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Solar Array Project

DOE/JPL-1012-53
Distribution Category UC-63b

Low-Cost Solar Array Structure Development

Abraham H. Wilson

June 15, 1981

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
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The JPL Low-Cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of low-cost solar arrays.

ABSTRACT

Early studies of flat-plate arrays have projected costs on the order of $\$50/m^2$ for installed array support structures. This report describes an optimized low-cost frame-truss structure that is estimated to cost below $\$25/m^2$, including all markups, shipping and installation. The structure utilizes a planar frame made of members formed from light-gauge galvanized steel sheet and is supported in the field by treated-wood trusses that are partially buried in trenches. The buried trusses use the overburden soil to carry uplift wind loads and thus to obviate reinforced-concrete foundations. Details of the concept, including design rationale, fabrication and assembly experience, structural testing and fabrication drawings are included.

ACKNOWLEDGMENTS

Many people at JPL have contributed toward this report. The author especially wishes to thank R. G. Ross, Jr. for his review of the work and for many suggestions, which are incorporated in this report.

Thanks are due also to D. M. Moore, who prepared the section on dynamic loads, and to Ron Miller of Boeing Engineering and Construction Co. for his contribution to that section.

Among the outside vendors (all in California) who contributed to this work are:

Area of Contribution	Organization	City
Frame	Kaiser Steel	El Monte
	[illegible]nauf	Los Angeles
Welding	L & W Manufacturing	South Gate
Press Brake	Tardiff Sheet Metal	Santa Ana
	Laurel Sheet Metal Products, Inc.	North Hollywood
Roll Formed Steel	California Steel & Tube	City of Industry
	North Star	Gardena
Treated Wood	Georgia Pacific	City of Industry
	Koppers	Wilmington
Wood Structures	Jones Lumber Co.	Los Angeles
Galvanox Paint	Cunningham Co.	El Monte
Trenching	Hood Corp.	Whittier
	Los Angeles Ditching Co.	Culver City
Gaskets	ANCO	El Monte

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SECTION I

INTRODUCTION

A. BACKGROUND

Previous studies funded by the Department of Energy's National Photovoltaics Program have identified the need to reduce the cost of array structures designed to support flat-plate photovoltaic modules in the field. This need is based on early estimates on the order of $50/m^2 (1980 dollars) for installed array structures (less modules), using the economies of scale associated with very large 200-MW photovoltaic central-station plants. At this cost, the structure represents nearly 40% of the projected cost of an array using 70¢/watt modules, and contributes approximately the same share of the total cost as the completed solar cells themselves do.

In an attempt to reduce the cost of large ground-mounted array structures, the Engineering Area of the Jet Propulsion Laboratory's Low-Cost Solar Array project has conducted a three-phase study. Its first phase, together with complementary studies sponsored by Sandia Laboratory, Albuquerque, New Mexico, identified a number of candidate low-cost array design concepts (References 1, 2 and 3). Of these, the frame structure shown in Figure 1 was selected as the most promising type of design for cost reduction.

In the second phase of the structure cost reduction effort the Jet Propulsion Laboratory (JPL) contracted with Bechtel Corp. to conduct extensive sensitivity studies of the frame design concept to identify optimum configurations, key cost drivers, and technology gaps. This work identified foundation costs and wind loading levels as major cost drivers, and the selection of wind loading design level as a major technology gap (Reference 4).

The third phase of the structure cost-reduction effort was carried out in two parts, to address the problem areas of foundation costs and wind-loading levels. This report describes an extensive hardware optimization activity carried out in house at JPL to identify means of reducing the cost of foundations and other structural elements of large ground-mounted arrays. The effort has succeeded in lowering the costs from the initial $50/m^2 to less than $25/m^2 total installed price exclusive of the modules. A complementary study has been carried out under JPL sponsorship by Boeing Engineering and Construction Co. to develop detailed design guidelines for selection of wind-loading level design (Reference 5).

B. NOMENCLATURE

Communicating accurately about array structures and costs has been and is a difficult problem. This report uses the array nomenclature and construction concept illustrated in Figure 2 and adopted in Reference 6. Individual solar cells are interconnected electrically and encapsulated in an environmentally protected package called a module. A module can be thought of as a sheet of glass with solar cells bonded to the lower surface. The module is not considered part of the support structure in the analysis of array costs,

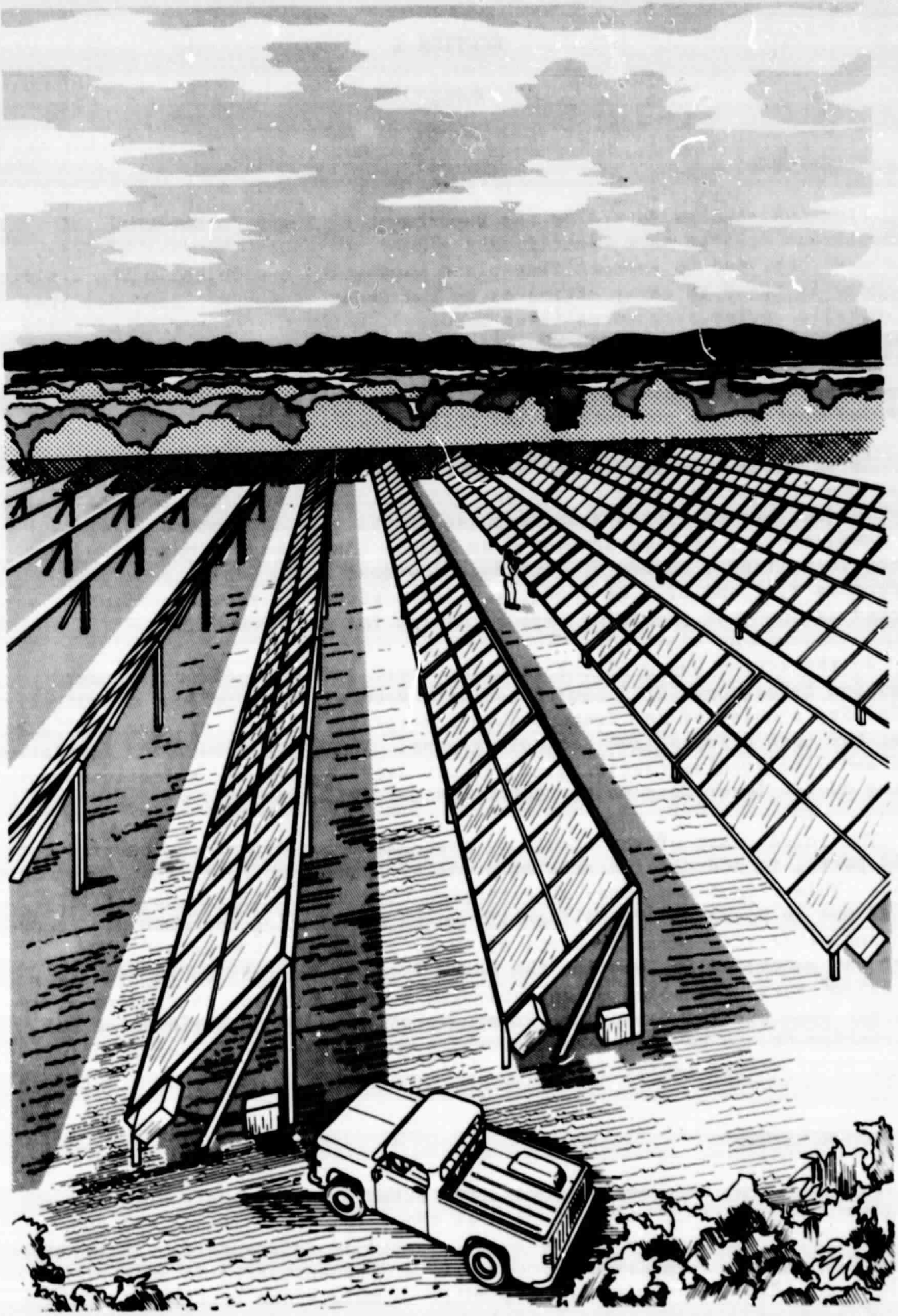

Figure 1. Solar Array Field Using Frame-Truss-Style Support Structures

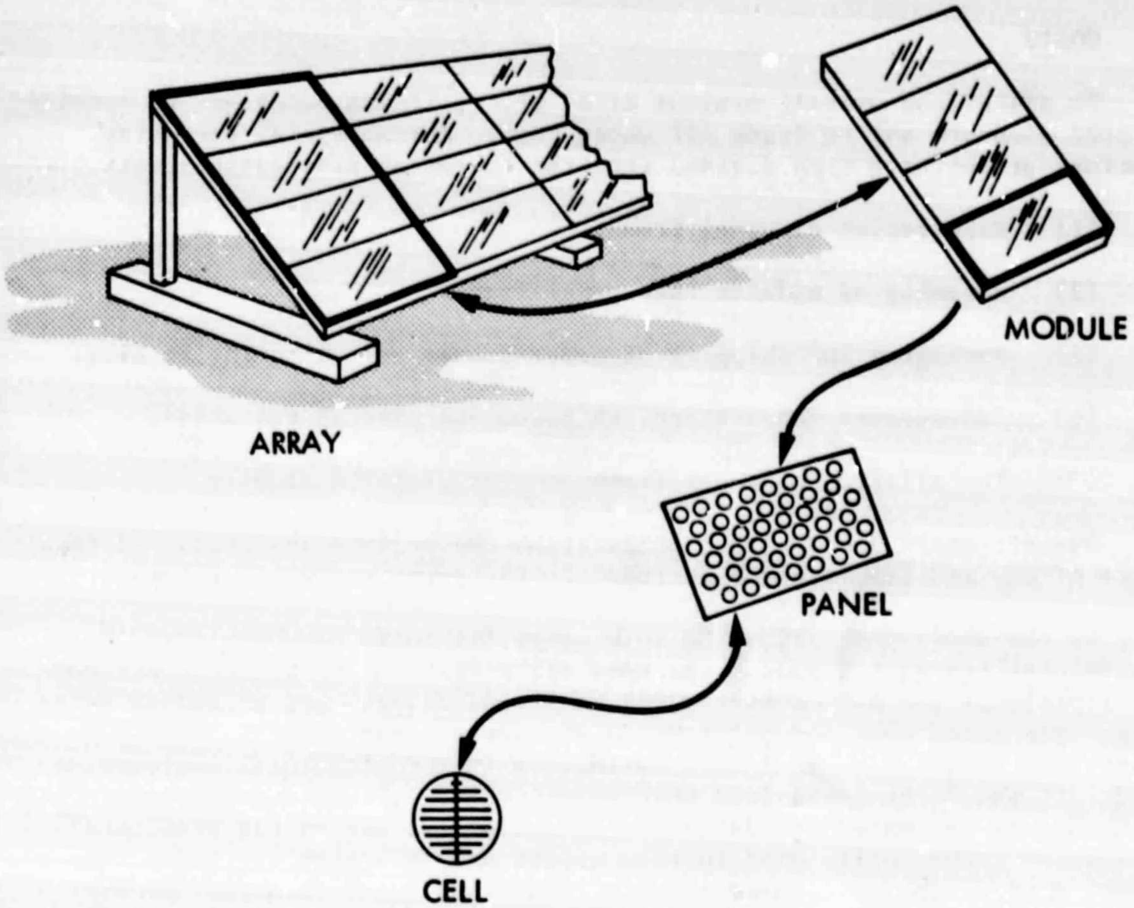

Figure 2. Flat-Plate Array Nomenclature

although it does act as a part of the total array structure in carrying loads, once installed. The size of the module affects the amount of structure required for its support and thereby influences the cost of the support structure. In this report, module size is treated parametrically, using 2 x 4-ft, 4 x 4-ft, and 4 x 8-ft modules.

The portion of the array other than the modules is referred to herein as the support structure and is subdivided into two major elements: the panel frame and the end supports (including foundations). This is different from many studies that do not include the panel frame as part of the array support structure. The concept of the panel frame considers the modules as being installed and interconnected in a large planar unit within a factory cost environment and then shipped to the field for final installation on the end supports to make a complete array. The fasteners used to secure the modules to the panel frame are considered to be part of the panel frame. These include hold-down straps and hardware. The gasket around the perimeter of the module, if used, is assumed to come with the module. Because the panel frame integrates to a high degree with both the modules and the end supports, its optimization requires a systems approach to the total array design.

C. COSTS

To achieve an overall minimum array price, it was necessary to consider all cost elements and to trade off among them. For analysis, the array structure prices have been divided into the following five categories:

(1) Fabrication of panel frame.

(2) Assembly of modules into panel frame.

(3) Packaging and shipping of panel frames and uncrating at site.

(4) End-support fabrication, shipping and site installation.

(5) Installation of panel frames on end supports at site.

Overall costs such as site preparation and engineering fees, and the prices of the modules, are not included in the array structure totals.

In the above discussion the term price (vs cost) has been used to signify that the quoted amount includes all profit and marketing costs and thus represents the bottom-line price to the purchaser, not including sales taxes. The terms cost and price are used more or less interchangeably in this report, due to the nature of cost estimating in the structural engineering field. It should be emphasized that unlike solar cell mass production costs, which must be estimated for future large factories, all of the structural fabrication technologies used in this effort are in active use today. As a result, most of the costs used in this report are based on actual vendor quotations for delivery in 1980. (Vendor quotations, by their nature, include profit, marketing costs, etc.)

D. UNITS

English units have been used in this report to facilitate discussion with certain vendors and metric units to facilitate comparison with other reports on array-structure costs.

SECTION II

DESIGN EVOLUTION

To identify additional means of reducing the cost of flat-plate array structures, a systems approach with multiple design, fabrication and test cycles was followed. Past experience at JPL has pointed up the extreme value of full-scale fabrication together with laboratory and field testing. All design and cost elements from materials selection, fabrication, assembly, shipping and installation were included so that the total installed cost could be minimized. Substantial use was made of private-sector companies specializing in each area of construction and installation. These firms provided quotations and made many suggestions on ways to reduce the cost. Promising suggestions were combined with fabrication and test results at each stage of the design evolution. The final design presented in this report represents the point where large-scale field application is needed to identify further cost-effective design improvements.

The following sections describe the cost reduction and design evolution of each of the major array support structure cost elements.

A. END SUPPORTS AND FOUNDATIONS

1. Conceptual Design Development

The Bechtel study (Reference 4) identified the foundation as a major cost driver and focused initial attention on means of reducing these costs. A review of foundation design practices indicated that a major foundation cost driver was the reinforced concrete required to carry overturning-moment loads caused by wind forces acting on the array. An initial approach to lowering foundation costs was subsequently formulated, based on the fact that the wind loads act predominantly as pressure loads normal to the array surface. Therefore, if the primary support members are positioned normal to the array surface, the load in these members and in their foundations will be predominantly tension and compression, and moment loads will be minimal. A disadvantage of this approach is that the structural support members must be installed at an angle, as shown in Figure 3.

To test this initial concept in the field, a structure was fabricated and an auger was used to drill the slanted foundation holes. This field testing found a substantial problem in removing rocks from the holes, and led to recommendations that a backhoed trench could be dug much faster and would be less expensive.

Consequently, a second support structure concept was devised based on steel truss end-supports designed to be emplaced in two backhoed trenches approximately 1.5 feet wide, 3.5 feet deep and 13 feet long. Although the truss members were initially sized to replace the reinforcing in the concrete, it became evident that the concrete might not be necessary if the weight of the overburden soil could be utilized to carry the array uplift loads. These ideas led to the design, construction and field testing of the second support structure shown in Figure 4.

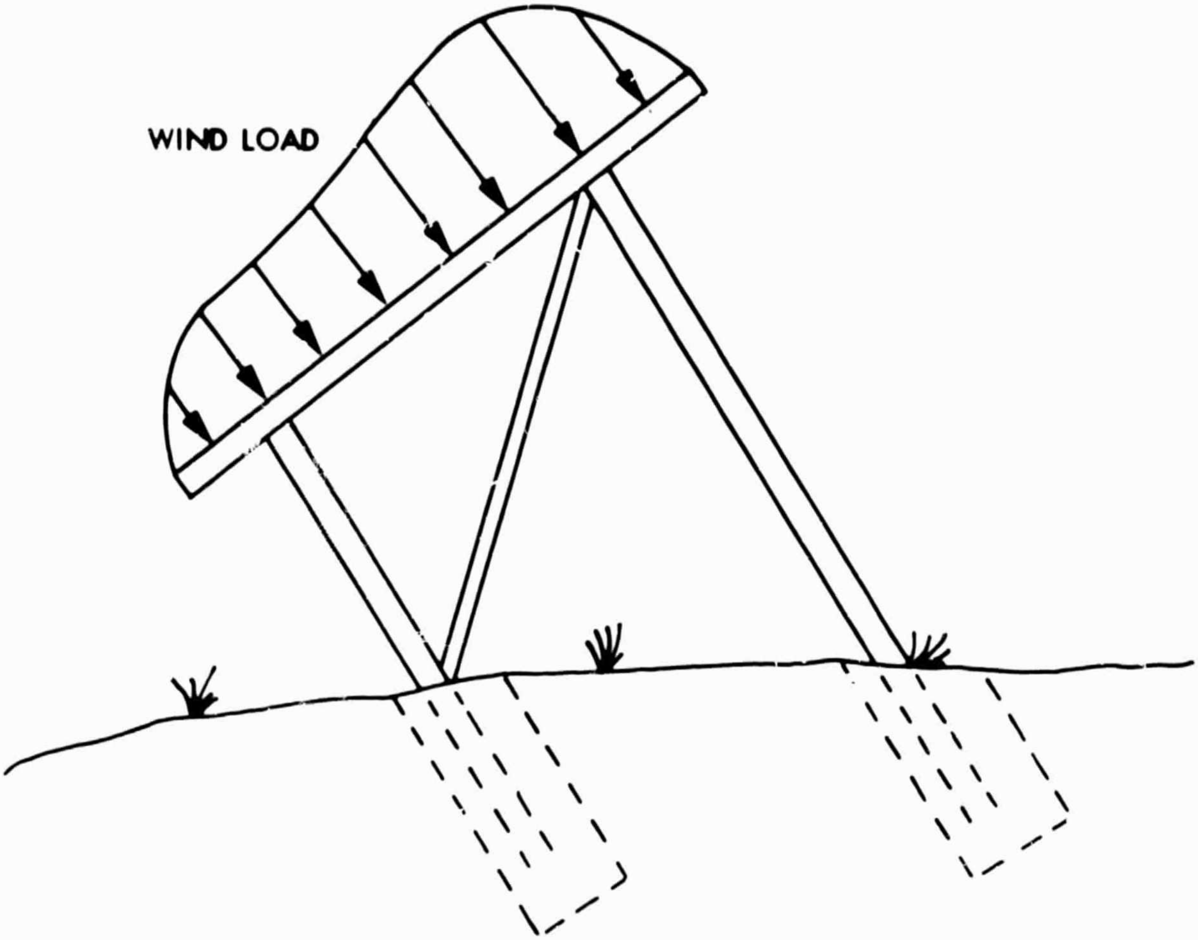

Figure 3. Initial Minimum-Moment Foundation Design

The results of this second phase of testing verified that the concrete could be successfully eliminated and that the end support costs could be reduced from approximately $40/m^2 for reinforced concrete to around $8/m^2 for the direct burial truss.

2. End Support Optimization

Because of the interaction of the end supports with the balance of the array, further design optimization was carried out in conjunction with the array as a whole. Five key areas were addressed:

(1) Steel vs wood construction.

(2) Site assembly vs field assembly.

(3) Bolted vs nailed vs welded construction.

(4) Environmental protection: post-galvanizing (hot dip), pre-galvanized sheet, Wolmanizing (for wood).

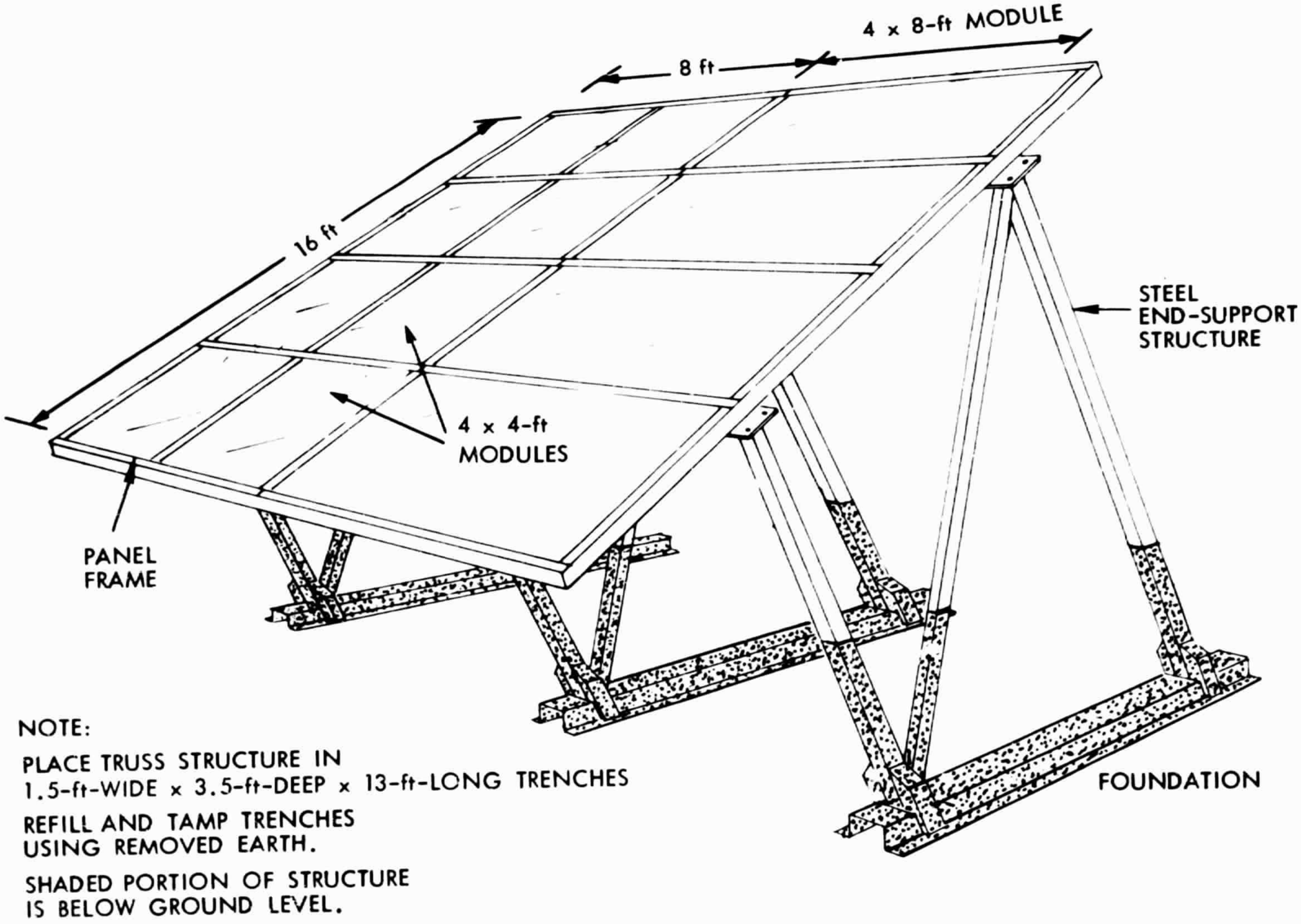

Figure 4. Solar Array Structure Based on Buried Steel Trusses and 16-ft-High x 8-ft-Wide Panel Frames

(5) 16-ft vs 8-ft slant height panel frames and corresponding end-support spacing.

a. Steel vs Wood. Simultaneous optimization was carried out on candidate end supports constructed of steel, wood, and a combination of both to determine which would lead to the least cost. End supports of each material were fabricated, tested and optimized using vendor recommendations and price quotations. Optimized wood construction was found to be cheaper than the steel construction by a factor of nearly 2. In addition, the wood showed a substantial structural load margin due to the fact that the minimum size of lumber recommended for such an application is structural-grade 4 x 4s. Trusses constructed using 4 x 4 lumber were determined to be capable of carrying array loads in excess of 60 lb/ft^2 under typical field test conditions with both normal and sandy soil (Figure 5). This provides an impressive load margin over typical 20- to 30-psf load requirements, and effectively eliminates wind-loading level as a cost factor for the end supports.

b. Site vs Field Assembly. The high cost of field labor places strong emphasis on the use of factory fabrication and assembly steps. The key counterbalancing force is the cost of shipping bulky built-up structures. To allow disassembly of the end supports for shipping, the initial wood end supports used bolted construction based on members pre-cut and drilled at the factory. The completed array in this case was 16 ft in slant height with end supports on 8-ft centers. As a result of total array optimization, the configuration was changed to an 8-ft slant height with end supports on 20-ft centers, as shown in Figures 6 and 7. This change reduced the number of end supports required by a ratio of 16:20 = 0.8 and also allowed the use of smaller end supports, which could be shipped assembled, 48 to a standard 40-ft truck. This change also allowed the cost-saving factory use of galvanized-steel nailing plates and power nailing. Tests using the nailed construction showed no failures with loads corresponding to array wind loads of more than 60 psf.

c. Environmental Protection. Discussions with industry representatives indicated that achieving 30-year life for a treated wooden structure in a buried or exposed environment is not difficult. In this study the cost of 0.4 lb/ft^3 Wolmanizing has been included for all wood used. The trademark Wolmanized is the property of Koppers Co. Inc., and its licensed treating companies. Wolmanized lumber and plywood meet the American Wood Preservers Association (AWPA) Standard P-5 and Federal Standard TT-W-550. Koppers recommends that the amount of Wolman CCA preservative injected into the wood be 0.4 lb/ft^3 of wood. Wolmanized pressure-treated lumber is relatively inexpensive, will not rot, and is termite-proof.

Koppers Co. has had substantial and excellent long-term experience with Wolmanized wood products in destructive environments, including mine ties and timbers and telephone poles in bogs and swamps. Before the use of Wolmanized wood members, mine timbers often had to be replaced after two to three years.

Figure 5. Static Load Testing of Wooden-Truss End-Support Structure

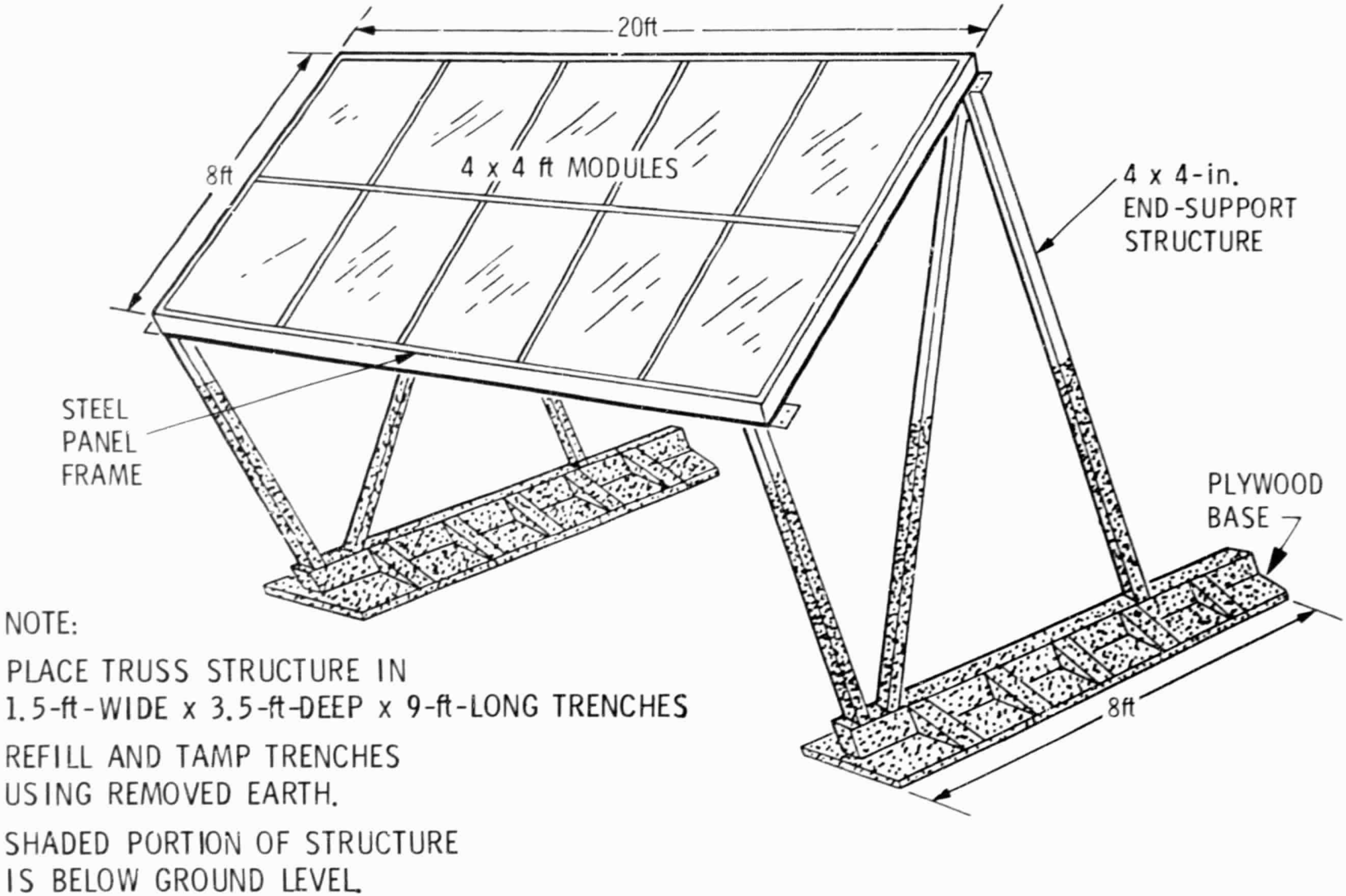

Figure 6. Solar Array Structure Based on Buried Wooden Trusses and 8-ft-High by 20-ft-Long Panel Frames

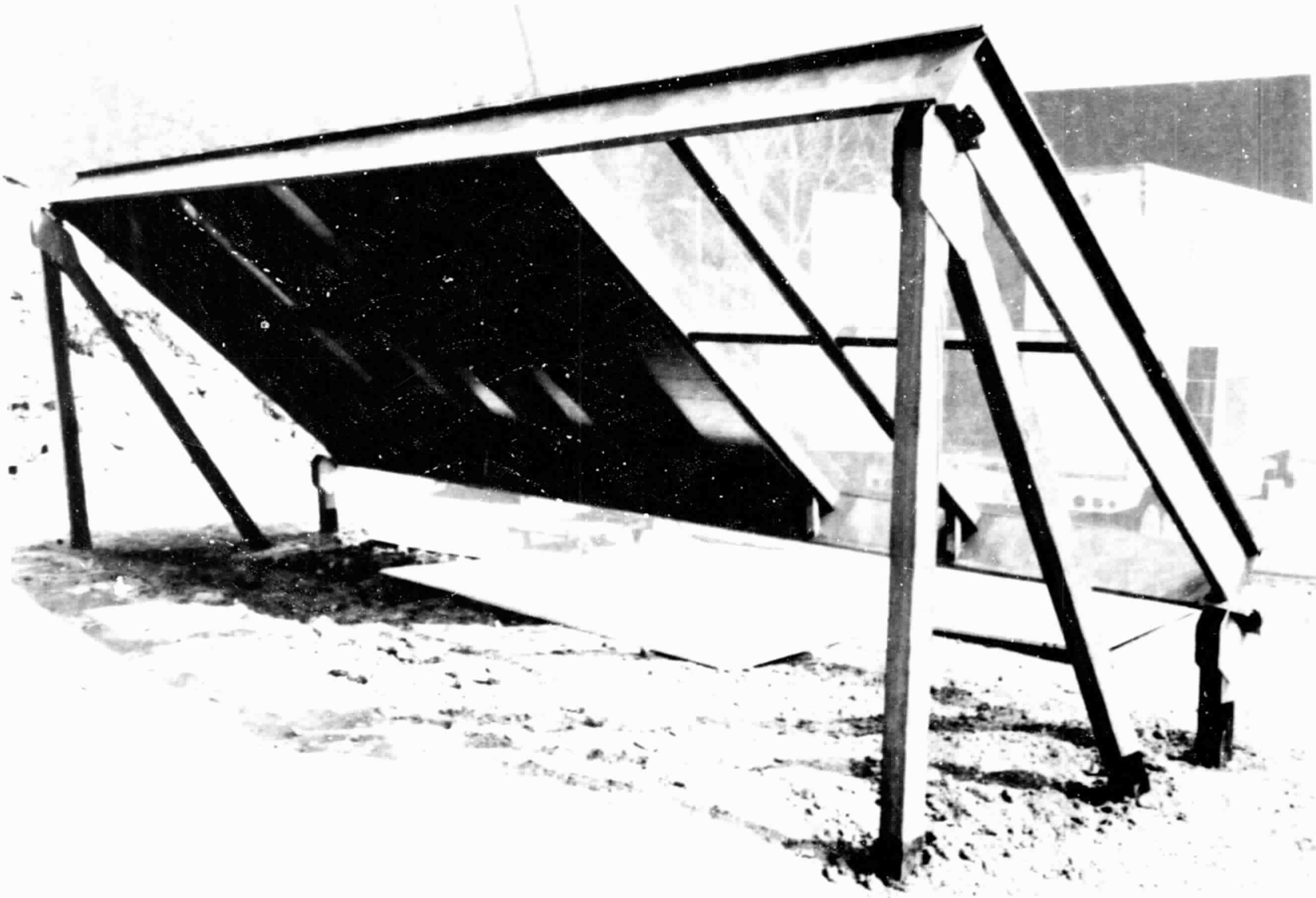

Figure 7. Prototype Frame-truss Structure Demonstrating Adaptability to Various-Sized Modules

With the use of Wolmanizing, the life is now measured in decades. Similarly, of thousands of Wolmanized telephone poles set in sandy soil, bogs and swamps in a project more than 30 years ago, not one has been removed because of biological degradation.

d. Field Installation. As shown in Figure 7, each panel frame is supported by two end-support structures. Each end support, with the exception of those at the ends of the arrays, supports two panel frames. The number of end supports for a row of panel frames is then (n + 1) where n is the number of panel frames. Assuming 20 panel frames in a row, the number of end supports required is 21, a configuration that provides reasonable access. Cost calculations therefore assume 5% more end supports than panel frames.

The trenching contractors consulted considered the task of installing an end support in the trench and then filling and tamping with earth to be very similar to work that they have done in the past. Several cost quotations on the task were received. The one qualification was that the ground be trenchable, since in certain soils the presence of rock or other substances precludes the effective use of a backhoe or a trencher. In those cases a different foundation would be required.

Location fixtures would be used by the trenching contractor to assure proper positioning of the end-support structures to accept the panel frames. With the guidance of technical representatives of the module manufacturer, the module-loaded panel frames would be installed on the end-support structures with four bolts. Care is necessary in handling and positioning the panel frame.

3. Final End-Support Design Summary

The final design of the array end supports (shown in Figure 6) uses 4 x 4-in. construction-grade lumber for the truss members together with 16-gauge galvanized-steel nailing plates and 16-penny galvanized nails for the truss assembly. Array uplift forces are carried by a plywood base attached to the below-ground horizontal truss member by galvanized-steel brackets (see Figure 8). Costs of materials and fabrication of the end supports are shown in Table 1. Detailed fabrication drawings are presented in Appendix A.

B. PANEL FRAME

1. Design Development

The concept of a panel frame stems from the need to support the individual modules and to transfer their loads to the ground through the end supports. To eliminate redundant structure and minimize field installation labor, the panel frame is designed to provide peripheral support to each module and allows module installation in a factory. The fully assembled panel frame with modules installed and electrically interconnected is then shipped to the field for installation on the end supports.

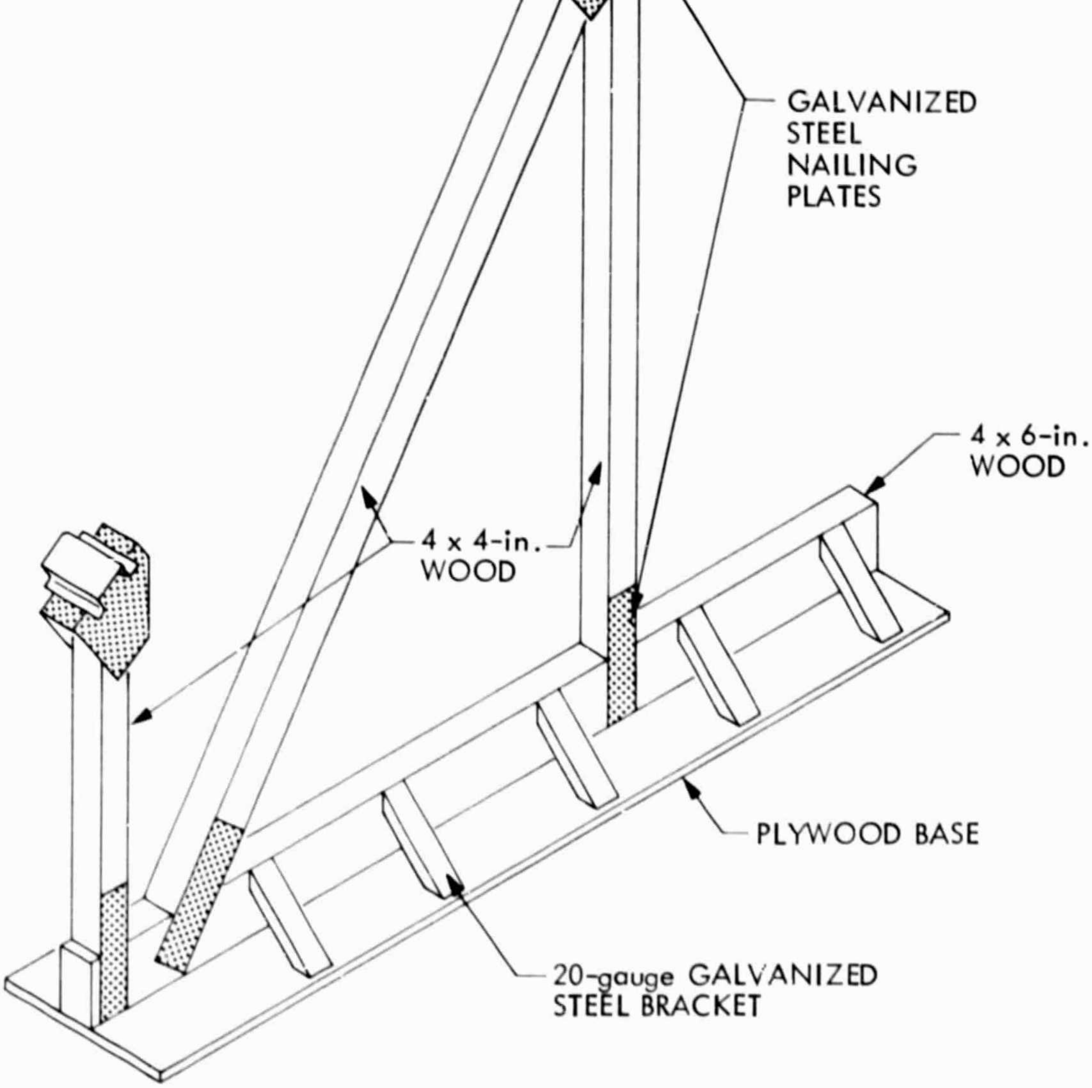

Figure 8. Final Wooden-Truss End-Support Design

This general panel concept was originally proposed by Bechtel (1) and has been adopted and further optimized in this study. The final design described below incorporates low-cost sheet-metal constuction and configuration to lower module installation costs. At $11/m^2$ the total panel cost is 40% less than previous designs.

Table 1. End-Support Cost Breakdown (Based on 1000 End Supports)

Item No.	Quantity	Part or Identifying No.	Nomenclature or Description	Specification	Material or Note	Material Cost ($)	Fabrication Cost ($)
1	1	10097882-101	Front column	4 x 4 x 47.38 in.	Const. gr. S4S	6.47	0.20
2	1	10097882-102	Rear column	4 x 4 x 112.62 in.	Const. gr. S4S	8.06	0.20
3	1	10097882-103	Diagonal brace	4 x 4 x 127.15 in.	Const. gr. S4S	9.00	0.40
4	1	10097882-104	Base beam	4 x 6 x 96 in.	Const. gr. S4S	8.40	0.20
5	1	10057882-105	Plywood base	16.0 x 96.0 x 0.50 in.	CDY 5-ply	6.45	2.00
6	3	10097882-106	Plate	16 ga (.064) stl	Galv. sheet G 90	0.72	1.50
7	3	10097882-107	Plate	16 ga (.064) stl	Galv. sheet G 90	0.72	1.50
8	10	10097882-108	Channel brace	18 ga (.052) stl	Galv. sheet G 90	1.98	3.80
9	1	10097882-109	Front bracket	16 ga (.064) stl	Galv. sheet G 90	0.85	1.80
10	1	10097882-110	Rear bracket	16 ga (.064) stl	Galv. sheet G 90	1.48	2.00
11	2	10097882-111	Hat section pad	10 ga (.138) stl	Galv. sheet G 90	1.84	1.80
12	4	10097882-112	Bar	1.00 x 10 ga (.138) x 3.25	Galv. sheet G 90	0.04	0.50
15 - 19 22 - 25			Hardware			1.90	0.00
					TOTALS:	47.91	15.90

Douglas Fir S4S, Wolmanized or equal, to .4 lb/ft^3 penetration; plywood also Wolmanized to .4 lb/ft^3.

Assembly of Items 4, 5 and 8 to form base	$ 4.50
Assembly of Items 10, 11 and 12 to form top pad	0.90
Assembly of Items 9, 11 and 12 to form bottom pad	0.90
Balance of structure, nailing operations	4.50
Total cost of support structure f.o.b. vendor plant	$10.80

1.05 supports/panel frame: 1.05 ($47.91 + $15.90 + $10.80) = $78.34 per array section, or $5.27 per square meter.

2. Panel Frame Optimization

As with the end supports, the panel frames were optimized using multiple design, fabrication and test iterations. Specific areas included:

(1) Sheet-metal constuction.

(2) Module interface design.

(3) Fabrication techniques.

(4) Structural strength.

(5) Environmental protection.

(6) Packaging and shipping.

a. Sheet Metal Construction. Review of earlier panel-frame designs indicated a possibility of reducing fabrication costs by using structural members custom-fabricated from steel sheet instead of using standard hot-rolled members. Custom members were favored because of the high degree of repetition within a large array field and the relatively few member designs required. The automotive industry is an example of the use of such techniques for chassis members.

Initial consideration focused on tapered beams, but was soon redirected due to poor material utilization (large fraction of scrap). Constant cross-section rolled sheet beams appeared to be preferable.

Based on favorable estimates for rolled sheet beams, an early prototype 16 x 8-ft frame was fabricated at JPL using 20-gauge galvanized steel box beams with support points 4 feet from the ends, as shown in Figure 4. This design was load-tested to 50 psf with no failures and then was shown to several steel fabricators for comment and cost estimates. Kaiser Steel engineers suggested that the use of an open C section instead of the box section would substantially reduce fabrication cost.

Based on these comments, a new frame was fabricated at JPL, incorporating Kaiser's suggestions. C sections 4.5 in. deep with 1.5-in. flanges and 0.5-in. lips were formed from 18-gauge steel for the 16-ft members and from 20-gauge steel for the 8-ft members. When this structure was load tested, failure due to buckling of the compression flange occurred at an acceptable 48 psf.

Estimates of production costs were obtained from Kaiser Steel for two versions of the frame: one accommodating four 4 x 8-ft modules and one accommodating eight 4 x 4-ft modules. Based on 50,000 frames for 4 x 8-ft modules, the f.o.b. price of the frames crated for shipment was \$9.80/m^2, a 50% reduction from previous designs.

b. Module Interface Design. The present concept is to have the manufacturer of the panel frames supply them to the module manufacturer, who will install the modules in the panel frame. The module manufacturer will then transport the module-loaded panel frames to the site for installation. When the above-described panel frame was assembled in a complete array in April, 1980, it was found difficult to change modules, and difficult to locate modules properly on the frame. To overcome these problems, two changes were made. The 16-ft slant height (Figure 4) was reduced to 8 ft (Figure 6) to improve field access, and the flange on which the module is supported was changed to provide a recess to locate the module and to increase ease of installation (Figure 9). The length or span was increased from 8 feet to 20 feet. This greater span between end supports required a much deeper section on the long beams, but the cost of the panel frame per square meter of module was affected only slightly. This was more than offset by the savings due to the reduced number and size of end supports and easier assembly.

Figure 9 illustrates the frame-member cross sections with frameless module interface detail. The module is constructed and equipped permanently with a mounting gasket and light-gauge sheet-metal bezel. The bezel is not designed for structural support, but it protects the edge of the glass from hailstone impact and provides low-cost protection of the vulnerable module edge during handling and field replacement. It also provides a convenient electrical ground point for testing individual modules for electricai circuit isolation from ground.

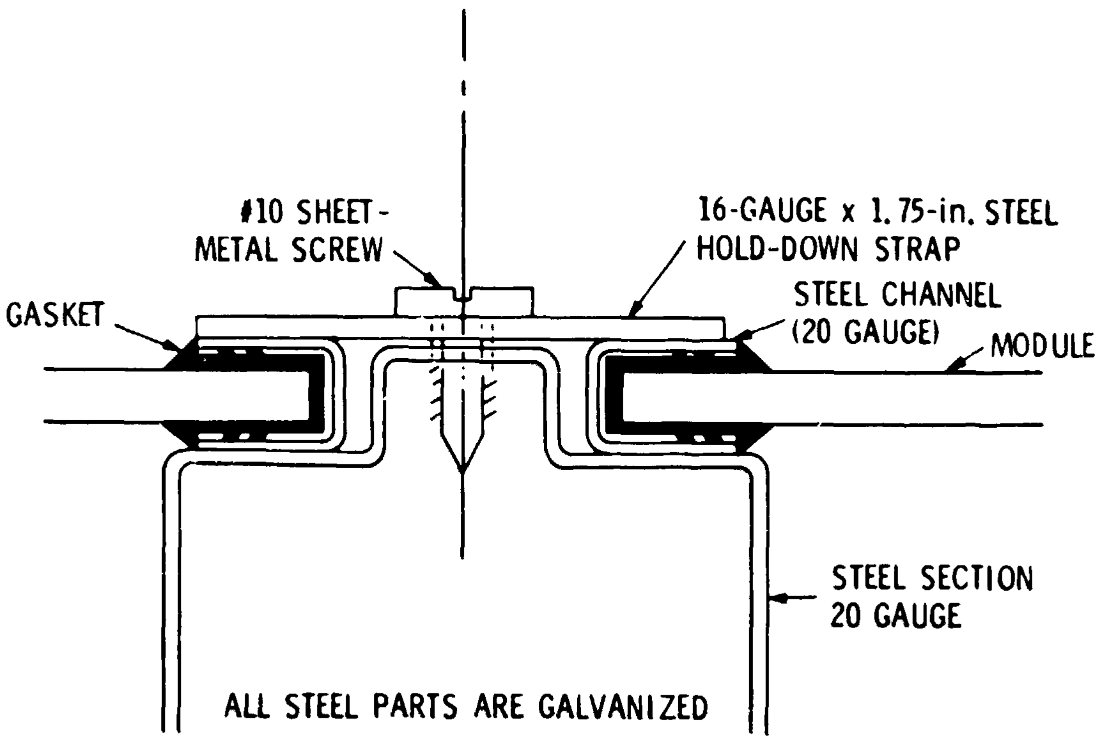

Figure 9. Module-Panel Frame Interface Design

The panel-frame top surface, to which the hold-down strap is mounted, is a hat section, slightly shallower than the module bezel. In this way the hold-down strap cannot overload the module and serves as a pocket for module location, which greatly simplifies module assembly in the panel frame.

c. Fabrication Techniques. The various sheet-metal sections used to fabricate the panel frame can be made by roll forming or by using a press brake. The price per foot of the section is less in the case of roll forming, but the initial tooling cost is greater. Based on discussions with fabricators, the break-even point is about 20,000 feet for members 2 ft, 4 ft or 8 ft long.

Referring to JPL drawing 10097883 (Appendix A): in each frame using ten 4 x 4-ft modules, there are two 20-ft pieces of Section A, two 8-ft pieces of Section A, four 8-ft pieces of Section B and five 4-ft pieces of Section C. This amounts to 56 ft of Section A, 32 ft of Section B and 20 ft of Section C per panel frame.

For 500 frames this would require 28,000 ft of Section A, 16,000 ft of Section B and 10,000 ft of Section C, an average of about 12,000 ft of each section. At this point, roll forming and press-brake costs would be about equal. The cost per foot of section would be higher for roll forming, but the cost to splice short sections made on a press brake to make each 20-ft member would offset this disadvantage.

All of the frame members are joined by conventional welding.

d. Structural Strength. Recent wind-tunnel tests (Reference 5) conducted by Boeing Engineering and Construction Co. for JPL indicate that for a reference wind of 100 mph, arrays that are located behind a suitable fence or behind each other will experience maximum pressure loadings of about 15 psf. This value may be as high as 25 psf at the exposed end of an array, but exists only for a short distance along the array. The average pressure on such an array would be about 20 psf.

Proof tests on the 8 x 20-ft panel frame showed that it can withstand loads of more than 35 psf normal to the panel frame when applied upward and more than 40 psf when applied downward (see Figures 10 and 11). The lower strength associated with the uplift loads reflects the lower buckling strength of the lower beam flange, which is not stiffened by the module and its hold-down clamp. When the panel dead-weight load of approximately 5 lb/ft^2 is included, the resistance of the panel to uplift or downward wind loads is seen to be about equal. Also, in the case of the 8-ft-slant-height panel frame, the wind load is only about 80% of that on a 16-ft-slant-height panel frame, using the 1/7 power law relating wind velocity to height above ground. These factors cause the effective wind load tolerance of the 8 x 20-ft panel frame to be about equivalent to that of the 16 x 8-ft frame.

Although a moderate margin exists between the strength at the panels (35 lb/ft^2) and typical wind loading levels (20 lb/ft^2) it was not considered cost effective to reduce the structural strength further because such a

Figure 10. Static Loading Test of Panel Frame Using Uniformly Distributed Sand (Downward Load)

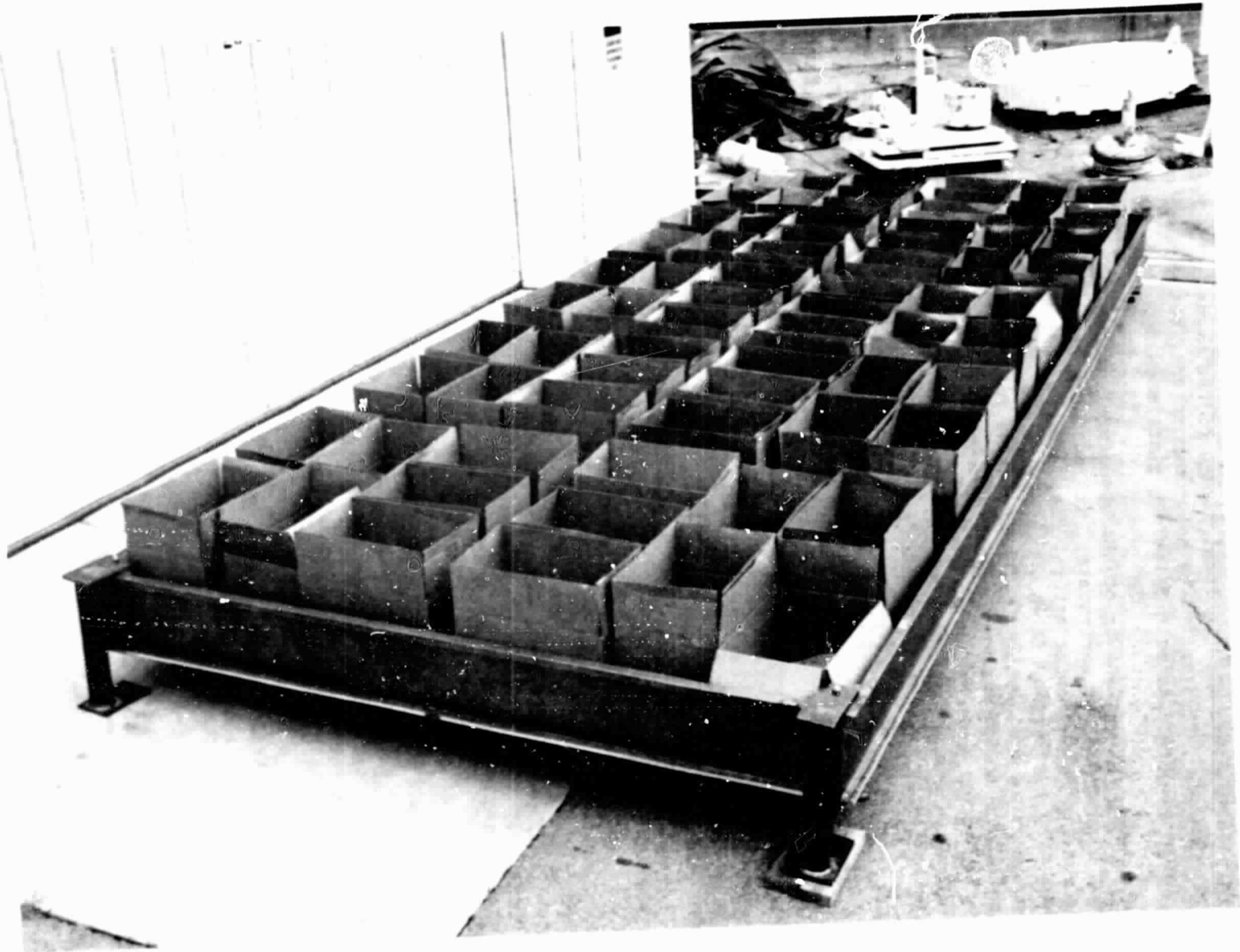

Figure 11. Static Loading Test of Panel Frame to Simulate Maximum Wind Uplift Forces

reduction corresponds to only a small cost saving, and would increase risk of failure due to snow, ice and handling loads. This is particularly true because of the thinness (0.052 in.) of the primary 20-ft beams and the sensitivity of the buckling failure mode to local damage of the beams. The total weight of the 8 x 20-foot panel, including hold-down straps, but without modules, is only 295 lbs. Complete with 3/16-inch glass modules, it is only 755 lbs.

Finally, understanding of the structure's response to dynamic loads, such as wind gusts and earthquakes, was needed. It was decided to shake-test the structure to determine natural frequencies, mode shapes, and damping ratios. The test set-up is shown in Figure 12. Figure 13 shows the mode shapes, natural frequencies (f), and damping ratios (r) for the first six modes. The mode shapes shown are taken from a finite-element dynamic analysis of the structure made by Boeing Engineering and Construction Co., which is performing an analytical study of the response of this and other photovoltaic array structures to wind gusts as follow-on work to that discussed in Reference 5.

The measured frequency for the lateral-sway mode was approximately 6 Hz, higher by a factor of $\sqrt{2}$ than the 4-Hz frequency shown in Figure 13 for this mode. In a field installation, adjacent 8 x 20-ft panel frames share common vertical support posts. This means that the mass involved in the lateral sway mode in a field installation will be twice the mass involved during the test. Therefore, the lateral-sway frequency of a field installation involving multiple 8 x 20-ft arrays will be lower than that of a single array structure to the extent indicated above.

Because wind-gust frequencies are of the order of 1 Hz and the lowest natural frequency of the subject structure is 4 Hz, it may be concluded that load amplification factors due to dynamic interaction between wind gusts and the structure will be low. This conclusion is borne out by the study of the response of photovoltaic array structures to wind gusts being made by Boeing. The previously measured load capability of the structure (35 lb/ft^2) is therefore considered to provide adequate margin for both static and dynamic wind loading.

The dynamic response of the structure to earthquake loading, however, required careful consideration. Figure 14 shows the response spectra of elastic systems to the very strong earthquate at El Centro, California, in May, 1940. This earthquake had a maximum ground acceleration of 0.33 g and was assigned an intensity of X on the Modified Mercalli Intensity Scale. This intensity scale is a measure of effects on buildings, persons, and soils. The Richter magnitude scale, which appears frequently in the news media, is a measure of energy released at the epicenter and is not a direct measure of ground effects. ANSI A58.1-1972 (Reference 7) gives a Modified Mercalli Intensity of VIII-XI for the earthquake at San Fernando, California, on February 9, 1971, which registered 6.1 on the Richter scale.

The maximum ground acceleration of 0.33 g of the El Centro earthquake corresponds to Zone 3 on the seismic risk maps given in ANSI A58.1-1972 (Reference 7). Designing for a ground acceleration of 0.375 g is recommended for Zone 4 areas, which are specific sites where earthquakes of Modified Mercalli intensity of X and over have occurred.

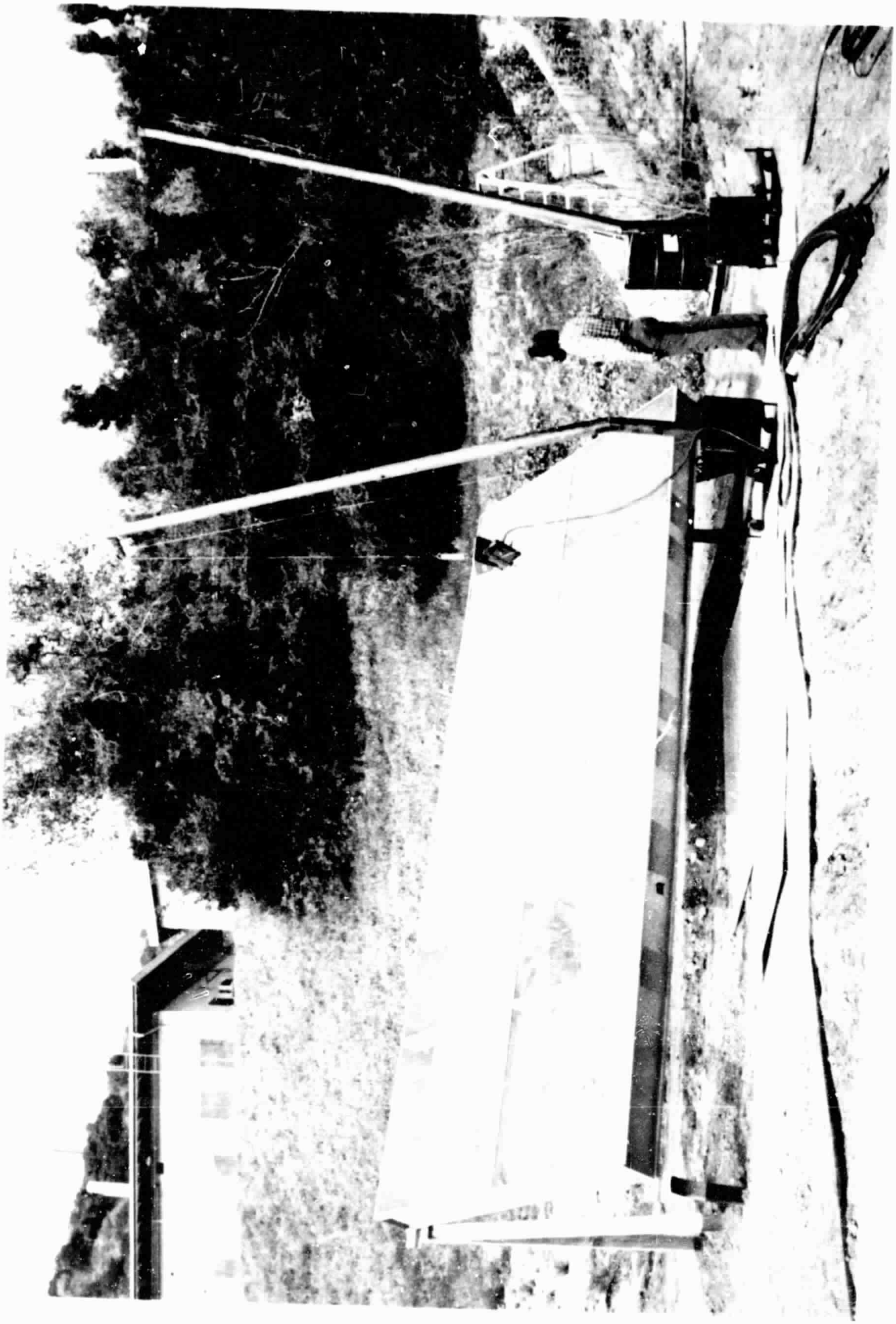

Figure 12. Modal Vibration Testing of Field-Installed Array

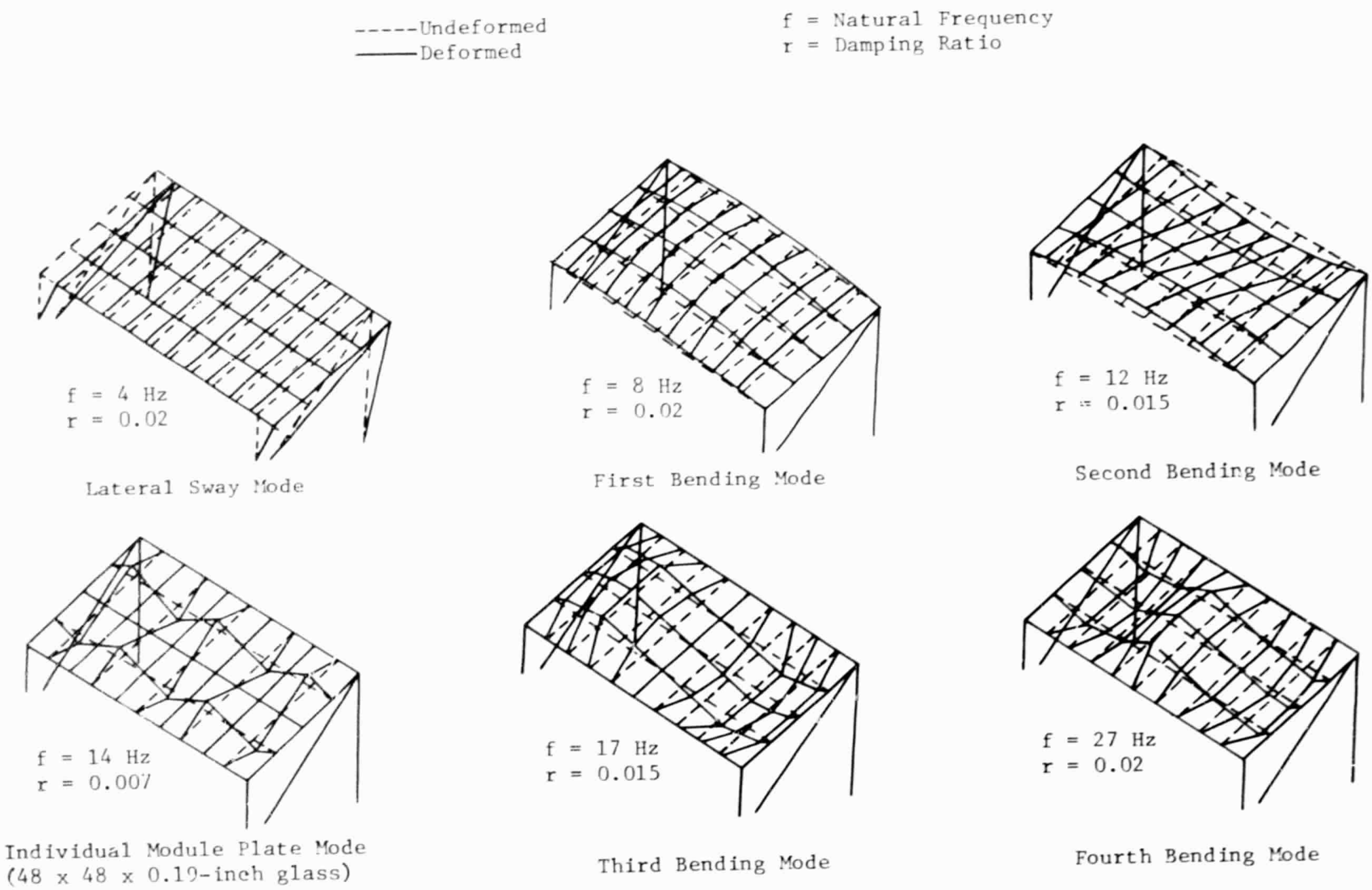

Figure 13. Measured Mode Shapes and Frequencies of Low-Cost PV Array Structure

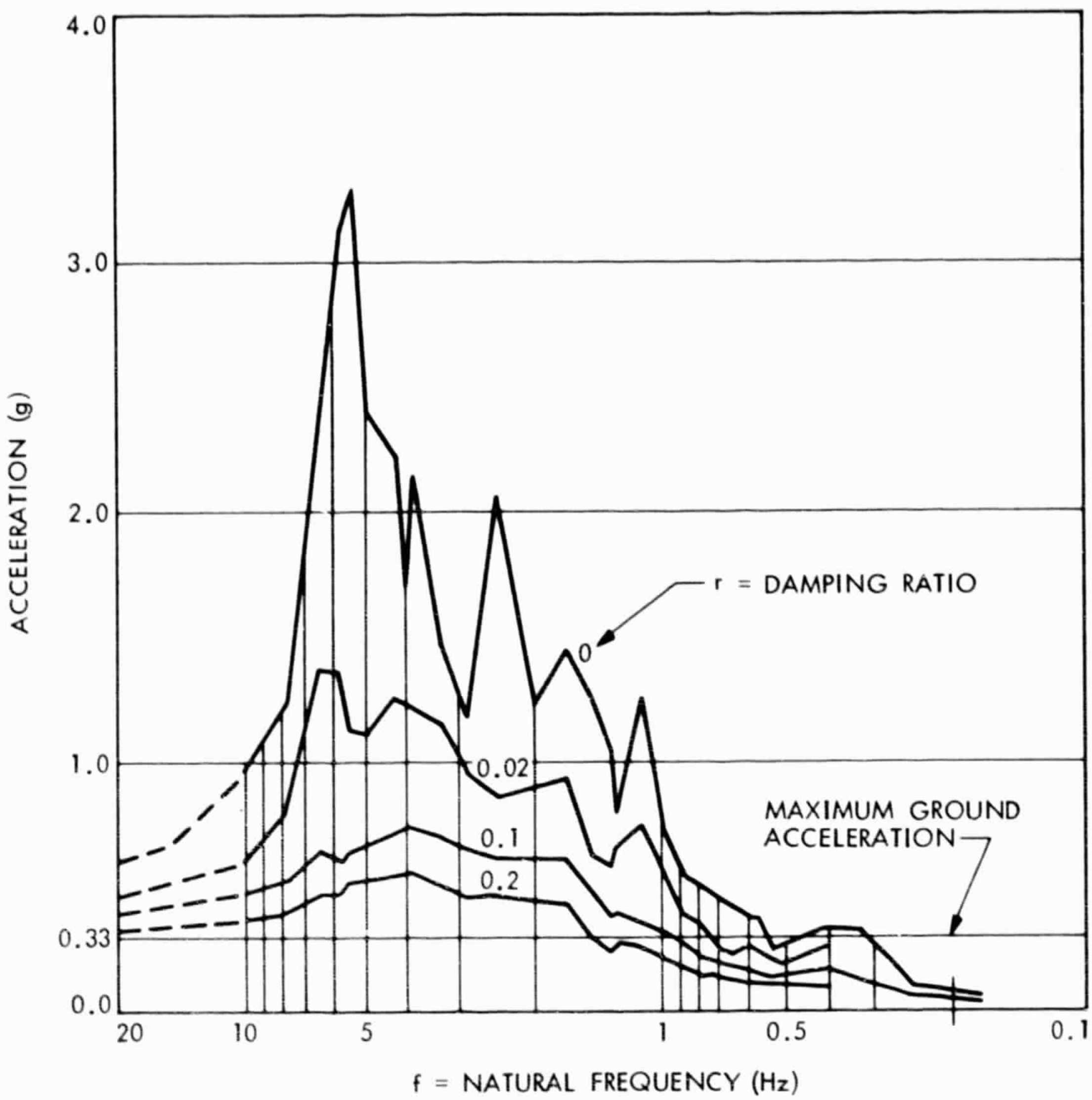

Figure 14. Response Spectra for Elastic Systems: El Centro, Calif., Earthquake, May, 1940 (Adapted From Blume, Newmark and Corning, 1960)

Designing for earthquake loads corresponding to those expected in Zone 3 on ANSI's seismic risk map seems appropriate for earthquake-prone regions. Using response spectra specified by the U.S. Atomic Energy Commission for the design of nuclear power plants (Reference 8) and a maximum ground acceleration of 0.33 g, Boeing analyzed the structure and determined that for an assumed damping ratio of 0.02, the bending stress in the short wooden 4 x 4s at the lower edge of the array is about 2700 psi. This stress is primarily associated with the 4-Hz lateral sway mode shown in Figure 13 and the 1.2 g load corresponding to that frequency and 0.02 damping ratio shown in Figure 14. The fiber-bending stress at the elastic limit of Douglas fir is 8100 psi (Reference 9) which represents a more-than-adequate margin of safety.

In addition, the structure shown in Figure 12 was static-load tested to verify its ability to withstand earthquake ground motion that would initiate the lateral sway mode. A static load was applied in a lateral east-west direction in the plane of the array, in 50-lb increments. At a load of 1200 lb, significant yielding but no structural failure was observed. At this point the test was discontinued. This load level corresponds to 0.8 g. Noting that yielding occurred, which implies a high damping ratio, it is seen that the response spectrum of Figure 14 shows a structural response of 0.7 g for a 0.1 damping ratio at 4 Hz. Again the ability of the structure to withstand severe (Zone 3) earthquakes is demonstrated.

e. Environmental Protection. The steel used in the panel frame and the support structure is protected from corrosion by galvanizing. This affords protection in most environments, but may not be adequate when subjected to the severe salt-spray exposures of some coastal locations.

In the case of weldments like the panel frame, it is possible to hot-dip galvanize the entire frame or to use members with a heavy galvanizing (G-90) and to paint welded areas with a zinc paint such as Galvanox. The latter method was chosen for four reasons: (1) The difference in the cost of galvanized steel and ungalvanized steel is only about 1¢ per pound, while the cost of hot-dip galvanizing is about 14¢ per pound; (2) before hot-dip galvanizing, the steel is treated to cut grease, and any degreasing solution that is trapped in the frame may attack the steel; (3) because of the large frame size (20 x 8 x 1 ft), most galvanizing facilities would not have tanks of adequate size to hot-dip the part properly; (4) hot-dipping distorts thin-section parts.

The cost of the Galvanox paint in large quantities is about $20 per gallon. The vendor claims that one gallon will cover about 280 square feet. (JPL experience with an 8 x 20-ft panel frame was that it required about 1 pint of paint for proper touch-up.) All vendors queried preferred to use the G-90 galvanizing and touch-up with Galvanox.

Because of the 13¢/lb lower cost the brackets for the end supports were also made of G-90-galvanized sheet steel.

f. Packaging and Shipping. It is necessary to provide protection against damage in handling and shipping the panel frame with modules installed. This is accomplished partly with a reusable fixture mounted to the truck bed and partly by using suitable corrugated-board separators. It is planned that the panel frames will be shipped on end to keep modules vertical during shipment.

The cost of shipping depends on where the panel frames are fabricated, where the modules are assembled and the location of the field site. In this study it is assumed that the panel-frame fabricator and the module manufacturer are in the Los Angeles area; the field site is assumed to be near Barstow, California, about 150 miles from Los Angeles.

Discussions with shippers suggested that a 40-foot flatbed truck could carry 14 panel frames, each loaded with modules. Based on more than 10 truck-loads, the cost of shipping from the fabricator to the site and returning the truck to Los Angeles was about $450 per load.

3. Final Panel Frame Design Summary

The final design of the panel frame is shown in Figure 15 and Appendix A. It uses 11-in.-deep 18-gauge galvanized-steel beams for the main outside members and 4-in.-deep 20-gauge galvanized sheet-steel beams for the 8-ft cross members. The internal 4-ft members used with 4 x 4-ft modules are 2.5 in. deep and are made of 20-gauge galvanized sheet steel. The entire structure is welded and then touched up with a suitable zinc paint.

Detailed costs are tabulated in Table 2 for 4 x 4-ft modules. Since modules have typically been 120 cm or 47.24 in. long, actual dimensions of modules are only nominally 4 ft. The JPL drawings included in this report (Appendix A) provide dimensions based on 120-cm x 120-cm modules.

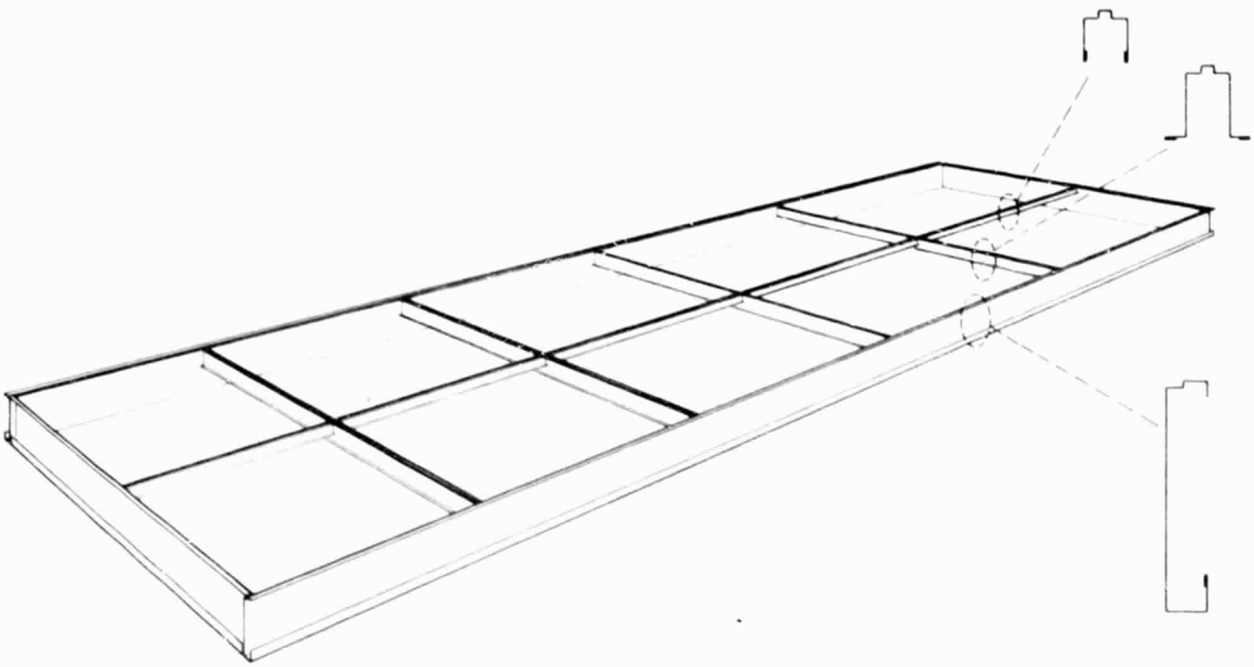

Figure 15. Final Galvanized-Steel Panel Frame (4 x 4-ft Modules).

Table 2. Breakdown of Panel Frame Costs (Based on 100,000 Panel Frames)

Item No.	Quantity	Part or Identifying No.	Nomenclature or Description	Specification	Material or Note	Material Cost ($)	Fabrication Cost ($)
1	2	10097883-101	Channel, side	18 ga. (.052) stl.	Galv. sheet G-90	39.60	10.40
2	4	10097883-102	Plate, triangle	10 ga. (.138) stl.	Galv. sheet G-90	1.20	.80
3	2	10097883-103	Channel, end	20 ga. (.040) stl.	Galv. sheet G-90	12.00	4.00
4	4	10097883-104	Hat section	20 ga. (0.40) stl.	Galv. sheet G-90	16.80	8.70
5	5	10097883-105	Channel	20 ga. (.040) stl.	Galv. sheet G-90	6.60	3.65
6	27	10097883-106	Strap	16 ga. (.014) stl.	Galv. sheet G-90	12.90	3.85
7	10	10097883-107	Diagonal brace	20 ga. (.040) stl.	Galv. sheet G-90	2.30	.65
					TOTALS:	91.40	32.05

Vendor quotations for welding the members to form the frame per Drawing No. 10097881, and for touching up with zinc-enriched paint where required, was an additional $34 per frame.

Shipping and handling of parts between fabrications and module manufacturer, $10.50 per frame.

On this basis the cost per panel frame is $91.40 + $32.05 + $34.00 + $10.50 = $167.95, or $11.31 per square meter.

SECTION III

OVERALL COST SUMMARY

Tables and graphs provided in this section summarize the total cost (price) picture of the final optimized structural configuration shown in Figure 6 and detailed in Appendix A.

Tables 3 and 4 start by summarizing the detailed costs in 1980 dollars per 8 x 20-ft array, based on fabrication quantities ranging from two to 100,000. For a nominal array efficiency of 10%, these quantities correspond to array fields ranging from 3 kW to 150 MW. The quantity sensitivities were developed by obtaining quotations for various order quantities and interpolating as required.

Table 5 and Figures 16 and 17 present the same data in terms of 1980 dollars per square meter of array area. A very low cost of only $\$25/m^2$ is obtained for large multi-megawatt production volumes. Even with small volume corresponding to single purchases for arrays of 100 kW, the total price remains below $\$50/m^2$.

Table 3. Cost per 8 x 20-ft Array Section (1980$)
(Ten 4 x 4-ft Modules) vs Production Volume

ITEM	NUMBER OF PANEL FRAMES					
	2	20	250	3,500	21,000	100,000
A. Panel frame	580	380	240	180	170	168
B. Assemble modules on (A)	75	56	42	30	17	17
C. Package (B)	38	32	25	20	9	9
D. Ship (C) to site	50	45	42	39	35	35
E. End Supports	200	150	100	60	55	54
F. Package (E)	15	8	6	4	2	2
G. Ship (F) to site	40	25	20	15	12	12
H. Uncrate (E)	6	4	3	2	2	2
I. Dig Trench & Install (E)	150	100	50	35	25	24
J. Uncrate (A)	10	8	6	4	3	2
K. Install (A) on (E)	80	70	50	35	30	30
Cost per array section	$1,244	878	584	424	360	355

(8 x 20 ft = 14.86 m^2; to convert to 1980 $\$/m^2$, divide each value by 14.86)

Table 4. Cost per 8 x 20-ft Array Section (1980$) (Twenty 2 x 4-ft Modules) vs Production Volume

ITEM	NUMBER OF PANEL FRAMES					
	2	20	250	3,500	21,000	100,000
A. Panel frame	600	400	260	200	190	188
B. Assemble modules on (A)	108	80	60	40	22	21
C. Package (B)	38	32	25	20	9	9
D. Ship (C) to site	50	45	42	39	35	35
E. End supports	200	150	100	50	55	54
F. Package (E)	15	8	6	4	2	2
G. Ship (F) to site	40	25	20	15	12	12
H. Uncrate (E)	6	4	3	2	2	2
I. Dig trench & install (E)	150	100	50	35	25	24
J. Uncrate (A)	10	8	6	4	3	3
K. Install (A) on (E)	80	70	50	35	30	30
Cost per array section	$1,297	922	622	454	385	380

Table 5. Array Structure Cost-Quantity Sensitivity (1980 $\$/m^2$)

		Ten 4 x 4-ft modules per panel frame						Twenty 2 x 4-ft modules per panel frame					
		NUMBER OF ARRAY SECTIONS						NUMBER OF ARRAY SECTIONS					
		2	20	250	3,500	21,000	100,000	2	20	250	3,500	21,000	100,000
1.	Panel frame & hold-down straps	39.03	25.57	16.15	12.11	11.44	11.31	40.38	29.92	17.50	13.46	12.79	12.65
2.	End supports & installation cost at site	23.55	16.82	10.09	6.39	5.38	5.25	23.55	16.82	10.09	6.39	5.38	5.25
3.	Assembly of modules in panel frame	5.05	3.77	2.83	2.02	1.14	1.08	7.27	5.35	4.04	2.69	1.48	1.41
4.	Packaging, shipping & uncrating	10.02	8.21	6.86	5.65	4.24	4.24	10.02	8.21	6.86	5.65	4.24	4.24
5.	Installation of panel frame with modules on end supports	5.38	4.71	3.36	2.36	2.02	2.02	5.38	4.71	3.36	2.36	2.02	2.02
	TOTALS	83.03	59.08	39.29	28.53	24.22	23.90	86.60	62.04	41.85	30.55	25.91	25.57

To obtain the above values from Tables 3 and 4:

Item 1 is A divided by 14.86

Item 2 is (E + I) divided by 14.86

Item 3 is B divided by 14.86

Item 4 is (C + D + F + G + H + J) divided by 14.86

Item 5 is K divided by 14.86

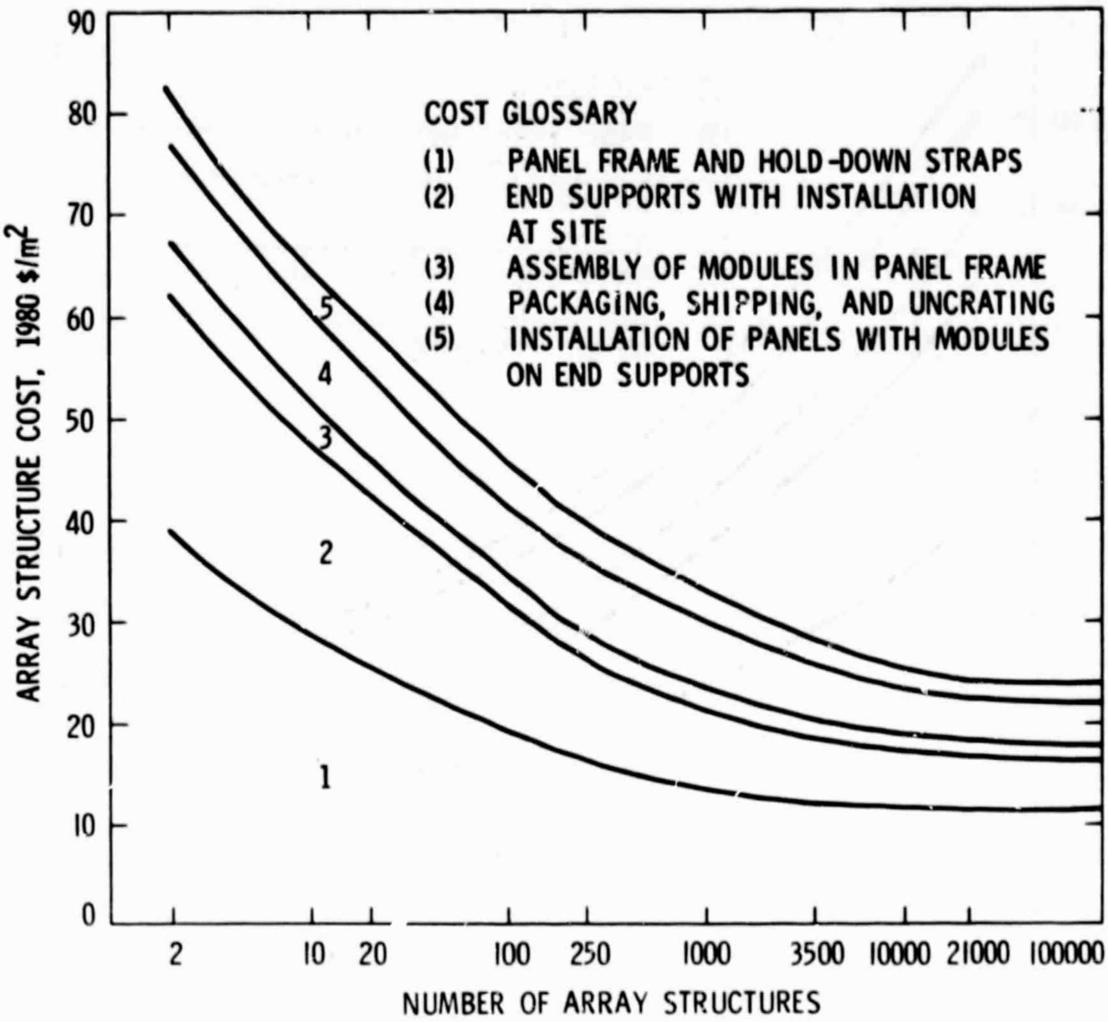

Figure 16. Array Structure Cost-Quantity Sensitivity Based on Ten 4 x 4-ft Modules per Frame

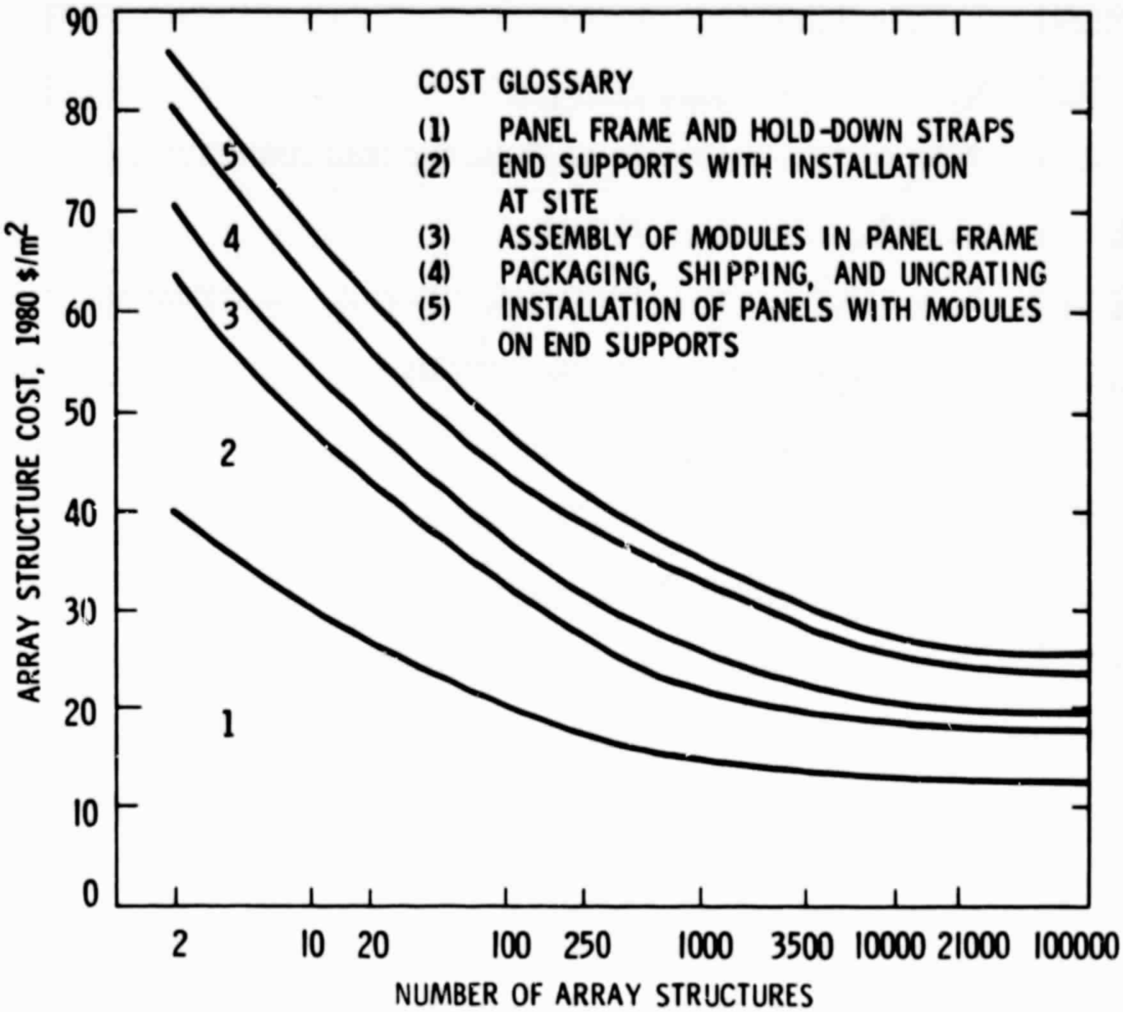

Figure 17. Array Cost-Quantity Sensitivity Based on Twenty 2 x 4-ft Modules per Frame

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4. Module/Array Interface Study, Report No. DOE/JPL 954698-78/1A, Prepared for JPL by Bechtel National, Inc., Research and Engineering Operation, San Francisco, California, August 1978.

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8. "Design Response Spectra for Seismic Design of Nuclear Power Plants," Regulatory Guide 1.60, U.S. Atomic Energy Commission, 1973.

9. Roark, R.J., Formulas for Stress and Strain, Fourth Edition, Mc-Graw-Hill Book Co., New York, New York, 1965.

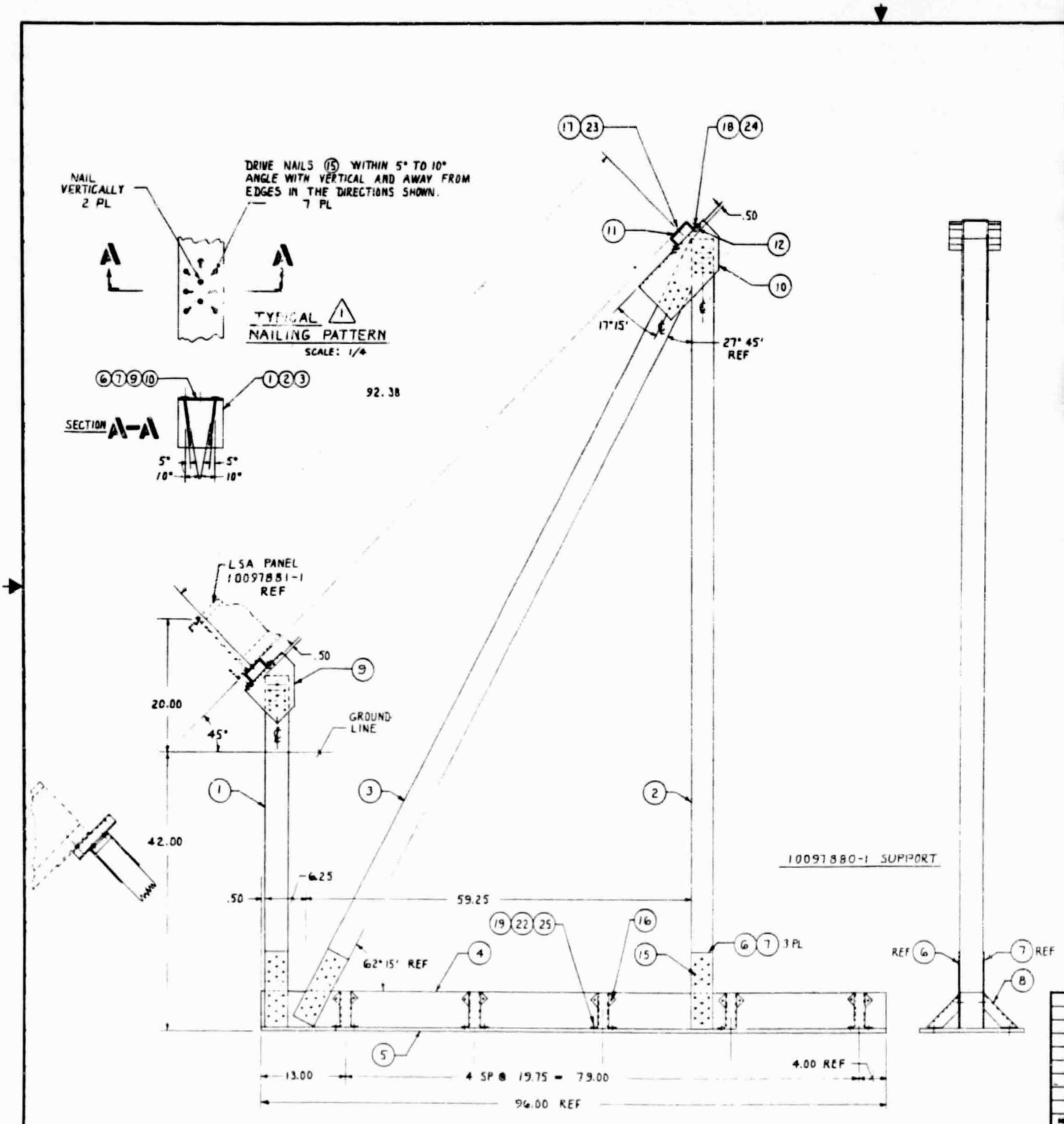
APPENDIX A

JPL DRAWINGS OF ARRAY STRUCTURE

The following drawings provide details of the construction and assembly of the JPL panel and support structure discussed in this document:

JPL Drawing Numbers

10097880
10097881
10097882
10097883



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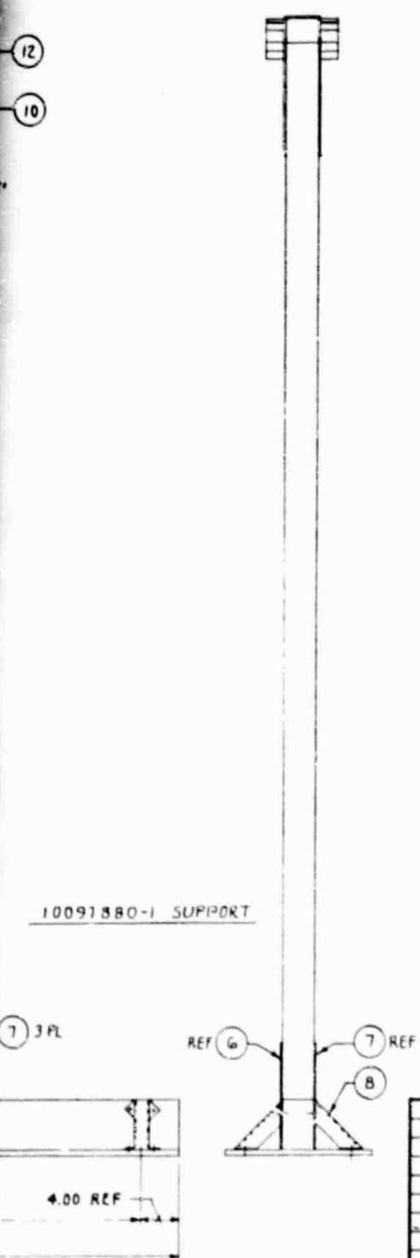

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NOTES: UNLESS OTHERWISE SPECIFIED

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20	25			COML	.25 INCH LOCK WASHER		STL H GALV	
8	24			COML	.38 INCH LOCK WASHER		STL H GALV	
2	23			COML	.50 INCH LOCK WASHER		STL H GALV	
20	22			COML	.25 INCH FLAT WASHER	1.50 OD X .06 THK	STL H GALV	
	21							
	20							
20	19			COML	HEX BOLT & NUT	.25-20UNC X 1.00 LG	STL H GALV	
8	18			COML	HEX BOLT & NUT	.375-16UNC X 1.00 LG	STL H GALV	
2	17			COML	HEX BOLT & NUT	.50-13UNC X 1.00 LG	STL H GALV	
20	16			COML	SHEET METAL SCREW	.25 X 1.25 LG TYPE "A" PAN HEAD	STL H GALV	
162	15			COML	NAIL, COMMON WIRE	16 d	STL H GALV	
	14							
	13							
4	12			10097882-112	BAR			
2	11			10097882-111	HAT SECTION PAD			
1	10			10097882-110	REAR BRACKET			
1	9			10097882-109	FRONT BRACKET			
10	8			10097882-108	CHANNEL BRACE			
3	7			10097882-107	PLATE			
3	6			10097882-106	PLATE			
1	5			10097882-105	PLYWOOD BASE			
1	4			10097882-104	BASE BEAM			
1	3			10097882-103	DIAGONAL BRACE			
1	2			10097882-102	REAR COLUMN			
1	1			10057882-101	FRONT COLUMN			

PARTS LIST

D 10097880

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—	LSA

APPLICATION

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MACHINE FINISH ✓
DO NOT SCALE DRAWING
INTERPRET DWG PER MIL-STD-100

MATERIAL: SEE PARTS LIST

CONTRACT NO.

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DR	MACGLASHAN	10-14-80
CHK		
STRU		
MATL		
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ENGR	[signature]	11-7-80
	[signature]	11/4/80

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
RELEASED THROUGH SECT. 356

LSA SUPPORT

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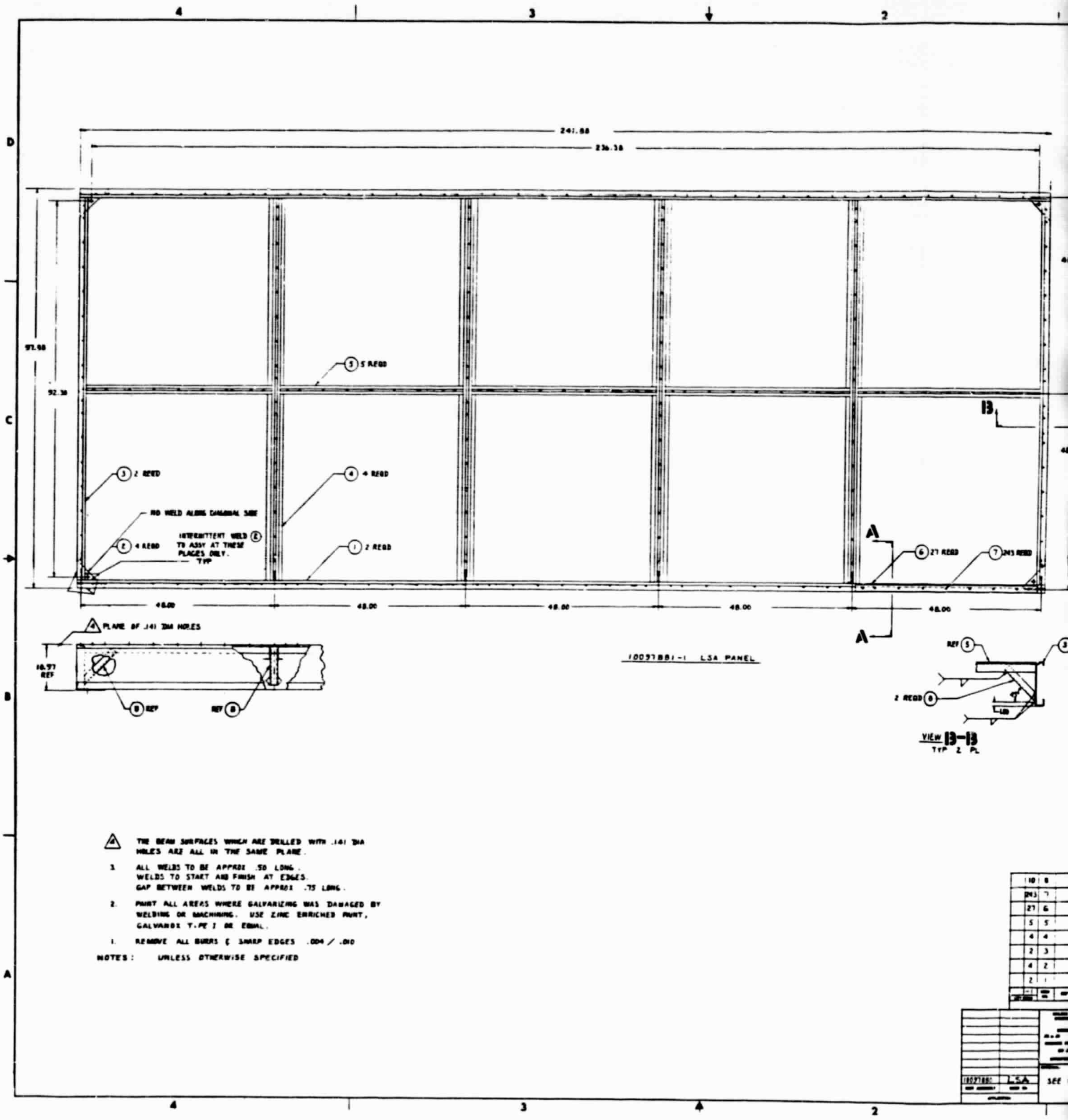

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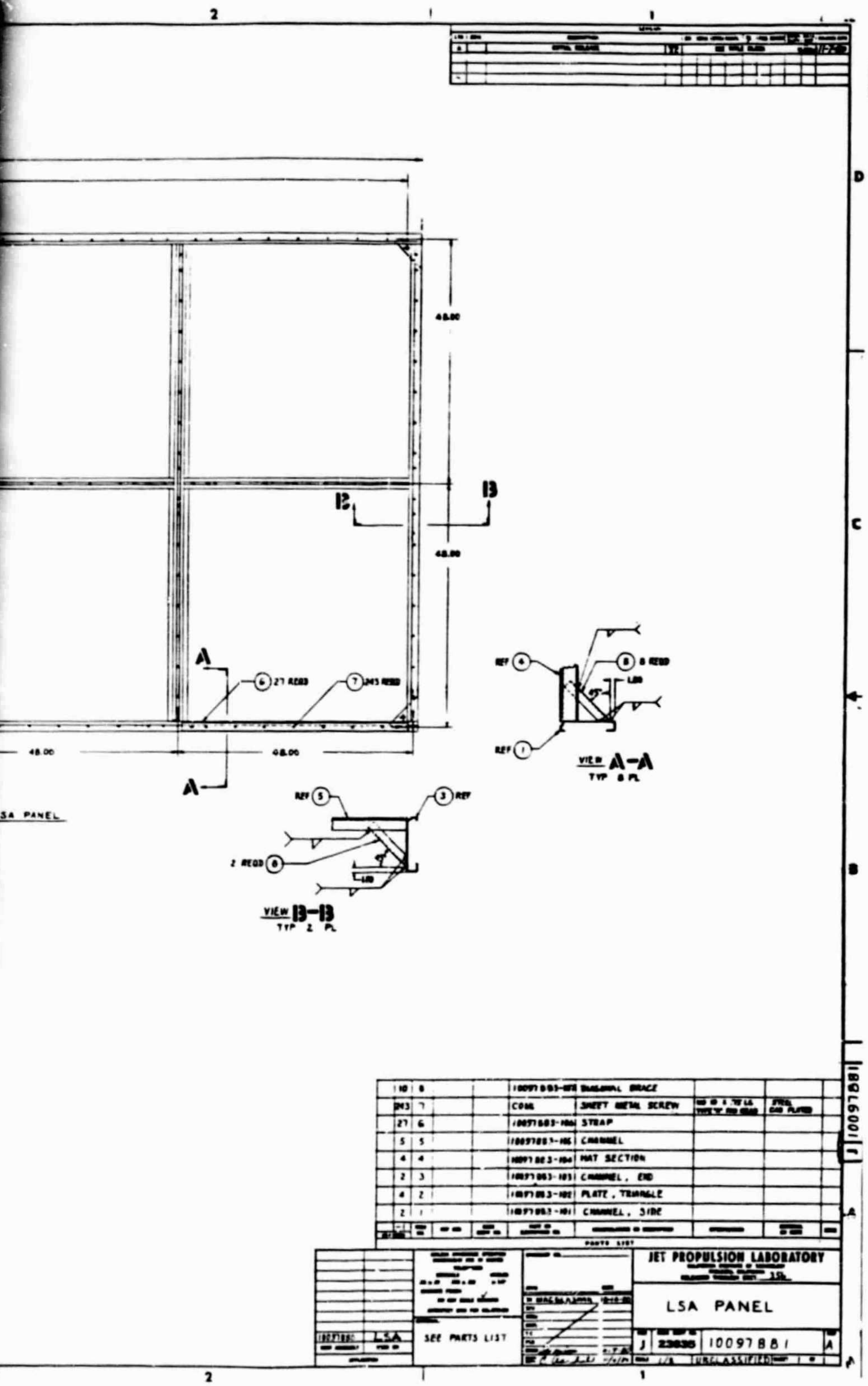

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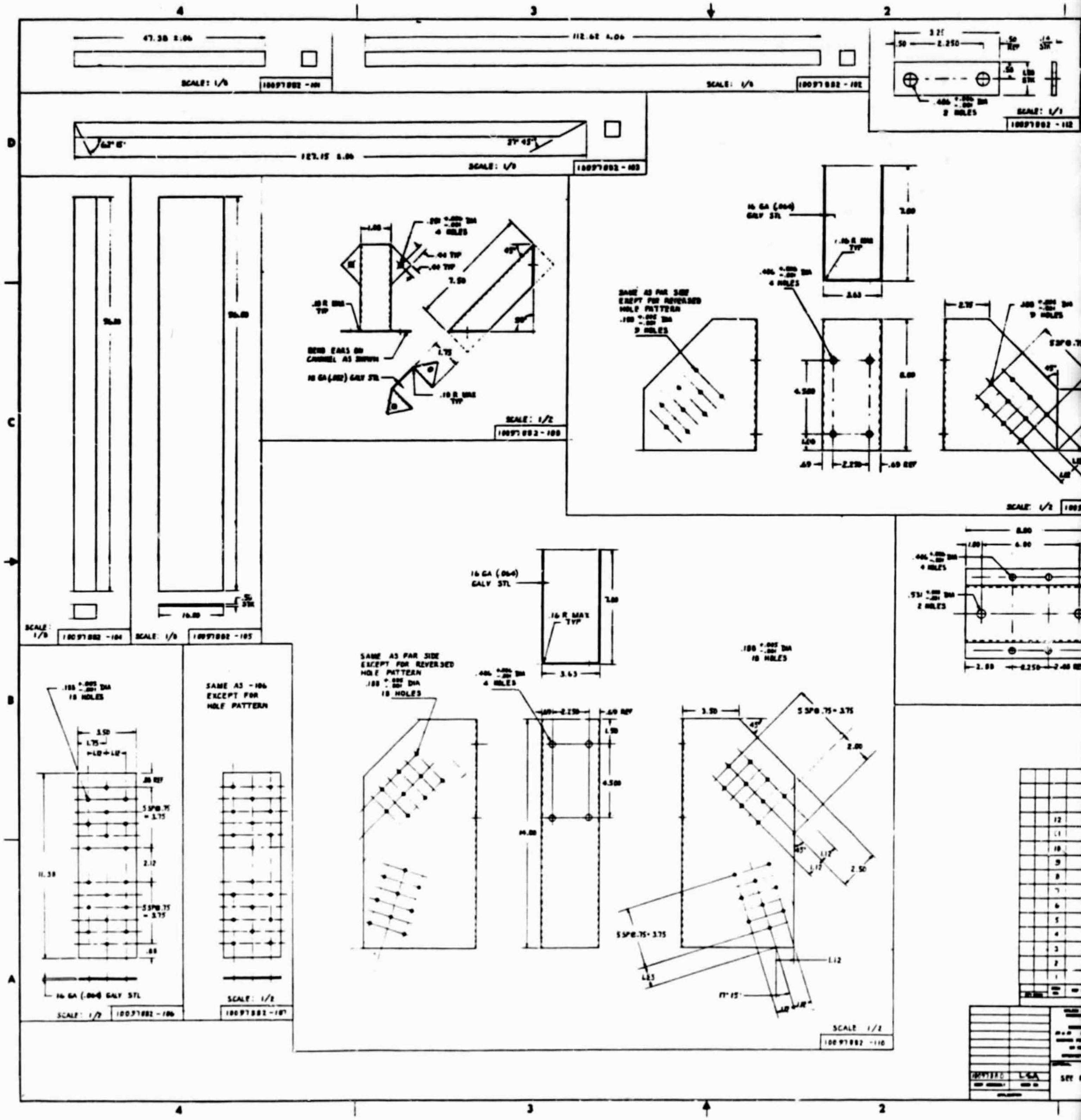

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SAME AS FAR SIDE EXCEPT FOR REVERSED HOLE PATTERN
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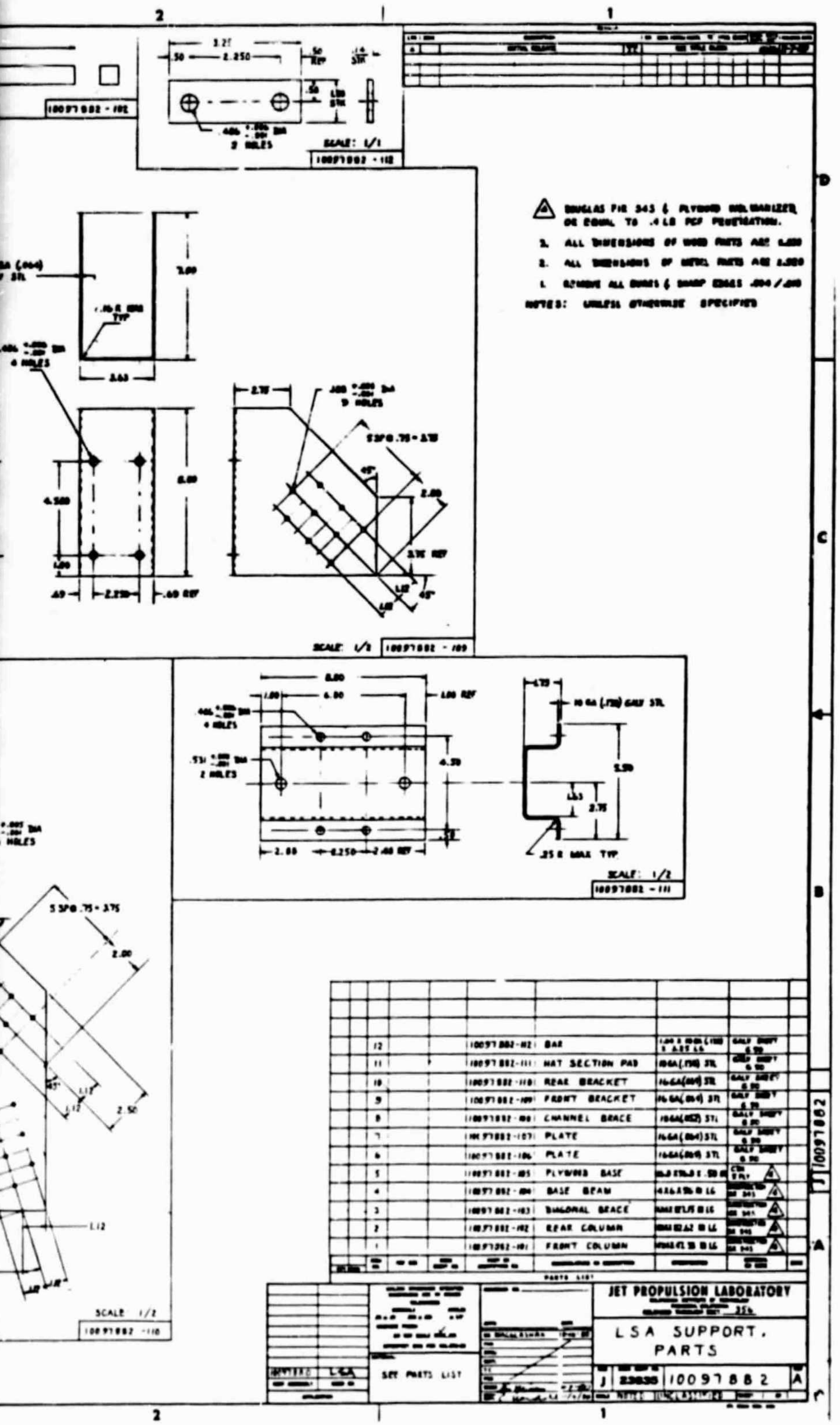

NOTES: UNLESS OTHERWISE SPECIFIED
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3. ALL DIMENSIONS OF WOOD PARTS ARE
DOUGLAS FIR 343 & PLYWOOD OR EQUAL TO .4 LB PCF PENETRATION.
12 10097882-112 BAR
11 10097882-111 HAT SECTION PAD
10 10097882-110 REAR BRACKET
9 10097882-109 FRONT BRACKET
8 10097882-108 CHANNEL BRACE
7 10097882-107 PLATE
6 10097882-106 PLATE
5 10097882-105 PLYWOOD BASE
4 10097882-104 BASE BEAM
3 10097882-103 DIAGONAL BRACE
2 10097882-102 REAR COLUMN
1 10097882-101 FRONT COLUMN
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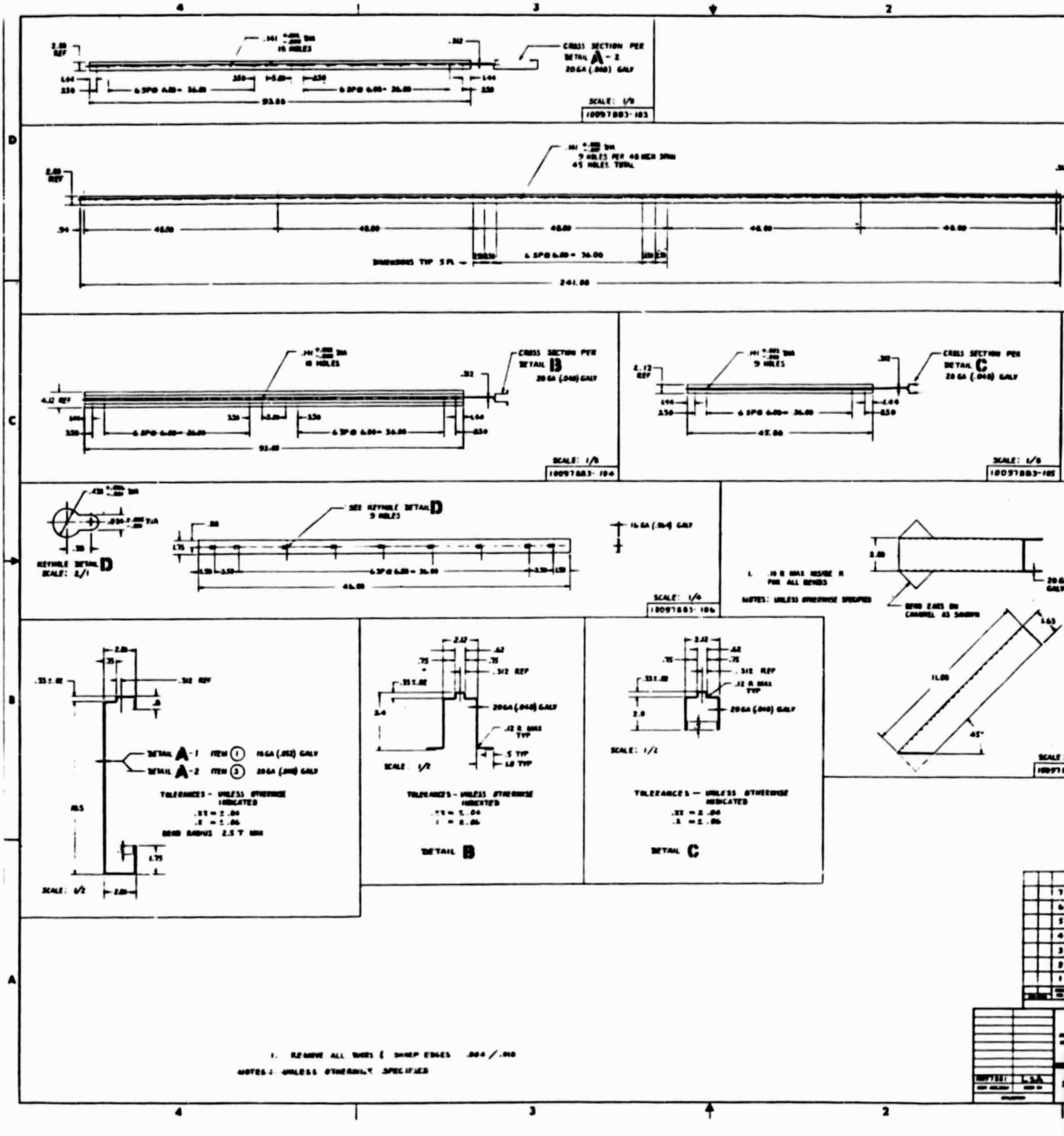

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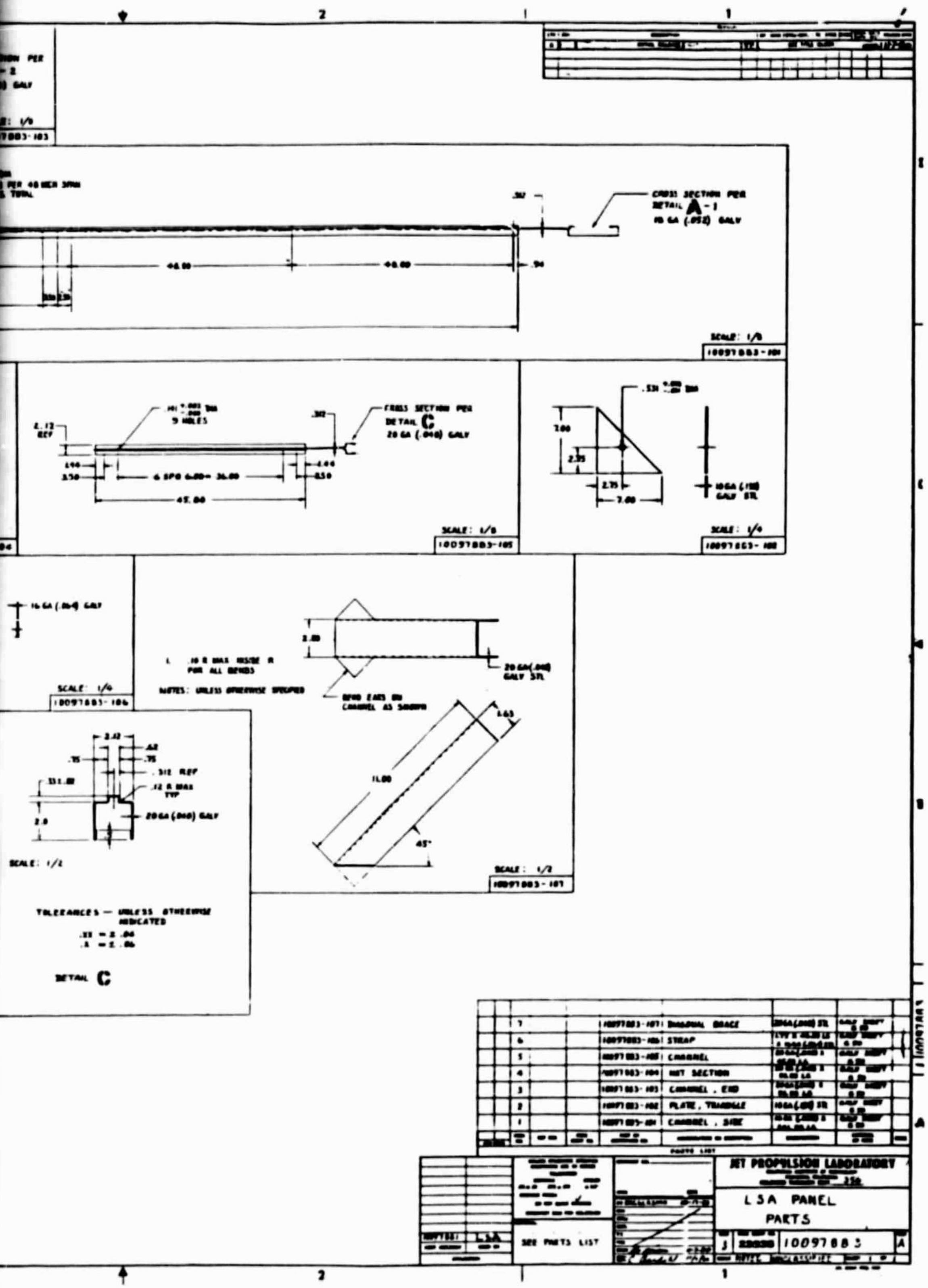

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