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DEVELOPMENT OF MASS-PRODUCIBLE LINE-FOCUS TRACKING CONCENTRATING SOLAR COLLECTORS—CATEGORY 1: COLLECTORS

255

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July 1983

Work Performed Under Contract No. FC04-80CS30264

Acurex Corporation
Mountain View, California

U.S. Department of Energy

Solar Energy

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DEVELOPMENT OF MASS-PRODUCIBLE LINE-FOCUS TRACKING CONCENTRATING SOLAR COLLECTORS -- CATEGORY 1: COLLECTORS

July 1983

Acurex Project 7791
DOE Contract DE-FC04-80CS30264

For

U.S. Department of Energy
Albuquerque Operations Office
Albuquerque, New Mexico 87115

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LIST OF SYMBOLS

SYMBOL	DEFINITION
A	Single module aperture area
Cp	Specific heat of working fluid
E	Geometric end-loss factor
f	Module focal length
g	Gravitational constant
H	Hour angle
I	Direct solar radiation
K	Incident angle modifier
L	Module trough length
$\dot{M}$	Mass flowrate
$(\dot{M}Cp)_r$	$\dot{M}Cp$ product for drive string of six
$(\dot{M}Cp)_a$	$\dot{M}Cp$ product for calorimeter
n	Day of the year
P_a	Calorimeter heater input power
ΔP	Pressure drop
Q_c	Collected energy
Q_i	Incident energy
Q_L	Receiver heat loss
R	Ratio of specific heat at average receiver fluid temperature to specific heat at average calorimeter fluid temperature
T_{amb}	Ambient temperature
T_b	Average bulk receiver fluid temperature; $(T_{in} + T_{out})/2$
T_{in}	Receiver inlet temperature
T_{out}	Receiver outlet temperature
T_{in_i}	Initial receiver inlet temperature

LIST OF SYMBOLS

SYMBOL	DEFINITION
T_{out_i}	Initial receiver outlet temperature
ΔT	Drive string differential temperature; average bulk fluid temperature minus ambient temperature; $(T_{in} + T_{out})/2 - T_{amb}$
ΔT_a	Calorimeter differential temperature
ΔT_ℓ	Calorimeter differential temperature with loop operating but with calorimeter heater off
ΔT_r	Receiver differential temperature; $T_{out} - T_{in}$
w	Module width
δ	Declination angle
θ	Incident angle
η_t	Direct normal thermal efficiency at $\Delta T = 0$; optical efficiency
η_θ	Energy conversion efficiency at incident angle θ
η_0	Energy conversion efficiency at $\theta = 0$; direct normal thermal efficiency
ρ	Density of the working fluid
τ	Time of day, 24-hr clock

SECTION 1

INTRODUCTION AND SUMMARY

This report presents the results of a technical study carried out by Acurex Corporation under Department of Eenergy (DOE) cooperative agreement DE-FC04-80CS30264, Development of Mass-Producible Line-Focus Tracking Concentrating Solar Collectors -- Category 1: Collectors. The technical effort included the detailed design of a low-cost, mass-producible, line-focusing parabolic trough solar collector, the fabrication and test of a prototype drive string for this design, and the conceptual definition of a plant for its mass production.

The design represents a significant advancement in the state of the art for cost-effective, medium-temperature (93° to 315°C) solar thermal collectors. Significant improvements were made in the areas of collector performance, manufacturing costs, installation costs, and reliability to yield a major reduction in the cost of delivered thermal energy.

The Acurex Model 3011 collector drive string of six modules is presented in figures 1-1 and 1-2. Figure 1-1 views the prototype drive string from the east with an east-west orientation as it is installed in the Acurex Solar Energy Test Facility. Figure 1-2 indicates the three major subsystems for each drive string: reflector module, thermal, and drive. The reflector module subsystem includes the module structures assembled with reflector panels. The thermal subsystem consists of receiver assemblies, receiver

Figure 1-1. Model 3011 Collector, Acurex Solar Energy Test Facility Installation

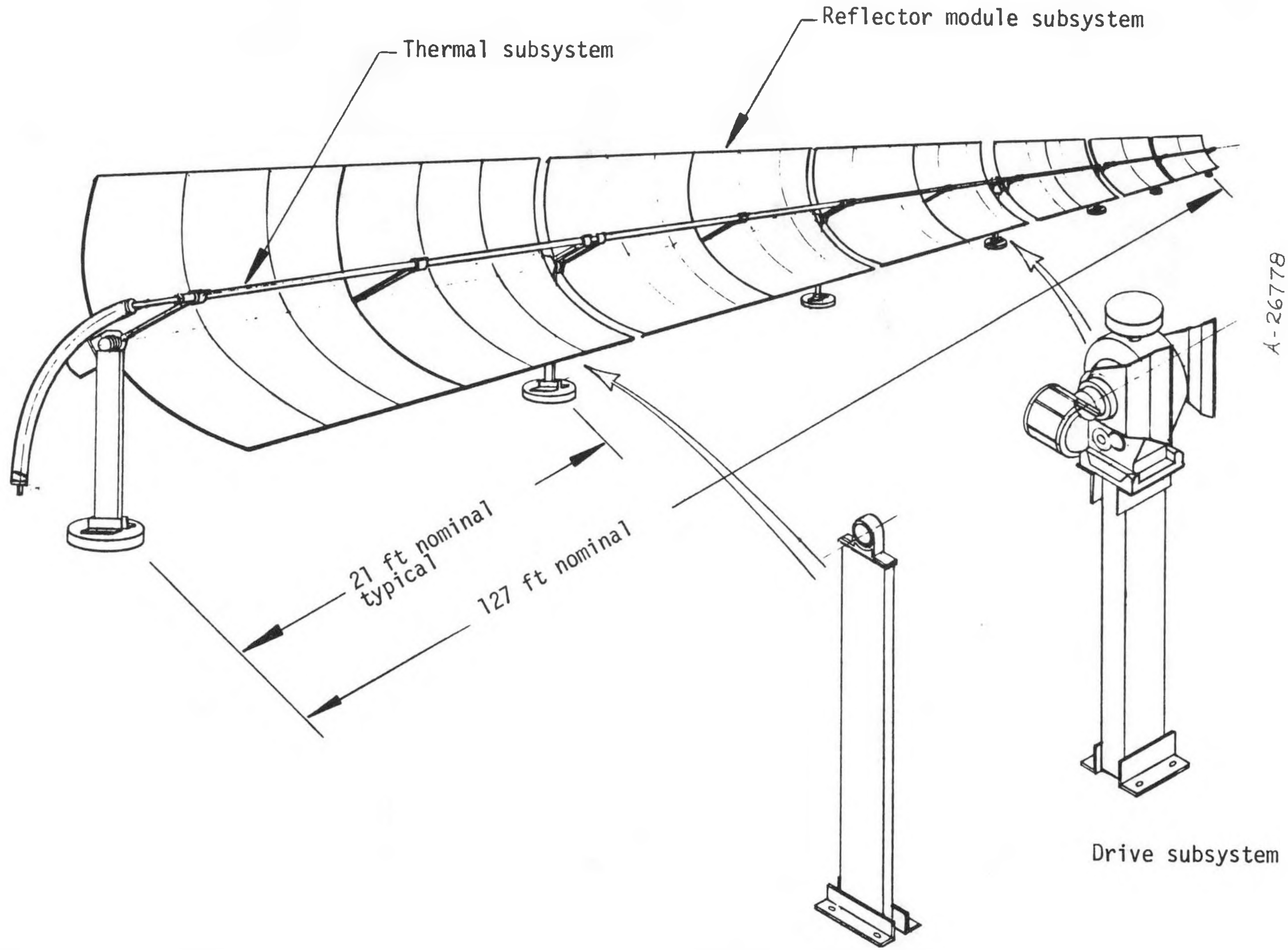

Figure 1-2. Collector Subsystems

supports, and flexhoses. The drive subsystem includes the drive post and the nondrive support posts, all of which are assembled with pivots and bearings.

The primary objective of this design effort was to improve the cost effectiveness of medium-temperature solar thermal collectors by improving performance while simultaneously reducing installed cost and recurring operations and maintenance costs. The design is based on our previous experiences in manufacturing the Acurex Model 3001 parabolic trough collectors and in the system design, collector installation, construction management, field startup, and operation of six thermal trough collector systems.

The specific areas targeted for design improvements were as follows:

- Improve total efficiency by optimizing optical efficiency and minimizing thermal losses
- Reduce manufacturing cost by designing for automated high-production approaches
- Reduce drive string field alignment cost by designing self-aligning subassembly mating interfaces
- Reduce field installation cost by factory assembly and checkout of subassembly components in single shippable units
- Reduce shipping cost by increasing module packing density
- Reduce operation and maintenance costs by specifying elements such as sealed gearboxes, self-lubricating bearings, sealed receiver assemblies, and galvanizing to meet the service life requirements

The design improvements were made and a complete drive string of six collector modules was fabricated and installed in the Acurex Solar Energy Test Facility. The drive string components were manufactured with methods representative of mass production. The components fabricated included: modules, receivers, flexhoses, and drive and nondrive supports. The foundations and field piping were installed for the convenience of testing and were not specifically considered as part of the improved design. The tracker and electrical systems used for control of the drive string were previously existing Acurex components. The prototype fabrication efforts revealed several minor design changes required before production drawings could be released for manufacturing.

Thermal and mechanical tests were performed on the drive string of six collector modules and on a single module. The drive string of six was mounted in an east-west orientation while the single module was fitted to a two-axis tracking structure. Both test units were operated with water from ambient to 100°C and with Therminol 66 at fluid temperatures from ambient to 340°C.

A production plan was developed for the mass production of the drive string of six collector modules. Factory requirements were determined on a conceptual basis for the assembly line layout, component manufacturing requirements, storage, shipping, receiving, quality control, machine shop, and office space. A concept for flow of work through the production plant was also developed. Cost estimates were made for materials and labor and an estimate was made of the cost benefit due to the production learning curve. Finally, a production buildup schedule for the conceptual production approach was generated.

The remainder of the report is divided into three sections. Section 2 covers the design improvement efforts. Section 3 describes the prototype fabrication of the improved design and provides test results. Section 4 presents production planning information required for mass production of the improved design.

SECTION 2

DESIGN

This section summarizes the design approach used for the improved solar collector. The DOE and Acurex design goals are presented, the reflector module, thermal, and drive subsystems are described, and selected subsystem trade-off analyses are presented.

2.1 DESIGN GOALS

Acurex based its design goals on the DOE program goals for line-focus tracking concentrating solar collectors, but with some modifications for improving product cost effectiveness. The DOE program goals for 1985 are as follows:

- Peak thermal efficiency of 71 percent at 204°C and 65 percent at 315°C
- $10/ft^2 collector cost not including installation
- 10- to 20-yr lifetime

These goals assume a production rate of 5 million ft^2/yr with costs expressed in 1980 dollars. A performance/cost trade-off analysis indicated a modification of these goals. Therefore, the Acurex goals are the same as the DOE program goals except that the peak thermal performance goal at 315°C was reduced to 63.9 percent and the uninstalled cost goal was reduced to $8.26/ft^2. This new efficiency goal was based on the following parameters:

- Direct normal insolation = 1,000 W/m^2
- Ambient wind speed = 5 mph
- Ambient temperature = 15.5°C
- Reflectivity of reflector = 0.95
- Transmissivity of glazing = 0.91
- Intercept factor = 0.96
- Absorptivity of receiver = 0.955
- Shading factor for receiver = 0.975

Due to the present limitations in state-of-the-art receiver assembly designs, Acurex believes that medium-temperature thermal energy can be most cost effectively delivered by a solar collector operating at slightly reduced efficiency compared to the DOE goals, but with significantly reduced capital and operating costs.

2.2 DESIGN DESCRIPTION

The new Acurex Model 3011 collector design has significantly improved performance and is less expensive when compared to the previous Model 3001 design. It was projected that by improving glass reflectivity, receiver absorptivity, and intercept factor the optical efficiency could be boosted 9 points to 77 percent. It was also projected that the receiver heat loss on a per unit aperture area basis could be reduced by 14 percent by improving concentration ratio. Figure 2-1 shows curves of the existing Model 3001 performance and the projected performance of the new Model 3011 collectors. The 1985 DOE performance goals are included. Note that the 204°C target efficiency is exceeded while the 315°C target efficiency is matched within 2 percent. Additional collector improvements can boost performance further. These improvements, planned for the near term, will result in collector performance exceeding the DOE performance goals before 1985.

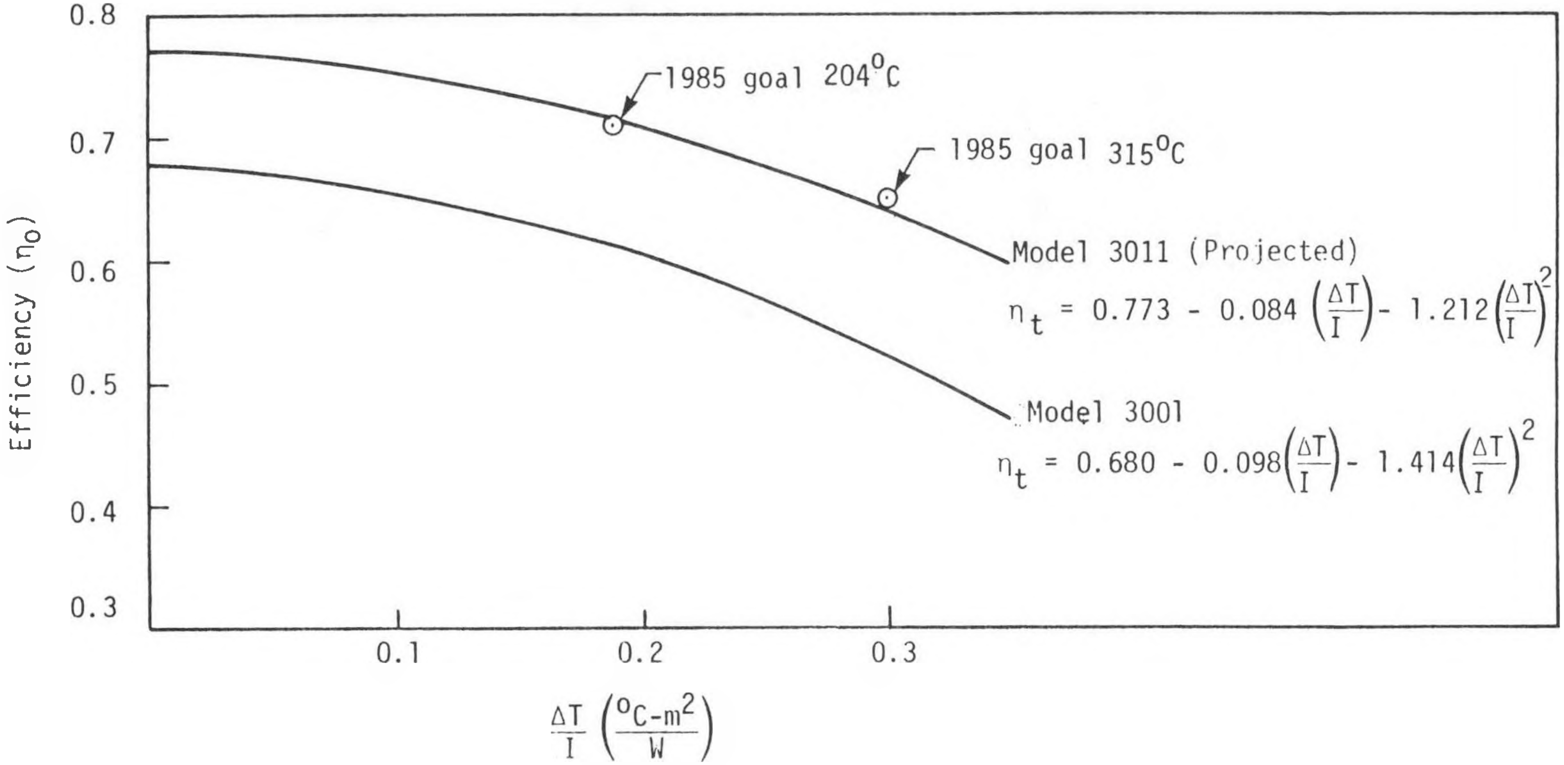

Figure 2-1. Collector Performance Curves

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The new collector was designed for significantly lower manufacturing, installation, and life cycle costs. Table 2-1 summarizes these costs for the existing Model 3001, projections for the redesigned Model 3011, and the 1985 DOE goals. The projected redesigned Model 3011 collector cost represents a significant (approximately 17 percent) reduction in installed cost compared to the 1985 DOE cost goal.

A life cycle cost analysis was performed to annualize collector costs. This life cycle cost was combined with an annual collector performance model to obtain a cost of energy as a function of collector operating temperature. Figure 2-2 shows this cost for the existing Model 3001, the redesigned Model 3011, and the DOE 1985 goal. The Model 3011 indicates significantly lower life cycle cost than the Model 3001 and slightly lower than the DOE goal for all operating temperatures.

The redesigned Model 3011 collector was designed for the following overall operational characteristics:

- 25-mph operating wind speed
- 80-mph survival wind speed in stowed position
- Withstand 3/4-in. diameter maximum hail size at 55 ft/sec maximum speed
- -29° to 49°C ambient temperature operating range
- Perimeter wind fence required with 50 percent maximum porosity
- 3- to 15-gpm flowrate operation range for water or heat transfer oils
- 400-psi maximum operating pressure
- 93° to 315°C average bulk fluid temperature range at outlet
- 1/4-g lateral and 1-g vertical acceleration survival due to seismic loading with any collector orientation

Table 2-1. Cost Comparison of Model 3011 Collector in Dollars per Square Foot of Aperture (1980 Dollars)

Item	Current Model 3001 Design	Projected for Model 3011 in 1985	1985 DOE goal
Collector	24.77	8.26	10.00
Shipping	1.50	0.75	0.75[a]
Foundations	3.00	1.20	1.20[a]
Installation (collector and interconnecting piping)	3.00	2.50	2.50[a]
Electrical (power and control)	2.25	2.25	2.25[a]
Control hardware (other than trackers)	1.00	1.00	1.00[a]
Total Installed Cost	35.52	15.96	17.70
Life Cycle Cost ($/ft^2-yr)	4.17	1.87	2.08

[a]The 1985 DOE goal does not specify these costs. They are assumed to be the same as the 1985 Model 3011 projections.

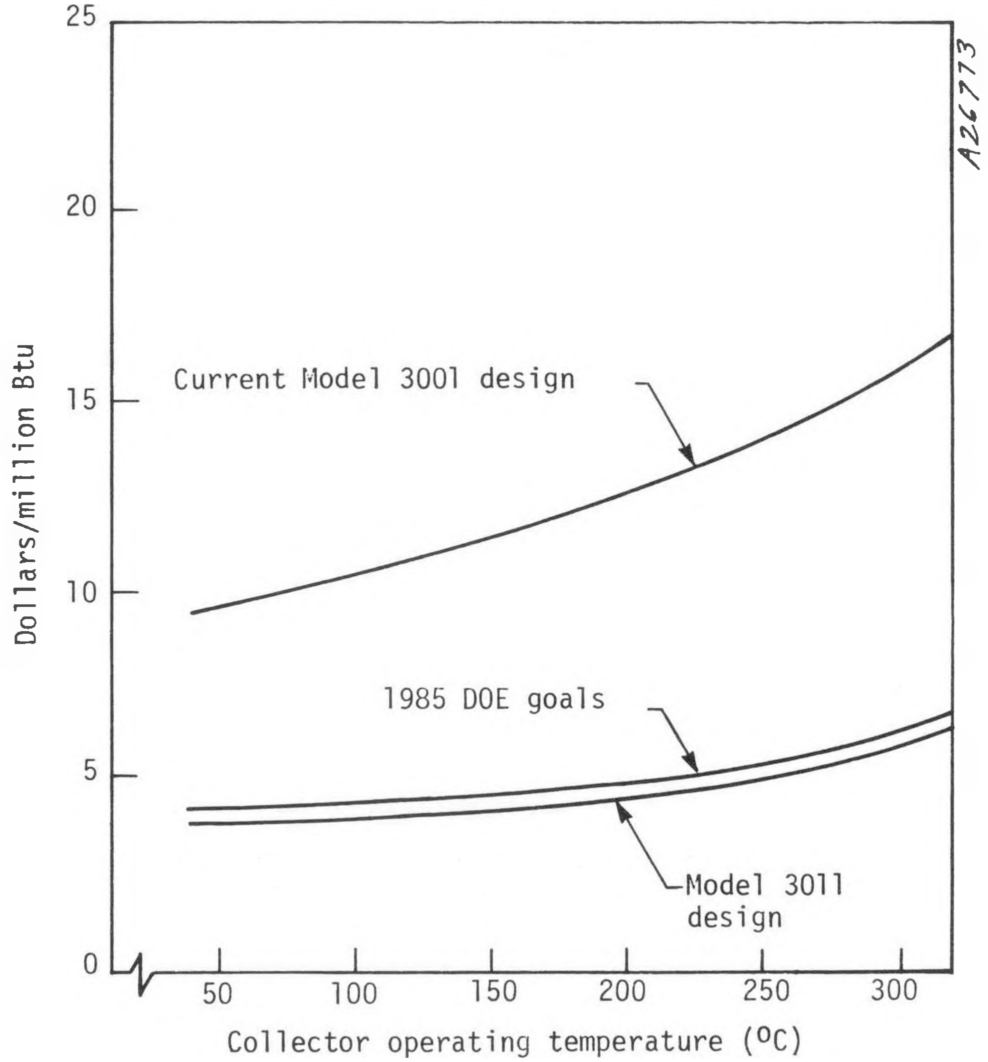

Figure 2-2. Annual Collected Energy as a Function of Operating Temperature

The following subsections describe the reflector module subsystem, thermal subsystem, and drive subsystem.

2.2.1 Reflector Module Subsystem

The reflector module subsystem is shown in figure 2-3. It consists of the module structure and reflector panel. The module structure is a steel torque tube with rib framework of welded and riveted construction. The backbone is an 8-in. diameter torque tube nominally 20 ft long. Reflector panels are supported by ribs riveted to stamped flanges. These flanges are positioned in a fixture and welded to the torque tube.

Module-to-module connections are provided by the torque tube end cranks. One crank is welded directly to the torque tube while the other is attached by roll pins after the tube weldment has been galvanized, making it adjustable. The attachment of one crank by roll pins compensates for tube distortions resulting from the fabrication and galvanizing processes. The cranks and a receiver support bracket are jig-welded to the torque tube at the factory, thereby eliminating field alignment of either receiver tubes or modules.

Structurally, the cranks transmit the torque along the tracking axis but are flexible enough to accommodate post misalignment tolerances. The cranks also locate the tracking axis nearly coincident with the reflector module center of gravity, thereby reducing the weight moment contribution to the torque requirements for the drive. A high packing density for shipment of modules is achieved by an offset in the crank which allows nesting of the modules in shipping containers.

The ribs are mounted to the torque tube in pairs, each rib forming half of the structure aperture. The rib assembly consists of a center rib member, two stiffeners, and a short right angle flange. The rib has a stamped

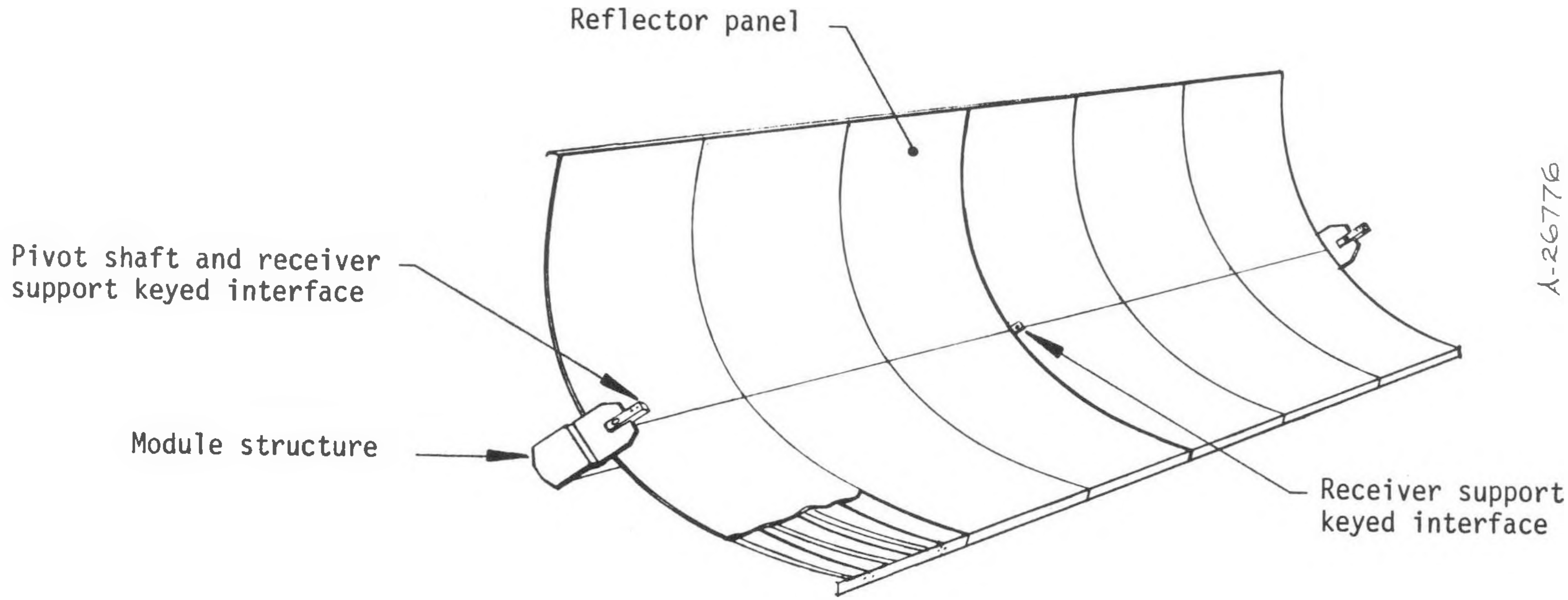

Figure 2-3. Reflector Module Subsystem

quasiparabolic concave edge which provides a base to hold the reflector panel in a parabolic shape and compensates for the deflection due to reflector panel stiffness. Two stiffeners are riveted, one to each side of the convex rib edge. The stiffeners increase the lateral section strength thereby eliminating the need for a stablilizing back cover.

The end of each rib is secured to an edge retainer that runs the length of the module. The retainer provides rib-end alignment and a mounting surface for an edge clamp. Both the retainer and the clamp have the same material cross section. The edge clamps apply compressive loads in the plane of the reflector panel substrate which buckle the panels into conformance with the ribs. There are six reflector panels per module and three sets of half-aperture ribs to support each panel.

Once the panels are installed, they are an effective shear web and provide a high degree of stiffness to the module structure. Prior to panel installation, structure handling stiffness is provided by cross braces at each corner of the module; these are required only during the fabrication process.

The reflector panel is a thin glass laminate consisting of two silvered glass mirrors bonded to a steel substrate. Six of these reflector panels, each 8 ft long by 40 in. wide, are mounted to a single module. The backing sheet for the laminate is 0.7-mm thick galvanized carbon steel coated on both sides with an epoxy primer paint. The back side of the sheet has an additional coating of thermosetting polyester silicone paint. Low-iron, chemically tempered, thin glass sheets (0.9-mm thick) are bonded to the front side of the sheet with a thermoplastic pressure-sensitive acrylic adhesive. The panel is manufactured in the flat form, then is flexed and fastened into the parabolic shape during final assembly of the reflector module assembly.

2.2.2 Thermal Subsystem

The thermal subsystem consists of the receiver components and the flexhoses, as shown in figure 2-4. The receiver components include the receiver tubes, glazing tubes, support collars, vibration dampers, support rings, and seals. These components are factory assembled with self-aligning subassembly interfaces that require minimal field installation time.

There are two versions of the receiver: a fixed receiver for a module next to the drive and a common design for the other five modules in a drive string. The fixed receiver has a welded extension tube to bridge the gap across the drive unit. The fixed receiver is also fitted with a welded support ring in one location to prevent rotation of the entire thermal subsystem. It is secured near the drive allowing axial thermal expansion in either direction away from the drive.

The black-chrome plated carbon steel receiver tubes are 1.25-in. outside diameter by 0.083-in. wall thickness. The tube diameter was selected to minimize heat loss area while maximizing the reflected energy intercepted. The tube wall thickness was selected to minimize receiver sag to maintain a reasonable concentricity between it and the glazing tube. The plated receiver tube has an absorptivity of 0.955 and an emissivity of 0.24 to 0.28 at 300°C in the freshly plated, unaged condition. It can handle water at 232°C and 400 psi or heat transfer oil to 343°C where the maximum film temperature allowable is 371°C.

The receiver tubes are interconnected with standard swage-type tube fittings. The fittings are swaged and hydrostatically pressure-tested at the factory to minimize field assembly and checkout.

The Pyrex glazing tubes are 2.125-in. outside diameter by 0.090-in. wall thickness. The glazing tubes reduce convective heat losses from the

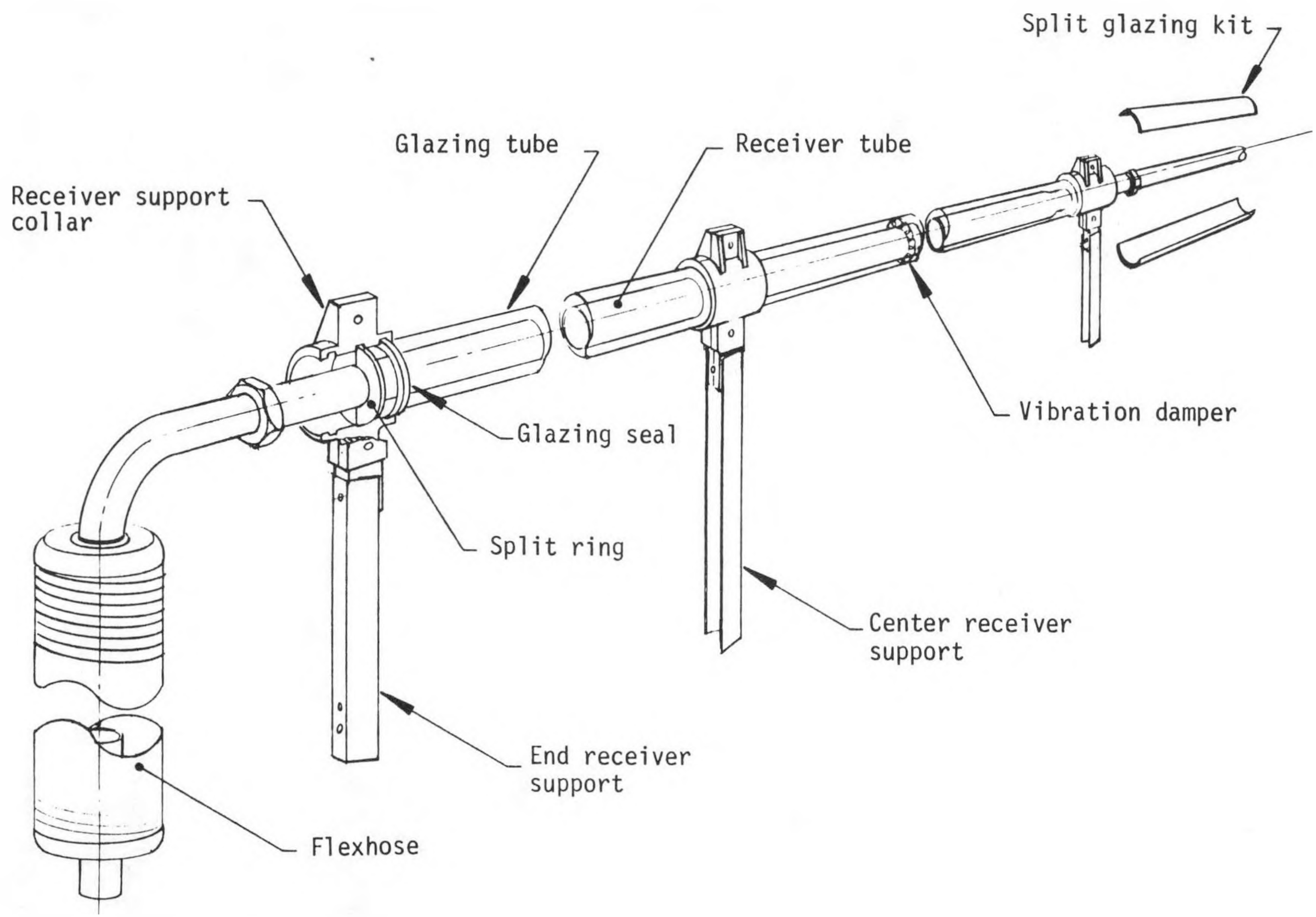

Figure 2-4. Thermal Subsystem

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receiver tube and protect the black chrome receiver tube from the environment. The diameter was selected to minimize convective losses through the annular air gap between the receiver and the glazing tube. The tubing has a transmissivity of 0.91.

The support collars are die-cast aluminum to achieve low unit cost in mass production. They support the glazing tubes and the split rings which in turn support and center the receiver tubes. Each collar is fitted with two standard silicone lip seals to hold the ends of the two glazing tubes in place and provide an environmental seal. The seal material is highly compliant to accommodate large glazing diameter manufacturing tolerances. The collars are subject to concentrated sunlight so they are electroless nickel-plated to provide a high-reflectivity surface. This minimizes the collar and seal temperatures. A single bolt holds each pair of collar halves to stamped, hot-dipped galvanized support struts. The struts are bolted by single bolts to keys welded to the torque tubes. The struts and support collers are both self-aligning, eliminating field adjustment of the receiver assemblies.

The split rings which support the receiver tubes are held in place by grooves in the support collar halves. The ring material is stainless steel to minimize heat loss and prevent corrosion. For the fixed receiver tube, the split rings are welded to the receiver tube to anchor the receiver to the collar at the drive unit.

The vibration dampers are coil springs wrapped around the receiver tube thereby preventing the receiver tube from striking and breaking the glazing tube during shipment. They are not removed after installation because their small size does not impact performance.

Once the receiver assemblies are installed, the receiver tubes at the intermodule interfaces and at the drive interface must be sealed from the environment. Between modules, environmental sealing is accomplished with split glazing kits consisting of two Pyrex glass half-cylinders which fit around the support collars and are held in place by two extension springs. Silicone seals are provided to seal environmentally the split glazing to the receiver collars. The use of the split glazing approach allows collection of sunlight at off-normal incident angles for an increase in intercepted reflected energy.

The receiver is insulated at the drive interface using fiberglass insulation with aluminum jacketing and sealant.

A flexhose is located at each end of the drive string. It carries high-temperature and high-pressure heat transfer fluids, while simultaneously accommodating axial thermal expansion of the receiver tubes and rotation of the collector. The flexhose consists of a flexible, corrugated stainless-steel hose, covered with a wire braid suitable for the internal pressure loads. The pressure hose is insulated with a fiberglass mat, and provided with an outer protective metal stripwound sheathing. This outer sheathing limits the bend radius of the flexhose assembly, which results in minimizing the flexhose stresses while providing a weather barrier. The flexhoses are anchored to support brackets bolted to the tops of the drive string end-post foundations. The fluid connection is made by welding a fitting to the hot-dip galvanized support bracket suitable for the flexhose and field interconnecting piping interfaces.

2.2.3 Drive Subsystem

The drive subsystem consists of a gearbox and motor, its support post, nondrive support posts, and pivots. The gearbox, motor, and drive post assembly and the nondrive support post assembled with a pivot bearing are shown in figure 2-5.

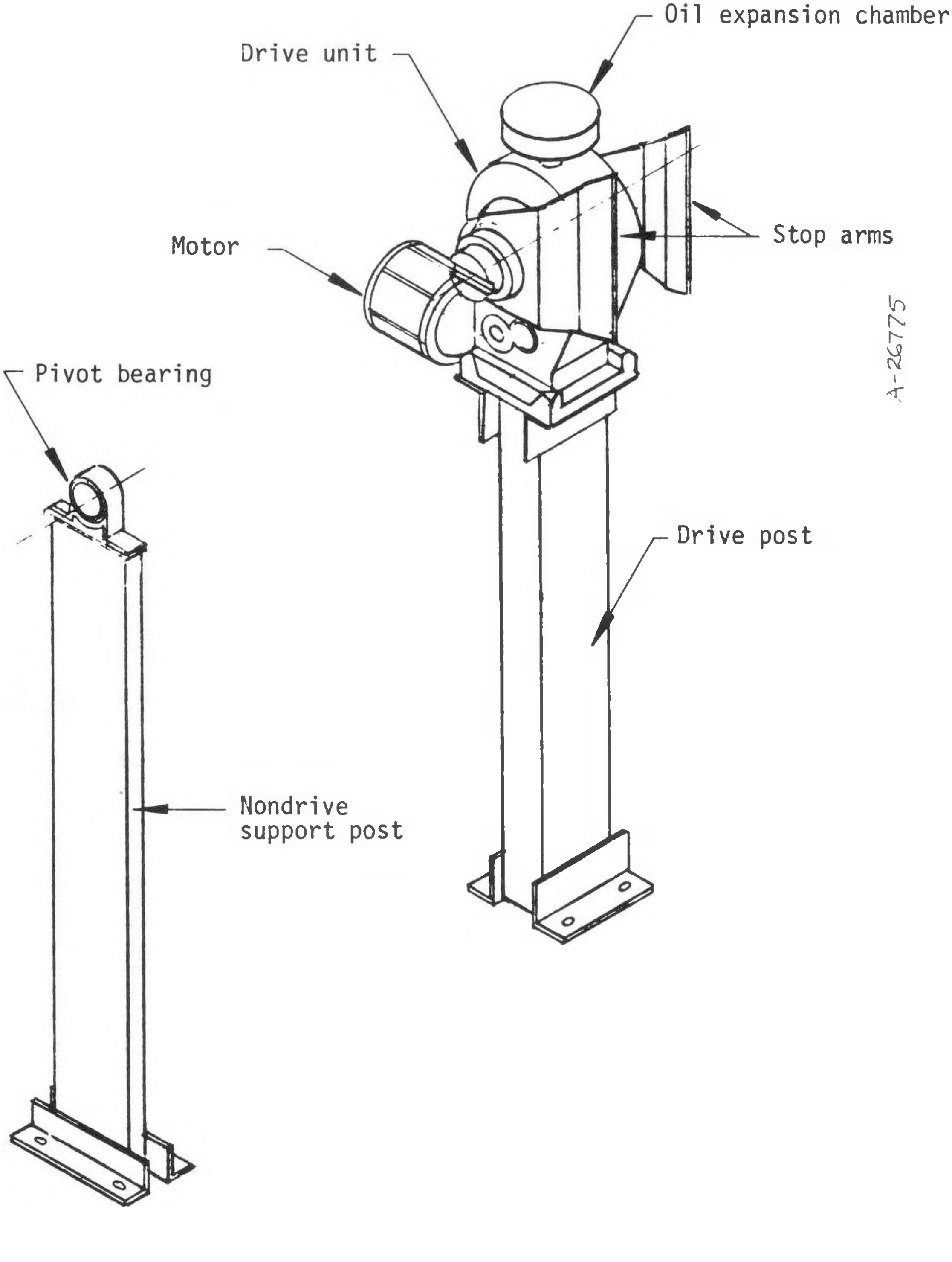

Figure 2-5. Drive Subsystem

The gearbox was custom-designed for this specific drive application. It incorporates a worm-gear speed reducer and a spur-gear double-speed reducer to provide an overall speed reduction of 1,000:1. A slip clutch is located between the spur- and worm-gear speed reducers to limit maximum gearset torque due to wind loading and provide braking. The clutch is factory preset to allow drive string tracking at wind speeds well above 25 mph. A pair of stop arms designed to resist 80-mph winds are attached to the gearbox output shafts. At the extremes of drive string rotation the arms contact hard stops that are integrally cast on the gearbox housing. An oil expansion chamber is fitted to the top of the gearbox housing. It contains a rolling diaphragm which seals the gearbox from the environment yet allows oil expansion during high ambient temperature operation.

The gearbox is driven by a permanent magnet ac stepper motor. This motor provides the extremely fast and accurate start and stop capability required for accurate sun tracking, yet has a low startup current requirement. The motor, having no brushes, requires little maintenance and can be stalled without overheating.

The drive support post is a 4-in. by 8-in. rectangular steel tube with a pair of angle brackets welded to each end for interfacing with the foundation and gearbox. The 8-in. side of the drive support post is oriented parallel to the drive string centerline to resist drag, torsional, and axial loads. The nondrive support post is similar, except for the 2-in. by 8-in. cross section and a pivot bearing assembly centrally located at its top. The 8-in. side of the nondrive support post is oriented perpendicular to the drive string centerline to resist drag forces. Both posts are bolted directly to their foundation footings thereby greatly reducing required material sizes by distributing the loadings over relatively large foundation areas.

The pivot bearing assembly consists of a 3-1/2-in. diameter nickel-plated steel pivot shaft, an injection-molded sleeve bearing, and a stamped steel housing. The bearing operates at low speed with a relatively high static load allowing use of a self-lubricating, reinforced plastic bearing material and a split housing. The pivot shaft has machined keyways that self-align during installation to the module pivot cranks eliminating the need for adjustments in the field.

2.3 SUBSYSTEM TRADE-OFF ANALYSES

Subsystem trade-off analyses were performed to define the guidelines and constraints for the modified collector design. Once the basic decision was made to develop the torque tube and rib steel structure with flex glass, the new design (including parts that had not been changed from the existing Model 3001 design) was analyzed to determine if all aspects were optimal. Of all the design details investigated there were four key areas for trade-off analyses that determined the basis for the improved Model 3011 design:

- Reflector module aperture width
- Lengths of reflector modules and drive string
- Type of drive unit
- Component environmental protective coating

Trade-off analyses for these design details are discussed in the following subsections.

2.3.1 Aperture Width

To determine reflector module aperture width, the details of material availability, shipping, collector costs, and installation costs were defined for aperture widths in the range of 7 to 8.5 ft. The key aspect of material availability is the flex glass panel length. The maximum length of flex glass readily available from producers is about 8 ft. This provides an aperture width of 7 ft based on the design goal of reflector panels consisting of one-piece mirrors bonded to one-piece substrates for rim-to-rim installation. Based on the assumption that truck shipment is the principal mode of transportation for factory-assembled collector modules, the maximum width of cargo is 8 ft and the maximum cargo height is 8.5 ft.

We determined that rigid steel, reuseable shipping containers packed with six modules each were optimum for shipping to field installations. Allowing for the container itself and clearances between the collector rim and the container, the collector aperture width is limited to 7 ft.

The total installed cost for drive strings of six for a typical industrial process heat installation is shown schematically in figure 2-6. In the figure, the total installed cost is the sum of collector costs, installation costs, and balance of system costs. There is a reasonably linear reduction in installation and balance of system costs between apertures of 7 and 8.5 ft because in this size range the cost driver is primarily the number of square feet of aperture that need be installed for a given energy output. The collector costs, however, rise sharply above aperture widths of about 7.5 ft because increasingly nonstandard material sizes must be used in fabrication. From figure 2-6 it appears that an aperture width of 7.5 ft is optimum when total installed cost is considered. However, primarily for the convenience of shipping but also because of the limitation on available flex glass panel length, an aperture width of 7 ft was selected for the Model 3011 collector.

2.3.2 Module and Drive String

Design trade-offs for module lengths in the 10 -to 40-ft range and drive string lengths in the 80- to 200-ft range were investigated. For the

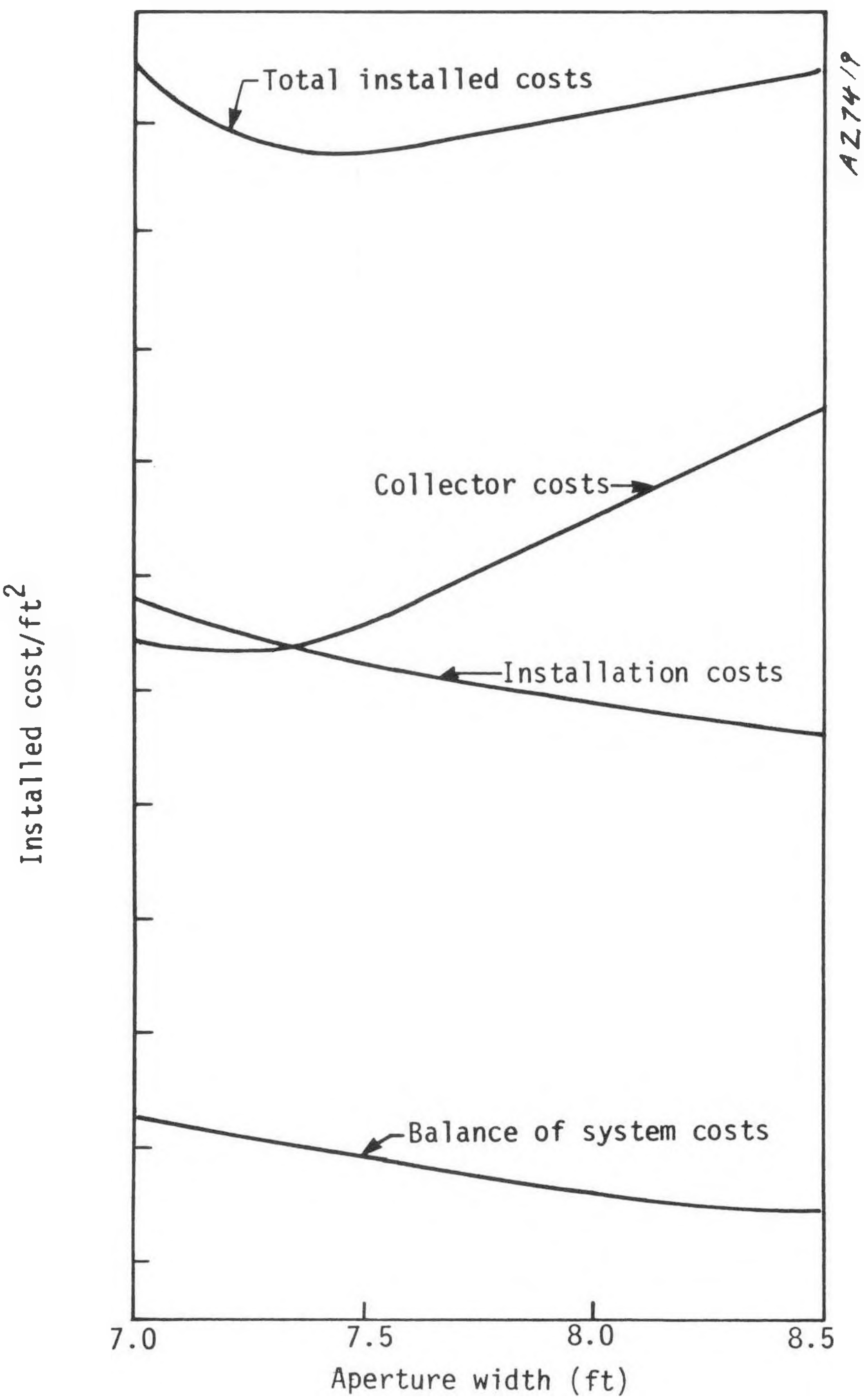

Figure 2-6. Total Installed Cost as a Function of Aperture Width

design trade offs, the same key design elements as for aperture width and new elements were defined:

- Material availability
- Handleability in the factory
- Shipping
- Collector costs
- Installation costs
- Cost penalties associated with installation of shorter-than-optimum drive string lengths due to site space constraints
- Structural constraints

These design elements are discussed in the following paragraphs.

Material availability, handleability in the factory, and shipping apply only to module length and indicate that a 20-ft module is optimum. We assumed that the module length would be either 10, 20, 30, or 40 ft to provide a straightforward approach for drive string lengths. Since the torque tube length most commonly available is about 20 ft and the torque tubes are the only module components where availability is related to length, a 20-ft long module is best. To minimize required floor space for mass production and for reasonably sized material handling equipment, a 20-ft module length is about the maximum that can be conveniently manuevered through an assembly line. With respect to shipping, containers for modules longer than 20 ft become unreasonably large. Also, since flatbed truck trailers are nominally 20, 40, or 45 ft long, it would not be efficient to ship 30-ft modules. Furthermore, shipping crates for 40-ft modules designed for sufficient rigidity to provide for proper handling are excessively heavy and expensive.

The trend of total installed cost for module lengths of 20 and 40 ft as a function of group lengths of 80 to 200 ft is shown in figure 2-7. These

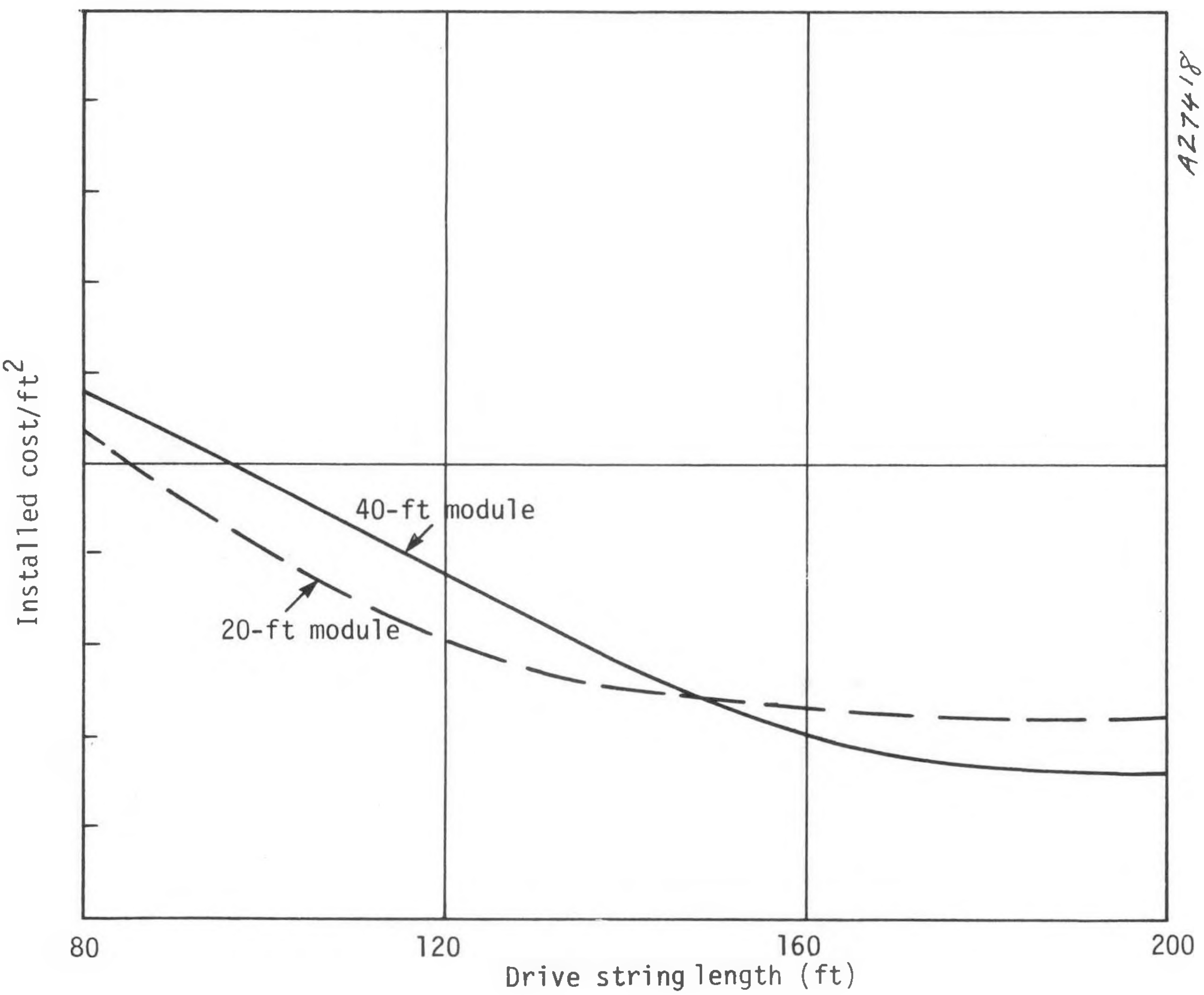

Figure 2-7. Installed Cost of 20- and 40-ft Modules Versus Drive String Length

trends were determined by estimation of the complete drive string cost, the field installation cost including shipping, electrical, piping, instrumentation and control, and the balance of system cost including site preparation and construction engineering costs. The use of five 40-ft modules to make a drive string 200 ft long is the lowest cost but results in an odd combination of three modules on one side of the drive and two on the other, a nonoptimum condition for the drive. By contrast, the drive string of six modules providing a 120-ft group length appears to be about the shortest practical configuration since costs for shorter strings rise quickly.

Through our system installation experience we have found that space constraints of individual sites often require use of drive strings shorter than our basic design. A cost penalty occurs whenever a drive string which has been optimally designed for a given length is installed with fewer collectors per string. These trends are shown schematically in figure 2-8 for 20-ft module drive strings of 120, 160, and 200 ft lengths. The dashed line is the same as the 20-ft module case of figure 2-7 and provides a basis for comparison. The cost penalty for installing optimal 120-ft strings as 80-ft strings is only about 1/3 of the penalty for 160-ft strings and about 1/6 of the penalty for 200-ft strings. From the standpoint of special site space constraints, use of the 120-ft drive string is by far the most cost-effective approach.

Structural constraints were investigated for module lengths to 40 ft. For lengths above 20 ft the torque tube and rib structure becomes increasingly inefficient. At 40 ft the torque tube must weigh more than twice the 20-ft torque tube in order to maintain equivalent stiffness. Also for a 40-ft module length a space frame structure involving numerous cross braces to maintain stiffness appears to be better than the torque tube and rib approach. Such an

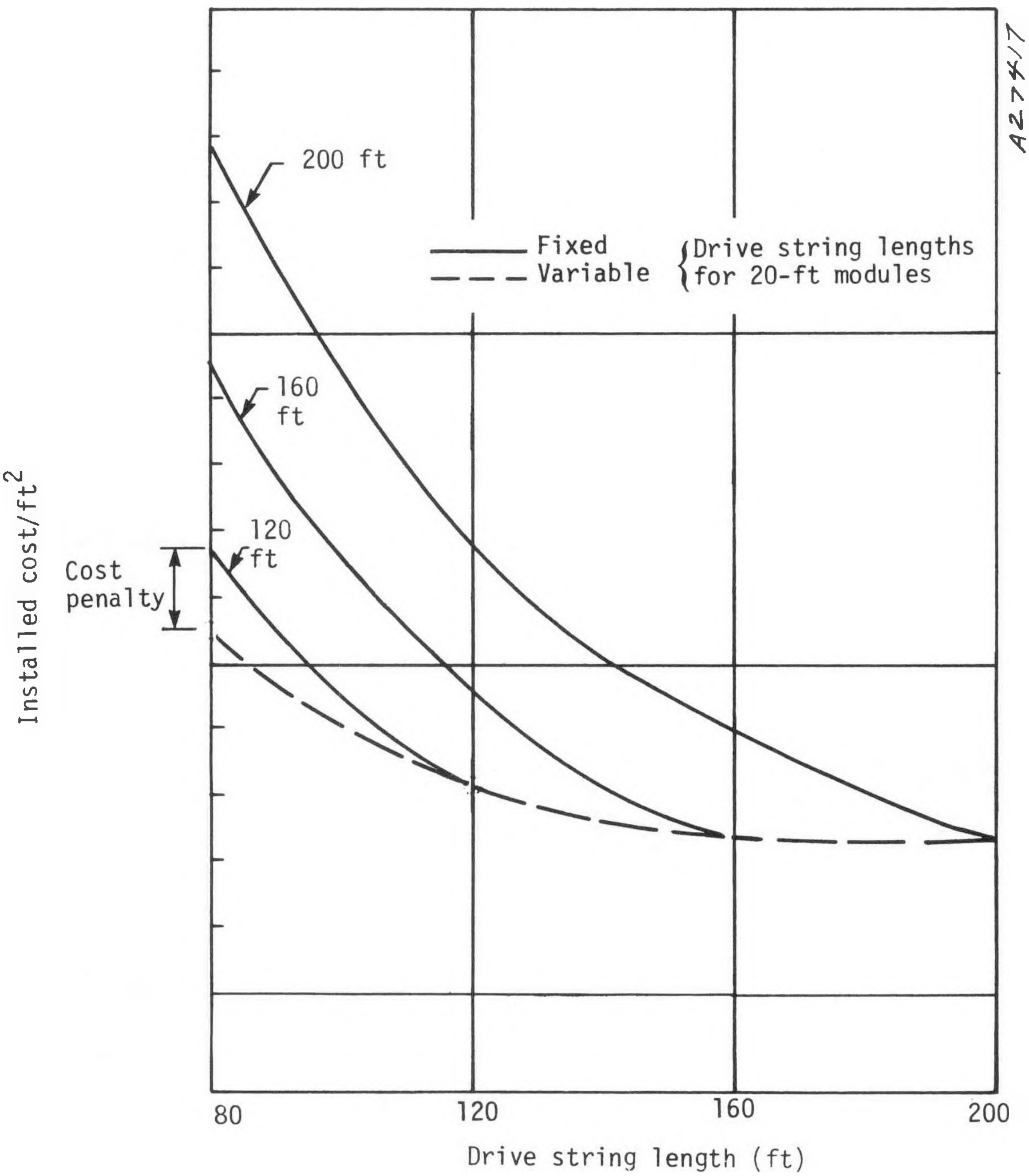

Figure 2-8. Cost Penalty for Installing Partial Length Drive Strings

alternate approach was outside the basic groundrules of the design being developed.

A drive string length of 120 ft consisting of six individual 20-ft long reflector modules arranged three on each side of a centrally located drive was selected for the Model 3011 collector based on the trade-offs discussed above.

2.3.3 Drive

The drive trade-off analysis was based on wind load data from wind tunnel tests supplied by Sandia that were conducted at Vought Corporation and at Colorado State University. The key factor in the drive design approach was the determination of a cost-effective method for the drive string to survive the 80-mph maximum wind criterion. One approach was to design a drive capable of rapidly stowing the drive string into a fixed and locked position during periods of high wind or simply holding the drive string in any fixed pitch orientation during these periods. A more cost-effective approach was adopted, whereby the drive string is allowed to feather or rotate to whatever pitch orientation the high wind may force upon it. Allowing the drive string to feather eliminates the need for a multispeed drive and allows use of a much smaller gear drive in conjunction with a wet slip clutch. The slip clutch provides sufficient dynamic braking to prevent the drive string from rapidly flipping from one stow position to the opposite stow position and causing impact damage.

In addition to the cost benefits discussed above, an electromechanical gearbox was selected for the improved design over other approaches such as a hydraulic drive system partly because of our satisfactory previous experiences with gearboxes and partly because the slip clutch drive approach eliminates the need for the multispeed capability provided by a hydraulic drive. The selection of a gearbox also aided the decision to design 120-ft drive strings since the next highest logical drive string length would be 160 ft, and the drive and drive motor required for this length are significantly larger and therefore more expensive.

2.3.4 Protective Coating

A protective coating analysis was made to determine the cost-effective approach to achieve a 20-yr service life for the collectors. The analysis included the cost of materials, labor, capital equipment, and touch-up maintenance for the following four coating approaches:

- Dry powder paint systems
- Wet paint systems
- Galvanization
- Weatherable steel

The galvanization approach included hot-dip galvanized components and pregalvanized sheet material. The weatherable steel considered was U.S. Steel's Cor-Ten.

The protective coating net present value, including touch-up cost as appropriate, is presented in table 2-2. A production rate of 1 million ft^2/yr was used for discount rates of 0, 5, and 10 percent for collector system lives of 10, 15, and 20 yr. Assuming a discount rate of 5 percent is most reasonable, the dry powder paint system is only \$0.04/ft^2 less than the galvanization approach for a system life of 20 yr. The galvanized protective coating approach was chosen for the collector design because the slight extra cost for galvanizing eliminated the potential problems of touch-up maintenance for the paint in future years.

Table 2-2. Protective Coating Net Present Value of First Cost With Touch-Up Cost ($\$/Ft^2$) at Production Rate of 1 Million Ft^2/Yr

Coating System	Discount Rate = 0%			Discount Rate = 5%			Discount Rate = 10%		
	[a]NPV at System Life of			[a]NPV at System Life of			[a]NPV at System Life of		
	10 yr	15 yr	20 yr	10 yr	15 yr	20 yr	10 yr	15 yr	20 yr
Wet paint	2.27	2.27	2.56	2.27	2.27	2.41	2.27	2.27	2.34
Dry powder paint	1.84	2.13	2.41	1.84	2.02	2.15	1.84	1.95	2.02
Galvanization	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19
Cor-Ten	2.25	2.25	2.54	2.25	2.25	2.39	2.25	2.25	2.32

[a]NPV = Net present value

SECTION 3

PROTOTYPE FABRICATION, INSTALLATION, AND TESTING

Upon completion of the improved collector design, prototype modules and subsystem components were fabricated, installed in the Acurex Solar Energy Test Facility, and tested for thermal and mechanical performance. The following subsections describe the fabrication and installation of components, summarize the test objectives and results, and discuss the testing approaches.

3.1 PROTOTYPE FABRICATION AND INSTALLATION

A total of seven modules with associated support subsystems were fabricated for installation in the Acurex Solar Energy Test Facility. A complete drive string of six modules was installed in an east-west orientation as shown in figure 1-1 (see section 1). The seventh module was installed in the Acurex two-axis-tracking test stand as shown in figure 3-1. All components were fabricated wherever possible with methods representative of mass production.

The module torque tube and rib assemblies were fabricated with precision alignment fixtures. Initially, torque tubes were installed individually in a welding fixture where prepunched rib flanges were located, clamped in place, and GMAW-welded. Next, the torque tubes were shipped to a vendor to be hot-dip galvanized. One torque tube was not galvanized due to schedule constraints and was therefore painted with electrostatically

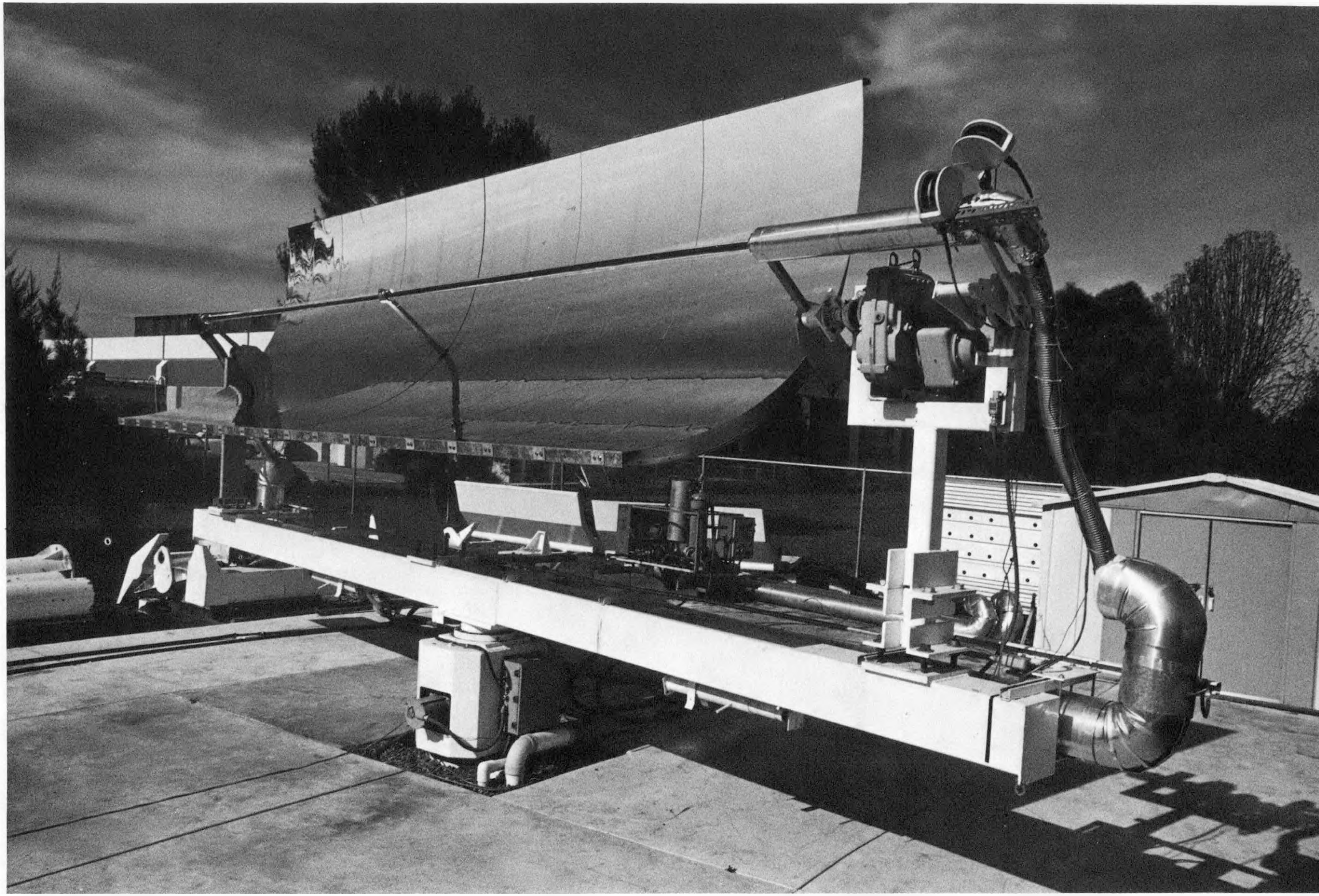

Figure 3-1. Acurex Two-Axis Test Stand

deposited polyester paint. All the galvanized tubes needed rework upon return from the plating shop. Many of the rib flanges were bent requiring straightening or, in some cases, replacement. This problem was due to shipping and handling damage. Also, the plating had lumps and drippings much like candle wax on the rib flanges. Such areas required hand grinding to ensure a parallel fit between ribs and rib flanges. Finally, the galvanized torque tubes were mounted individually in an alignment fixture for installation of ribs.

Module ribs were fabricated from three basic components: contoured ribs, stiffeners, and edge retainer end brackets. The ribs were machined to the parabolic shape using an N/C milling machine. In production this approach is unfeasible and would be replaced by use of a hardened progressive die set. The milling machine approach, however, saved months of lead time to prepare tooling. Rib stiffeners were stretch-formed to an approximate parabolic shape then electrogalvanized. Rivet holes were center-punched on one stiffener using a template, then two stiffeners were clamped, one to a side, to the rib. Next, the rib and stiffener assemblies were match-drilled and pop-riveted together. Finally, edge retainer end brackets were similarly match-drilled and pop-riveted to the rib assembly ends.

Completed rib assemblies were clamped to torque tube rib flanges in the alignment fixture. The fixture was also used to lock the tips of the ribs in the parabolic shape. While held in the fixture, the ribs were match-drilled to the torque tube rib flanges by using the prepunched rib flange holes as guides. Nine 3/16-in. diameter pop rivets were installed to hold each rib in place. Flat stiffener straps were next pop-riveted diagonally across the backs of three ribs at each of the four corners of the modules.

Upon completion of rib installation, the semifinished module assembly was moved from the rib alignment fixture to an assembly and transport cart. The rib ends were then tied together with edge retainer brackets. With the module held upright six glass rim-to-rim reflector panels were installed. The panel installation was accomplished by loosely aligning the panels by hand against the ribs then drawing them tightly to the parabolic shape by means of galvanized steel edge clamps. We found that the edge retainer end brackets pivoted on the ribs preventing proper rib-to-panel conformance. This problem was corrected by lengthening the end brackets and doubling the number of retaining pop rivets thereby eliminating the pivoting effect. Completed modules were towed by automobile using the transport cart to the nearby Acurex Solar Energy Test Facility for installation.

The drive string of six modules was installed on poured-in-place concrete pier foundations suitable for local soil conditions. The existing design Morse Chain gearbox was installed with the drive string before the new design gearbox was available. The custom-designed mass producible gearbox was retrofitted after thermal testing was partially completed by disassembling the drive string and remounting the support posts to locations approximately 1 ft closer to the drive post. The drive string foundations were installed with an extra set of anchor bolts to accommodate this planned change. The foundations were, therefore, not optimized for actual field installations.

A single module was installed on an existing two-axis tracking test fixture. Only minor mounting modifications were required to accommodate the new module. All existing electronic tracking, control, and fluid loop connections were directly applicable to the new module.

Posts for the drive string of six modules were machined from standard hot-rolled steel shapes. The mounting flanges were GMAW-welded to the box tubes with the aid of simple fixtures. The steel split bearing housings for the nondrive support posts were stamped from bar stock then machined. The bearing bottom halfs were then GMAW-welded to the posts. The split bearing inserts were injection-molded in a custom-built single-cavity mold. All posts and the top bearing cap were hot-dip galvanized, then installed in the test facility.

Pivots for module-to-module connections were machined from steel bar and nickel-plated. Special pivots were built to temporarily adapt the Morse gearbox to the drive string. The special pivots were deleted later upon installation of the custom drive which provided integral pivot connections.

Receiver tubes were fabricated from 1-1/4-in. diameter by 10-ft long resistance-welded carbon steel tubing. Using conventional swaging dies, half of the tubes were swaged to 1-in. diameter at one end. A single ferrule swage-type 1-in. diameter tube fitting was GTAW-welded to one end of the other half of the tubes. All tubes were then specially packaged and shipped to a vendor for black chrome plating. A modified Harshaw process was used for plating whereby extra rinse steps were added to enhance high-temperature stability. Upon return to Acurex, pairs of receiver tubes were GTAW-welded together providing 20-ft long assemblies with one swaged end and one tube fitting end. A short length of 1-1/4-in. diameter unplated tube and one receiver tube split support ring were GTAW-welded to one of the tubes. This tube became the fixed receiver tube for thermal expansion control. After welding, each assembly was hydrostatically tested at 650 psi, then installed in the drive string.

Receiver glazing was fabricated from 4-ft and 2-ft lengths of Pyrex tubing fused to form 10-ft lengths because unfused tubes had an unacceptably long lead time for procurement. This fabrication method resulted in two slight fusing bands about 1/2-in. wide on each glazing tube.

Receiver supports were sand-cast of aluminum and nickel-plated to increase reflectance. In production the supports will be die cast. Sand casting was chosen for prototyping to avoid die making costs and a long lead time delivery.

The stripwound flexhoses were purchased as complete insulated assemblies, hydrostatically tested by the vendor, and fitted with 1-in. single ferrule swage-type tube nuts.

The drive and nondrive posts were installed and aligned on the foundations using conventional surveying techniques. The original plan was to add shims between the foundation tops and the bottoms of the posts. Adding shims proved to be difficult since a 1/8-in. change in shim thickness at a single anchor bolt changed the pivot centerline location for that post by as much as 1-in. We concluded that either the posts needed to be double-nutted onto the anchor bolts then grouted or the foundations needed to be a great deal more accurately poured and finished.

A spreader bar and cable arrangement was used to hoist the modules in place. A forklift was used for lifting because of equipment availability. Field installations will use a telescoping boom crane. The modules were initially installed with the aperature downward. A downward module orientation required the installation crew to jockey the modules into position so the pivot crank key would align with the pivot. Later, when the custom-designed gearbox was retrofitted, the modules were reinstalled with the reflector upward. This approach was an improvement since the crank keys immediately aligned with the pivot keyways and much less time was required for adjustments. Extra care was required, however, because personnel were sometimes exposed to concentrated sunlight and the reflector panels were exposed to such hazards as dropped wrenches.

The receiver assemblies proved very easy to install since no adjustments were required for alignment. Receiver tubes were easily shifted axially by a single worker for engagement and makeup of the tube fittings. Upon completion of receiver installation the split glazing kits were fitted at each intermodule interface and the receiver was insulated at the drive.

Finally, the entire drive string and associated flow loop piping were hydrostatically pressure tested at 650 psi. Upon completion of installation, testing began for both the single module and the six-module drive string.

3.2 TEST OBJECTIVES

A test program was conducted for the improved Model 3011 prototype collector to measure both thermal and mechanical performance. A complete drive string of six modules was mounted in an east-west orientation and a single module was fitted to a two-axis tracking test stand. The testing was conducted at the Acurex Solar Energy Test Facility in Mountain View, California. The modules were arranged in the available space in the test facility to provide the maximum opportunity for testing at direct normal conditions. Two separate test programs were run, each with both water and Therminol 66 as heat transfer fluids.

The overall objectives of the test programs for the improved Model 3011 prototype collector were:

- Determine the energy conversion efficiency over the collector temperature operating range for water and Therminol 66
- Verify proper mechanical fit and function

- Verify acceptability of thermal expansion allowances
- Determine fluid pressure drop characteristics
- Establish product lifetime through accelerated cycling

3.3 TEST RESULTS

The test objectives were achieved by developing and executing a test matrix for both the six-module drive string and the single module. The drive string test matrix is presented in table 3-1; the single module test matrix in table 3-2. The following subsections describe the test results using these tables for outlines.

3.3.1 Thermal Performance: Six-Module String

The near normal energy converson efficiency (test 6-1, table 3-1) for the drive string of six modules is presented in figure 3-2. Table 3-3 lists the plotted data points. The tests were run with insolation levels between 762 and 960 W/m^2. Each data point consists of the average of 10 data scans taken over a 5-min period at 30-sec intervals. Using Therminol 66 as the working fluid, data points were taken at ΔT values from 121° to 305°C.

For the seven data points shown, a second-order polynomial was generated with efficiency as the dependent variable and ΔT and ΔT^2 as the independent variables. A least-squares multiple linear regression was used on an in-house computer to generate the equation. This curve fit indicates an optical efficency of greater than 80 percent. The flow loop for the test was operated with water at its lowest possible differential temperature which verified that the optical efficiency was at least 79.7 percent (test 05, table 3-3).

Table 3-1. Test Matrix -- Six-Module Drive String

Number	Test	Fluid/ Temperature Range (°C)	Purpose
6-1	Near normal energy conversion efficiency	Water/ ambient; oil/100° to 340°C	Measure the energy conversion efficiency of the drive string as a function of temperature for water and heat transfer oil at $\Theta \approx 0$
6-2	Incident angle modifier determinationn	Water/ ambient	Measure energy conversion efficiency as a function of incident angle
6-3	Receiver heat loss	Oil/100° to 300°C	Measure receiver heat loss as a function of fluid temperature
6-4	Response time determination	Water/ ambient	Establish length of test periods for thermal testing
6-5	Receiver fluid pressure drop	Water/ ambient; oil/100° to 340°C	Measure the pressure drop of the fluid across the drive string including flexhoses
6-6	Thermal and mechanical cycling	Oil/100° to 340°C	Establish baseline thermal and mechanical product lifetimes
6-7	Receiver thermal expansion	Oil/340°C	Verify proper receiver expansion
6-8	Mechanical fit and function	--	Verify proper component assembly and operation

Table 3-2. Test Matrix -- Single Module

Number	Test	Fluid/ Temperature Range (°C)	Purpose
1-1	Normal incident energy conversion efficiency	Water/ ambient; oil/100° to 300°C	Measure the energy conversion efficiency of a single module as a function of temperature for water and heat transfer oil at $\Theta \approx 0$
1-2	Incident angle modifier determination	Water/ ambient	Measure energy conversion efficiency as a function of incident angle
1-3	Receiver heat loss	Oil/100° to 200°C	Measure receiver heat loss as a function of fluid temperature
1-4	Response time determination	Water/ ambient	Establish length of test periods for thermal testing
1-5	Optical efficiency	Water/ ambient	Determine the optical efficiency wherein $\Delta T/I \approx 0$

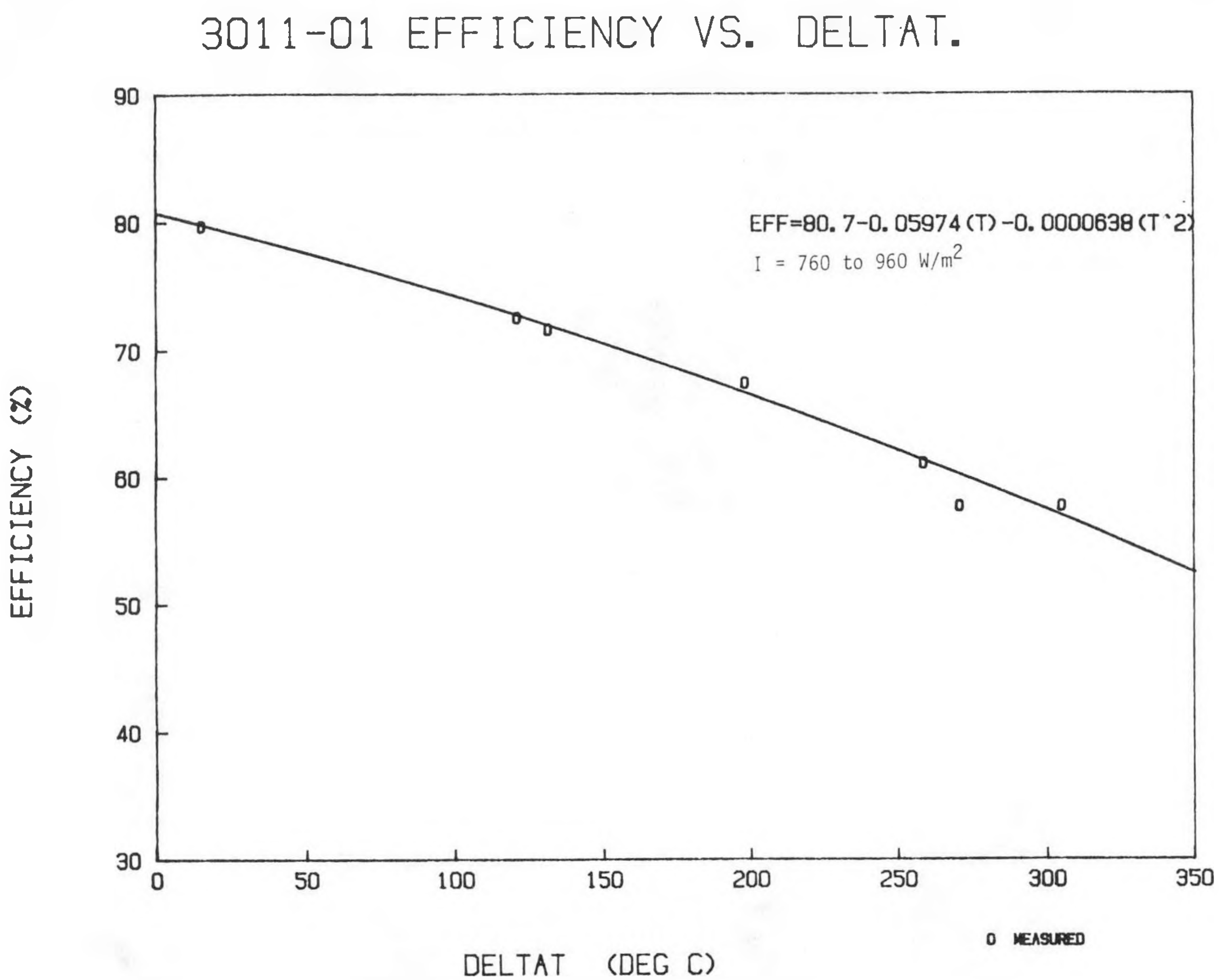

Figure 3-2. Preliminary Acurex Model 3011 Near Normal Thermal Performance for a Drive String of Six Modules

Table 3-3. Preliminary Acurex Model 3011 Near Normal Thermal Performance for a Drive String of Six Modules

Test Number	Energy Conversion Efficiency η_o (percent)	Fluid Parameter $\Delta T/I$ (°C-m^2/W)	Insolation I (W/m^2)	Differential Temperature ΔT		Working Fluid
				(°C)	(°F)	
05	79.7	0.016	953.6	15.3	27.5	Water
3	72.5	0.126	960.1	121.0	217.8	Therminol 66
4	67.4	0.211	938.9	198.1	356.6	Therminol 66
5	57.7	0.355	762.4	270.7	487.3	Therminol 66
13	61.1	0.286	904.0	258.6	465.5	Therminol 66
14	57.7	0.329	927.5	305.1	549.2	Therminol 66
15	71.6	0.148	888.2	131.4	236.5	Therminol 66

Note: Each test consists of the average of 10 data scans taken over a 5-min period at 30-sec intervals.

The incident angle modifier (test 6-2, table 3-1) for the drive string was derived from the data presented in figure 3-3. For this all-day test both insolation and efficiency were determined for the drive string every 6 min from 11:00 a.m. until about 4:00 p.m. Pacific Standard Time on January 6, 1982. The incident angle corresponding to the time of day is also shown on the plot. The angle was calculated from the following equation:

$$\cos \Theta = (1 - \cos^2 \delta \sin^2 H)^{1/2}$$

where δ is approximated by

$$\delta = 23.45 \sin \left(360 \frac{284+n}{365} \right)$$

and

$$H = 15° (12-\tau)$$

The test was run with city water as the fluid which provided a $\Delta T/I$ factor ranging from 0.009 to 0.016. When $\Delta T/I$ is nearly zero the measured efficiency is approximately equal to the optical efficiency of the drive string. The incident angle modifier, K, may, therefore, be calculated from the following equation:

$$K = \frac{\eta_\Theta}{\eta_o E}$$

The quantities η_Θ and η_o were directly measured and E was calculated from:

$$E = 1 - \frac{f}{L} \tan \Theta \left(1 - \frac{w^2}{48f^2} \right)$$

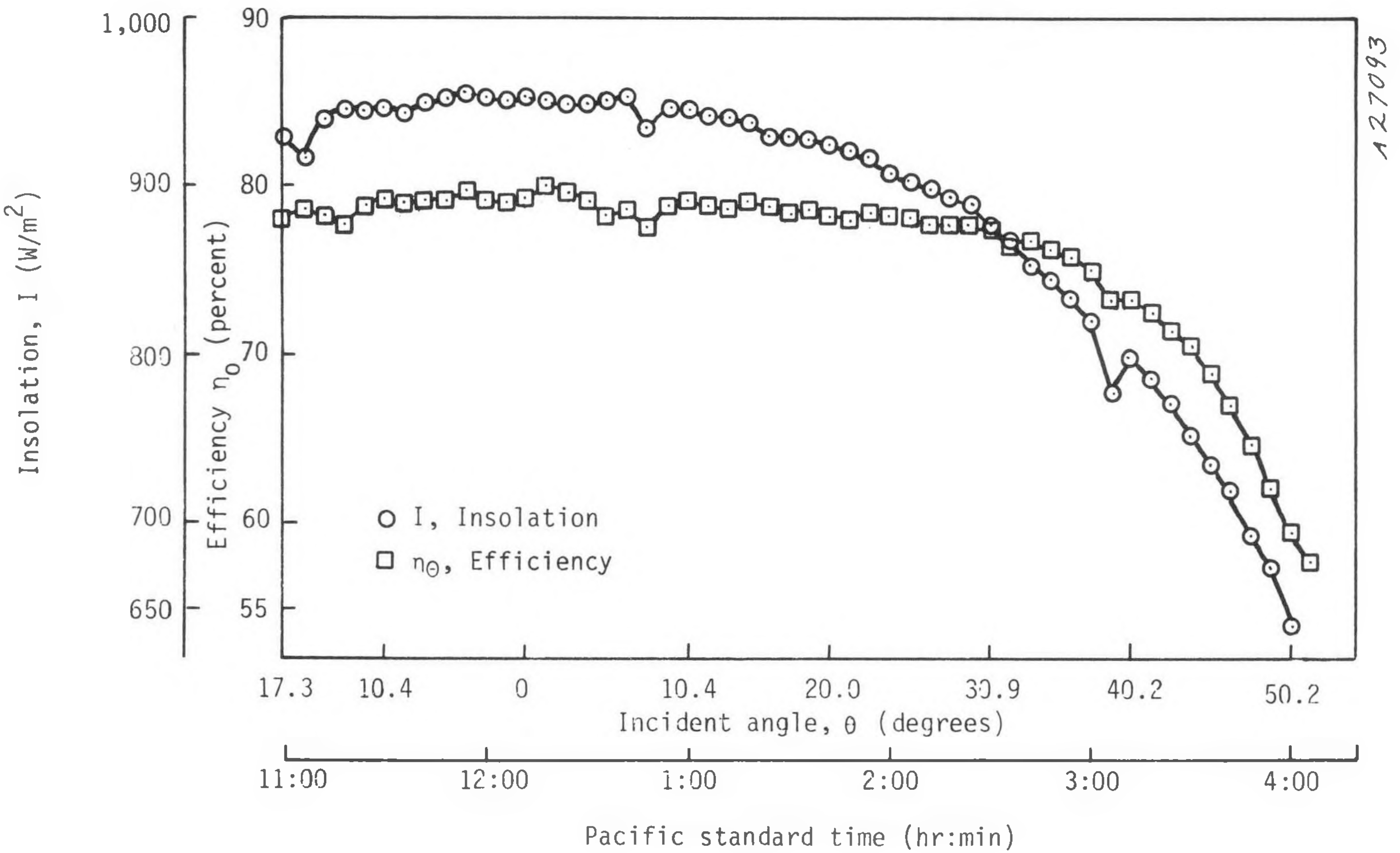

Figure 3-3. All Day Insolation and Efficiency for Six-Module Drive String

where

$$\Theta < 80°$$

Assuming f = 21 in., w = 7 ft, and L = 20 ft for the collectors, the equation becomes:

$$E = 1 - 0.1167 \tan \Theta$$

for incident angles not exceeding 80°.

The incident angle modifier was calculated for selected incident angles as shown in table 3-4. The efficiency shown was obtained from the plotted data presented in figure 3-3. The incident angle modifier is unity until the incident angle is over 40°.

The receiver heat loss for the drive string (test 6-3, table 3-1) for a 10-gpm Therminol 66 flowrate is presented in figure 3-4. The string was positioned to face the northern horizon thereby completely shading the receiver from the sun. The heat loss is presented as energy loss per unit area as a function of the difference between average bulk receiver fluid temperature and ambient temperature. The differential temperature capability of the test facility was limited to about 200°C for the drive string because of the available fluid heater power. A differential temperature of nearly 300°C was achieved for similar tests performed for the single module (subsection 3.3.2, below) because there was less overall heat loss. For this reason and for comparison, the curve fit shown in figure 3-4 was generated for the single module receiver heat loss data. The drive string heat loss data closely agree with the single module heat loss data curve fit.

Table 3-4. Incident Angle Modifier for Six-Module Drive String, Test 05, January 6, 1982

Test Time	Efficiency η_Θ (percent)	Incident Angle Θ (degrees)	Geometric End Loss E (-)	Incident Angle Modifier K (-)
12:12	79.3[a]	0.7	0.999	1.0
1:00	79.2	10.4	0.979	1.0
1:42	78.4	20.0	0.957	1.0
2:30	77.5	30.9	0.930	1.0
3:12	73.4	40.2	0.901	1.0
4:00	59.5	50.2	0.860	0.9

[a]Assumed optical efficiency for $\Theta = 0$.

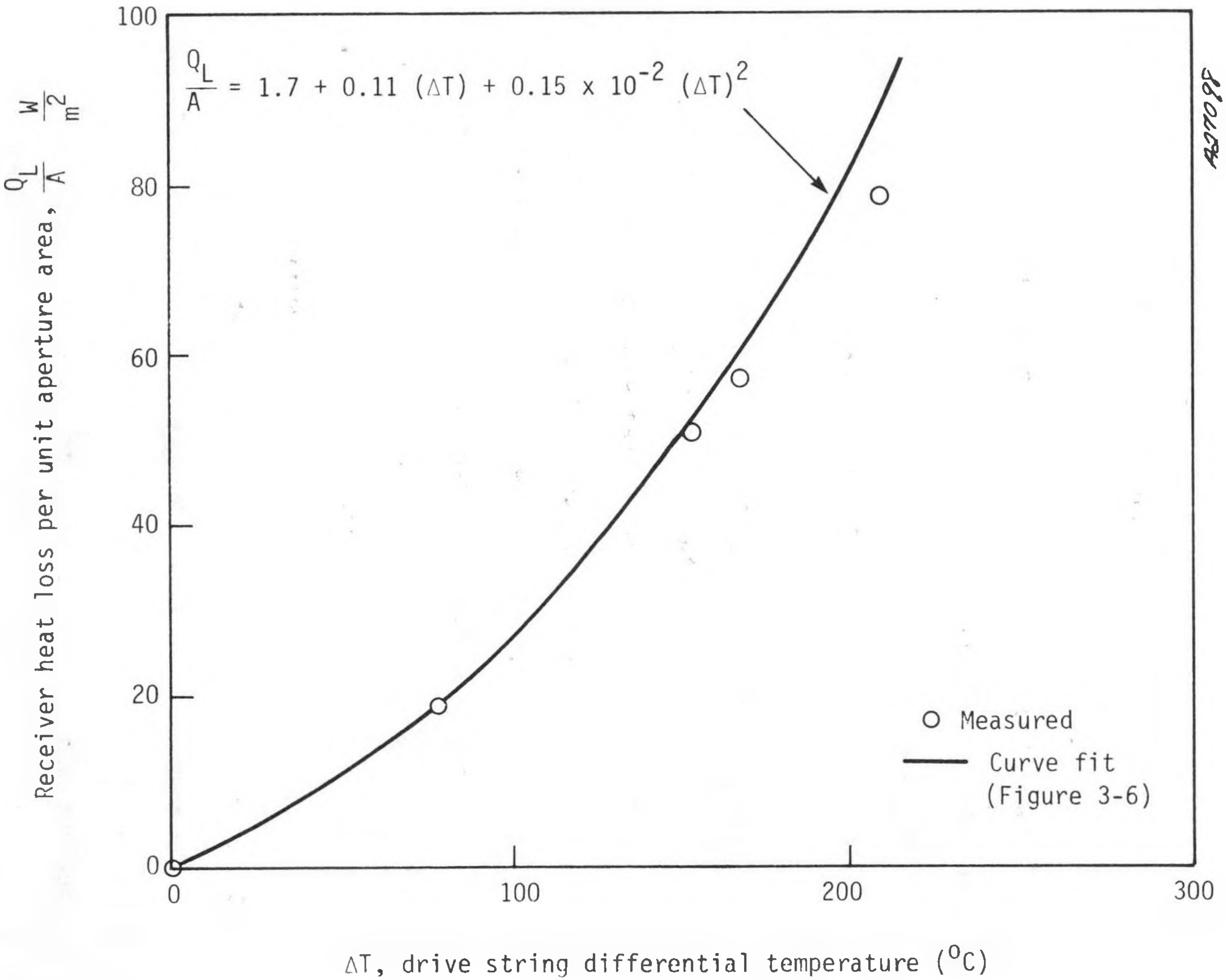

Figure 3-4. Drive String Receiver Heat Loss

The drive string thermal response time (test 6-4, table 3-1) with water is shown in figure 3-5. The string was operated until steady state was achieved, then a step change in insolation was made by rapidly desteering. The response time was assumed to be the time required for the outlet temperature to reach 90 percent of its final value. The measured response time was about 1 min. It was assumed that 5-min test data measurement periods, or five times the response time, would be sufficient to achieve steady-state conditions for efficiency measurements.

3.3.2 Thermal Performance: Single Module

Measurement of the normal incident energy conversion efficiency (test 1-1, table 3-2) was attempted for a single collector on the two-axis tracking test fixture. A satisfactory steady-state condition was not achieved, however, with high-temperature oil testing. Inlet temperature excursions of 1°C caused the efficiency to change by as much as 10 percent. Because of this sensitivity, the higher temperature two-axis test results were disregarded in favor of the drive string results reported herein.

The incident angle modifier (test 1-2, table 3-2) for the single module was determinded by the same method as the drive string. The energy conversion efficiency was measured at selected incident angles while the $\Delta T/I$ factor was maintained near zero. The resulting incident angle modifier as a function of incident angle is presented in table 3-5. Note that the incident angle modifiers for the single module and drive string agree closely up to about incident angles of 45°.

The receiver heat loss for a single module (test 1-3, table 3-2) is shown in figure 3-6 as a function of drive string differential temperature

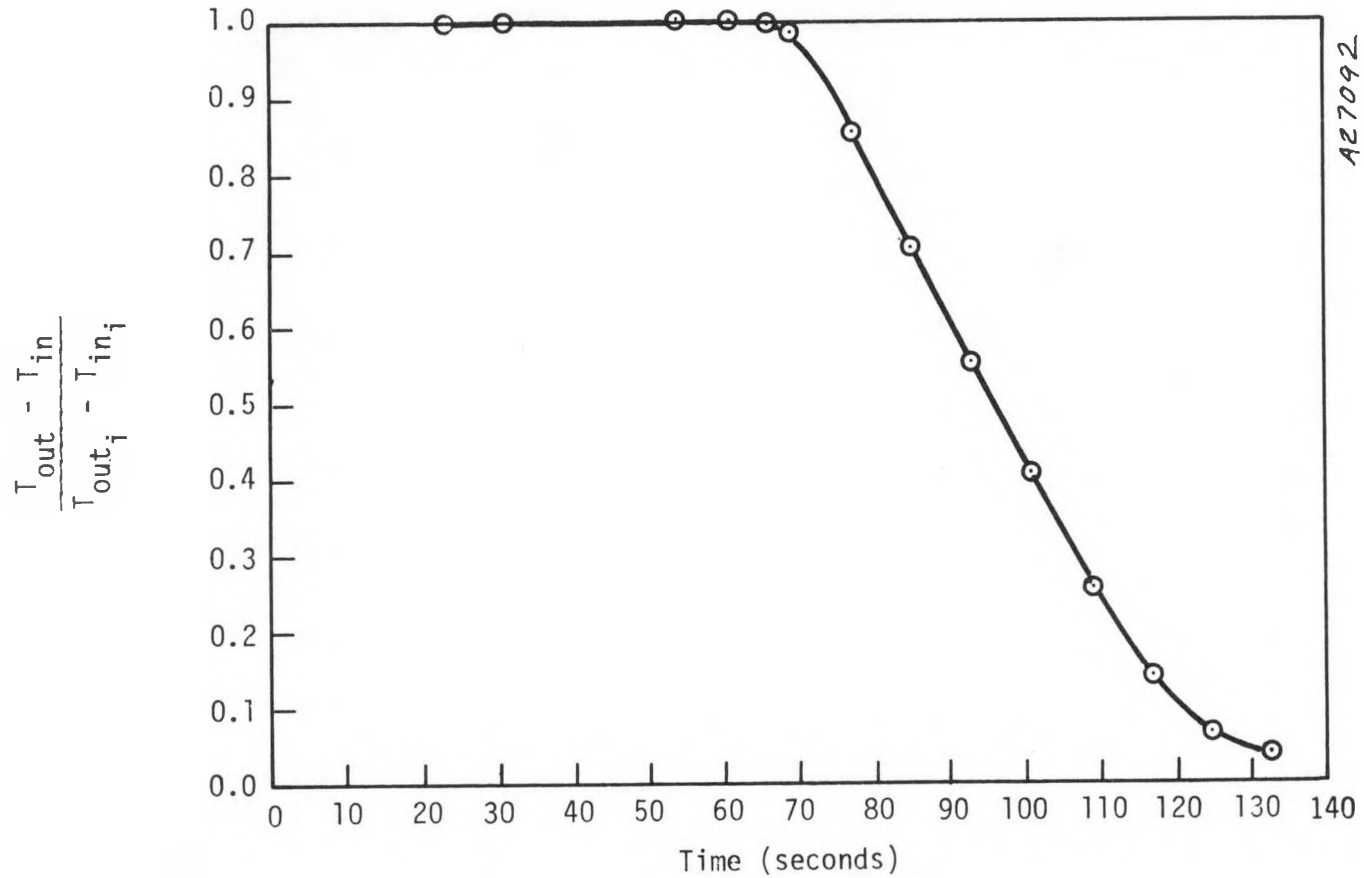

Figure 3-5. Drive String Thermal Response Time

Table 3-5. Single Module Incident Angle Modifier

Incident Angle Θ (degree)	Incident Angle Modifier K (-)
0	1.0
10	1.0
15	1.0
30	1.0
45	0.9
60	0.6

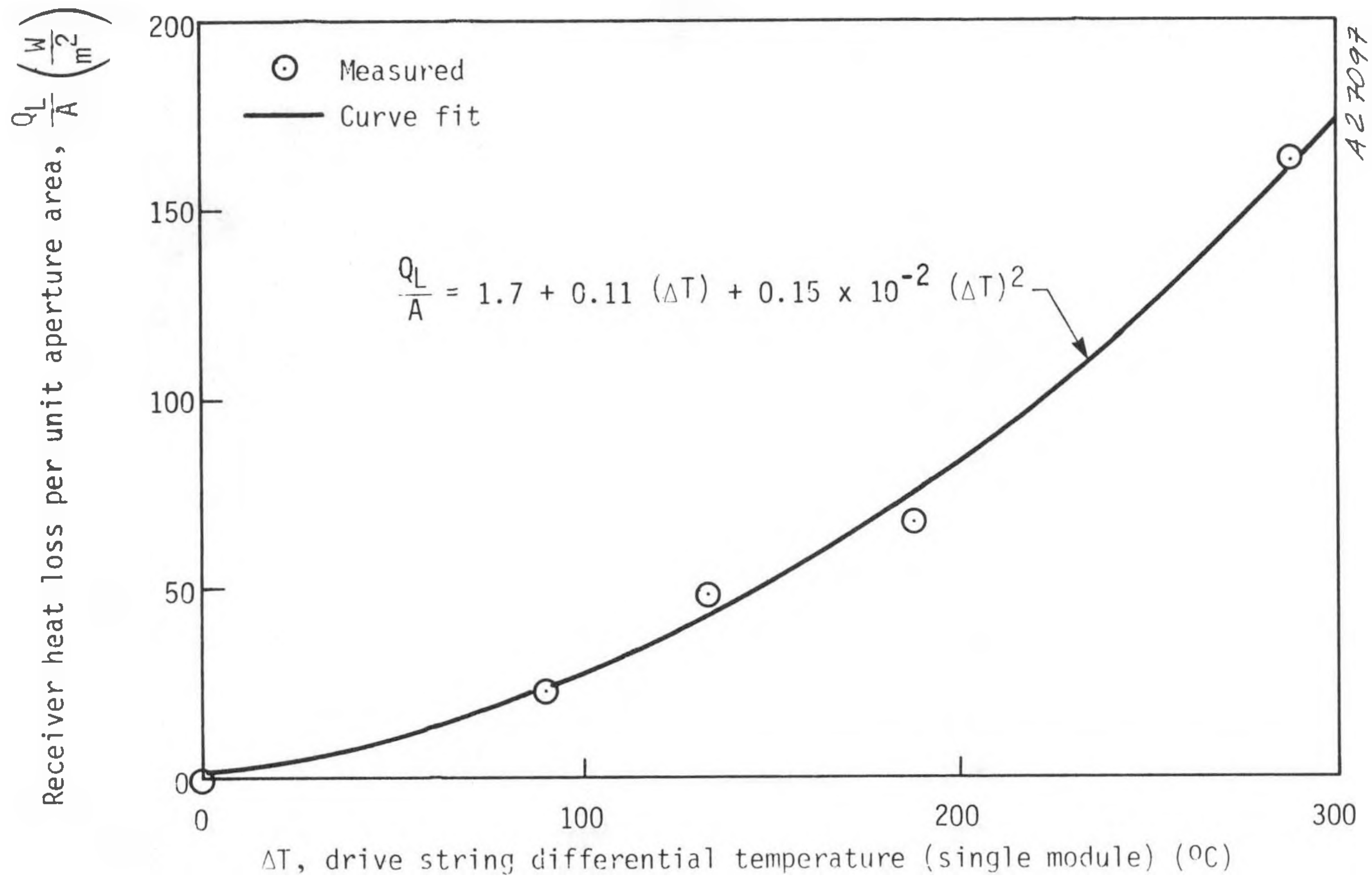

Figure 3-6. Single Module Receiver Heat Loss

minus the ambient temperature. The method of testing was the same as the drive string. The curve fit was generated in-house by a least-squares multiple linear regression program for differential temperature data from less than 100°C to nearly 300°C.

The thermal response time for a single module (test 1-4, table 3-2) with water is shown in figure 3-7. The testing approach and results were identical to the drive string except the measured response time was about 35 sec. Again, 5 min test data measurement periods, or five times response time, were used for testing.

The optical efficiency (test 1-5, table 3-2) was measured for a single module with water. Two tests were run with measured optical efficiencies of 78.1 and 78.4 percent. Cool city water was pumped through the system in an open loop mode to provide a near zero value for the $\Delta T/I$ factor for the efficiency equation. This approach was the same as for similar drive string tests.

3.3.3 Pressure Drop and Accelerated Lifetime Tests

The fluid pressure drop (test 6-5, table 3-1) across the receiver and flexhoses was measured for the drive string using water and Therminol 66. The Therminol 66 pressure drop results are presented in figure 3-8 for flowrates to 20 gpm for approximately 100°, 200°, and 300°C. The temperatures indicated were average bulk fluid temperatures occurring with the drive string stowed and all energy input from the test facility fluid heater.

Rapid thermal and mechanical cycling tests (test 6-6, table 3-1) were run to simulate lifetime testing for the drive string. Accelerated mechanical cycling was achieved by replacing the standard drive motor with a special high speed motor. This motor drove the string from south horizon to inverted north stow and back in approximately 1 min. In this manner, mechanical cycling

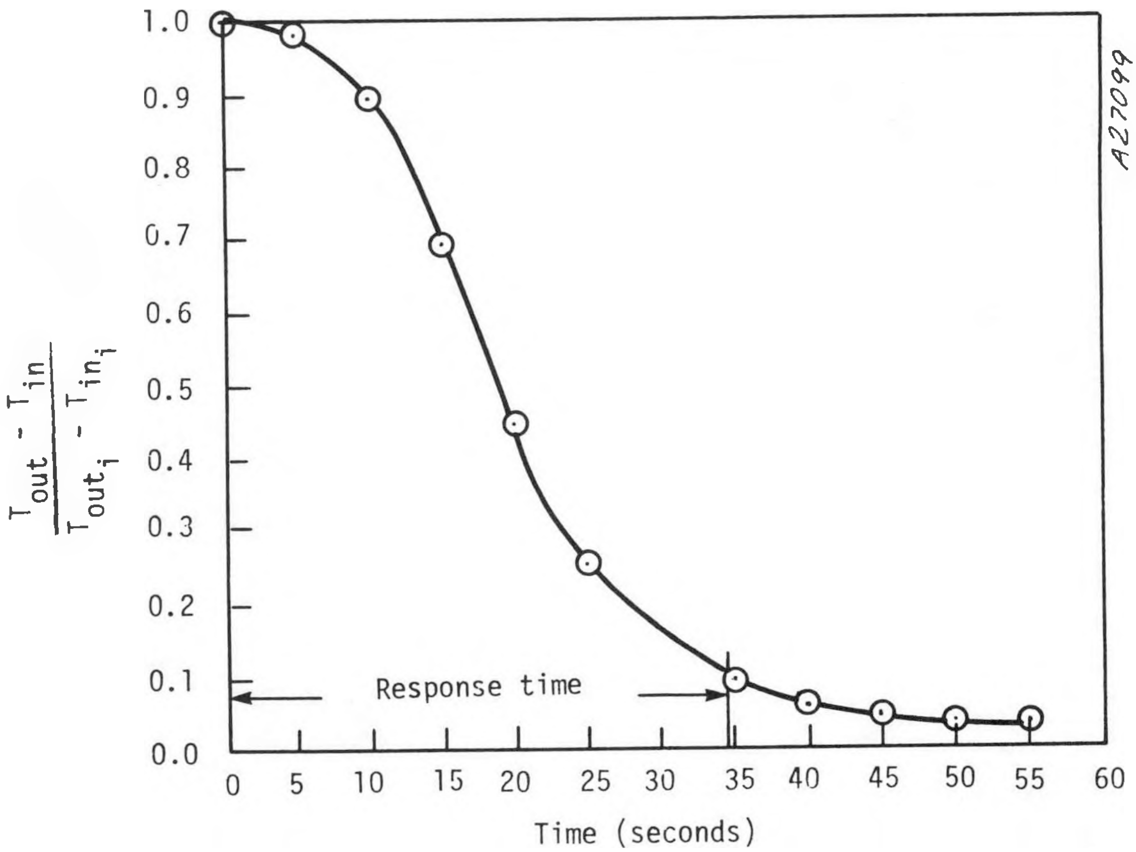

Figure 3-7. Single Module Response Time

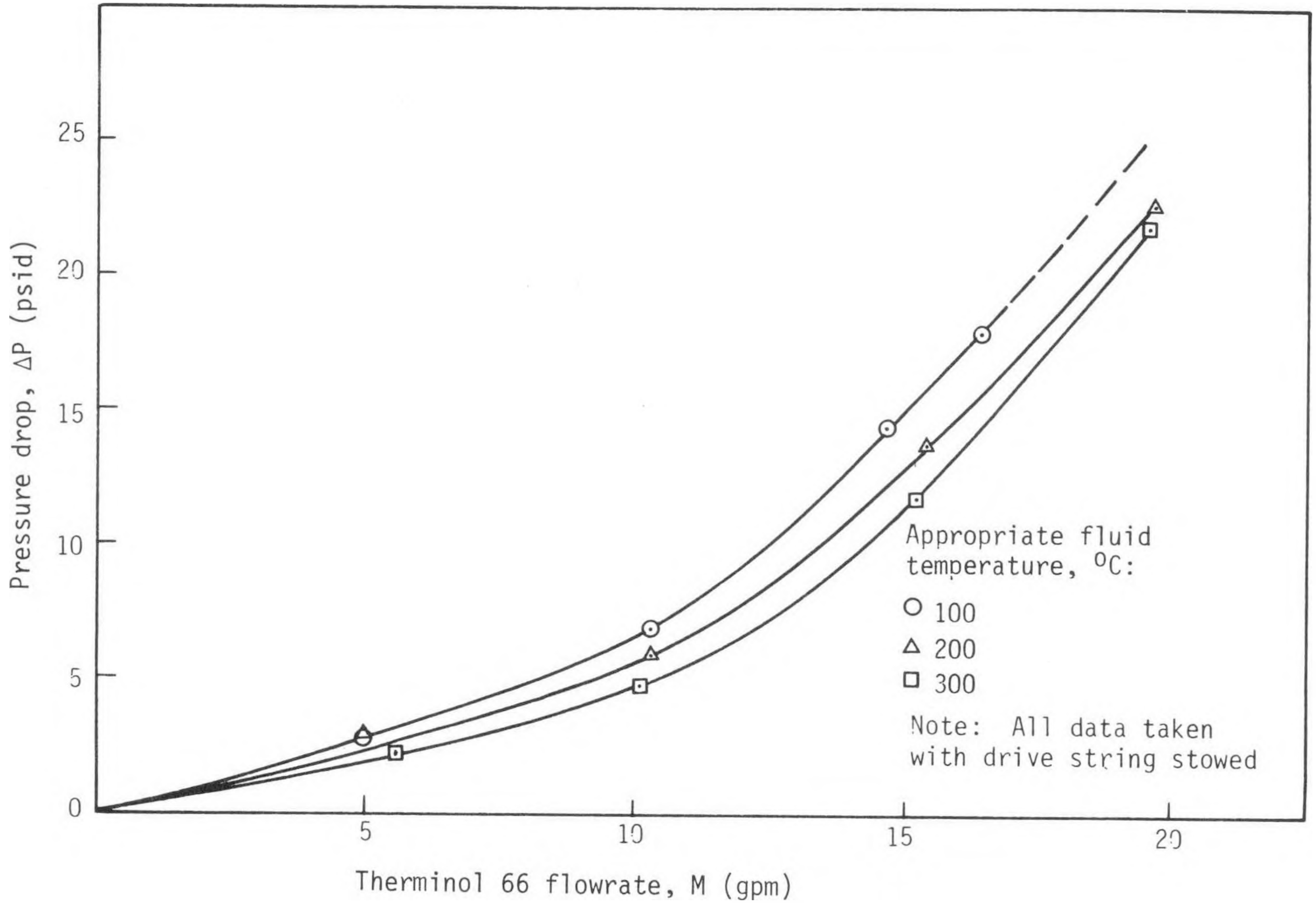

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Figure 3-8. Drive String Pressure Drop

was conducted for 4,000 cycles while a constant 10-gpm flowrate of Therminol 66 was maintained. The cycling was performed on an 8 hr/day basis that included daily warmup and cooldown periods covering a range of temperatures from 30° to 260°C.

The 4,000 accelerated mechanical cycles were equivalent to over 10 yr of operation. The only problem encountered during mechanical cycling was with the pivot bearing inserts. The locator tabs on these inserts were sheared off allowing the inserts to move laterally outside of their housings. The pivot bearing assembly was repaired by adding positive metal stops to the bearing housings to limit lateral travel. It is also planned to increase the size of the bearing insert locator tab and change some tolerances for improved fit of the bearing assembly.

Thermal cycling was conducted with the drive string equipped with the normal slow-speed drive motor. Twelve thermal cycles were run from 100°C up to 340°C then back to 100°C receiver outlet temperature while the string was sun tracking. Each cycle took about 60 min which was the limit of the test facility fluid heating and cooling capabilities. No problems were encountered during these tests.

Receiver thermal expansion (test 6-7, table 3-1) was measured during the thermal cycling tests discussed above. Receiver length change from ambient to peak operating temperature was measured from the fixed receiver anchor point adjacent to the drive to the extreme receiver ends in each direction. A reference line was marked at a fixed location near the drive string end receiver supports. A second reference line was marked on the receiver tube. The separation distance between these two lines was measured upon thermal cycle initiation and upon reaching maximum temperature. The difference between these two distances was the receiver expansion. The greatest receiver expansion occurred on the west or downstream end of the receiver. For the various thermal cycles the maximum receiver expansion averaged 2.65 in. which correlated closely with the calculated thermal expansion for steel receiver tubing. Also, no mechancial interferences or improper operation were noted for the receiver when expanded to the maximum length.

3.3.4 Fit and Function

The mechanical fit and function (test 6-8, table 3-1) observations for the drive string were noted during installation in the test facility. All components were installed with only minor modifications required. First, the pivot bearing housings required shimming to achieve proper alignment. This unplanned shimming will be eliminated by changing tolerances and specifying additional requirements for stamping the components. Second, the receiver glazing seals allowed rainwater intrusion between glazing and receiver. By relocating the seals in the receiver support collars, water intrusion was eliminated. Finally, the flexhose flexible ducting that serves as a retainer for the field installed flexhose insulation was difficult to keep in place. The ducting would occasionally slip off the support ring which is welded to the flexhose. A second generation prototype flexhose has been designed to provide a smaller diameter support ring to more properly match the flexible duct inside diameter. Also, alternate duct materials with improved spiral wire reinforcement are being considered.

3.4 COMPARISON OF PREDICTED AND MEASURED THERMAL PERFORMANCE

Near normal thermal performance in terms of efficency was measured for a prototype drive string of six modules. As discussed in section 3.3.1, from figure 3-2 a curve fit of the measured data was generated as follows:

$$\eta_o = 0.81 - 0.63 \left(\frac{\Delta T}{I}\right) - 0.15 \left(\frac{\Delta T}{I}\right)^2$$

for

$$760 \leq I \leq 960 \text{ W/m}^2$$

A similar expression was generated by Sandia Laboratories for the previous Model 3001 collector as follows (see figure 2-1):

$$\eta_o = 0.68 - 0.098 \left(\frac{\Delta T}{I}\right) - 1.414 \left(\frac{\Delta T}{I}\right)^2$$

The following projected improved Model 3011 collector efficiency was derived directly from the Sandia-derived equation (see figure 2-1):

$$\eta_o = 0.77 - 0.084 \left(\frac{\Delta T}{I}\right) - 1.212 \left(\frac{\Delta T}{I}\right)^2$$

The optical efficiencies for all these equations and their calculated efficiencies for 204°C and 315°C bulk fluid temperatures are shown in table 3-6. The optical intercept point of 81 percent for the measured 3011 performance was not directly measured. Rather, a data point was recorded at 79.7 percent where the $\Delta T/I$ factor was 0.016 (°C - m^2)/W. This near-zero point was entered into the curve fit calculation which yielded a theoretical optical efficiency of 81 percent.

Table 3-6. Summary of Collector Optical and Thermal Efficiencies

Goal, Projection, or Measurement	Optical Efficiency η_t (percent)	Direct Normal Thermal Efficiency η_o (percent)	
		204°C	315°C
1985 DOE Goals	--	71.0	65.0
Model 3011 Measurements	81	69.0	61.0
Projected Acurex Performance	77	71.4	63.9
Model 3001 Measurements	68	61.4	52.8

The measured efficiencies are below the Acurex performance projections by about 2-1/2 to 3 percentage points. The apparent explanation is that the receiver heat loss per unit aperture area was higher than predicted, due in part to higher than predicted emissivity of the black chrome receiver tubes.

3.5 TEST AND ANALYSIS METHODS

The Acurex Solar Energy Test Facility flow loop is shown schematically in figure 3-9. The loop consists of a portable fluid cart and a portable calorimeter cart arranged in series with test collector systems. The calorimeter cart is used in place of the usual flowmeter and assumed oil heat transfer properties to eliminate the difficulty of obtaining accurate individual measurements of $\dot{M}$ and Cp. With the calorimeter cart the $\dot{M}Cp$ product is determined directly by measuring the temperature rise created by a resistance heater. Input power to this 6-kW heater is measured by a power transducer.

The collector inlet temperature and fluid flowrate are controlled by the main fluid cart temperature and flow controls. In general, tests were run with constant flowrate and inlet temperature. The collector outlet temperature was allowed to vary with isolation and ambient conditions.

The basic energy conversion efficiency equation is:

$$\eta_\Theta = \frac{Q_c}{Q_i} = \frac{(\dot{M}Cp)_r \Delta T_r}{6IA \cos \Theta}$$

where $$(\dot{M}Cp)_r = R(\dot{M}Cp)_a$$

and $$(\dot{M}Cp)_a = \frac{P_a}{\Delta T_a + \Delta T_\ell}$$

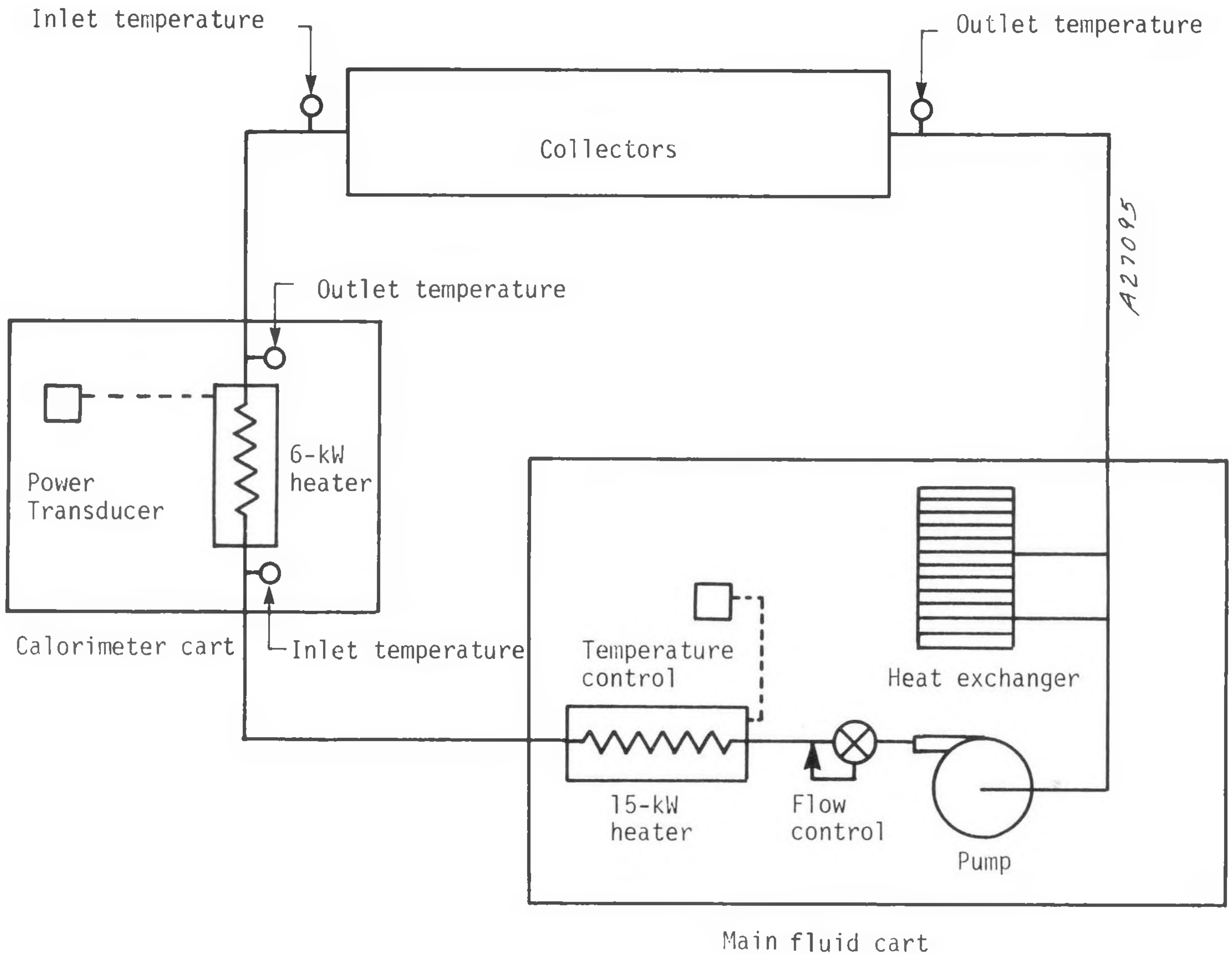

Figure 3-9. Acurex Solar Energy Test Facility Flow Loop

The quantity, R, was derived from manufacturer's published data for Therminol 66 for specific heat variation with temperature.* Since the fluid temperature in the calorimeter was less than receiver average fluid temperature, the calorimeter fluid specific heat was less than the receiver fluid specific heat. By assuming the slope of the manufacturer's specific heat versus temperature curve was correct in the relatively narrow temperature range of interest, R was calculated as the ratio of the receiver fluid to the calorimeter fluid specific heat. In this manner the term $(\dot{M}Cp)_r$ was eliminated from the efficiency equation.

The term ΔT_ℓ was included in the equation for $(\dot{M}Cp)_a$ to offset the small amount of calorimeter heat loss. This heat loss was determined by operation of the fluid loop in the normal mode but with the calorimeter heater off. In this mode the drop in temperature due to heat loss was measured and used to adjust the $(\dot{M}Cp)_a$ product upward.

3.6 COMPARISON OF CALORIMETER AND FLOWMETER MEASUREMENTS

A turbine flowmeter supplied by Sandia Laboratories, was installed in the collector flow loop to check the calorimeter cart measurements. The flowmeter was installed just upstream of the drive string at a location as close as possible to the collector inlet temperature measurement probe. The collector inlet temperature was used to determine the Therminol 66 density at the flowmeter from manufacturer's published data. The average bulk receiver temperature was used to determine the Therminol 66 specific heat.

The test results for a representative drive string efficiency measurement are presented in table 3-7. The calorimeter-based efficiency was

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*Monsanto Product Bulletin No. IC/FP-64.

Table 3-7. Representative Drive String Efficiency Test Results
Test 100004

Receiver Inlet Temperature T_{in} (°C)	Receiver Outlet Temperature T_{out} (°C)	Flowrate $\dot{M}$ (gpm)	Insolation I (W/m^2)	Efficiency η_o (percent)	
				Calorimeter Basis	Turbine Flowmeter Basis
196.39	235.87	9.95	934.8	67.4	68.0

determined using the methods described in section 3.5. The turbine-flowmeter-based efficiency was determined as follows:

From published data,

$$\rho = 7.40 \text{ lbm/gal for } T_{in} = 196.39°C$$

$$Cp = 0.544 \text{ cal/gm°C for } T_b = 216.13°C$$

For direct normal insolation to the drive string of six:

$$\eta_o = \frac{Q_c}{Q_i} = \frac{\dot{M}Cp\ \Delta T_r}{6IA}$$

Substitution of published data and measured parameters (table 3-8) yields η_o = 68.0 percent. The published-data-based efficiency is very close to the calorimeter-based efficiency of 67.4 percent for the same test and within the data measurement accuracies.

SECTION 4

PRODUCTION PLANNING

This section presents the production plan for the mass production of the Acurex Model 3011 collector. An approach for an ultimate production capacity of 5 million ft^2 was developed. The following subsections present the mass production approach, factory requirements and layout, factory work flow arrangement, cost estimates, and a production buildup approach.

4.1 MASS PRODUCTION APPROACH

The approach for mass production was determined by first grouping collector subassemblies by the degree of automation involved for their production. Next, key factory subassembly production rates required to build up production to 5 million ft^2/yr were determined. Assumptions were made regarding vertical integration to define those components that would be factory fabricated. Finally, factory quality assurance requirements were defined to establish their needed floor space. By defining these basic elements the specific conceptual factory requirements were determined.

4.1.1 Subassembly Production

Semi-automatic techniques will be used to produce the individual collector structures. Semi-automation is required for attachment of rib flanges, pivot cranks, and miscellaneous small brackets to collector torque tubes and for attachment of ribs to rib flanges simply because of the extremely large number of such operations that are required. The approach for collector structure assembly is summarized as follows:

- Assembly line stations for the flow of collector structures designed for maximum line balance
- Semiautomatic operation of these stations. Manual labor is used for inserting work pieces in fixtures for automatic machines to perform welding and riveting operations as required
- Minimal offline operations such as rib stamping

Manual techniques organized on an assembly line basis will be used to produce the receiver and drive post subassemblies. Automated production techniques cannot be justified since these items are relatively small, as in the case of the receiver, or not very numerous, as in the case of the drive post. The nondrive support post production will also be approached manually because of its simplicity of manufacture.

The remainder of drive string components, including semifinished parts that feed the assembly lines, may be most easily fabricated by a standard machine shop capability. Only one item, the parabolic-shaped rib, need be fabricated by use of a hardened progressive die set mounted in a high-tonnage press. Simple stamping presses, cutoff saws, lathes, and milling machines are the key elements required for machine shop production of the remaining fabricated items.

4.1.2 Plant Production Rate

Based on 140 ft^2 of aperture per 7 ft by 20 ft collector module, fabrication of approximately 36,000 modules per year will yield a 5 million ft^2 annual production rate. Assuming the work year has 240 work days and each work day can be divided into single or double 8-hr shifts or three shifts providing 21 hr of production time, a plant could produce

5 million ft^2/yr if a minimum of seven collector assemblies per hour could be produced. Our analysis indicates that an output of 4.6 collector assemblies per hour or one collector every 13 min is a reasonable goal for a cost-effective assembly line. Since this production rate cannot be met with a single plant even if operated three shifts a day, a two-plant, two-shift-per-day operation was adopted (see table 4-1). If the conceptual plant had two assembly lines, the annual production target could be achieved with a single plant but a reasonable production buildup proved difficult to accommodate for such a plant.

The following discussion is limited to a single plant producing about 74 collectors per day on a two-shift basis. The nominal plant output is 2.5 million ft^2/yr. Simultaneous startup of two similar plants is risky for mass production of a new product. Rather the second plant should be started after the lessons in operation of the first plant have been learned.

4.1.3 Vertical Integration

The extent of vertical integration for collector production determines those components that are made in the factory and those that are procured from vendors. Such make/buy decisions can involve multiple trade-offs between supplier schedules and costs versus machine acquisition, labor training, and raw material supplied. For production of the drive string components, however, make/buy decisions fall into two clearly defined categories: components fabricated by standard machine operations, and those fabricated by state-of-the-art processes.

For components involving standard machine operations, the plant will include a machine shop capability. Providing the plant is located reasonably close to an industrial area trained labor and supervisory help should be readily available. The requirements and processes for some aspects of

Table 4-1. Overall Production Rates Required for a Nominal Output of 5 Million Ft^2

Number of Shifts	Hours Per Working Day	Collectors Per Hour	Collectors Per Day	Yearly Module Production Per Plant	Total Yearly Aperture Production (ft^2)
a) One Plant Operation					
1	8	18.60	149	35,760	5,006,400
2	16	9.30	149	35,760	5,006,400
3	21	7.09	149	35,760	5,006,400
b) Two Plant Operation					
1	8	9.30	74	17,760	4,972,800
2	16	4.65	74	17,760	4,972,800
3	21	3.54	74	17,760	4,972,800

production are complicated and specialized. These processes will not be part of the production line:

- Black Chrome Plating -- A plating facility is capital cost intensive and provides only a small added value to the collector product. Since the process involved is state of the art, development is required to train labor and define the details of the plating steps by cut and try methods. A black chrome plating capability is simply too specialized and costly for use in the production line.
- Reflector Panels -- It is not practical to manufacture reflector panels as part of the production line. Assuming the basic glass sheets are purchased from a glass manufacturer, they must be tempered, cut to size, silvered, then bonded to specially prepared steel substrates. These steps can involve costly glass breakage and large amounts of floor area for each step in the process.
- Rib Stamping -- Due to the size of the stamping press and its associated decoiling and leveling stages and the weight of the sheet metal coils, rib stamping will be accomplished outside the factory. It is most cost effective to have the rib dies made and the stamping performed at the shop of a single vendor.

4.1.4 Quality Control Requirements

In addition to the routine quality control inspections for incoming parts, factory-fabricated parts, assembly stations, and shipping, there are two requirements unique to collector production. First, the optical quality of the reflector panels as installed in the module structure will be checked by use of a fixture located adjacent to the production line for statistical testing of individual modules. The device will employ a light source capable of shining a parallel beam anywhere on the reflective surface and a simulated receiver to determine if the beam is reflected at the proper angle. Second, a testing laboratory will be required to periodically check the optical properties of incoming components. The emittance and absorptance of black chrome receiver tubes, the transmittance of receiver glazing, and the reflector panel reflectance will require statistical checking to maintain quality. Such a laboratory requires a controlled environment for instrument stability.

4.2 FACTORY REQUIREMENTS

To implement the mass production approach discussed above, the assembly line with component manufacturing requirements must be defined. In addition, machine shop, storage, quality control, shipping, and office space requirements must be defined. The subsections below discuss these items for the conceptual factory for collector production.

4.2.1 Assembly Line

The assembly line consists of five stations for subassembly of components. The operations performed and the required input for each station are summarized in table 4-2. The stations are as follows:

- Station 1: The rib flanges, pivot cranks, and center receiver supports are welded to the torque tube. The welding is accomplished by mounting the torque tube in a rugged fixture, loading components manually, then performing the welding with an automatic welder.
- Station 2: The rib attachment holes are punched in the complete torque tube weldments from station 1. The weldments are mounted in an extremely rigid accurate fixture and tightly clamped. A programmed punching machine punches the rib flange rivet holes.

Table 4-2. Summary of Assembly Line Station Inputs and Operations

Station	Operation	Input
1	Assembly of torque tube weldments	Torque tubes, pivot cranks, end plates, rib flanges, center receiver supports
2	Punch holes in rib flanges	Output from station 1
3L, 3R	Attach ribs to rib flanges, attach edge retainers	Output from station 2, ribs, edge retainers
4	Mount reflector panels	Output from station 3, reflector panels, edge clamps
5	Load modules into shipping crates	Output from station 4

- Station 3: Station 3 is divided into two identical stations, 3L and 3R to maintain assembly line balance since the operations herein are the most time consuming. The punched torque tube weldments are mounted in fixtures at either station 3L or 3R, whichever is open. Ribs are then inserted into appropriate jig elements for riveting to the rib flanges. The rib rivet holes are punched during the rib stamping process to ensure an accurate relationship between the mounting holes and the rib parabolic contour. Rivets are manually loaded into each rivet hole then an operator clinches the rivets with a pneumatic rivet tool suspended overhead. Finally the edge retainers are installed on the rib ends and riveted in place using the same riveting tools.
- Station 4: The reflector panels are conformed, concave side downward, on a soft surface mandrel located between stations 3L and 3R that is the same size as the module. Next, the torque tube/rib subassembly is lowered onto the mandrel. Finally, edge retainers are bolted in place using pneumatic wrenches with preset torque limits.
- Station 5: Completed collector assemblies are loaded in shipping crates.

Subassembly movement throughout the assembly line will be accomplished by an overhead conveyor with motorized trolleys. The hoist attachment is made at station 1 to the torque tube weldment which has holes provided for this purpose. This attachment stays firm until the completed assembly is loaded in station 5. At that point the hoist is detached, and the trolley/hoist combination is returned to the beginning of the line via a return track. The conveyor system thus travels in a close-loop "racetrack." Suitable offline bypasses will be provided so that any interruption in flow at any station does not immobilize the whole assembly line.

In contrast to the assembly racetrack system which has to carry at most a complete assembly, the final loading must be able to carry a packed shipping crate. Since cost is strongly impacted by lifting weight, a separate system is used for eventual flatbed trailer loading. The separate system could either be a separate back-and-forth monorail designed for the higher loads or a specially designed shipping crate roller system. For high frequency loading, a separate monorail has proven to be the more cost-effective solution and is assumed herein.

4.2.2 Component Manufacturing Requirements

For the determination of component manufacturing requirements it is assumed that all items fabricated by common machine operation will be kept in-house so eventual plant requirements are established. Components to be manufactured involve the following four categories:

- Inputs to the first four assembly line stations
- Receiver assembly
- Support posts
- Drive string components

The following subsections provide detailed requirements for each of these categories.

4.2.2.1 Assembly Line Components

The assembly line components for input to the first four assembly stations are summarized in table 4-3. Fabrication operations involve die cutting, hole punching, and forming. Only one item, the crank key, requires milling, drilling, and tapping operations.

Table 4-3. Summary of Components for Input to Assembly Line Stations 1 Through 4

Components		Quantity per Collector	Fabrication Operations
Number	Name		
211	Torque tube end plate	1	Die cut, hole punch
212	Torque tube	1	None
213	Rib flange	18	Die cut
214	Support flange	1	Die cut, hole punch
221	Pivot crank (fixed)	1	Die cut, form, hole punch
223	Crank key	2	Milling, drill
226	Pivot crank (adj.)	1	Die cut, form, hole punch
231	Rib	36	Die cut, form, hole punch
236	Edge retainer	2	Roll form, hole punch
242	Edge clamp	12	Guillotine cut, hole puch
243	Edge clamp washer	36	Brake, hole punch
245	Rectangular washer	72	Die cut, hole punch
--	Reflector	6	None
270	Center receiver support	1	Die cut, hole punch
272	Module brace	4	Die cut, hole punch
Misc.	Fasteners and washers	501	None
100-02	Butt weld connector		None

4.2.2.2 Receiver Components

The receiver components and the operations required for their assembly are summarized in tables 4-4 and 4-5. For part number 332, a minor finish machining operation is required for this cast component including drilling three holes. The split glazing edge and end seals will be supplied by a specialty vendor. The major process performed out of house is the black chrome plating discussed in subsection 4.1.3. As shown in table 4-5 the only process required for receiver assembly is GTAW. A single operator with hand-held welding equipment will handle all receiver weldments.

4.2.2.3 Support Post Components

The components for the nondrive support post and the drive post are summarized in table 4-6. Table 4-7 presents the assembly operations required for those posts. Only the pivot shafts require lathe and mill work. The shafts are critical items since they determine the module-to-module alignment for the drive string. The nickel plating for the pivots will be done out of house.

4.2.2.4 Group Specific Components

Group specific components include the flexhoses and flexhose anchor support brackets which are bolted to the drive string end support post bases for field piping interconnection. The required components are summarized in table 4-8 and the assembly operations are presented in table 4-9.

4.2.3 Machine Shop

The production machine shop will be equipped with one each of the following machines (except two 25-ton punch presses):

- 100-ton punch press
- 60-ton punch press
- 25-ton punch press

Table 4-4. Receiver Assembly Components

Components		Quantity per Drive String	Fabrication Operations
Number	Name		
310	Swaged receiver tube (plated)	5	None
315	Plain receiver tube (plated)	1	None
321	Extension tube	1	None
325	Receiver glazing tube	12	None
326-01	Support ring small I.D.	10	Die cut
326-02	Support ringe large I.D.	24	Die cut
328	Vibration damper	12	None
332	Support collar half	36	Machine finish casting, hole drill
342	Split glazing half	4	None
344	Split glazing end seal	12	None
345	Split glazing edge seal	4	None
350	End receiver support	12	Die cut, hole punch, brake
360	Center receiver support	6	Die cut, hole punch, brake
363	Center receiver spacer	12	Die cut, hole punch

Table 4-5. Receiver Assembly Operations

Description	Input	Process
Receiver tube weldment	Plain receiver tube as plated; butt weld connector body	GTAW
Extension tube weldment	Extension tube; butt weld connector body; large I.D. support ring	GTAW
Fixed receiver tube weldment	Receiver and extension tube weldments from above; plain receiver tube	GTAW
End receiver tube weldment	Receiver tube weldment from above; swaged receiver tube; ferrule and nut	GTAW

Table 4-6. Support Post Components

Components		Quantity per Collector	Fabrication Operations
Number	Name		
406	Support post tube	1	Cut
407	Support post base angle	2	Cut, hole punch
411	Bearing base	1	Cut, hole punch, form
415	Bearing cap	1	Cut, hole punch, form
416	Bearing insert	2	Form
420	Pivot shaft	(2/3)	Cut, turn, tap, mill, nickel plate
421	End pivot shaft	(1/3)	Cut, turn, tap, mill, nickel plate
441	Drive post tube	(1/6)	Cut
442	Drive post base angle	(1/3)	Cut, hole punch
444	Drive post top angle	(1/3)	Cut, hole punch

Table 4-7. Support Post Assembly Operations

Description	Input	Process
Pivot bearing base weldment	Bearing base; weld nut	Spot weld
Nondrive support post weldment	Pivot bearing base weldment from above; support tube; base angles	GMAW
Nondrive support post assembly	Nondrive support post weldment from above; pivot bearing insert; pivot bearing cap; bolts and washers	Emplace and fasten
Drive post weldment	Drive post tube; base angles; top angles	GMAW

Table 4-8. Group Specific Components

Components		Quantity per Drive String	Fabrication Operations
Number	Name		
505	Flexible hose	2	None
510	Flexible sheathing	2	Cut to length, remove wire
511	Sheathing support	2	None
512	Flexhose insulation	8	Cut to length
521	Hose anchor support	2	Saw to length, bend, hole punch
522	Support channel	2	Die cut
523	Hose anchor plate	2	Die cut, hole punch
--	Elbow	2	Weld

Table 4-9. Group Specific Component Assembly Operations

Description	Input	Process
Flexhose assembly	Flexhose, flexible sheathing, insulation, clamps	Double wrap insulation, install sheathing over insulation, clamp
Hose anchor support	Hose anchor support, support channel, anchor plate, elbow	GMAW

- 10-ft power brake
- Power cut-off saw
- Slip roll
- Power tube bender
- Vertical mill
- 12-in. swing lathe
- 12-ft shear

For welding small subassemblies outside of the assembly line it is estimated that two welding stations are required. One of the stations will be equipped to handle work lengths of 21 ft for receiver welding.

The initial mass production approach assumes the rib stamping operation is performed by vendors. Ultimately, when rib stamping is brought in-house, it will be performed by a 200-ton press, in one progressive pass which will die cut the rib contour from a continuous sheet of material, punch the attachment holes, and bend the rib end. Continuous sheet stock will be fed from a roll which has been passed through a decoiler and leveler. Including the decoiler and leveler, the rib stamping equipment is 50 ft long and 9 ft wide.

4.2.4 Component Storage

All components will be stored inside at either a central location or locations local to their associated assembly operations. The central location is intended for small bulk storage items such as fasteners. Assuming that small items are resupplied to work stations once every 8-hr shift and that a 6-week supply is maintained, a floor space of about 200 ft^2 is adequate. Local storage of components includes the following:

- Torque tubes: Five bays of 100 torque tubes each located adjacent to the torque tube weldment stations will provide about 7 days of production. Each bay is 14 ft high, 5 ft wide, and 21 ft long.
- Ribs: Ribs will be stored beside assembly station 3. A daily production requires 2,664 ribs. A storage area 1 ft wide, 4 ft long, and 15 ft high will stack 2,000 ribs. Hence, two such stacks at assembly station 3 are adequate.
- Reflector Panels: A 4 ft by 8 ft floor area adjacent to assembly station 3 will be adequate for the approximately 500 panels required for each day's production.
- Receivers: The receiver tubing will require a storage area 22 ft long by 1 ft wide, 14 ft high with a 9 ft maneuvering aisle for a forklift material handler. The required floor space is approximately 220 ft^2.
- Shipping Crates: Shipping crates will be returned from the installation site at essentially the same rate as completed collectors are shipped so no specific crate storage is required. It is assumed, however, that about four crates covering 640 ft^2 of floor space are required to be positioned for loading at all times.

4.2.5 Quality Control Floor Space

Floor space for the quality control requirements described in subsection 4.1.4 is as follows:

- Collector Optical Tests: A floor space of 22 ft by 44 ft is estimated for the test fixture and for maneuvering one collector.

- Quality Laboratory: An air conditioned room of 22 ft by 24 ft is required for optical tests of components.

4.2.6 Shipping

Collectors will be shipped to the field installation sites as fast as crates of six modules each can be loaded onto flatbed trucks. Assuming that two collector crates and associated small components are loaded onto each 45-ft flatbed trailer, about six shipments will be made daily. Four spare flatbed trailers should be available at the plant site at all times to provide for scheduling problems. Inside the plant, storage space should be allowed for four fully loaded crates. This requires 1,500 ft^2 of floor space to allow for access for maneuvering the crates. An additional 1,500 ft^2 are required for receiver, support post, and group specific component crating and loading.

4.2.7 Offices

About 3,700 ft^2 of office space is estimated to accommodate the supervisory and other indirect personnel. Table 4-10 summarizes personnel requiring separate offices and those personnel located in an open area outside the offices.

4.3 PLANT LAYOUT AND WORK FLOW

The overall plant layout necessary to satisfy the factory requirements discussed above is presented in figure 4-1. Approximately 40,000 ft^2 of floor space on one level is required for production of 74 collectors per day allowing for future expansion into areas such as rib stamping.

Based on the layout of figure 4-1, the flow of components for each of the production assembly activities is defined by the following figures:

Table 4-10. Plant Personnel

Separate Offices	Open Area
Plant Manager	Secretary/Receptionist
Material/Production Control Manager	Draftspersons (two required)
Production Manager	Expediter
Purchasing Manager	Clerk
Manufacturing Engineering Manager	Planner
Manufacturing Engineers (two required)	
Industrial Engineer	
Material Control	
Quality Assurance Manager	
Plant Superintendent	

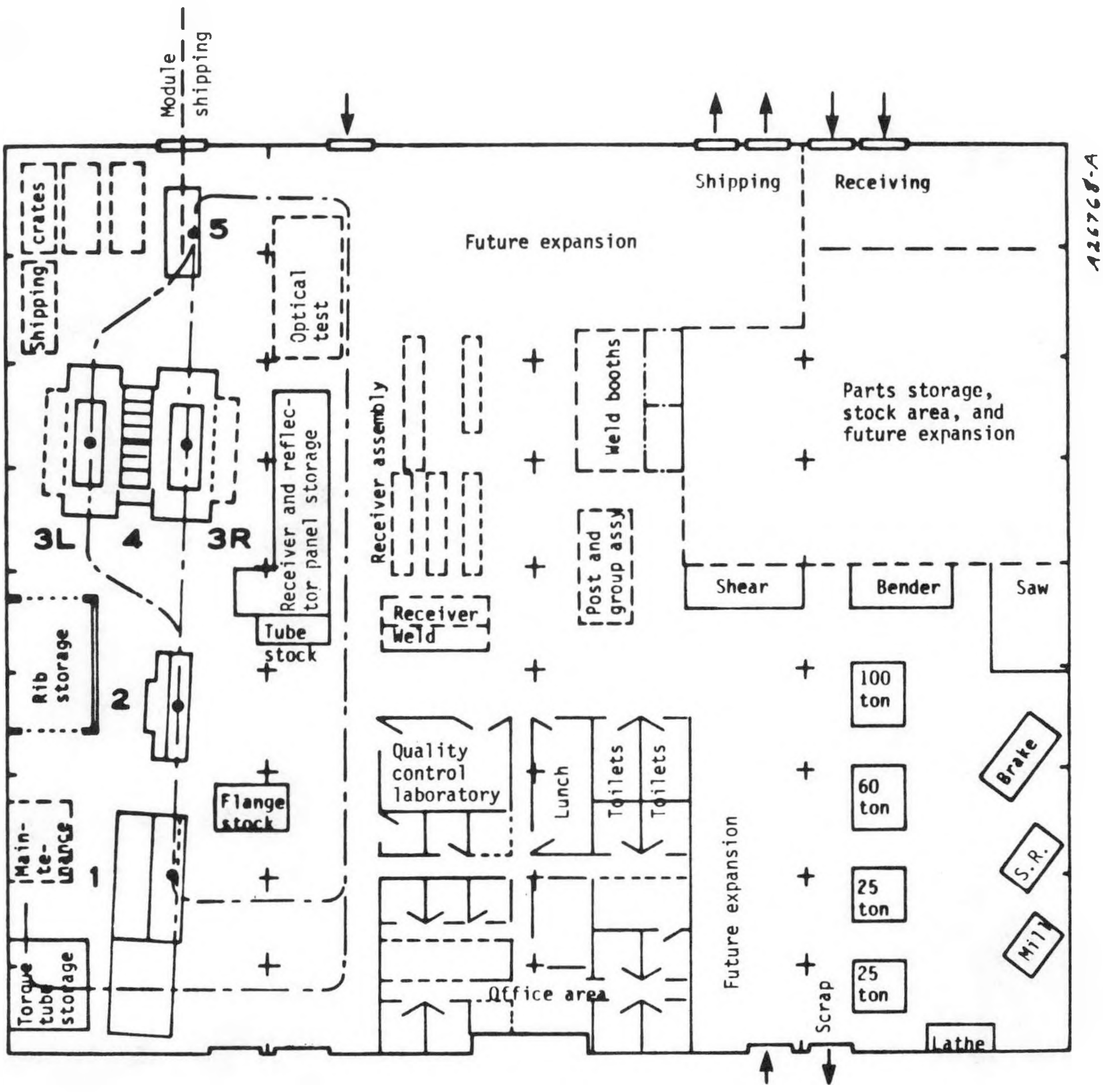


Figure 4-1. Overall Plant Layout

Figure	Description
4-2(a)	Flow of Components, Assembly Station 1
4-2(b)	Flow of Components, Assembly Station 2
4-2(c)	Flow of Components, Assembly Station 3
4-2(d)	Flow of Components, Assembly Station 4
4-2(e)	Flow of Components, Assembly Station 5
4-2(f)	Flow of Components, Receiver Assembly
4-2(g)	Flow of Components, Post Assembly
4-2(h)	Flow of Drive String Specific Components

The bold dashed lines on each figure indicate the component flow for the specific activities. The bold triangles and circles indicate locations of brief storage and locations for work to be performed, respectively.

4.4 COST ESTIMATES

Cost estimates were made for materials and labor for a single plant production rate of 2.5 million ft^2/yr. A conceptual production buildup rate was generated for two production plants to provide a 5 million ft^2/yr production by 1985. A learning curve was then defined based on the buildup rate, estimated current collector costs, and projected 1985 costs. Collector costs, the production buildup estimate, and learning curve are presented in the following subsections.

4.4.1 Material Costs

Material costs for the module assembly, receiver assembly, post assemblies, and group-specific assemblies are summarized in table 4-11(a) through 4-11(d), respectively. Costs are shown for drive strings of six modules including an adder for scrap and spoilage. We found that maximum vendor quantity discounts were reached very soon after initiation of

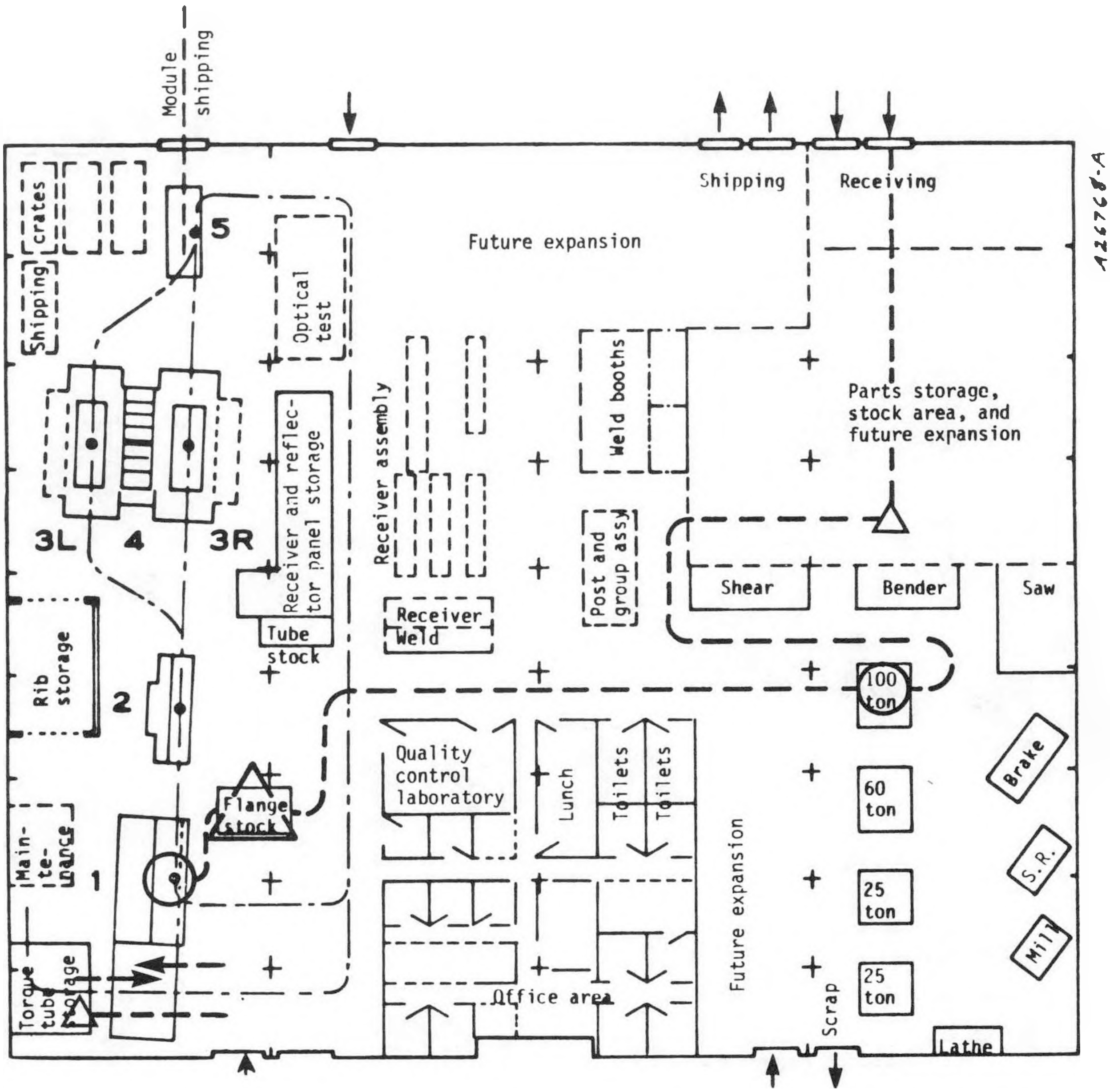


Figure 4-2(a). Flow of Components, Assembly Station 1

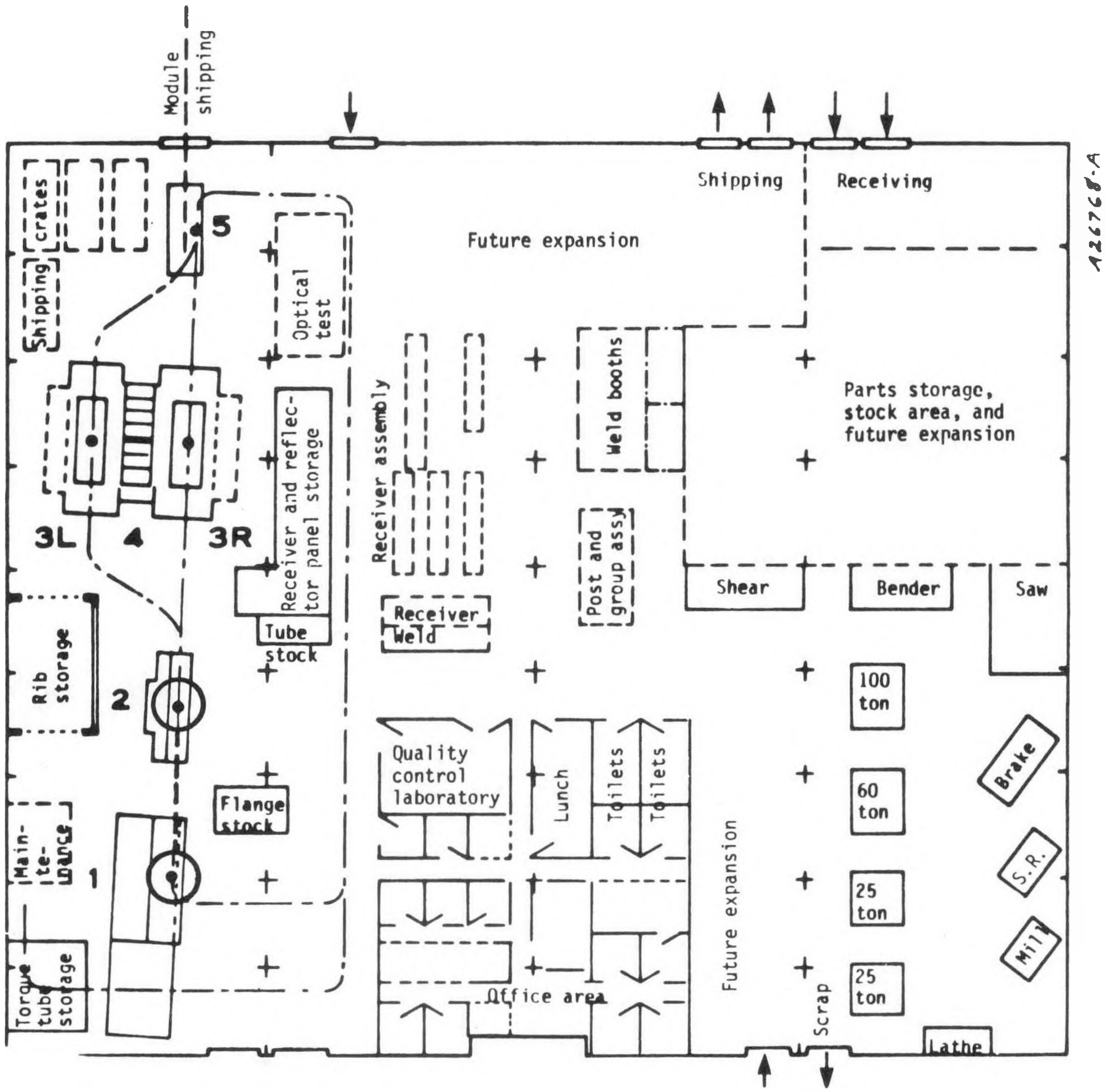


Figure 4-2(b). Flow of Components, Assembly Station 2

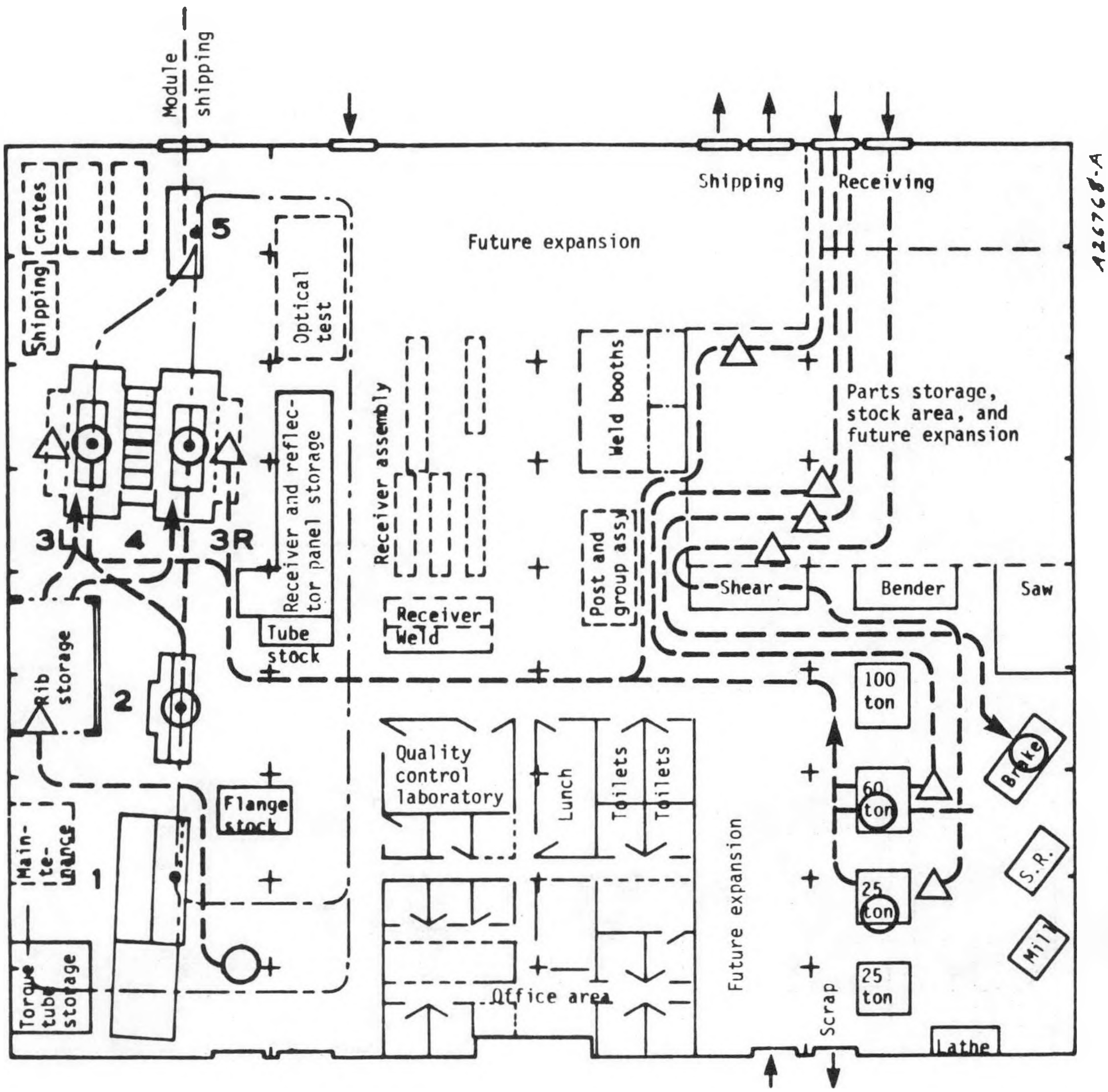


Figure 4-2(c). Flow of Components, Assembly Station 3

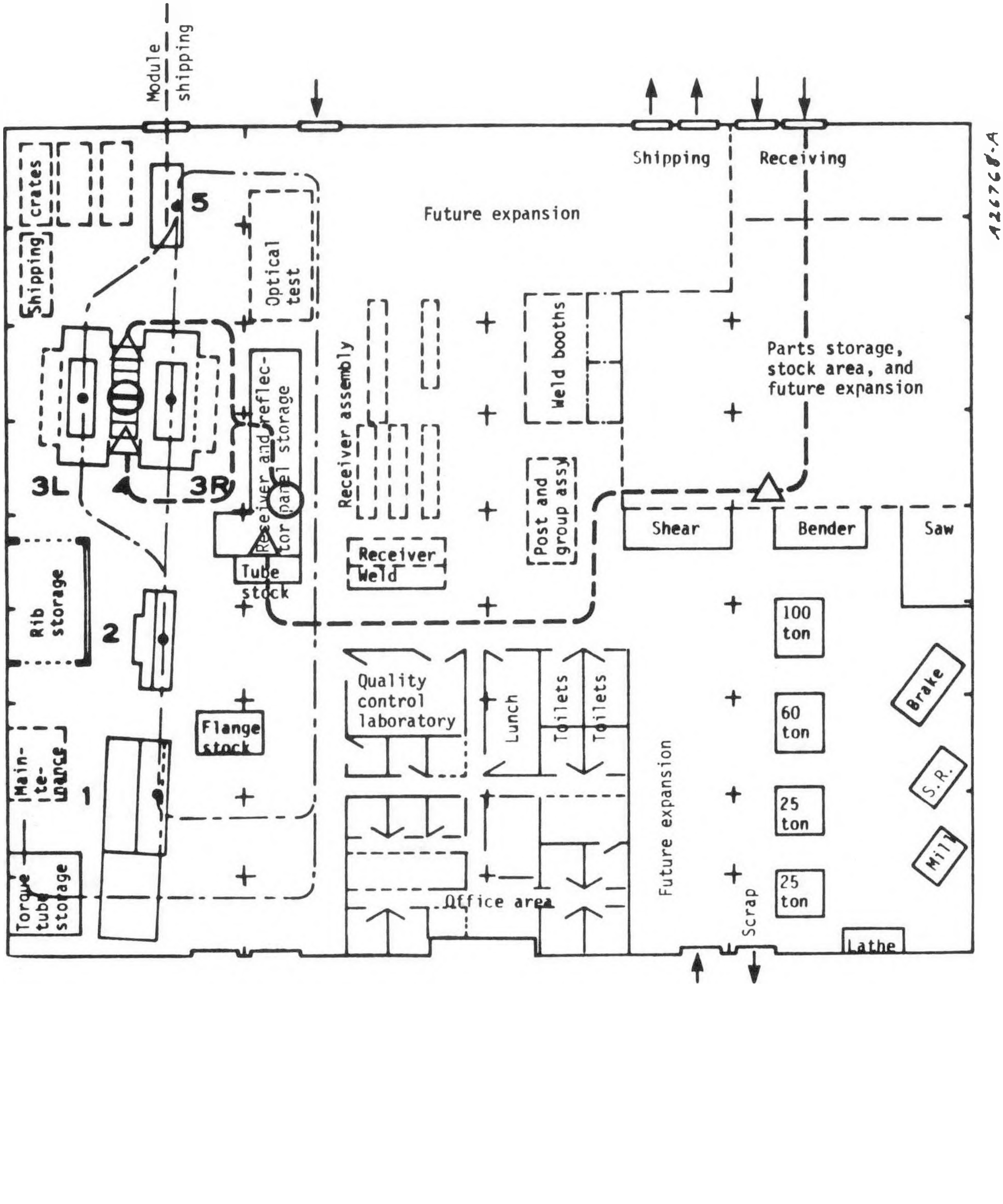


Figure 4-2(d). Flow of Components, Assembly Station 4

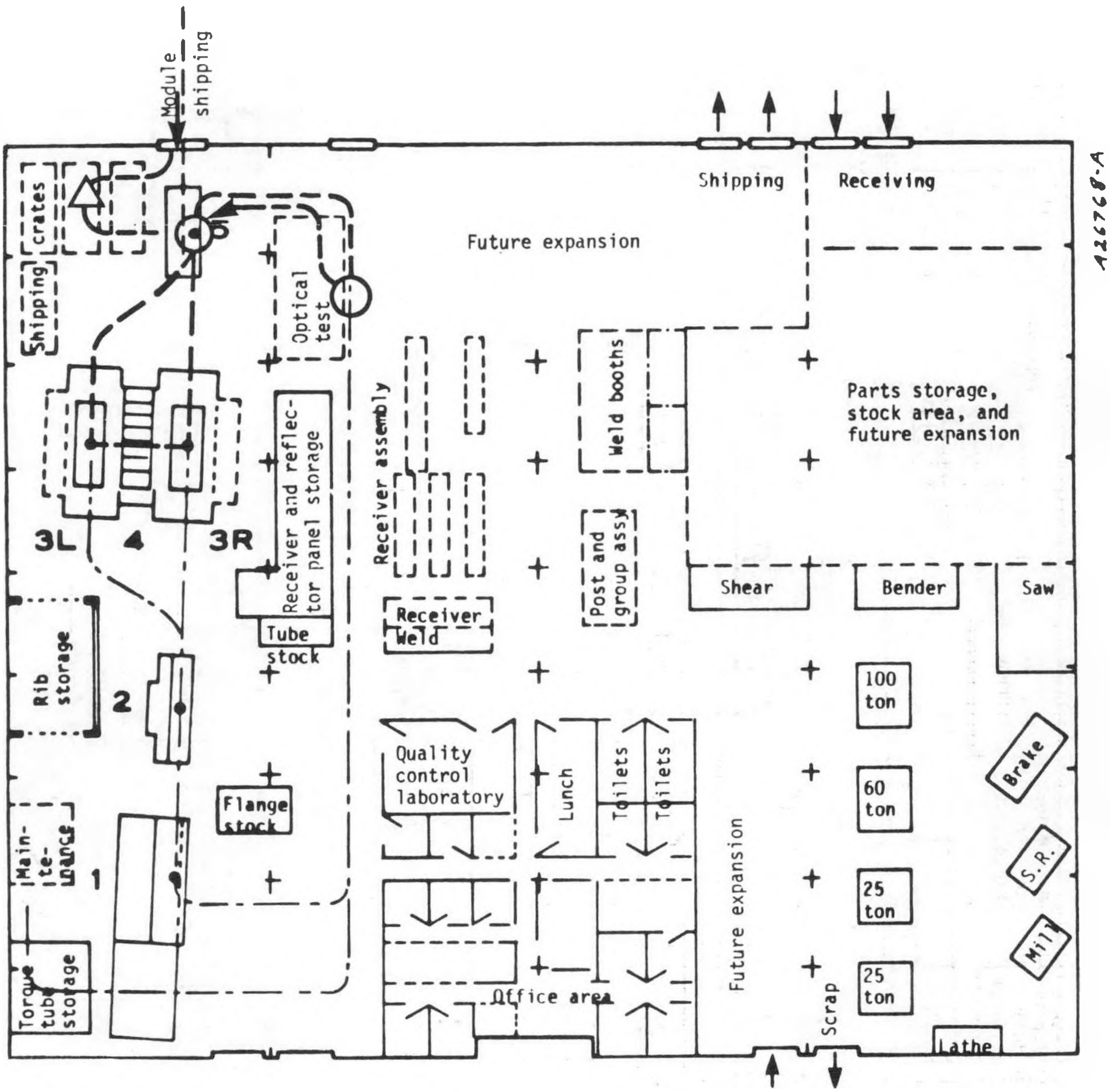


Figure 4-2(e). Flow of Components, Assembly Station 5

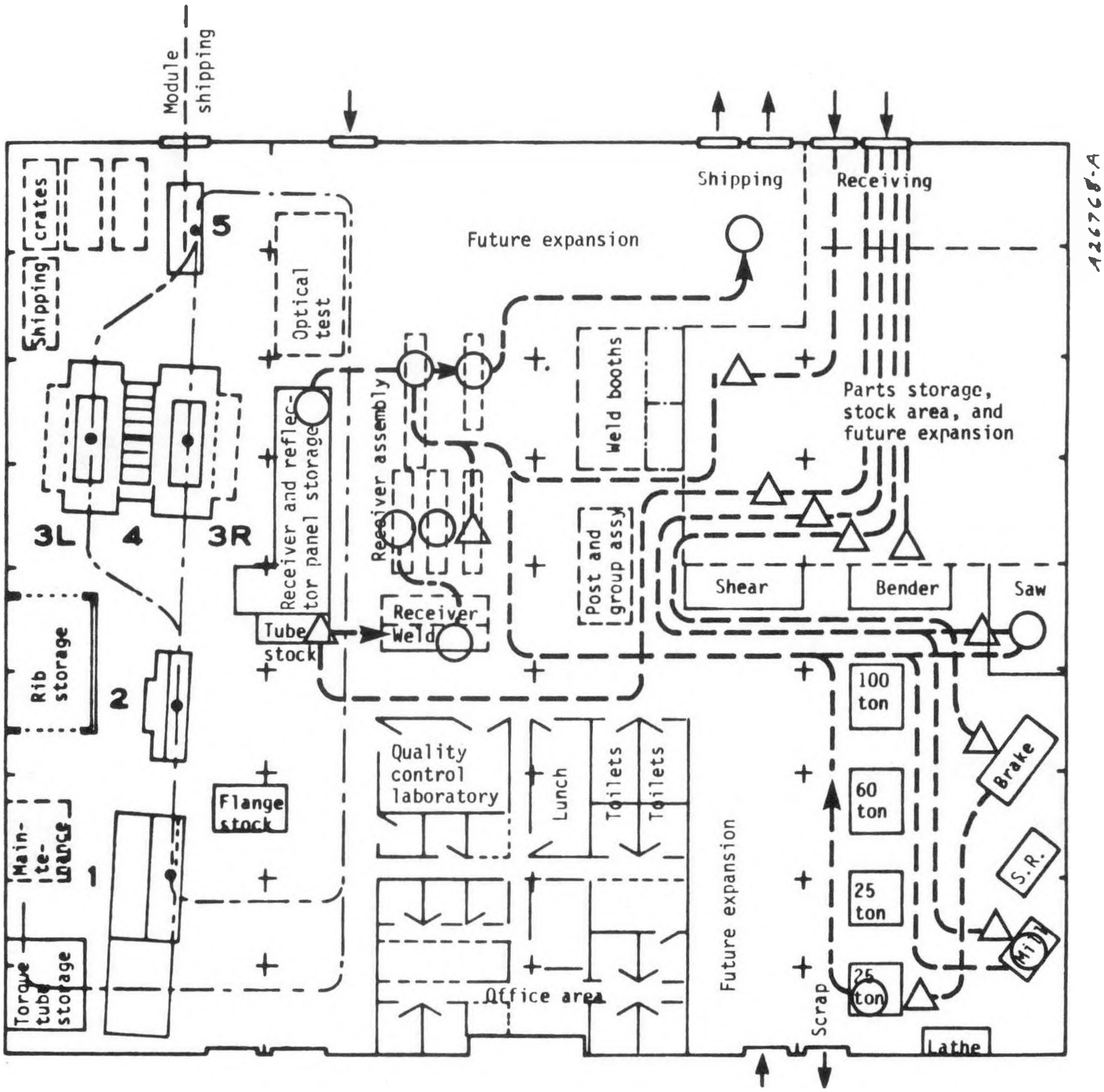


Figure 4-2(f). Flow of Components, Receiver Assembly

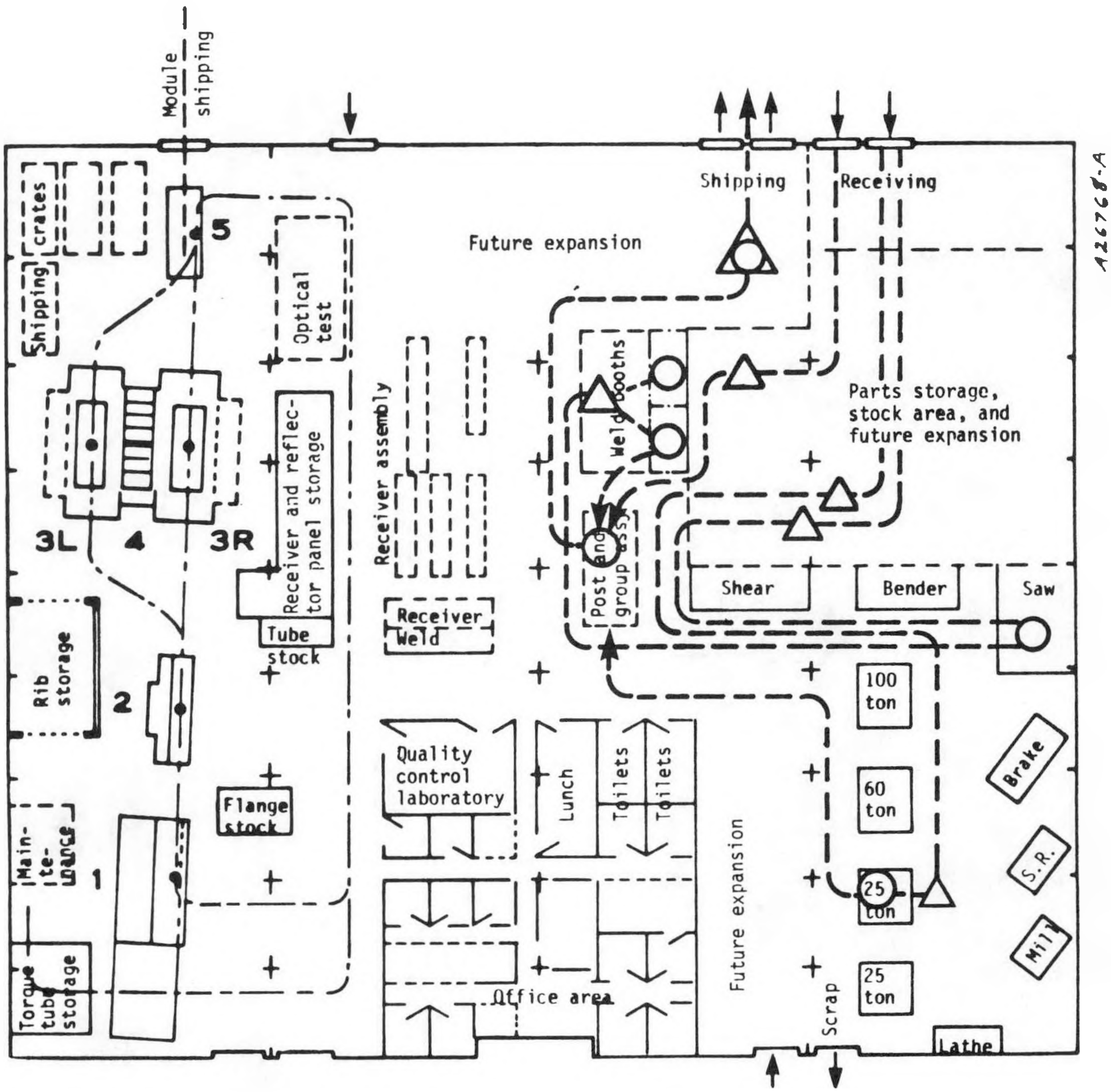


Figure 4-2(g). Flow of Components, Post Assembly

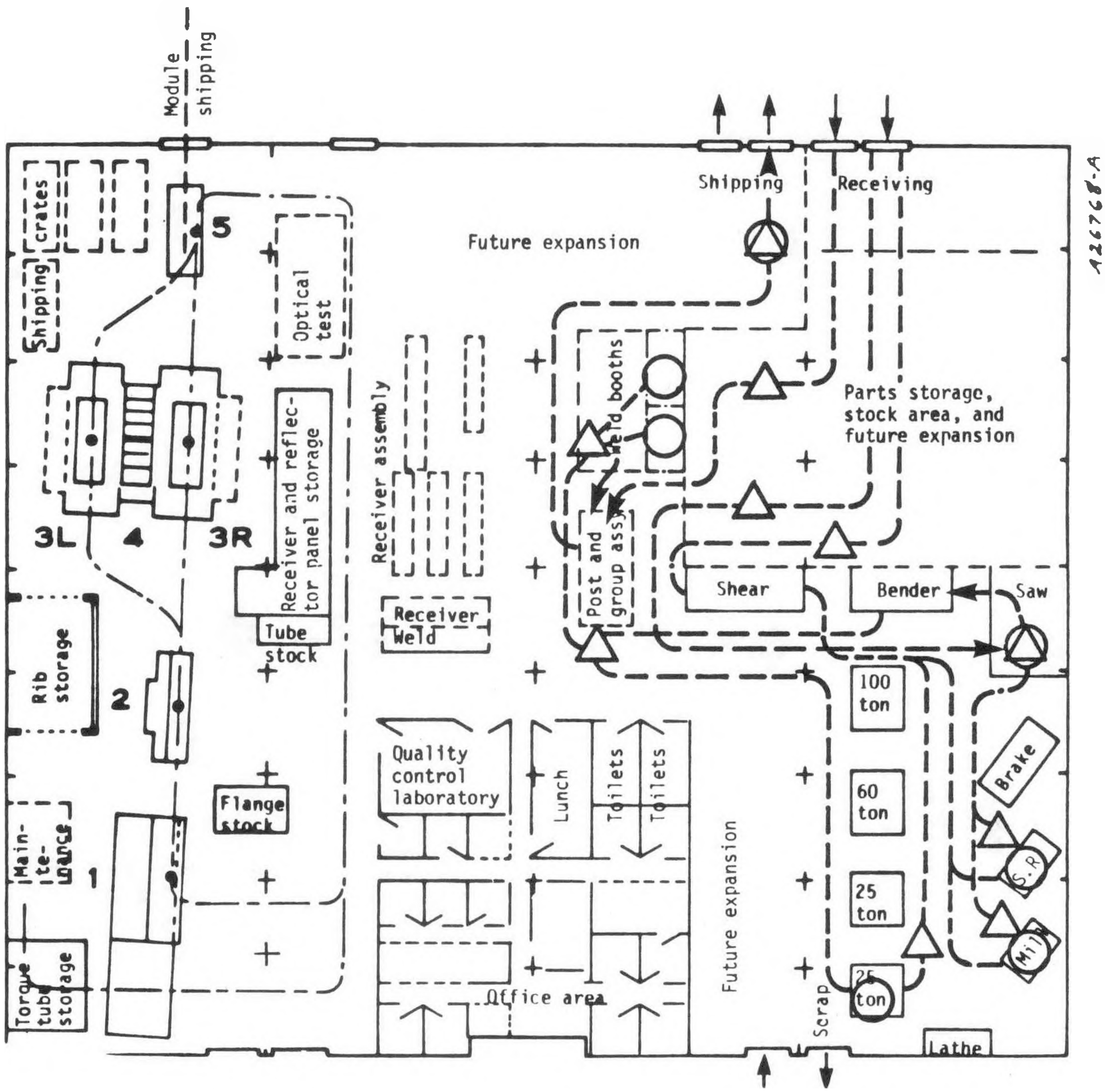


Figure 4-2(h). Flow of Drive String Specific Components

Table 4-11(a). Material Cost Estimates: Module Assembly

Part Number	Description	Number Required per Drive String	Cost per Item ($)	Scrap and Spoilage (percent)	Cost per Group ($)
212	Torque tubes	6	199.80	1.5	1,216.78
213	Rib flange	108	2.66	2.0	293.03
214	Center receiver support	6	1.35	2.0	8.27
211	Torque tube end cap	6	4.74	2.0	29.02
221	Pivot crank (fixed)	6	10.20	2.0	62.42
223	Key	12	0.20	2.0	2.45
226	Pivot crank (adjustable)	6	10.49	2.0	64.20
231	Rib	216	3.74	4.0	840.15
232	Rib stiffener	432	2.86	2.0	1,260.23
237	Rib angle	216	2.63	2.0	579.44
270	Center receiver support	6	2.12	3.0	13.11
236	Edge retainer	12	21.40	3.0	264.50
272	Module brace	24	1.24	1.5	271.92
245	Rectangular washer	216	0.24	2.0	52.90
243	Edge clamp washer	216	0.89	2.0	196.16
242	Edge clamp	72	2.44	3.0	180.95
--	Miscellaneous	lot	351.58	5.0	308.61
--	Reflector panels	36	133.35	5.0	5,040.63
--	Fasteners	lot	258.00	8.5	282.24
	Module Total				10,967.01

Table 4-11(b). Material Cost Estimates: Receiver Assembly

Part Number	Description	Number Required per Drive String	Cost per Item ($)	Scrap and Spoilage (percent)	Cost per Group ($)
310	Swaged receiver tube	5	39.65	2.5	203.21
315	Plain receiver tube	1	37.92	2.5	38.87
321	Extension tube	1	5.22	2.5	5.35
326	Support ring	34	1.45	1.5	50.04
328	Vibration damper	12	0.35	0.5	4.42
332	Support collar	36	17.50	2.0	642.60
325	Receiver glazing	12	19.72	2.5	242.56
342	Split glazing	4	15.00	2.5	61.50
344	End seal	12	1.78	1.5	21.68
345	Edge seal	24	1.82	1.5	44.34
350	End support	12	1.78	2.0	21.79
360	Center support	6	1.10	2.0	6.73
363	Center spacer	12	0.62	2.0	7.59
371	Fixed receiver insulation jacket	1	1.38	2.5	1.42
372	Fixed receiver insulation	2	1.74	2.0	1.78
Misc.	Threaded plug	5	1.15	2.0	5.87
--	Threaded cap	7	0.82	2.0	5.86
--	Split glazing end seal	12	0.63	2.0	7.71
--	Fasteners	lot	14.63	8.5	15.48
	Total				1,387.02

Table 4-11(c). Material Cost Estimates: Post Assemblies

Part Number	Description	Number Required per Drive String	Cost per Item ($)	Scrap and Spoilage (percent)	Cost per Group ($)
406	Support post tube	6	63.23	2.0	386.97
407	Support post base angle	12	3.69	2.0	45.17
411	Bearing base	6	17.50	2.0	107.10
412	Bearing base plate	6	11.14	2.0	68.18
415	Bearing cap	6	17.50	2.0	107.10
416	Bearing insert	12	12.80	2.0	156.67
420	Pivot shaft	4	67.00	3.0	276.04
421	End pivot shaft	2	56.00	3.0	115.36
441	Drive post tube	1	52.10	2.0	53.14
442	Drive post base angle	2	14.30	2.0	29.17
444	Drive post top angle	2	13.64	2.0	27.83
--	Fasteners	lot	4.89	8.5	5.34
	Total				1,378.07

Table 4-11(d). Material Cost Estimates: Group-Specific Assemblies

Part Number	Description	Number Required per Drive String	Cost per Item ($)	Scrap and Spoilage (percent)	Cost per Group ($)
505	Flexhose	2	369.72	2.5	757.93
510	Flexible sheating	2	3.90	3.0	8.04
511	Sheathing support	2	20.00	2.0	40.82
512	Flexhose insulation	8	2.49	3.0	20.54
521	Hose anchor support	2	2.36	2.0	4.81
522	Support channel	2	0.77	2.0	1.57
523	Hose anchor plate	2	1.89	2.0	3.85
--	Elbow	2	1.52	2.0	3.10
Misc.	Clamps, screw, ferrules, nuts	lot	4.20	8.5	4.59
450	Drive unit	1	1,865.00	1.5	1,892.98
451	Drive motor	1	450.00	1.5	456.75
	Total				3,194.98

procurement. It was therefore assumed that the material costs shown in the tables are representative of costs for the full single plant annual capacity.

4.4.2 Labor Costs

Labor requirements per shift for a single plant operating at 2.5 million ft^2/yr are shown in table 4-12. The number of people required for each category is shown for the assembly, machine shop, material handling, quality control, and shop maintenance. The total number of people required per shift for the various labor categories is shown in table 4-13. To achieve full plant capacity the cost per year for this labor for a two-shift operation is $2,676,000/yr.

4.4.3 Production Buildup and Learning Curve

The baseline cost for manufacturing collectors at the rate of 2.5 million ft^2/yr is the sum of material and labor cost from tables 4-11 and 4-13, as shown in table 4-14.

A conceptual production buildup rate was assumed for first one then two plants as shown in figure 4-3. The single-shift production rate begins at 100,000 ft^2/yr with the first plant at the end of 1981. The production rate is ramped up linearly throughout 1982 as the labor and management staff are hired. By the end of 1982 the production rate has reached 1 million ft^2/yr. In early 1983 a second shift is started and production is ramped up again but more rapidly as labor is hired. The single-plant maximum capacity is reached late in 1983. The go-no-go decision point for the second plant is at the end of 1983. If the decision is made to go ahead with the second plant, the year 1984 is allowed for setup of that plant while the first plant operates at full capacity. The second plant begins operation in 1985 and 9 months are allowed to build its production up to the maximum. A full production rate of

Table 4-12. Labor Requirements (per Shift)

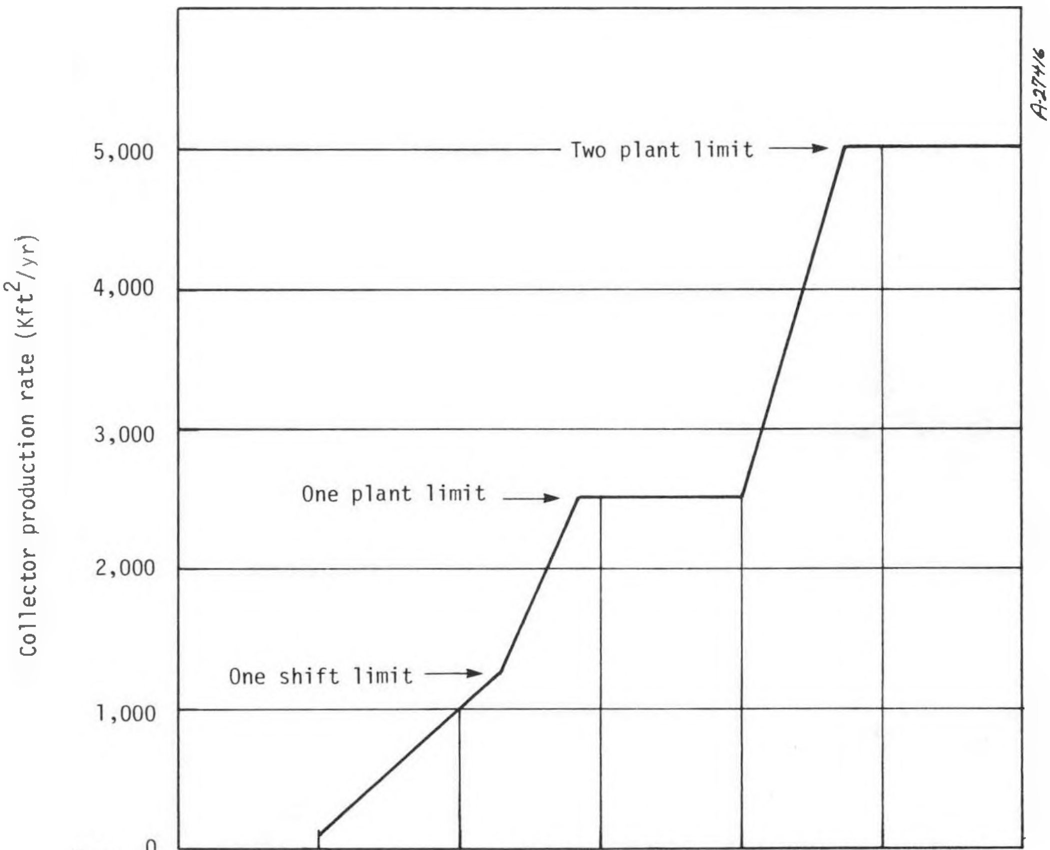
Station	Category	Number
Assembly Line		
1	Mechanical assemblers	2
	Leadman	1
2	Mechanical assemblers	2
	Leadman	1
3L	Mechanical assemblers	2
3R	Mechanical assemblers	2
3	Leadman	1
4	Mechanical assemblers	2
	Leadman	1
5	Helpers	2
	Journeyman	1
Receiver Assembly		
	Mechanics	6
	Welder	2
	Leadman	1
Post and Group Specific Assemblies		
	Mechanics	2
	Welder	2
	Leadman	1
Machine Shop		
Shear	Machinist	1
Bender	Machinist	1
Saw	Machinist	1
Brake	Machinist	1
Slip roll	Machinist	1
Mill	Machinist	1
Lathe	Machinist	1
100-ton press	Machinist	2
60-ton press	Machinist	2
25-ton press	Machinist	1
25-ton press	Machinist	1
Shop	Journeyman	1
Shop	Leadman	1
Shop	Helper	2

Table 4-12. Concluded

Material Handling		
Station	Category	Number
Receiving	Helper	4
Shipping	Helper	2
Collector loading	Helper	2
Stockroom	Helper	1
Tool crib	Helper	1
Quality Control		
	Inspectors	4
Shop Maintenance		
	Machinist	2

Table 4-13. Labor Costs (per Shift)

Category	Number	Estimated Fringed Wage ($/yr)	Cost ($K/yr)
Helper	14	15,000	210
Mechanical assemblers, mechanics	18	18,000	324
Machinist, Leadman, Welders	26	24,000	624
Journeyman, QC inspectors	6	30,000	180
Total	64		1,338



Year		1981	1982	1983	1984	1985	1986
Production Kft^2	Annual		520	1,720	2,500	4,040	5,000
	Cumulative		520	2,240	4,740	8,780	13,780

Figure 4-3. Production Buildup

Table 4-14. Baseline Collector Cost

Cost Element	Cost and Basis	Total Cost ($\$/ft^2$)
Materials	\$16,927.08 for drive string of six modules providing 840 ft^2	20.15
Labor	\$2,676,000/yr for one plant, double-shift operations	1.07
Total		21.22

5 million ft^2/yr is achieved by the end of 1985, by which time a cumulative output of 8.78 million ft^2 will have been produced.

A learning curve for cost reduction was developed for the collector product based on the cost elements summarized above, the production buildup rate of figure 4-3, and the projected 1985 collector cost per square foot presented in section 2. Figure 4-4 shows this learning curve in 1980 dollars as a function of cumulative collector aperture area produced in square feet. The collector cost per square foot is steady for the 4 months of production while the backlog of initial materials is consumed. After 4 months, costs steadily drop until the projected cost of \$8.26/ft^2 (see table 2-1) is reached in 1985 when the production rate is 5 million ft^2/yr and the cumulative production is 7.45 million ft^2. This cost reduction represents an 86 percent learning curve that experience has shown is representative of mass-produced products having a similar steel content.

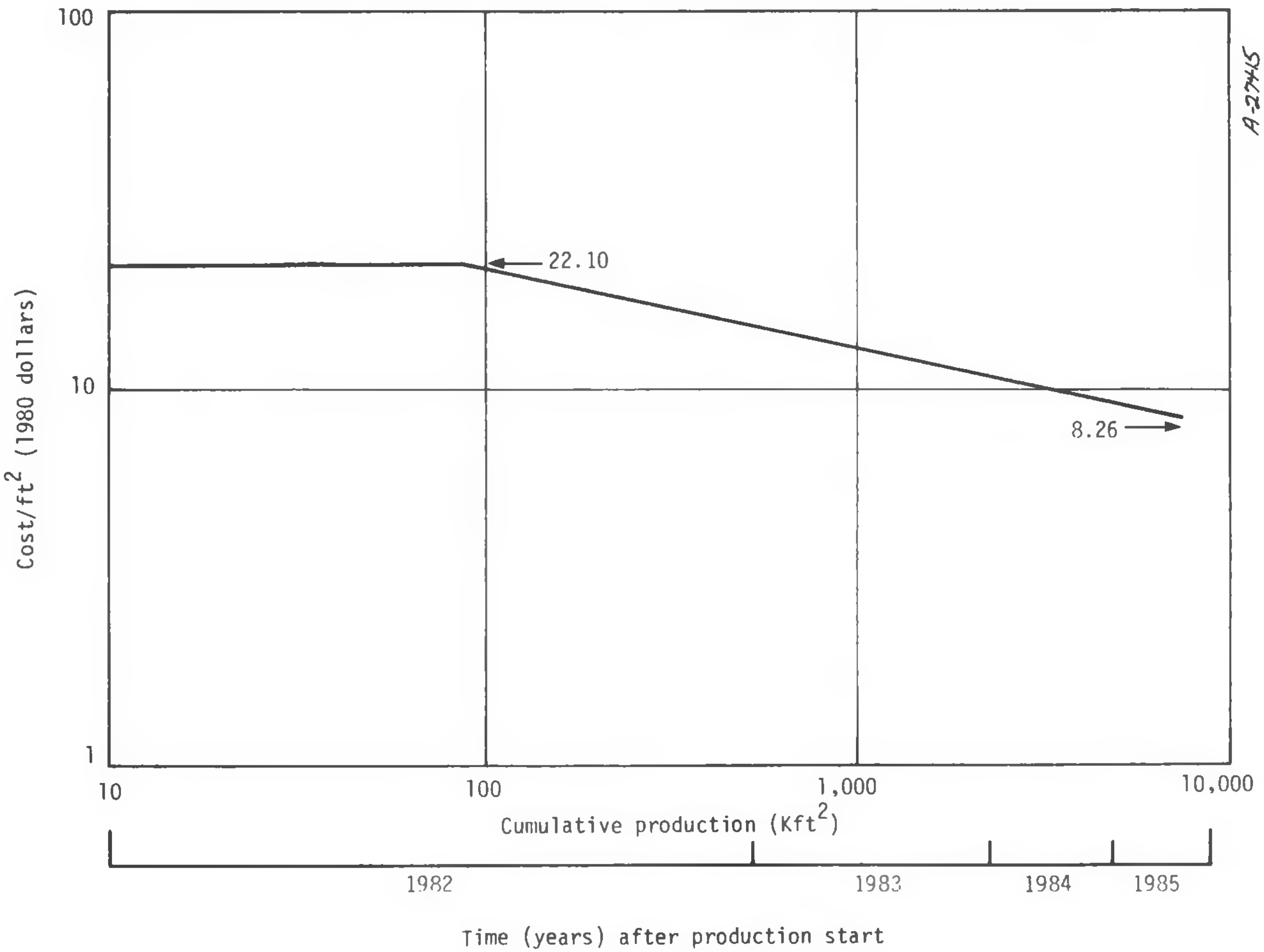


Figure 4-4. Learning Curve