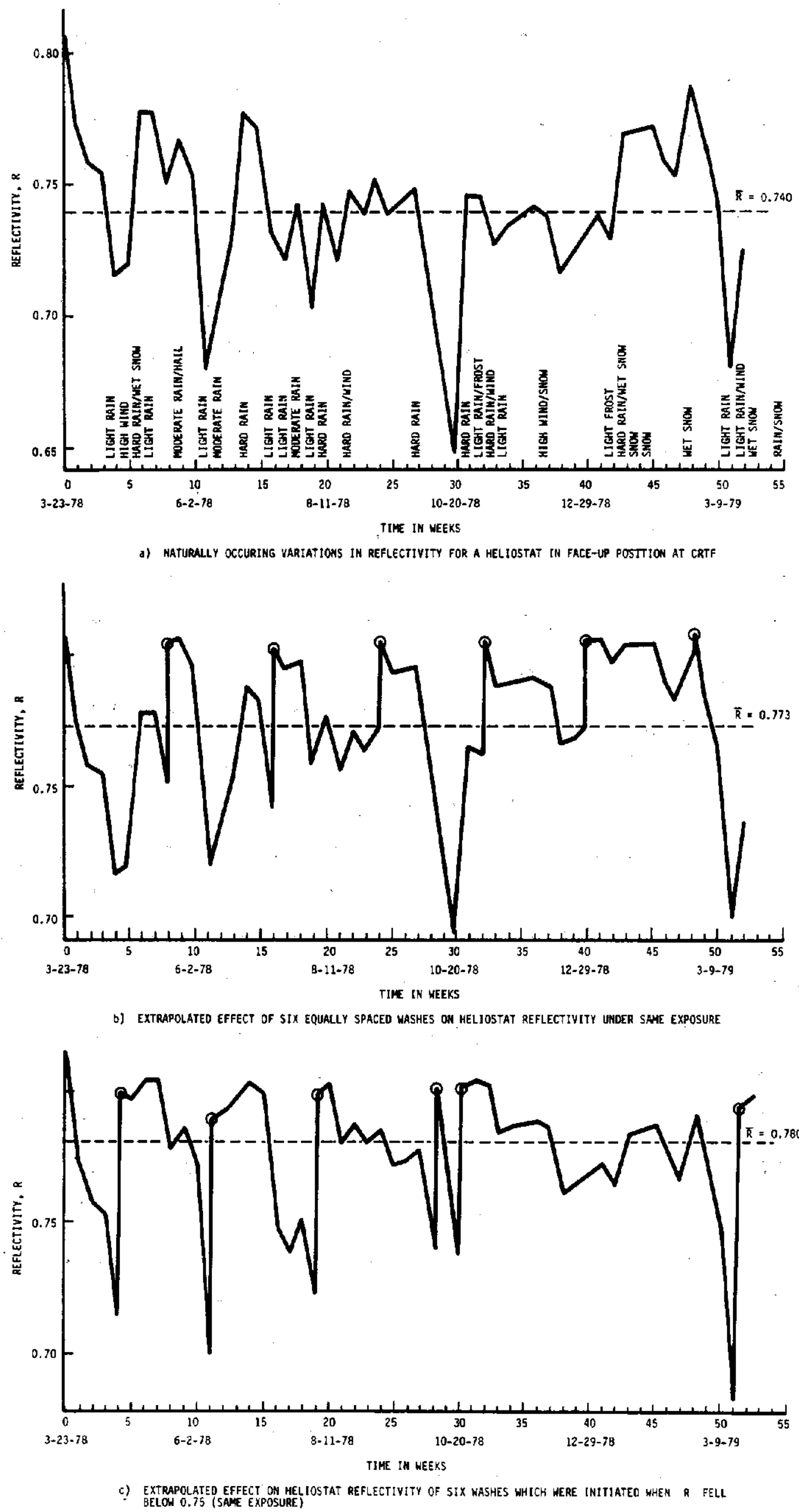

Figure 1-1. Effect of Timing of Cleaning Events on Annual Average Reflectivity

cleaning effectiveness. Several characteristics of washing system economics illustrated by this example were useful in establishing guidelines for the washing system design:

- Wash cycle time has a significant effect on the cost per wash. More than 80 percent of the cost per wash is a result of parameters which are proportional to the time for one complete wash cycle. Only 5 percent of that time is spent in travelling to and from the fill station. If each heliostat wash required only 1.5 min instead of 2.5 min, the cost per wash would be reduced from $3,486 to $2,338, a 33 percent savings. Therefore the major design emphasis was on reducing the time spent to wash each heliostat.
- Almost 70 percent of the cost per wash is credited to operating labor. Depending on the washing frequency involved, a sizeable amount of capital could be invested to economically eliminate one or both operators. For a washing frequency of only six times a year, as much as $90,000 in capital expenditure could be justified to increase the washing system automation to the point where one operator could be used instead of two. The experimental washing system was therefore designed such that only one operator is required for system control and supervision.
- Vehicle capacity is not a critical parameter. If the nominal vehicle capacity is reduced by half so that the time for one truck cycle was 4 hr (half of an 8-hr shift), the total cycle time would only increase by 1 percent for t_W = 2.5 min and 2 percent for t_W = 1.5 min. The advantages of reduced capacity are lower vehicle weight (over 800 lb removed per 100 gal of capacity), which relieves the soil loading and thereby minimizes vehicle modifications which would be required to deal with the loading problem. There are also associated reductions in capital due to a smaller tank requirement and gross vehicle weight rating.

FMI originally recommended the use of a three axle truck equipped with flotation tires as the mobile base of the washing system. As a cost saving measure, Sandia elected to provide a vehicle to FMI. A 1966 5-ton three axle stake truck was obtained by Sandia from disposable government equipment. This vehicle was then cosmetically and functionally refurbished. The final cost of the vehicle ready for mounting of the washing system was on the order of $15,000. Since the duty cycle of the washing vehicle is not severe and the vehicle need not be road worth, refurbishment of a used vehicle is a reasonable means of reducing the washing system capital cost.

Capital costs were also minimized by reducing the weight of the structural system components and by utilizing simple off-the-shelf components whenever possible.

1.1.2 System Flexibility

The second concern addressed in the design process was effective application of the washing system at various solar central power plant sites and to a variety of heliostats. Cleaning effectiveness is dependent upon both cleaning system deployment strategy as discussed in the previous section and cleaning technique employed.

Several test programs have been conducted to determine the cleaning effectiveness of a variety of mirror washing techniques. Cleaning variables examined included sprays of various water qualities, with sheeting agent and detergent added, ultrasonic vibration, high-pressure sprays and various combinations of the above. In general very little variation in results has been observed.

The minimum system requirements specified by Sandia, i.e., water spray cleaning with or without a mechanical (contact) component allow experimental evaluation of the most straightforward and most promising mirror washing techniques. Tests performed previously by FMI under contract to DOE indicated that a high-pressure spray alone was in most cases capable of restoring close to original mirror reflectivity (2). Water spray at 100 to 200 psi has been shown to be over 90 percent effective in removing accumulated dirt when properly applied to glass surfaces. There is also evidence that washing with a mechanical scrubbing action can result in a cleaning effectiveness of close to 100 percent by breaking the strong physical bonds which are established between certain soiling components and the reflective surface. The total cleaning cycle therefore includes the following operations which can be used independently or in combination:

- Wetting down of the mirror front surface
- Mechanical scrubbing of prewetted surface
- Rinsing the treated surface.

In order to maintain the experimental nature of the washing system, as many spray and wash parameters as possible were made adjustable.

Design constraints which may vary among solar plant sites are typically related to soil conditions, heliostat dimensions, and protruding heliostat superstructure. While the prototype design was based on the characteristics of the Barstow site, and dimensions and mirror access restrictions of the Solar One heliostat, provisions for simple modifications to the washing system were incorporated in the design to accommodate the expected range of variations in these conditions for heliostat fields in general.

Soils and geotechnical design considerations are site-specific. Repetitive washing vehicle traffic through the heliostat field will result in soil compaction due to wash water runoff, spillage, vehicle weight, and vibration unless appropriate methods of soil stabilization are employed during construction. Unfortunately, this is an uncontrolled compaction with uneven settlement. This could cause shifting of the heliostat foundation and severe misalignment of the washing vehicle. While some tolerance for misalignment of the heliostat/washing vehicle can be designed into the system, consideration should be given to site preparation prior to heliostat foundation installation to maintain general overall site stability. Compaction problem can also be alleviated by keeping the overall vehicle weight as low as possible, by increasing the vehicle footprint by using flotation tires or other means, or by installing a water collection subsystem on the washing vehicle to catch the wash water runoff.

Reports on the soil conditions at the Barstow site of the Solar One power plant were solicited and reviewed prior to the experimental system design. Of major concern were reports of major soft soil areas in the heliostat field. The conclusions and recommendations resulting from the site review are presented in Appendix D. Although a fully loaded tanker truck reportedly experienced no trouble in getting through the soft areas of the field, FMI suggested that the heliostat washing system not be operated in the localized soft areas unless the soil was stabilized in some way.

The overall mirrored surface of the Solar One heliostat was approximately 22.5 ft. wide and 22.4 ft. high. This was fairly typical of the second generation heliostats which had been developed through 1981. Excess height and width capacity would be designed into the heliostat washing system to allow for some overrun of the Solar One heliostat during cleaning and to allow application of this system to those heliostats with slightly larger mirror surface areas. More extreme variations in reflective area dimensions could be accommodated by increasing the scale of particular aspects of the system without changing the overall design.

One particular feature of the Solar One heliostat had a significant impact on the washing system design. That is a drive motor located at the center of the heliostat which protrudes 15 inches beyond the front plane of the mirrors when the heliostat is in a vertical orientation.

Washing the mirrors in transit, i.e., as the washing vehicle drives by the heliostat, would be the ideal scenario in that wash time would be minimized. The degree of system control required to do this effectively while avoiding the protruding motors is excessive at this experimental stage of system development. A park and wash strategy was therefore adopted for the near term system, with pass and wash a design goal for future system development.

The heliostat angle necessary to prevent motor protrusion beyond the mirror plane is 55 deg from vertical. This would require a washing system with an 18 ft reach 19 ft above the ground in order to wash the top of the heliostat. Thus mirror adjustment was determined not to be a viable means of avoiding the motors during a wash sequence.

In fact, the vertical orientation was determined to be the preferred mirror position for washing in order to minimize the reach required of the washing system from the vehicle.

The application of deep pile brushes which deflect when passing over the motor housing were considered as a means of avoiding the protruding motors. A brush more than 5 ft in diameter would be required to provide sufficient motor clearance and effective brush/mirror contact. The weight of this component especially when wet was judged to be excessive, resulting in severe design consequences for the overall system.

In the case of a horizontal cleaning cycle with mirror surface restoration starting at one side of the heliostat and moving horizontally across it, interference with the drive motors can be overcome by lifting the cleaning brushes over them. This will not affect cleaning effectiveness since the motors are located in a vertical area about 24 inches in width which is not covered by mirrors. Interference with the electric elevation drive motor is still a problem during a vertical sweep; it can be eliminated by splitting the cleaning cycle into two separate passes, namely, one to the left of the motor housing and one to the right of it. Such an approach demands either doubling of the cleaning time or doubling of the equipment required to perform the cleaning cycle in one pass. A vertical cleaning cycle, also requires that the cleaning equipment be moved to the top of the horizontal edge of the heliostat, which places it approximately 25 ft above ground. Based on these preliminary considerations, a horizontal cleaning cycle was selected.

1.1.3 Washing System Safety

In addition to cost considerations and physical constraints, safety was a prime factor to address in the washing system design. The system was devised to ensure both operator safety and heliostat protection.

In order to protect personnel and equipment, the system has several overrides and backup limiting controls to stop the washing sequence. For example, the washing system will not operate if the vehicle is in motion or if the driver's door is open. Also, system motion is halted when interference with the motor housing or pedestal is sensed or predetermined position limits are exceeded. In addition the motors selected to drive the cleaning assembly are sized so that they cannot exert enough force to damage the heliostat.

The safety features of the system will be more fully described in Section 2 of this report which presents a detailed description of the mobile heliostat mirror washing system.

1.1.4 References

1. Doane, J.W., et al., "The Cost of Energy from Utility-Owned Solar Electric Systems, A Required Revenue Methodology for ERDA/EPRI Evaluations," California Institute of Technology, Pasadena, CA, June 1976.
2. Tremblay, P.T., and E.C. Poulin, "Development of an Automatic Heliostat Cleaning System," Foster-Miller Associates, Inc., Waltham, MA, June 1980.

2. DESIGN DESCRIPTION

The mobile heliostat mirror washing system, designed and fabricated by FMI under contract to Sandia, is illustrated in the artist's rendition of Figure 2-1 and presented as-built in the photographs of Figure 2-2.

The truck mounted washing system consists of a 28 foot vertical wash arm upon which are mounted two full length water spray headers and two full length reciprocating nylon bristle brushes. Also mounted on the wash arm are potentiometers which measure and control the wash arm to mirror distance, an inclinometer which keeps the wash arm at the same vertical angle as the mirrors, and a number of backup limit switches which prevent damage to the mirrors. This wash arm is attached, via a pivot at its center to maintain verticality, to an extending arm which can move the brush out from the truck up to 4 feet. The extension of this arm is adjusted to establish mirror to brush distance. The outer tube of the extender arm forms part of a trolley carriage which rides along the top of a 7 x 29 ft aluminum truss, thereby translating the brush arm assembly horizontally across the face of the heliostat. This truss is mounted on the driver's side of a 5-ton flat bed truck and is centered at the cab. This position allows the driver/operator to use the heliostat pedestal as a reference for alignment of the washing vehicle and also provides the best vantage point for washing cycle supervision.

In order to minimize overall system weight all structural components are fabricated from 6063 or 6061 aluminum except as noted in the following detailed descriptions. Other considerations which guided the design were minimum overhung weight to reduce the torque on the truck and low center of gravity to minimize any overturning moments on the truck in motion.

Torque motors are used for the extending arm and trolley drives so that the force exerted by the washing system can be limited to prevent damage to either the heliostat or washing system.

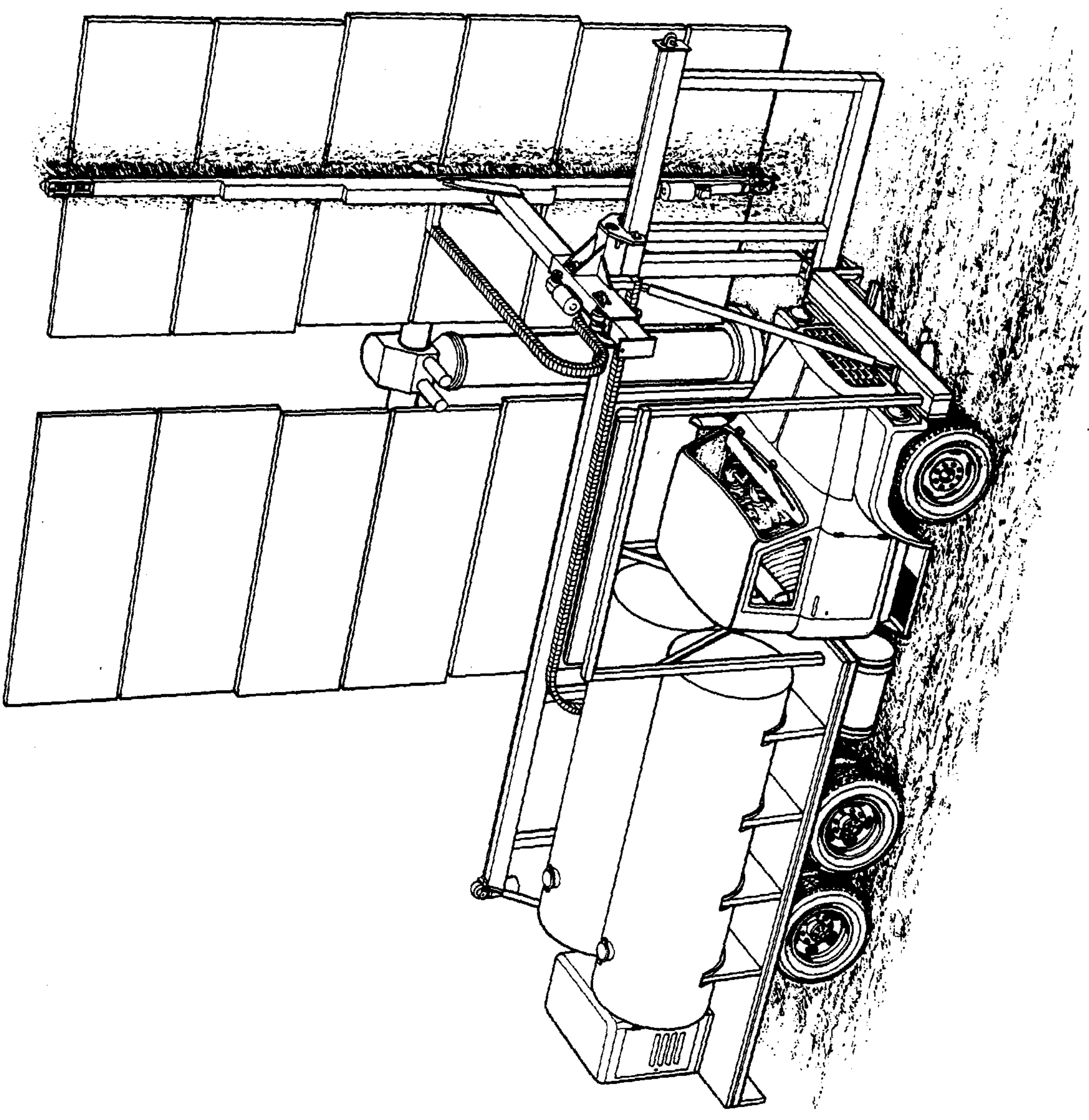

Figure 2-1. Artists Rendition of Mobile Heliostat Mirror Washing System

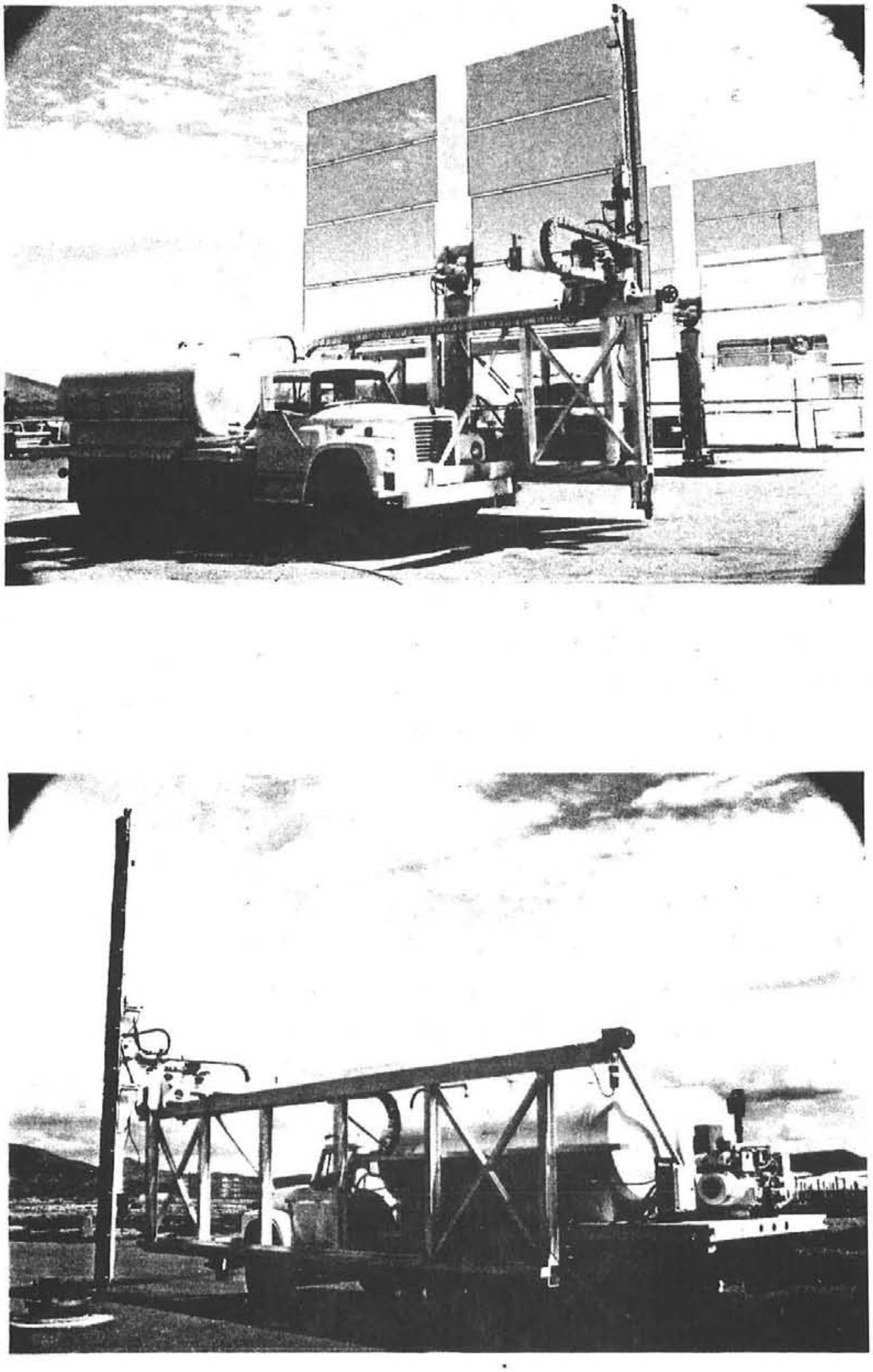

Figure 2-2. Photographs of As-built Mobile Mirror Washing System

Water for spray cleaning is supplied from two parallel 1000 gallon fiberglass tanks mounted on the flat bed. Although the two tank system was selected due to its low profile and only deionized or filtered water is expected to be used for heliostat mirror maintenance, the two tanks would allow a detergent wash and water rinse procedure with only minor changes in system plumbing. A small roller pump is driven by the truck power take-off and provides up to 30 gpm at 200 psi.

The power for the trolley, extender, vertical adjustment and brush motors, and also the control system is generated by a gas generator which is mounted on the rear of the truck bed.

2.1 Wash Arm Details

The 28-foot wash arm is fabricated from three sections of 3 x 16 x .188 rectangular tubing. This construction, typical of the various system structural components, was selected so as to achieve the required strength and stiffness with minimum use of special fabrication techniques. The tubes are standard stock items.

Two spray headers and dual reciprocating brushes are mounted along the full length of the vertical wash arm. Thirty-five flat fan spray nozzles with a spray angle of 95 degrees are tapped into the lead header at 8-inch intervals. The trailing header has seventy 50 degree flat fan spray nozzles spaced 4 inches apart. The lead header nozzles are directed at an angle to spray ahead of the wash arm. These nozzles are used to wet down the mirrors before contact washing with the brushes. They deliver a total of 8.4 gpm of water at 100 psi. The trailing header nozzles are directed straight at the mirror and they deliver a total of 16.8 gpm at 100 psi. The trailing header spray rinses the soil loosened from the mirror by the brushes. The trailing header is also used alone, i.e., without the leading header spray and reciprocating brush contact for spray-only mirror cleaning.

The spray nozzles are made out of brass and consist of four parts: cap, orifice tip, strainer with 100 mesh stainless steel screen and adapter. Nozzle orifice tip and strainer are easy to replace and all orifice tips are interchangeable. Orifice tips can be adjusted directionally without disturbing the pipe connection.

The piping schematic for water delivery to the spray headers is presented in Figure 2-3. The two 1000 gallon fiberglass tanks selected store sufficient water to wash 80 to 100 heliostats when a one minute heliostat traverse time is employed. These tanks are 48 inches in diameter and 139 inches in length. Each tank was fabricated with extra UV inhibitors to resist degradation due to constant exposure to solar radiation, a baffle to restrict water surging during starts and stops, integral vent, fillwell with splash guard, lift lugs and plumbing couplings as necessary. These tanks are tied into a matched skid assembly constructed of hot rolled steel with 4 skid bands. The assembly is then bolted into the truck bed.

The two tanks supply a common header to feed a roller pump powered by the truck engine thru a PTO connection. The pump housing and rotor are made of Ni-resist alloy with polypropylene rollers and Viton seals for highest compatibility with pumped liquids. The pump also has factory lubricated shielded ball bearings which require no further greasing and a stainless steel solid shaft for strong resistance to wear and corrosion. Maximum pump output is 41 gpm at 100 psi or 39 gpm at 150 psi with 1000 rpm pump speed.

Once through the pump, the washing fluid is directed back to the tanks by a normally closed 2-way solenoid valve until a signal that the wash sequence should begin is received. The fluid supplies only the trailing (main) header unless the control system signals a second normally closed solenoid valve to release flow to the leading header. The water system also includes a Y-strainer, water drain at the tank supply junction and pressure relief valve factory set at 220 psi. The system consists of aluminum piping and connections and flexible hose to accommodate the travel of the brush arm in, out and across the heliostat.

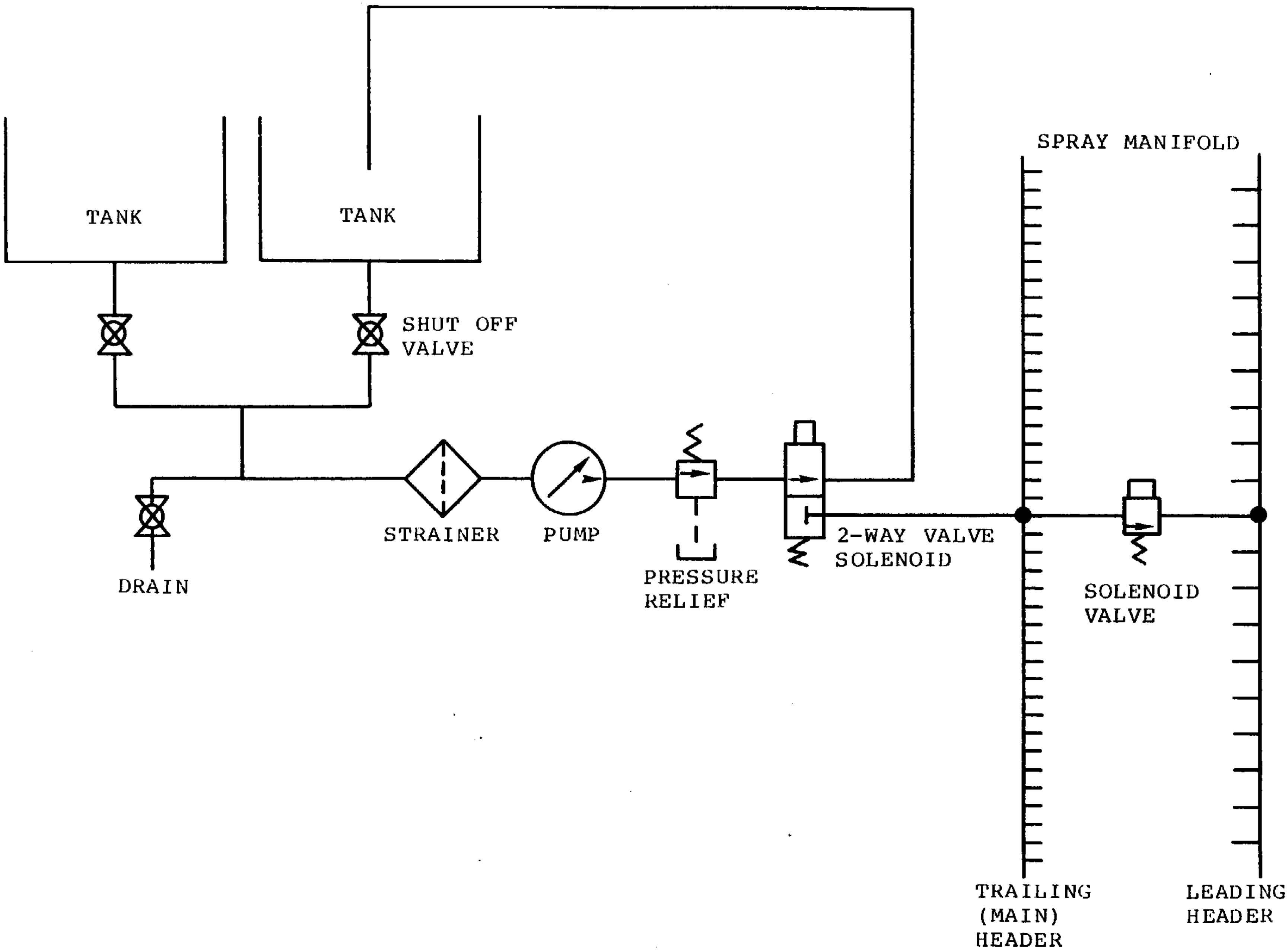

Figure 2-3. Water System Schematic

The water flow rates for both headers can be easily altered by changing the pump/engine speed from the cab. This will also change the spray delivery pressure. Alternately the orifice tips can be exchanged to increase or decrease flow at a given pressure.

The mechanical washing component of the system is dual reciprocating brushes. Black nylon bristles, crimped for brush fullness, were selected for resistance to degradation due to exposure to solar ultraviolet radiation, for low water retention and for resistance to taking a set. A bristle diameter of 0.016 inches and length of six inches were originally selected to provide the desired brush stiffness and conformability to the mirrors which at Solar One are up to 1/2 in. out of plane. During system testing, however, the stiffness of these brushes was found to be inadequate as they drooped severely after being wetted. These brushes were later replaced with larger diameter bristle brushes by Sandia. The brushes were inserted in aluminum T-extrusions which ride on polyurethane wheels in guide blocks spaced at 2 foot intervals along the full height of the wash arm.

The brush pair is driven by a 1/2 Hp single phase AC motor with shaft mounted 20:1 ratio worm gear reductor. The motor is mounted at the lower extremity of the wash arm for ease of access. The brushes are connected to brush motor crank arms via aircraft cable and pulley attachments which have 3 positions to allow for varying the brush stroke length.

The wash arm is also the location of several limit switches which protect the mirror and wash system in case of interference with the wash process or extremes of motion and several sensors which provide information on wash arm location and orientation to the control system. These components are described in more detail in a subsequent section of this report.

The total weight of the brush arm was held to approximately 350 pounds to minimize the forces exerted on the wash arm positioning system and the truck.

2.2 Wash Arm Positioning System

Wash arm positioning during the cleaning process is achieved through motor control of motion along three axes. The brush arm can rotate about a pivot at its center in a vertical plane perpendicular to the wash vehicle axis. It is translated toward and away from the mirrors by motion of the extender arm to which it is attached. In addition, the extender arm is part of a trolley which rides back and forth along the length of a truss mounted to the operator's side of the truck, thus sweeping the brush arm horizontally across the mirror surfaces.

2.2.1 Extender Arm

The brush arm is supported at its center pivot by trunion arms attached to a tube which extends out from the wash vehicle. The trunion arms clamp onto a 2-inch diameter steel pin which rides in a center bearing block filled with oil impregnated porous bronze bushings. The trunion arms raise the brush arm center to approximately 2 feet above the vehicle, which should coincide with mid height of the Solar One heliostats. The tube is fabricated from two 8 x .19 x .35 x 3.00 channel sections continuously welded along top and bottom. A direct current linear actuator mounted inside the extender tube, with tie rod connected to the wash arm in a pin and clevis arrangement, drives the rotation of the brush arm about the pivot. This provides for matching wash arm/mirror vertical alignment.

The extender arm rides in and out of an outer tube which is part of the horizontal motion trolley. The outer tube is fitted on the top, bottom and sides with 8 pairs of aluminum center polyurethane wheels with roller bearings. These wheels support the varying reaction loads exerted during wash arm extension and retraction and the side loads resulting from brush drag during the spray/wash process. Extender arm speed and direction are controlled by a limited torque motor with integral dc tachometer which is mounted to the outer extender tube. Motor output is through a 60:1 single reduction worm gear to a drive drum which exerts force on a cable attached to the trunion arms and back plate of the extender arm. The extender arm drive system was designed for a maximum speed of 10 ft/min.

2.2.2 Trolley

The trolley supports the extender and brush arm assemblies and translates them horizontally as it moves along a truss mounted to the side of the wash vehicle. The trolley rolls along on top of the upper truss beam on 4 polyurethane wheels mounted to a 7" x 8" x 6' rectangular base tube oriented parallel to the main truss axis. Two additional wheels mounted on each of two trolley base end plates provide lateral support for the trolley on the beam. In addition an 82-inch vertical tapered I-beam with a wheel on its lower end is attached to the front center of the trolley. This member serves to counteract the torque exerted on the trolley by the overhung weight of the wash arm. The reaction leg wheel rolls on the bottom horizontal truss beam along the front of the truss.

The trolley is driven by a limited torque motor with integral dc tachometer and encoder. The motor output is through a 60:1 single reduction worm gear to a drum drive/cable system similar to the extender drive arrangement. In this case a cable is attached to the back trolley end plate, runs around the drive drum, through the upper truss beam, around an idler pulley located at the front end of the truss and is attached to the front trolley end plate. The system is designed to achieve a trolley traversing rate of 25 ft/min.

2.2.3 Truss

The washing system truss elevates the wash arm to an appropriate height and serves as the track for the trolley's horizontal motion. The truss is made up of 6" by 8" upper and lower beams separated by 6 foot I-beam sections with cross bracing at the two truss ends. The upper and lower beams are rectangular tubes fabricated from channel sections. The truss, which has an approximate weight of 630 pounds, is centered at the truck cab to facilitate washing system positioning at the heliostat.

The truss is supported on the operators side of the vehicle by two truss mounts - one attached to the end of a beam affixed to the truck front bumper and the other attached to the truck bed just ahead of the rear wheels. The truss mounts are secured by lower lateral braces which connect to the truck undercarriage framing. The truss is further supported by three diagonal braces attached to the top truss beam. Two of these diagonal braces cross over the truck (fore and aft of the tanks) and are anchored to a section of angle bolted to the truck bed. The third diagonal anchors to an angle section bolted to the front bumper beam. Since there are both multiple diagonal brace anchoring positions and truss mount attachment positions, overall truss height adjustments of several inches are possible to compensate for minor variations in heliostat mirror/ground clearance specifications. The truss is attached to the truck through flexible cup mounts to reduce stresses during vehicle acceleration and deceleration.

2.3 Control Subsystem

The mobile heliostat washer controls subsystem accepts input from a set of transducers, limit switches, and operator control units and regulates the speed (by pulse rate) of two motors, the direction of rotation of three motors, and on/off control of the brush drive motor, two solenoid valves and a number of status and warning lamps. The controls allow for either automatic operation from the truck cab or remote manual operation.

The system control package is shown schematically in Figure 2-4. The main system components are an electronic controls package, a system status panel, an automatic control unit, and a manual control unit. These are presented as built in the photographs of Figures 2-5 and 2-6.

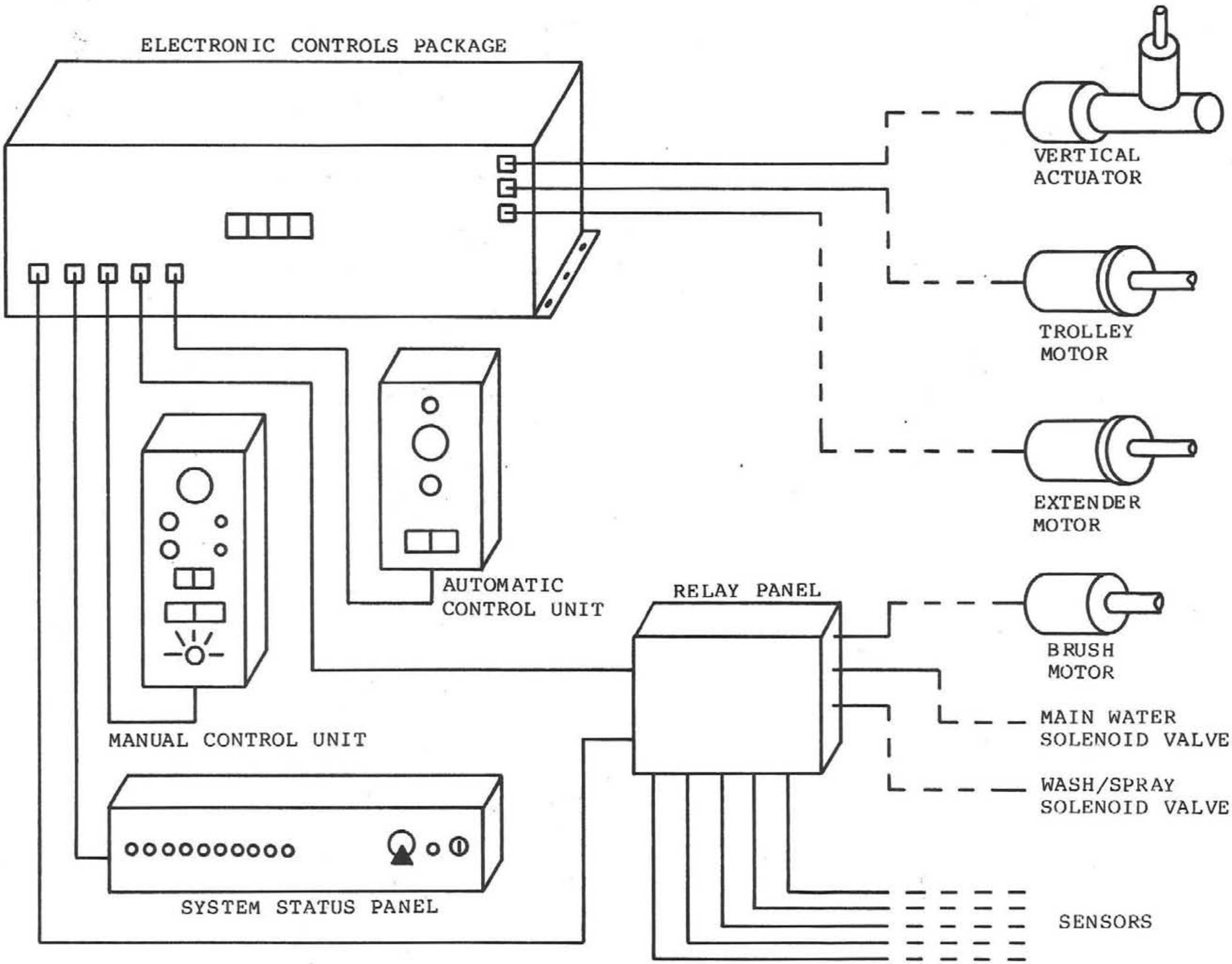

Figure 2-4. Control System Schematic

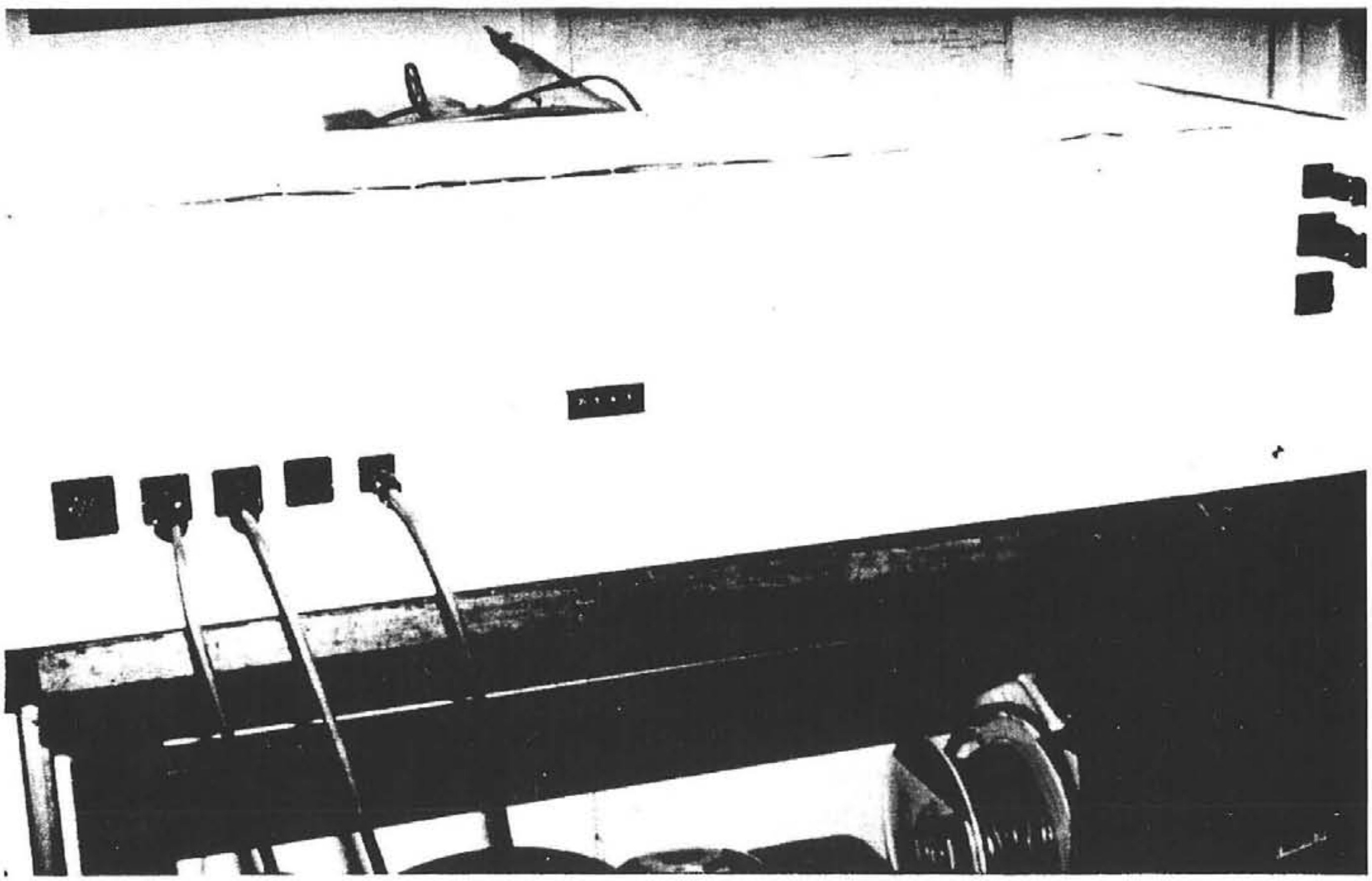

Figure 2-5. Electronic Controls Package as Built

Figure 2-6. Status Panel, Manual Control Unit and Automatic Control Unit as Built

2.3.1 Electronic Controls Package

The electronic controls package is a fully enclosed unit to which sensors, control units, status panel, relay panel, and position control motor cables are connected. A set of digital thumbwheels is also located on the package for input of variable data. Parameters adjustable via thumbwheel input are trolley forward traversing speed, brush arm to mirror distance for spray only cleaning mode and brush arm to mirror distance for spray and wash cleaning mode. The trolley return speed is set at maximum at all times to reduce the total cleaning cycle time. The package is mounted on a frame under the truck bed to shield it from direct sunlight and water splashback during cleaning.

Upon power-up, a micro computer in the electronics package enters a program which is stored in a permanent and unchangeable memory unit on the computer board. In the course of the program the computer will perform a sampling of all transducers, limit switch inputs and control unit input and respond appropriately. Any action that is to be taken is not delayed by more than about 10 ms.

This assembly includes the following:

- Three electronic control boards which provide closed-loop analog feedback control of three independent dc motors.
- Three switched-type power amplifiers for each of three motors.
- One single board computer.
- One set of four digital thumbwheels.
- Two oscillators assembled on small separate card.
- Isolating I/O modules for all discrete input and output signals. External lines will carry 12-volt signals at up to 100 ma.
- Power supplies as required using a single 117 V, 60 Hz input.

- A (NO) power relay for the 117V power which will close as ac power is turned on provided a chain of safety switches are closed.

The package features are illustrated in Figure 2-7. More detailed specifications of the above components are presented in Appendix E.

2.3.2 System Status Panel

The system status panel illustrated in Figure 2-8 supports operator supervision of the mirror cleaning process and aids in problem diagnostics. It is a long thin package intended for mounting in the truck cab above the operator's door. The panel is connected to the electronics package via a cable which includes several pairs of twisted wire plus a No. 16 power cord. This panel includes a key-operated control subsystem power-on switch, a power-on indicator light, an operating mode selector switch (spray only/spray and wash) and operating status and fault indicator lights.

The lights are incandescent to be visible in strong daylight although it is assumed that wash operations will take place at night in order to avoid interference with plant operation. The lights are normally off and are lit when the condition identified is encountered. The operation lights identify whether a heliostat cleaning cycle is in progress, when the system is in the process of transferring the brush arm over the Solar One heliostat drive motors, if the manual control station is in control of the system, and when one of the interlock safety features is preventing the system from operating. Only the last signal requires a response, that is, the interlock feature generating the signal must be identified and the offending condition corrected before the cleaning process can begin.

Operating faults encountered during a cleaning cycle will cause the cleaning sequence to be interrupted and will return the system to "home" position, i.e., fully retracted extender arm, extreme forward trolley position. The fault indicator lights are then used to determine the conditions which prevented completion of the washing cycle.

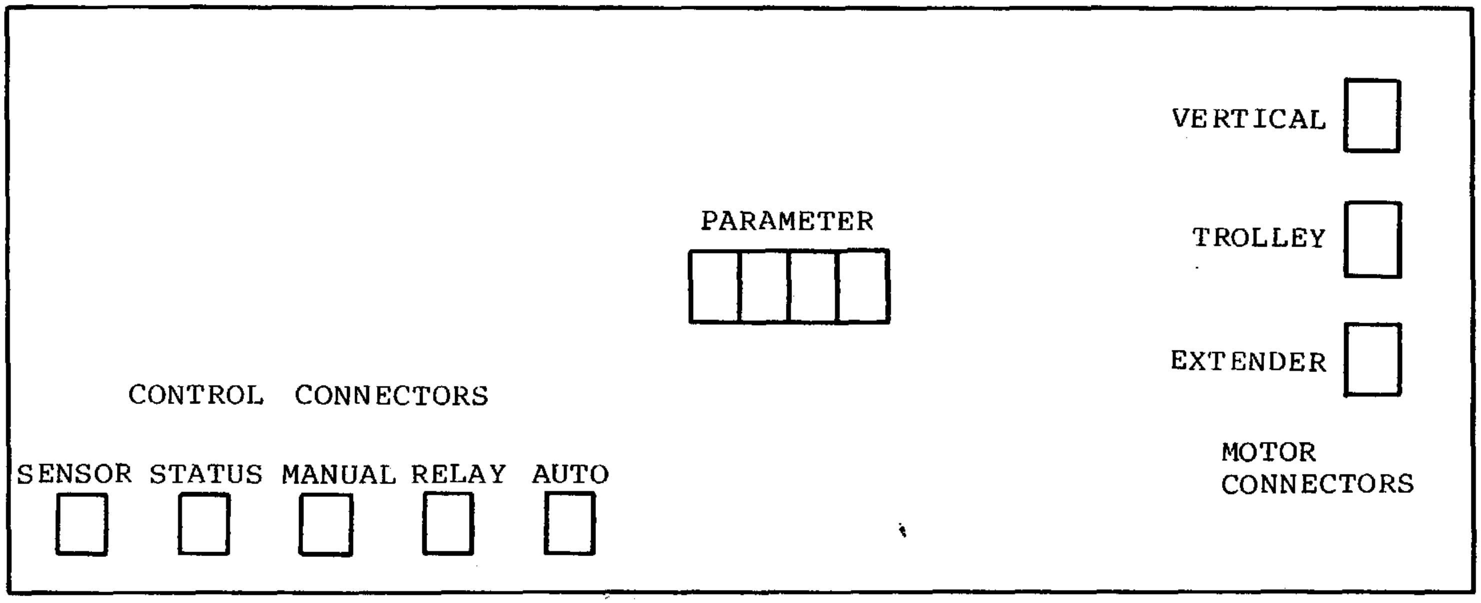

Figure 2-7. Electronic Controls Package

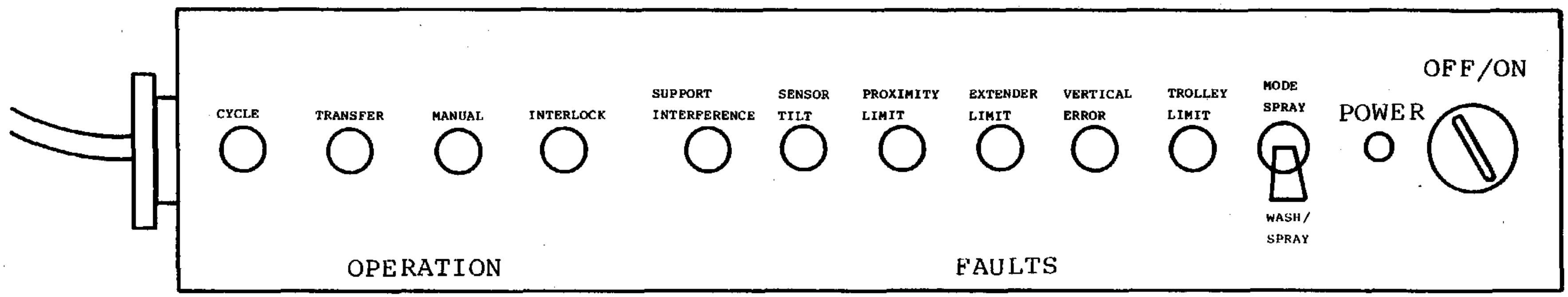

Figure 2-8. System Status Panel

Conditions which would generate fault signals include incorrect positioning of the washing vehicle with respect to the heliostat and operator judgement error in positioning of the trolley prior to cycle initiation. For example if the truck were positioned too close to the mirror, the brush arm could not be retracted enough to bypass the motors and sensors would contact the heliostat pedestal during the bypass operation. This would generate a "support interference" signal. Likewise if the truck were positioned too far away from the heliostats or if the trolley were positioned ahead of the leading edge of the heliostat, the cycle would begin with full extension of the extender arm without making mirror contact and an "extender limit" signal would be generated. A "trolley limit" signal would result at the end of a cycle if the truck were parked too far forward to complete a heliostat wash and would result while trying to jog the trolley forward to the leading edge of the mirror if the truck were parked too far back. A "vertical error" could be caused by the heliostats not being vertical or by misalignment of the vertical inclinometer on the brush arm. Fault signals could also be generated due to more fundamental problems such as incorrect motor bypass parameters in the system logic or failure of system electronics. The latter error sources, however, should only be suspect if all the more obvious fault sources have been ruled out.

The indicator lights also provide information on system status during a cycle by identifying when the trolley and extender arm are in extreme positions such as "home" ("trolley limit" and "extender limit" lights on) or after complete mirror wash ("extender limit" light on).

2.3.3 Automatic Control Unit

Automatic mode of operation is the power-up mode for the controls. The automatic control station, which is small enough to be hand held, is located in the washing vehicle cab near the driver/ operator. The operator generally interacts with the control program from the automatic control unit. A sketch of the unit is shown in Figure 2-9. Only three controls are provided on this unit: a rocker

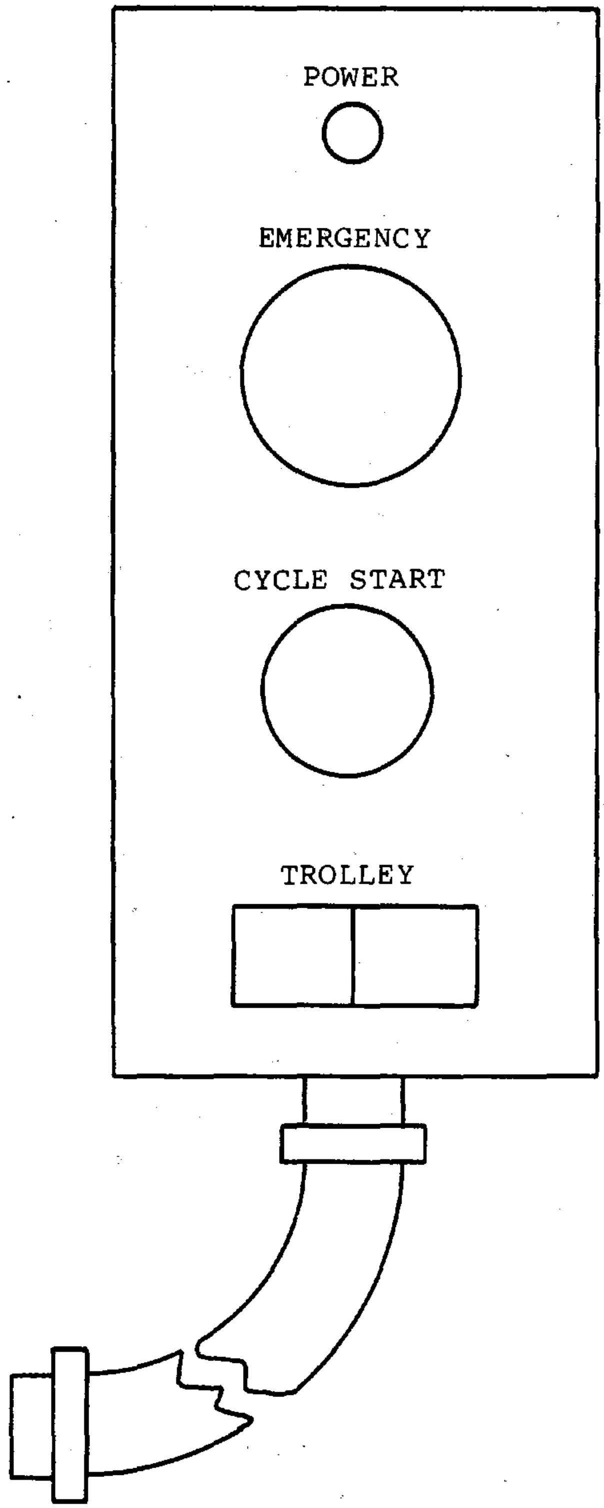

Figure 2-9. Automatic Control Unit

type switch for adjustment of trolley position on the main support frame, a momentary Cycle Start switch and an Emergency push button. The rocker type switch has a middle neutral position and is spring loaded to go back to neutral position when released. The Emergency button is mushroom shaped and colored red. The Cycle Start button is a spring loaded momentary contact type. An incandescent light indicates power-on.

The size of the unit is approximately 3 inches wide, 7 inches long and 2 inches deep. A cable of twisted wires with a connector plugs the unit into the electronics package.

In the automatic mode the operator adjusts the trolley start position and then initiates the washing cycle simply by depressing the cycle start button on the unit. The control system automatically locates the heliostat (normally vertical) and maintains the preprogrammed brush bar assembly to mirror distance required to accomplish the selected task (spray with brushing or spray alone). In order to avoid damage to the motor housings, the control system also senses the center of the heliostat and automatically retracts the brush bar assembly and advances the trolley to begin washing the second half of the heliostat. When the device comes to the end of the heliostat, sensors signal the device to retract the boom and return the trolley to the forward position.

If the emergency button is depressed at any time after control system power up the system immediately shuts down. The power up sequence must then be repeated to re-initiate a wash cycle.

2.3.4 Manual Control Unit

The manual control unit is also hand held and when plugged into the electronic controls package, this unit will take over from the automatic control unit. The manual control unit is approximately 3 inches wide, 7 inches long and 2 inches deep. It has a 24 foot cable with a connector for plugging into the electronic controls package.

The manual control unit features are illustrated in Figure 2-10. Two rocker type switches are used for control of the trolley and extender motor direction of motion. A dial controls the brush arm vertical orientation, overriding the vertical inclinometer signal. The three other switches are the spring loaded momentary contact type. All switches are similar to those used for the automatic control station. An incandescent light indicates control subsystem power-on.

In manual mode of operation the control program is designed to give the operator full motion control of the washing system. The hand held manual control unit allows operator control of the trolley and extender arm forward and reverse motions, and rotation of the arm out of vertical. The operator also may activate the brush motor or spray action and select automatic extender arm position control. The proximity null light was intended to signal brush arm to mirror distance by frequency of flashing, however, visual observation of the wash arm proximity was judged to be more desirable in the manual mode so that this light has been disconnected and is not used. However, embedded in the control program are restrictions designed to minimize the possibility of damage to the heliostat, or to the washer. Again the emergency button will shut down the entire wash system if depressed at any time.

2.3.5 Sensors

The safe and effective utilization of the mobile washing system requires input from several strategically located switches and transducers in addition to the operator's input from the control units. Table 2-1 lists the type, number and purpose of the sensors used. This list can be cross referenced by sensor designation with the system outlines of Figures 2-11 and 2-12 to determine the approximate location of each sensor.

Sensors A through E are located on the wash arm, as indicated in Figure 2-11. The vertical inclinometer (sensor A) is mounted above the wash arm pivot and generates a dc signal in proportion to the sine of the angle between the sensitive axis and the horizontal. The

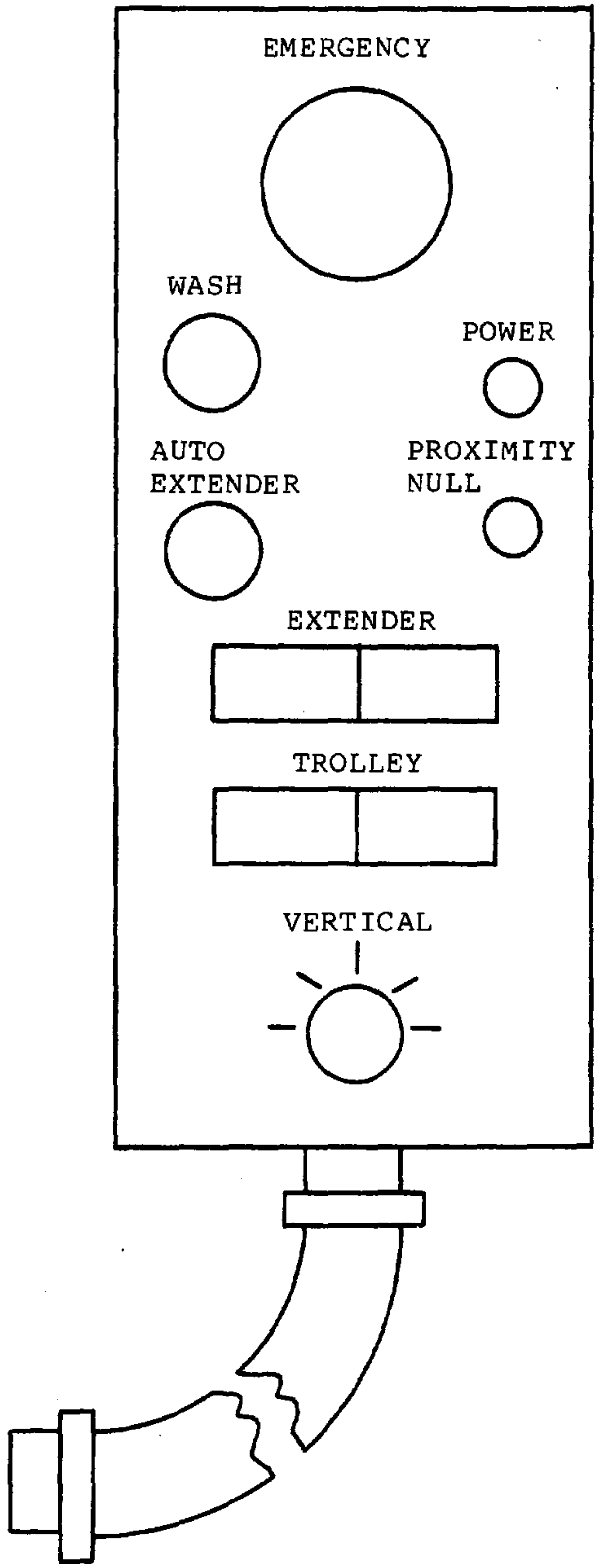

Figure 2-10. Manual Control Unit

Table 2-1. Summary of Sensors Used for Washing System Control

Designation	Item	Number	Signal
A	Vertical Inclinometer	1	Orientation of wash arm relative to vertical axis.
B	Linear Motion Position Transducer	2	Proximity of wash arm to heliostat mirrors.
C	Tilt Microswitch	2	Lateral force on linear motion position transducer; implied interference with horizontal motion.
D	Proximity Limit Switch	2	Minimum wash arm to mirror distance.
E	Lever Type Interference Switch	1	Interference of heliostat motors or pedestal with wash arm horizontal motion.
F	Lever Type Limit Switch	4	Forward or reverse limits of trolley or extender arm motion.
G	Pressure Switch	1	Air brake engaged/disengaged.
H	Limit Switch	1	Cab door open/closed.

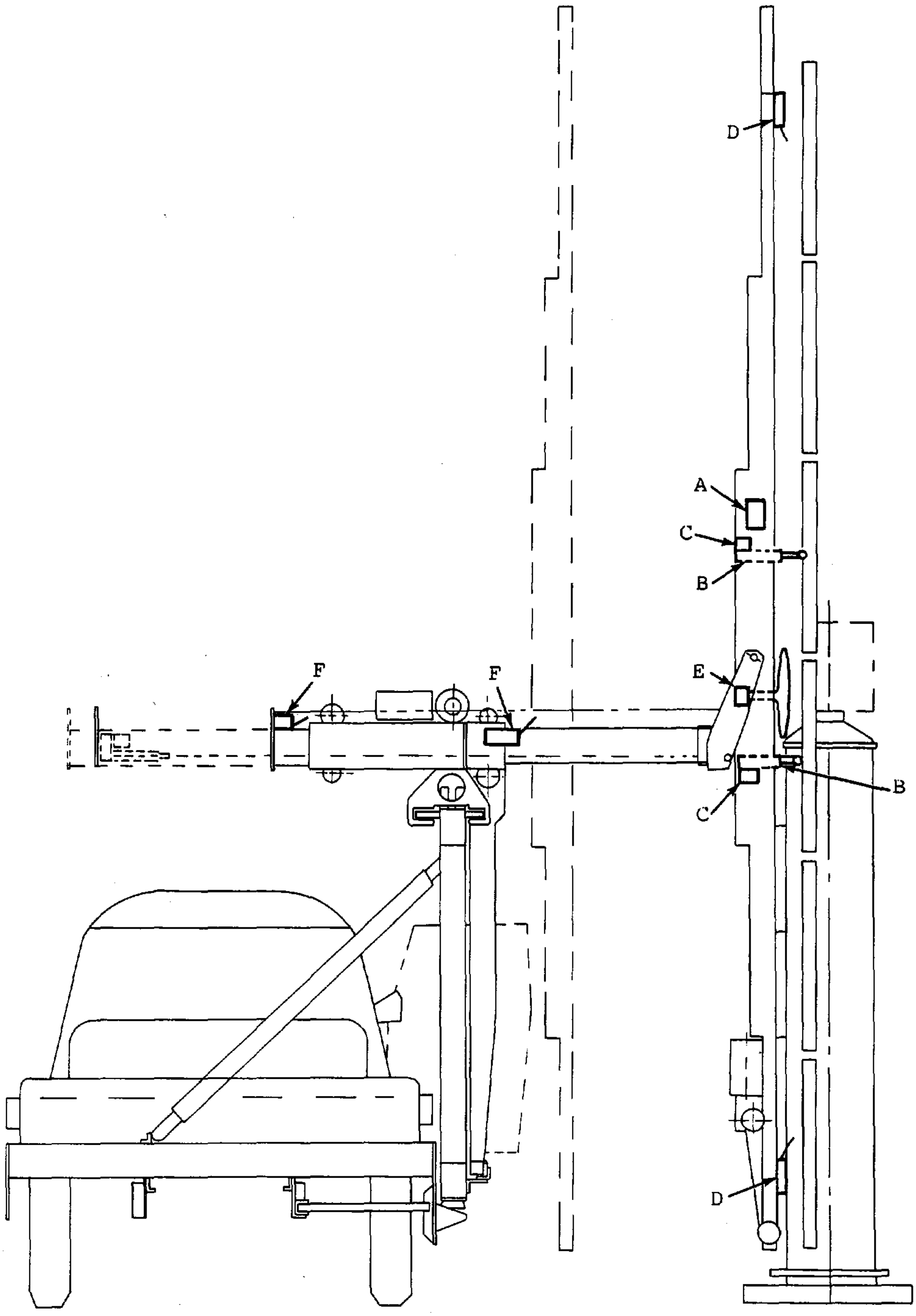

Figure 2-11. Location of Washing System Sensors

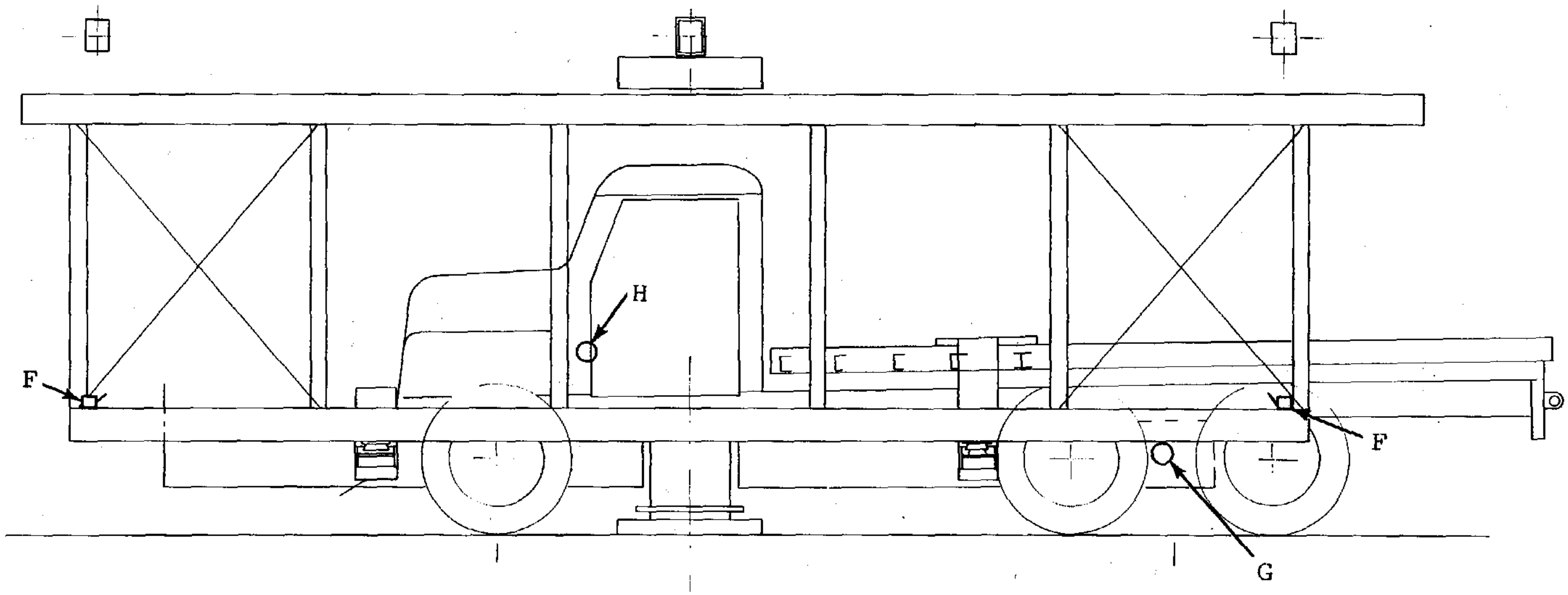

Figure 2-12. Location of Washing System Sensors

inclinometer output is used to control servo motor adjustment of brush arm to insure vertical orientation parallel to that of the mirror surfaces. The inclinometer selected for this application has a ±30 degree range with a non-linearity less than 0.2 percent of full scale and a resolution of better than 0.001 percent of full scale. Its operating temperature range is -25°F to +150°F.

Linear position transducers (sensors B) are mounted at two locations on the brush arm. Their main function is to provide the microcomputer with analog position feedback in order to maintain a preprogrammed distance between the wash arm and the heliostat mirrors. The distance selected for spray and wash mode of operation provides for brush contact with all the mirrors which are up to 1/2 inch out of plane. The distance selected for spray only cleaning provides for a minimum amount of spray overlap between nozzles so that spray impingement occurs along the full height of the heliostat. Although the microcomputer is not currently programmed to do so, the difference between the two signals could be used as a backup or alternative to the vertical inclinometer for wash arm/mirror vertical alignment.

The linear potentiometers used have a 6-inch stroke, ±0.1 percent linearity and require a maximum of 5 lbs operating force. They also have an internal water resistant seal and watertight rear connector for protection against spray splashback. The transducer shaft ends have been fitted with rod end bearings and soft rubber wheels to ride along the mirror surface as the trolley traverse proceeds.

Since the linear position transducer rods extend out ahead of the brushes it is possible to drive them against the mirror module sides during manual control of extender arm position and trolley traverse or under control system failure induced circumstances. These transducers have therefore been attached to the wash arm with spring loaded hinged brackets which deflect rather than bending the rods and distorting them under side loads. This deflection is limited by a microswitch (sensor C) located close to each hinged bracket. A signal from either microswitch will cause the wash arm to return to "home" position.

Also located on the wash arm are two lever type limit switches. These watertight, spring return switches are mounted between the reciprocating brushes on the wash arm structure. They signal a fault if the extender moves beyond the preprogrammed washing positions controlled by the linear potentiometers. This is a backup safety feature which protects the mirrors from impact with the wash arm as it extends from the vehicle either while being operated in the manual mode or due to failure of automatic distance control functions. One of these switches is located at each end of the wash arm and mirror contact with either switch will cause the extender arm to retract and the trolley to return to the forward position.

The same type of switch with a broadly looped rod lever extending ahead of the wash arm is located at the center of the wash arm (sensor E). This switch is intended to generate a signal when wash arm contact with the protruding heliostat motors is imminent. This prevents the trolley motor from driving the wash arm into the heliostat motors when full retraction of the extender arm does not provide enough clearance for the wash arm to bypass them. When a signal from this switch is received by the microcomputer the wash arm is again returned to the "home" position.

Lever type limit switches as described above are also used to indicate extreme positions of the extender arm and trolley (sensor F). They are located at the positions indicated in Figures 2-11 and 2-12. If the sensors determine that the extender arm is fully extended or that the trolley is at the far rear of the truss, the control system returns the wash arm to "home" position. If the extender arm is fully retracted or if the trolley is in the far forward position at the front of the truck status panel lights signal extreme positions but no control action results.

Additional system operating safety is achieved through control system interlocks. A pressure switch located in the truck air brake line prevents the control system from being activated unless the air brake is set or shuts off power to the system if the air brake is released. This interlock is intended to avoid the potential hazards associated with operation of the system with the truck in motion.

Similarly, a control system interlock is located in the cab door on the driver/operator side. This switch shuts down the system when the cab door is opened during a cycle. This safety feature protects against operator, system or vehicle damage which could result as the trolley passes in front of the operator's door.

2.3.6 Cable/Hose Carrier

Due to the relative motion of the various control components the cables connecting the electronic controls package to the extender and vertical actuator and connecting the relay panel to the brush motor, switches, sensors and solenoid valves could not be secured in fixed positions. Sufficient play was required in the cables to allow the components $\pm$10 feet of travel along the truss in either direction from the central control equipment location. Many of the cables also required an additional 4 feet of slack to accommodate the range of brush arm positions due to extender arm motion.

Two lengths of cable carrier were employed to protect and control the various cables and in addition the water hose running between the tanks and the wash arm spray headers. The first carrier ran from a fixed point at the center of the truss to the trolley while the second carrier supported cables and hose between the trolley and a tray attached to the trunion arms near the wash arm pivot. The carrier consisted of tough steel links 4 inches wide with a 2-1/2 inch opening. The links were capable of limited rotation in one direction only so that the carrier acted as a rigid support when extended in one direction, but would fold over itself with a radius of 10 to 15 inches when pulled in the other direction.

2.4 Interlocks, Failsafes and Variable Parameters

The development of an experimental system requires special attention to system safety features and system flexibility.

The various safety features included in the mobile heliostat mirror washing system have been described in previous sections. These include:

- control system interlocks on the vehicle air brake and cab door which prevent system operation when the vehicle is in motion or the cab door is open;
- torque motors which limit the force which can be exerted on the mirrors by the extender and trolley drives;
- failsafe microcomputer logic for operator, heliostat and washing system protection in both the automatic and manual control modes; and
- an emergency panic button on each of the control units which immediately stops all system functions.

Any error in truck positioning or extreme of washing system range results in the retraction of the brush arm from mirror proximity.

System flexibility is provided by a number of adjustable parameters which have also been previously described. In summary these include:

- brush arm to mirror spacing by thumbwheel input for automatic mode and by control unit input for manual mode;
- trolley forward traversing speed variation by thumbwheel input;
- spray pressure and flow adjustment by varying engine speed or by changing out the nozzle orifice tips;
- brush stroke length variation by cable attachment point to crank arm;
- spray only or spray and wash mode selection by status panel switch;
- automatic or manual control mode selection by cable plug into electronic controls package;
- vertical orientation of brush arm by dial adjustment in manual mode or by inclinometer orientation in automatic mode;

- truss height adjustment by alternate truss mount and brace support positioning.

An extra thumbwheel input is also available to accommodate potential expansion of system capabilities via system control logic input.

2.5 Washing System Power

Except for the pump which is driven through a truck engine PTO connection, all power consumed by the washing system is provided by an on board generator. A 12.5 kW ac generating set was provided by Sandia for this project and it proved to be more than adequate for driving the various motors and control system. Since the generating set is gasoline fueled as is the vehicle a fuel line was run from the generator engine directly to the vehicle fuel tank.

Sufficient excess power is available from this generator set to supply a truck-mounted lighting system which may be necessary for effective heliostat cleaning at night.

3. TEST RESULTS

The experimental heliostat mirror washing system designed and built by FMI underwent preliminary testing at FMI's facilities and was then shipped to Sandia's Central Receiver Test Facility (CRTF) for more comprehensive performance evaluation.

3.1 Tests at FMI

Because of time and budget constraints testing at FMI was limited. The purpose of the preliminary tests conducted was to confirm that control functions and safety features were operational. These initial tests resulted in minor design adjustments such as:

- increasing the motor torque limits to their maximum allowable values since there was little risk of damage and the additional torque was required to move the wash assemblies with the truck on a slight slope; and
- elimination of extender speed as a selectable parameter because the maximum speed designed into the system seemed appropriate.

FMI's test efforts were also constrained by the lack of a full scale heliostat. The heliostat was instead simulated by supporting an actual Solar One mirror module vertically at such a height as to allow contact of the two position sensors.

3.2 Tests at CRTF

A more comprehensive washing system performance evaluation was conducted by Sandia at the CRTF in July 1983. The tests were aimed at verifying system performance in the areas of controls, operation, safety and structural integrity. The test specifications and results as documented by Sandia personnel are reported here:

Test A - (CONTROLS) - Control of system from outside the truck cab. Connect the remote control box to the main controller located under the truck bed. Operate the system using all the available functions that can be controlled with the remote unit to include:

a) move trolley forward and rearward
b) extend and retract boom
c) oscillate brush assemblies
d) turn on water flow

Results - This test was to evaluate the capabilities of the controls.

a) Trolley travelled forward and back with no problem. Test was done again after changing trolley speed.
b) Boom extended and retracted in expected manner in both "Auto" extend and manual switch modes.
c) Brushes oscillate only in wash/spray mode with combination of wash button switch.
d) Not done at this time due to empty tanks.
e) Extension was smooth but retraction was jerky.

Test B - (SAFETY) - While the vehicle is moving, attempt to move the trolley and the brush bar assembly. These components should not move while the truck is in motion.

Results - When the parking brake is released, no part of the system is operational. With trolley in motion, the parking brake was released. The trolley immediately stopped. The status box was also inoperable when the parking brake was released.

Test C - (SAFETY) - With the driver side door on the truck cab open, attempt to operate the trolley assembly. The trolley should not move as long as the door is open.

Results - With the driver's door open, attempts were made to operate the trolley assembly. In one case, the manual mode was operational, on a subsequent trial, it was not operational. (At this point automatic control was not possible.)

Test D - (SAFETY) - While the trolley assembly is operating, open the driver side door. The trolley operation should halt once the door is opened.

Results - With the trolley assembly operating, the driver's side door was opened. The trolley immediately stopped. (Note - manual control only was tested.)

Test E - (STRUCTURAL) - With water tanks completely empty and trolley in full forward position, accelerate the vehicle to 10 mph as quickly as possible. Trolley assembly should not move rearward. Test operation of the trolley immediately after the test to see if trolley drive mechanism has been damaged.

Results - It is difficult to accelerate the vehicle to 10 mph quickly since a shift to second gear is required to reach this velocity. With truck in motion, (on asphalt) the trolley vibrates and pivots several inches about its attachment point. Trolley does not move rearward while the vehicle is accelerating forward to 10 mph. However, when the vehicle is decelerated from this velocity, the trolley does move rearward about two or three inches. It returns to its original position once the vehicle is completely stopped. The trolley was completely operational after completion of this test.

Test F - (STRUCTURAL) - Repeat Test E with trolley system completely rearward while bringing the vehicle to a halt from five mph within five feet. Trolley assembly should not move forward. Test operation of the trolley immediately after the test to see if the trolley drive mechanism has been damaged.

Results - This test was completed without complication. The trolley appeared to move backward about three inches during this exercise. The trolley assembly worked correctly following this test.

Test G - (SAFETY) - With the right hand water tank one half full, and the left hand water tank completely empty, drive the vehicle through a 180 degree left hand turn at 10 mph using the shortest possible radius. The truck must remain driveable, i.e., no swaying, tipping, or oscillating, that causes loss of control or difficult control, due to changing water loads.

Results - With the tank on the driver's side only one half full of water, this test was performed. In the area available to complete this test, the turn was nearer to a 360 degree turn. The driver during the test was an FMI employee. He commented that the truck felt somewhat unstable during this maneuver. It was difficult to maintain 10 mph velocity throughout the turn.

Test H - (SAFETY) - Repeat Test G with right hand tank completely full.

Results - With the tank on the drivers side completely full of water, the same procedure as in Test G was completed. No significant changes were noted.

Test I - (SAFETY) - With water tanks fully loaded and all equipment mounted on the vehicle, the vehicle is accelerated as quickly as possible up to 10 mph. The vehicle is then slowed to 5 mph gradually and from there braked to a complete stop within five feet. Water tank mounts should be inspected for damage or shifting. Braking should be smooth and consistent.

Results - With both tanks completely full of water, the vehicle was accelerated to 10 mph, slowed to approximately 5 mph and braked to a complete stop in about 6 feet. The tank on the passengers side slid forward in the saddles. The straps over the top appeared not to be tight. The saddles did not move with respect to the truck. When the tank slid forward, the sight glass broke.

Test J - (OPERATION) - While inside the truck cab, turn on the water flow system and adjust the water flow rate from minimum to maximum using the engine power takeoff. If possible measure or record the flow rates for engine rpm.

Results - The engine power takeoff worked only minimally to control water flow rate. It was not possible to measure water flow rates corresponding to engine rpm.

Test K - (OPERATION) - With a Barstow style heliostat in the vertical position and the truck on flat level ground, align the truck with the heliostat pedestal and begin a washing sequence. The brush bar assembly should extend to contact the mirror surface and automatically distance itself from the mirror. Once positioned it should automatically move rearward with the water flowing and the brush bars oscillating. As the assembly approaches the center of the heliostat, the brush bar assembly should retract sufficiently to clear the motor housings and resume operation once beyond the housings. Position sensors should not leave any permanent marks on the mirrors, brush bar verticality or parallelism to mirror surface should be maintained, brushes should be in contact with the mirror surface for the entire height of the heliostat and brush bar distance from the mirror surface should be maintained constant for the entire trolley travel. Examine the mirror surface for snagged brush bristles.

Results - Automatic washing sequence of Barstow style heliostat was completed. During the wash procedure, the brushes were not at the same level of contact over the vertical section of the heliostat. The top of the brush bar was much closer to the heliostat than the bottom.

While the brush <u>did</u> make contact with the heliostat at both extremes, the depth of contact varied. The difference in depth of contact from bottom to top was about two inches. (Note, there is a slight slope of the pavement on which the vehicle was setting. This caused the truck to tilt about 2 degrees from side to side.)

The top of the brush was approximately 2 inches lower than the top edge of the heliostat. Thus, the top 2 inches obviously did not get washed.

Indexing around the motors worked well. It appeared that spraying began slightly after brushing began.

Since deionized water was <u>not</u> used, water spotting was <u>very</u> evident after washing.

Although reflectivity measurements had been taken before and after washing, the readings were not very useful or meaningful. In some instances, the reflectivity post test was lower than the reading prior to washing.

The heliostat was cleaned with an industrial glass cleaner and a soft cloth. Reflectivity measurements were attempted, however, the reflectometer failed to work. Visually the reflective surface improved after hand washing.

No further testing was done at that time at the CRTF. The unit was scheduled to be delivered to the Solar One plant for application to the actual heliostats in the field. More performance information would then be derived after field operating experience.

Despite the occasional shortcomings of the system during the test series, the overall evaluation was positive. Sandia personnel responsible for testing reported that "the equipment operates well in the modes it was designed for."

4. RECOMMENDATIONS FOR IMPROVEMENT

The following recommendations for improvement are based on FMI's brief operational experience with the mobile heliostat mirror washing system. Problems are identified and adjustments are proposed which follow the same design and philosophy guidelines as the original system design.

All four trolley wheels do not support the total wash assembly load evenly along the full length of beam due to lack of flatness on the bearing surface. The top beam of the main truss is assembled by welding two aluminum channels together, making a box beam. The top surface of this beam should be flat and perpendicular to the sides along the entire length of the truss. This was difficult to accomplish without machining. By welding a flat plate to the top, irregularity in any one section would tend to be averaged.

Some difficulty was encountered in assembling the brushes and significant labor will be required to change out the brushes as assembled. The assembly problem comes from using two foot brush and tee support sections. After inserting the brush in the tee section, each piece had to be spliced in place on the brush arm. An alternative method would be to use as long a tee section as possible, likely ten foot, which then could be assembled in place. Only one splice would then be required.

Oscillation of the wash arm vertical control seemed excessive, apparently due to the soft mount system and loose drive mechanism. This problem is experienced when the extender is in motion and is then stopped. The deceleration is transposed into a torque on the truck bed through the frame mount. This transfers to the tires which act as very soft mounts causing the truck to tilt. The vertical control sensor picks up the tilt causing the actuator to adjust the wash arm position and oscillations are set up.

The vertical adjustment drive mechanism has loose tolerances which also allow the arm to experience some free motion. By adding a fluid damping system (shock absorber) to the wash arm it would be expected that the oscillations could be dampened quickly.

In situations where the truck is tilted the trolley and extender motors appeared to be undersized for starting torque. One solution would be to replace the gear boxes with higher efficiency units. Present gear boxes have less than a 50% efficiency at zero speed.

The trolley wheels were being side loaded causing them to ride at extreme ends of their shafts. This was due in part to the uneveness of the main beam. This problem could be surmounted by correcting the main beam problem as previously suggested and by placing spacers on the wheel shafts in order to hold their position.

By placing the control box in back of the main beam under the truck bed, it proved to be very difficult to access the controls inside for repair. While access to the inside of the electronic controls package should rarely be required, the problem could be solved by providing support and bracketing that would allow the box to be lowered and moved forward for easy access.

During preliminary testing it was discovered that the position transducer tilt brackets tend to be activated by the lip that surrounds the heliostat panels. This is due to the spring mechanism used on the sensor bracket and the high loads required to activate the position transducers. In order for the transducer wheel to ride over the edge it must depress the transducer with a force of 9 to 15 pounds. At the same instance a side load occurs perpendicular to the transducer load. This load is countered by the spring of the tilt bracket. When the initial spring load is overcome the bracket starts to tilt which decreases the angle between the transducer load and tilt load, the result being less force for depressing the transducer. The spring activated bracket should be replaced by a snap action tilt bracket that will be rigid until a specified load is applied. This load will be in direct proportion to the load required to depress the linear transducer. It might also be possible to replace the present transducer with one having a lower activating force. Another likely aid would be to replace the sensor wheel with one of a larger diameter.

Inconsistent operation of the control package was observed on several occasions during testing. Normally this problem occurred only after work had been performed on the electronic controls package internals. It was determined that the computer circuit board card edge connector did not fit the card. This allowed the card to shift positions causing misalignment of the connections. The solution to this problem is obviously to replace the existing card edge connector with an appropriately sized connector.

Inspection of the overall control system revealed that water damage to the system may result due to unprotected cable connectors. Watertight cable connectors should therefore be specified.

Reports from field users have indicated possible problems with computer control stability after brief operating periods apparently due to overheating of the electronic controls package. This system was designed to operate at night while the heliostat field was inoperative. The control box has sufficient surface area to reject normal operating heat under these conditions. If the system is to be operated during the heat of day, the control box will require increased cooling. This may be accomplished by simply adding a fan and air filter to the package.

5. COST ESTIMATE FOR NEXT UNIT

Since the overall heliostat mirror washing system design appears to have achieved the main objectives of the development program, a second unit would only vary in minor aspects as suggested in the previous report section, Recommendations For Improvement. An estimate of the cost of a second unit to be built in the near term has therefore been derived from the actual 1982-83 cost breakdown of the first unit, 1985 replacement costs of government furnished equipment (GFE) used in the first system, and vendor estimates of 1985 prices for several of the major cost components of the system. An estimate of the labor required for fabrication of the structures and assembly of the system have also been projected on the basis of the experience gained during the initial program.

5.1 Cost Breakdown of Washing System Components

Table 5-1 lists the costs of the major washing system components as incurred in late 1982-early 1983 and as projected for a second unit to be built in 1985.

Two of the original system higher cost items were actually GFE so that the original costs listed for these items are rough estimates.

A 1966 International Harvester 5-ton stake bed truck in fair to good condition was provided by Sandia from disposable government equipment. The used truck was refurbished functionally and cosmetically under a separate contract to FMI. The total acquisition and reconditioning cost was approximately $15,500. Since the vehicle is intended for use solely on the central receiver plant site and will typically operate at low speeds, it need not be a high performance vehicle. A refurbished used truck is an ideal choice based on cost and duty considerations. The availability of such a suitable vehicle is questionable, however, so the cost of an equivalent new model vehicle was obtained as a conservative estimate. The base price of a 1985 I-H model F1954 diesel stake truck with tandem rear axles and 20-foot bed was priced at $36,000.

Table 5-1. Washing System Materials Cost List

Item	Original Cost	1985 Estimate	Vendor Price
Vehicle	15,500*	36,000	✓
Controls System	11,885	12,000	
AC Generator Set	4,000*	7,500	✓
Fiberglass Water Tanks w/Accessories	5,384	5,400	✓
Aluminum Stock	3,087	4,600	✓
Sensors and Switches	737	850	
Hose and Cable Carrier	1,330	1,800	✓
Vertical Accelerometer	607	630	✓
Brush Guides	534	610	
Hose and Cable	922	1,060	
Brushes	418	480	
Nozzles	509	570	✓
Motors, Gearboxes & DC Actuator	1,692	1,950	✓
Trolley and Extender Caster Wheels	357	410	
Valves	623	720	
Resilient Mounts	304	350	
Plumbing Supplies	649	750	
Roller Pump	244	280	
Pneumatic Supplies	120	140	
Electrical Supplies	595	680	
Subtotal	49,497	76,780	
~13% Miscellaneous	6,370	9,990	
Raw Materials Cost	55,867	86,770	
Contractor's Markup, 30%	16,760	26,030	
Total Materials Cost	$72,627	112,800	

*GFE materials, approximate cost

The second GFE item was a used 12.5 kW ac generator set. A new 1982 unit would have cost on the order of $6,000. The cost of a used set was therefore estimated to be $4,000 in 1982. An equivalent 1985 model single phase ac diesel generator set with starting batteries, weather protection housing, and other appropriate options was priced by a vendor at $7,500.

Other than the GFE items, the highest component cost of the prototype washing system was for the control system. The original control system was a custom designed microprocessor based system with three remote input stations. While the next system would have the same general specifications as the original in order to maintain system flexibility, developments in the area of programmable controllers suggest that increased simplicity and reliability can be achieved with their use. Since a detailed evaluation of an alternate control system was not within the scope of this review of work, it has been assumed that an improved control system for the second washing vehicle could be obtained for approximately the same price as the original.

Another major cost category in the original system was aluminum stock for fabrication of the major structural components. Prices for several aluminum sections solicited from major suppliers indicated that the cost of aluminum has gone up a surprising 40 to 60% in the past 3 years. A median increase of 50% for the second unit structural materials was therefore assumed.

Various other vendor estimates indicate price increases from almost 0% for the fiberglass tanks with accessories to 35% for the hose and cable carriers. An intermediate price increase of approximately 15% was assumed for 1985 costs which were not confirmed by vendors. As would be the case if this system was contracted out to be built, a materials markup has been included in the total materials costs.

APPENDIX A
OPERATING INSTRUCTIONS

The mobile heliostat mirror washing system has two modes of control: an automatic mode, which provides full computer control of speeds and wash arm/mirror proximity as preset by the operator, and a manual mode which allows the operator to stand outside the vehicle to control spray only or spray and wash functions.

A.1 Pre-operational Checkout

At the beginning of each day's use a pre-operational checkout should be carried out:

1) Perform the vehicle and motor generator safety inspections in accordance with their respective operations and maintenance manuals.
2) Perform a visual inspection of the trolley and extender system, paying attention to any objects that may be blocking the paths of motion.
3) Are the water tanks full?
4) Open water valves.
5) Lubricate the position sensor rods with a suitable rubber lubricant.
6) Plug in the manual control cable.
7) Start the motor generator.
8) Start the truck engine.
9) Check for 9-15 psi air pressure on regulator.
10) Turn on all circuit breakers located in the electrical panel to the left of the generator.
11) Key on the power from the status panel located in the cab.

12) Using the hand-held manual control, move the trolley to both ends of its normal travel. Did it stop automatically when contacting the limit switches?
13) Move the extender out to its full extension position. Did it return and stop on contact with the limit switch?
14) Adjust the vertical control to demonstrate a full range of motion.
15) Engage the PTO in preparation for washing.
16) Push the wash button. The brushes should reciprocate with full water flow.
17) Disengage the PTO.
18) Key power off from status panel in cab.
19) Disconnect the manual control cable and plug in the auto control.
20) From inside the cab with the door closed turn the power key on. The trolley should automatically move to the extreme forward position.
21) While the trolley is in motion open the cab door. The trolley should stop and the interlock lamp should be lit. In order to restart after an interlock shut down, the stop button must be pushed, key turned off then on again. The trolley should immediately seek the home position.
22) Restart the system. The trolley should seek the forward position. Then release the emergency break. The trolley should stop!
23) Restart the system and push the emergency stop button. All systems should stop!
24) Restart and allow the trolley to move fully forward.

At this point the system is ready for field use.

A.2 Parameter Selection

If spray and wash mode is selected the wash brush distance thumbwheel (first from the left) should be set. If spray only is selected the second thumbwheel will be set to give a spray distance. The fourth thumbwheel will set the trolley traverse or wash speed.

The suggested settings are:

spray and wash	select 5-7
spray only	select 5-7
wash speed	select any

NOTE The system must be turned off before any thumbwheel selection is made.

A.3 Automatic Heliostat Washing

The following procedure should be followed for heliostat mirror cleaning in the automatic mode.

1) Approach the heliostat so that the truck is parallel to the mirror, between two and four feet away. Stop so that the pedestal lines up with the driver's window.
2) Set the parking break and insure that the driver's door is closed.
3) Turn the power key on.
4) The following lights should be on:

   Power, status panel
   Power, auto control unit
   Trolley limit
   Extender limit

5) Engage the PTO.
6) Using the automatic control unit move the trolley so that the brush aligns with the leading edge of the heliostat.
7) Push the cycle start button.

The cycle light will go on. The extender will move outward until the mirror is contacted by the position sensors. The extender will slow and establish the wash arm to mirror distance automatically as set by the thumbwheel. Then the brushes and water spray will turn on while the trolley traverses the first section of mirror. As the position sensors drop off the end of the first mirror the transfer light on the status panel will light and the extender will retract fully. Then the trolley will move rearward in order to clear the heliostat drive motors. When this preset distance has been covered the trolley stops and the extender moves towards the mirrors repeating the normal start cycle, as previously described. When the end of the mirrors is reached a second time the computer interprets this as the end of a complete cycle and the trolley moves to the home position. At this point the truck can be moved to the next mirror.

A.4 Faults Which May Occur During a Normal Cycle

Any time the key up operation does not produce the desired results it may be necessary to push the emergency stop button, turn the key off then on again. Any time the auto control is in use and the system is stopped, on key up the systems will automatically seek its home position: extender retracted and trolley fully forward.

FAULT Cycle has been started, extender moves out but misses the leading edge of the mirror.

Automatic Reaction - Extender Fault light is lit.
Extender retracts and trolley moves to home.

Action - Realign the trolley with the leading edge again and restart cycle.

FAULT With the wash cycle just started or in progress the system stops washing and the wash assembly seeks home position.

Automatic Reaction - Vertical error light is lit.

Action - Heliostat may not be set vertical within sensor tolerance limits. If not, do not wash or correct heliostat orientation.
- One position sensor possibly stuck. Lubricate sensor rod with rubber lubricant.
- Check inclinometer alignment.
- Restart cycle.

FAULT Position sensor wheels stick on leading edge of mirror causing the sensor to tilt.

Automatic Reaction - Sensor tilt light is lit.
- Wash assembly seeks home position.

Action - Be sure there is 9-15 psi air pressure on sensor regulator.
- Lubricate sensor rod with rubber lubricant.
- Restart cycle.

FAULT All systems stop during the cycle.

Automatic Reaction - Interlock light is lit.

Action - Check for improperly closed driver's door.
- Be sure emergency brake has not been released.
- Push stop button.
- Turn key off.
- Turn key on.
- System should seek home position.

A.5 Manual Control

The following procedure describes the options available for heliostat washing using the manual control unit.

1) Disconnect the auto control cable and connect the manual control. While the system is off make any changes desired in the thumbwheel selectable parameters.
2) Follow normal key up procedures.
3) Using the manual control rocker switch move the trolley so that it aligns with the leading edge of the mirror.
4) Adjust the vertical control knob so that the brush is parallel to the mirror.
5) Pushing the auto extend button will cause the computer to automatically move the extender to the wash arm to mirror spacing set by the thumbwheel selections.
6) The extender rocker switch can be utilized to manually set any wash arm/mirror spacing desired. If the rocker switch is used and the brush is forced too close to the mirror, the proximity limit light will be lit and the extender will seek its home position.
7) By pushing the wash button the spray or spray and brushes will activate depending on the mode selected at the status panel.
8) While washing, the trolley rocker switch must be activated in order to traverse the mirror. If the trolley is allowed to move too far into the heliostat center the position sensor tilt or support interface may be activated. This causes the fault light to be lit and the extender will seek home.
9) When the first half of the mirror is completed the rocker switches are used to transfer around the heliostat pedestal and motor drive.
10) In order to wash the second half of the mirror the same procedure is followed as on the first half.

APPENDIX B

MAINTENANCE

B.1 Vehicle and Generator

Proper maintenance procedures for the basic vehicle and the generator are covered in the owner's manuals.

B.2 Lubrication

The following schedule of lubrication should insure proper functioning of the system moving parts.

Grease fittings location	Type	Frequency
Trolley wheels	Lithium EP2 Grease	30 days
Extender wheels	Lithium EP2 Grease	30 days
Brush arm pivot pin	Lithium EP2 Grease	30 days
PTO universal joint	Lithium EP2 Grease	30 days
Main trolley Idler	Lithium EP2 Grease	30 days
Linear motion position sensor rod	Aerosol super silicone 45627	daily
Gearbox oil	HD Gear oil 150	yearly

B.3 Adjustments, Removal and Replacements

There are no special tools or techniques required to remove or replace the hardware used on the heliostat wash system. Visual examinations of the hardware and a review of the blueprints will make these procedures obvious. The only noteworthy adjustment procedures concern the wash arm vertical alignment and linear potentiometer positioning.

Adjustment of the vertical inclinometer is carried out as follows: Use the manual control box to set the brush arm to vertical. Verify this with a plumb bob and string hung from the vertical sensor pot to the ground. The distance from the string to the brush arm face should be uniform over its length. Remove the cover from the inclinometer box. Use a digital volt meter to verify that the voltage reading between pair D and pair B is -.005 volts. If it is not, loosen the mounting screws on the box and tilt until this reading is obtained.

The position transducers should not need adjustment, unless they have been removed from the wash arm. If removed or moved to a new location care should be taken to align the transducers with respect to each other. When fully extended they should be perpendicular to the arm and in the same vertical plane.

APPENDIX C

PARTS LIST AND SPECIFICATIONS BY SUBSYSTEM

C.1 Air and Water Systems

1) Water Pump - Hypro Roller Model 1700
2) Solenoid Valve - Lancer - No. 2L2LBG 6300 N/C
3) Solenoid Valve - Lancer - No. 2L2LBG 5300 N/C
4) Relief Valve - Anderson Greenwood No. 81P G68-8 220 psi Set Pressure
5) Water Tanks - Raven No. A7606 1000 Gallon

No. A5035	Skid
529302	2 inch Vent
50931	Baffle
50521	Fill Well
5059F	2 inch Half Couplings
51531	Lift Lugs

6) Bronze Sight Gauge - Eugene Ernest Products No. FEP28 38 inch centers
7) Spray Nozzles - WM. Steinen MFG. Co., Adjustable Fan-Jet: 1/8 Flat male 95° Tip 0.15 Brass; 1/8 Flat male 50° Tip 0.15 Brass
8) Air Regulator - Watts No. 216-2 0-8 psi
9) Air Cylinders
10) Bronze Strainer 1 1/4 inch
11) Ball Valves - 1 in. size, Ball Valves - 1 1/4 inch size
12) Miscellaneous Hose, Fittings, and Pipe

C.2 Electrical

1) Pressure Switch - SOR Inc. No. 6AC-AD3-B1A 10-100 psi
2) Switches - Cherry No. E72-40A - No. E7240H

3) Limit Switches - Aller-Bradly

No. 802T-HP
802T-IP
802T-A2P
Operators No. 802T-W3
802T-W14

4) Relay - P and B, KVP11DG Double Pole Double Throw, 12VDC
5) Electrical Enclosure - NEMA Type 4
6) Circuit Breakers - 30, 20 and 15 Amp., Ground Fault Type
7) Miscellaneous Wire and Cable

C.3 Controls

1) Linear Motion Position Transducers - Waters Mfg., No. LFW150A
2) Inclinometer - Columbia No. SI-701A
3) Trolley Control Motor - Electro Craft No. 0670-08-020-S
4) Extender Control Motor - Electro Craft No. 0670-08-020
5) Vertical Positioning Motor - Warner Electric, DC Actuator No. DCA-05PC-8
6) Brush Motor and Gear Reducer System - Boston Gear, No. SF318B-20-J5-FRTE-B
7) Power Supply - Triad No. P-546
8) Electronics Control Package:

Signal Control - Precision Drives Inc., No. P8000-SC
Power Control - Precision Drives Inc., No. P8012-PC
Computer Card - Precision Drives Inc., No. CM1000
Digital Reference Thumbwheel - Precision Drive Inc., No. DRU9000
Input Module - Opto-22, No. IDC5
Output Module - Gordos, No. ODCB

C.4 Mechanical

1) Pulley, Brush Cable Idlers - Ralmark Co., No. M-5B
2) Ball Bearings, Brush Idlers - W.S. Shamba and Co., No. WRO628ZZ
3) Trolley and Extender Wheels - Langley EQ. Co., No. PD-05201
4) Cup Mounts - Barry Controls No. UC-3500-T-10
5) Trolley Cable Carrier Assembly - Gleason Reel Co., Type 45 - 19.5 ft.
6) Extender Cable Carrier Assembly - Gleason Reel Co., Type 45 - 10 ft.
7) Stainless Steel Cable - SAVA Industries, No. 2126
8) Universal Joint, PTO - 15/16 x 1 inch Round 1/4 Key
9) Brushes - Precision Brush Products, Inc., 6 inch .016 Nylon Black Crimp
10) Trolley and Extender Flat Belt Pulleys - Eastern Bearing Inc., 7 in. OD, 3 1/4 Flat Face width, Browning Bushings No. FHP23K
11) Idler Pulleys, Idler, Extender and Trolley - Eastern Bearings No. AK84-1 7/16 Bore, Bearings No. Z99R12
12) Pulleys, Brush Drive - Ralmark Co., No. MS 202195-2.625 OD, Bearings No. P10K
13) Miscellaneous nuts, bolt and fasteners
14) Structural AL as required according to detailed Mechanical and Structural drawings
15) Gear Box, Boston Gear, No. F324B-60-G1

APPENDIX D

REVIEW OF SOIL CONDITIONS AT BARSTOW SOLAR PLANT SITE

The following conclusions and recommendations were derived based on a review of the report, "Geotechnical Investigation for the Proposed Solar Pilot Plant" by Woodward-Clyde Consultants, and discussions with the following people: Mr. William Butler, site supervisor for Townsend & Bowden, general contractors; Mr. Don Parker of Stearns & Rogers, a construction engineering firm involved in the initial site evaluation; and Mr. Vic Burolla, Sandia Technical Project Officer for the Heliostat Washing System Program.

D.1 Soil Loading Capacity

If site compaction was completed in accordance with recommendations in "Geotechnical Investigation for the Proposed Solar Pilot Plant" by Woodward-Clyde Consultants, then the site meets H-20-44 loading criteria. This specifies that the front wheels of a vehicle may carry a maximum of 8,000 lbs and the rear pair of axles may carry 16,000 lbs each for a total rear weight of 32,000 lbs.* It has been reported that the entire field was in fact watered and wheeled, achieving a compaction of 90%. This is consistent with the above report recommendations. We will therefore assume the H-20-44 loading limitations as constraints in the design of the mobile heliostat washing system.

D.2 Local Soil Stabilization

Despite the assurances that the entire field was adequately compacted, major soft soil areas in the field have been reported. These are located through approximately the last seven rows in the north-west quadrant and last seven to twelve rows in the north-east

* AASH 1973

quandrant of the heliostat field. It is also possible that other minor soft spots exist throughout the field. While the cause for this inconsistency in field soil conditions has not been identified, techniques for local soil stabilization have been investigated and are discussed here.

There are a host of chemicals and other products that can be used to improve the soil properties in the problem areas of the Barstow field. With the types of soil existing at the site certain additives have a long and widely known history of success. The principal additives recommended for use for the given conditions are portland cement and/or quick lime.

Cement is added to soil to improve strength and durability. The usual application is to pavement construction where soil-cement is substituted for aggregate base. Other successful uses have included slope protection for dams and levees and impermeable linings for canals and reservoirs. Cement usually proves effective as a stabilizing agent for coarse soils with a low percentage of fines or for fine soils having little plasticity. To produce true soil-cement (having high strength and adequate durability) the percentage of cement required is usually between 5 and 10 for sands and gravels and between 10 and 20 for silts and clays. Strengths approaching about one-half of that of concrete are not uncommon, with values of seven-day, confined compressive strength in the 500- to 700-psi range generally required to meet durability requirements. Lower cement content are sometimes used to produce cement modified soil which is similar to soil-cement, but does not meet durability requirements.

As with concrete, strength of soil-cement increases with time. Because development of strength begins as soon as water and cement are mixed, construction with soil-cement must be done according to a carefully controlled schedule. Long delays between addition of water and compaction are unacceptable. Construction with soil-cement may be done by a batch process or a mix-in-place process, according to the requirements and materials for a particular job. In the batch process, constituents are obtained from stockpiled materials, mixed, transported, and placed. A very uniform product can result if close control on all phases of the work is maintained. The essential elements of a mix-in-place operation include loosening of the material to be stabilized, addition of cement, addition of water, blending and compaction. The opportunity for nonuniformity is greater on a mix-in-place job, and sometimes greater cement content is specified to compensate.

Quicklime is an effective stabilizing agent for fine soils with high plasticity. The addition of quicklime (CaO) or hydrated lime [$Ca(OH)_2$] results in both a cementing action and an alteration of the physical chemistry of the soil-water system, with both having beneficial effects. The calcium in the lime reacts with available silicas in the soil to produce a cement, which increases strength.

Lime stabilization may be accomplished with less stringent schedule requirements than for cement stabilization, especially when the primary benefits are derived from alteration of soil-water chemistry. To this end, the lime-soil mixture is sometimes lightly compacted after blending, then remixed after a curing period, and compacted to specific density. The curing period allows for a more thorough dispersion of calcium ions through the soil. In most instances, lime stabilization is accomplished in a mix-in-place operation.

The recommended procedure to stabilize the problem areas economically is to remove the top 18 inches of soft surface sand, soak the area down (preferable by means of water jetting), then replace the surface in 6 inch lifts mixed well with 10-15% portland cement or quicklime. The site should be compacted in 6 inch lifts with sheepsfoot or heavy pneumatic rollers. The final 6 inch lift should be compacted with a smooth steel drum or heavy pneumatic rollers. Due to the proximity of the problem areas to heliostat foundations, excessive vibratory systems are not recommended.

The heliostat washing truck should be designed to incorporate smooth faced baloon tires to maximize the footprint of the truck and to minimize surface disturbance during operation.

If the soil is not stabilized in the localized soft areas of the field as suggested above, Foster-Miller recommends that the heliostat washing system not be operated in these areas.

APPENDIX E
SPECIFICATIONS FOR ELECTRONIC CONTROLS PACKAGE COMPONENTS

E.1 Trolley Motor Controls

The trolley motor is an Electro-Craft Model 0670-08-020-S which has a dc tachometer and an encoder mounted as an integral part of the motor. The maximum operating conditions for this motor are as follows:

Shaft Torque Load:	150 oz. in.
Speed:	3000 r/m (RPM)

The controls for this motor provides full 4-quadrant drive. The amplifier is of the switched type which yields full 4-quadrant control (no overhaul other than inertia). I/O specifications are as follows:

Output Voltage		$\pm$ 60V (min)
Output Current		$\mp$ 6.25A
Inputs:	Feedback	14.2V/Kr/m Tach Voltage
	Command	0-10KHz (TTL)
	Direction	HI/LO TTL

NOTE
Encoder output is used only to measure motor rotations, not as feedback.

Adjustments		a. Tach gain
		b. Velocity loop
		c. Compensation
		d. Torque limit
Overload Trip (Adjustable)		@ 150% of max. current for ~ 1 min.
Encoder:	Accuracy	100 lines/rev.
	Output	TTL, line driver

E.2 Extender Arm Motor Controls

The extender arm motor is Electro-Craft Model 0670-08-020 which has a dc tachometer as an integral part of the motor. The maximum operating conditions for this motor are as follows:

Shaft Torque Load:	150 oz. in.
Speed:	1000 r/m

The controls for this motor are similar to that of the trolley motor. The specifications are:

Output Voltage	± 26V (min)
Output Current	± 6.25A
Inputs: Feedback	14.2V/Kr/m Tach. voltage
Command	0-10 KHz (TTL)
Direction	HI/LO TTL
Adjustments	a. Loop gain b. Compensation c. Torque limit
Overload Trip (Adjustable)	@ 150% of max. current for ~ 1 min.

E.3 Vertical Positioning Motor Controls

The vertical positioning motor is an integral part of the actuator device used for positioning.

The controls for vertical positioning are similar to that of the trolley motor. The specifications are:

Output Voltage	± 15V
Output Current	± 15A peak ± 5A continuous
Input: Feedback	From vertical sensor ± 5V dc into 100K load
Command	± 10V
Adjustment	a. Loop gain b. Compensation
Overload Trip (Adjustable)	@ 100% of peak for ~ 1 min.

E.4 Computer and I/O Devices

The control computer is a single board design which, as a minimum incorporates the following features:

a. 8 bit processor
b. Decimal and binary arithmetic
c. Variable length stack
d. Interrupt capability (single & non-maskable)
e. User 4K EPROM, 1K RAM
f. 52 individually-programmable I/O lines
g. 6 interval timers
h. Input data latching
i. I/O handshake lines
j. 1 MHz clock
k. RS-232 compatible serial I/O interface controller with baud, bit/character, stop bits and parity selection
l. On-board (firmware) monitor for loading and debugging of programs.

The I/O modules are OPTO 22 type or equivalent. The modules are arranged in two groups of 16 and one group of 8 modules for a total of 20 output and 20 input modules. The modules are:

Input: 5V dc logic, 10-32V dc power (OPTO 22 model IDC5)
Output: 5V dc logic, 2-60V dc out (OPTO 22 model ODC5)

A four-digit thumbwheel input module is provided which is individually multiplexed by the computer. This input device is used to provide inputs for variables critical to system operation.

E.4 Oscillator

The oscillator circuit schematic is shown in Figure E-1. This circuit is used to convert a linear potentiometer position to a pulse train of variable frequency which then is read by the computer. There are two of these circuits.

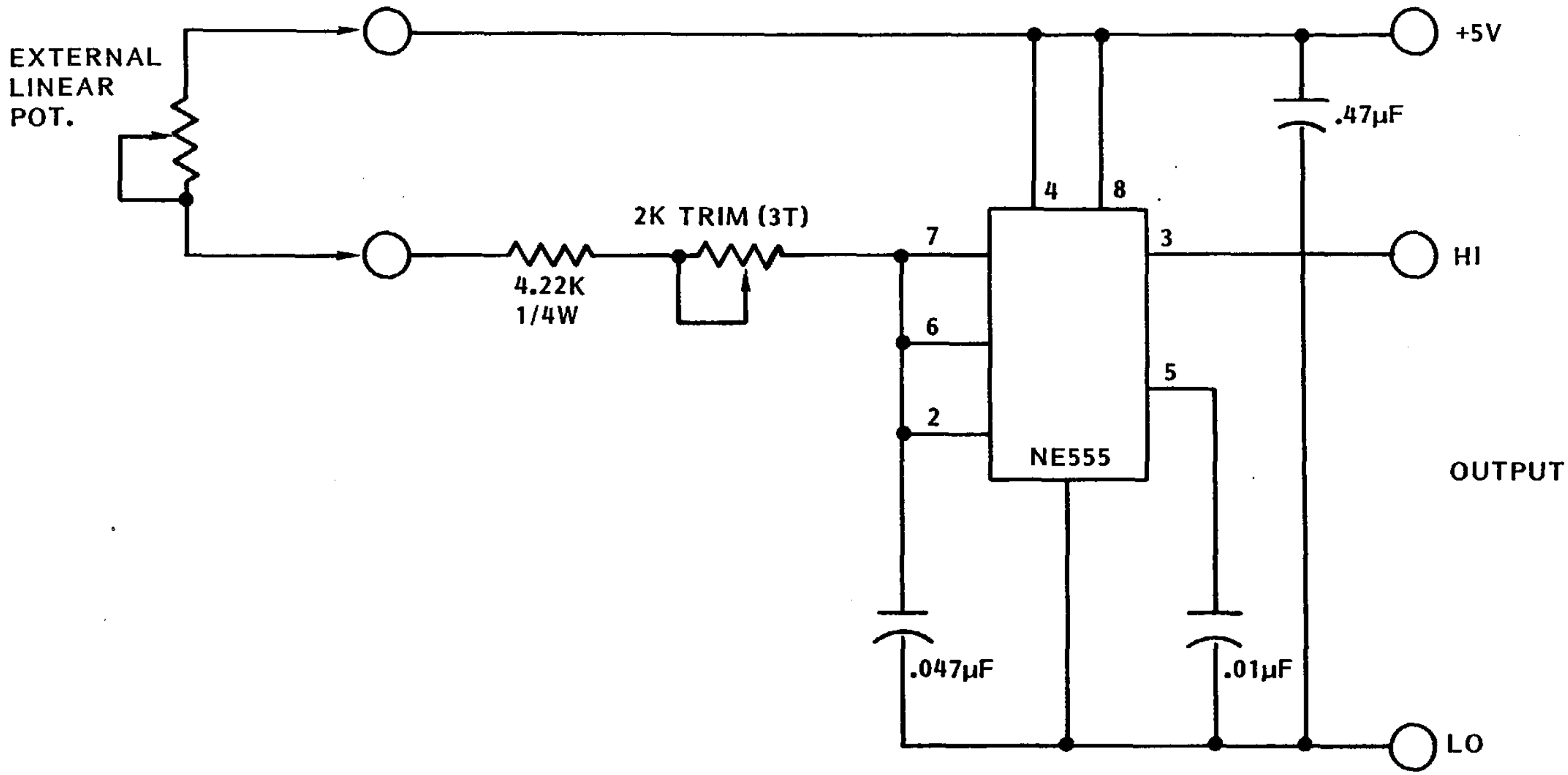

Figure E-1. Variable Frequency Oscillator

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