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PHOTOVOLTAIC MODULE ELECTRICAL TERMINATION DESIGN REQUIREMENT STUDY

FINAL REPORT

DRD NO. SE-3

JULY 1980

JPL CONTRACT NO. 955367

PREPARED BY:

F. J. MOSNA, JR.
J. DONLINGER

MOTOROLA INC./ITT CANNON

THE JPL LOW-COST SOLAR ARRAY PROJECT IS SPONSORED BY THE U. S. DEPARTMENT OF ENERGY AND FORMS PART OF THE SOLAR PHOTOVOLTAIC CONVERSION PROGRAM TO INITIATE A MAJOR EFFORT TOWARD THE DEVELOPMENT OF LOW-COST SOLAR ARRAYS. THIS WORK WAS PERFORMED FOR THE JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY BY AGREEMENT BETWEEN NASA AND DOE.

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1.0 INTRODUCTION

The purpose of this document is to provide additional details and information to supplement the data provided in the Executive Summary. The document consists of Appendices 2.0, 3.0, and 4.0 which address the major tasks of the project (criteria development; ranking; and results/conclusions, respectively) and Appendix 5.0, a series of mini-appendices addressing specific topics complementing the major task areas.

2.0 DEVELOPMENT OF TERMINATION SELECTION CRITERIA

2.1 INTRODUCTION

The development of the selection criteria represents a considerable part of the time spent on this report. This section is concerned with a listing of the termination selection criteria, together with a discussion of significant aspects of each one, a discussion of each of the application classes, and the constraints associated with each application class.

2.2 SELECTION FACTOR CRITERIA

Each of the selection criteria is discussed with respect to importance of the attribute, significant variables, examples of poor and excellent terminations, and justification of the rating value assigned. Ratings were assigned to each selection criterion on a scale of 1 to 4 where 1 = poor, unacceptable; 2 = fair, average; 3 = good, above average; 4 = excellent.

Primary termination requirements have been identified as follows:

- Adequate current capacity
- Low ohmic contact resistance
- Adequate electrical insulation (isolation voltage)
- Adequate weatherization
- Low cost.

Table 1 shows the selection criteria organization that evolved in this program.

An initial list of termination factors i.e., pertinent electrical termination attributes, was grouped into functional areas as shown in Table 1. Once grouped, the individual factors were further inspected for completeness and redundancy. This effort resulted in a total of 28 individual selection factors, that were grouped into five functional categories. Since each of

FUNCTIONAL

- Voltage Rating
- Current Rating
- Insulation and Seal Level
- Ground Provision
- Heat Dissipation
- Disconnect Cycles
- Contact Resistance and Pressure
- Reliability (MTBF)

MANUFACTURING

- Preparation Time
- Producibility
- Repairability
- Labor Skill Level
- Special Tools
- Safety

ENVIRONMENTAL DURABILITY

- Moisture
- Temperature Cycling
- Corrosive Atmosphere and Contamination
- Vandalism
- UV Radiation
- Vibration and Strain Relief

UTILITY

- Series and Parallel Connections
- Wire-to-Wire and Panel-to-Wire Connections

CODE

- NEC

COST

TABLE 1

SELECTION CRITERIA

the individual attributes have meaning in the selection of module connections, all will be retained as criteria for such selection. Certain of these factors such as "special tooling required" are binary in nature i.e., yes or no. Other factors, such as sealability, can be characterized in degree between two extremes i.e., excellent, good, fair or poor. It should be noted that any given factor or attribute can be characterized differently, depending on the solar module application type e.g., residential or remote. Termination costs will be addressed in later sections.

One can see that such a cataloging yields an abundant source of information for selecting solar module terminations by application type, but there remains the need to rank the candidate terminations by application type with a concise set of selective criteria. This is accomplished via conversion of the qualitative information into numerical equivalents. A scale of one to four has been selected for this exercise. In order to give to proper (equal) weight to applications sensitive areas, each termination factor will receive a factor from one to four. Actual rankings of generic termination types of application are the product of the termination attribute factor and application factor.

2.3 METHODOLOGY

2.3.1 FUNCTIONAL CATEGORY

- Voltage and current ratings - the parameters set for voltage and current ratings for each application are clear-cut in that a particular termination is either satisfactory or not. The importance of these criteria cannot be understated since insufficent capacity in either voltage or current would cause rapid failure.

The attribute ratings run the entire scale from 1 through 4. Those terminations found to be unsatisfactory or borderline in either voltage or current rating were assigned the value 1. Normally, failure in either of these two criteria would be justification for a termination to be eliminated from the candidate list. However, the two termination types rated lowest on this criterion (spring clip, and wire wrap due to limited wire size) were further evaluated with the idea that if they proved suitable in all other criteria, they would be worthy of recommendation of design changes to correct their faults. Ratings were made based on the conductor size the termination could accommodate, and the manufacturer's information on maximum ratings of voltage and current. An example of a termination rated excellent is the crimp type, due to it's current and voltage capabilities coinciding with the size of conductor used and its availability trough wire size #1/0 AWG.

. Insulation and Seal Level - These factors are discussed together only because most terminations with a high level of sealing generally are also well-insulated. Let it be understood that "insulation level" in this report refers to electrical isolation or dielectric, and "seal level" refers to environmental isolation. These are important aspects of a termination since lack of adequate insulation can cause injury and short-circuits; and as an added benefit, adequate insulation promotes good environmental durability. Some of the candidate terminations were available in both insulated and uninsulated forms. The insulated form was evaluated whenever possible. In cases where the termination was not available insulated, a supplemental insulation/seal was assumed to be utilized, where possible, prior to assigning a rating value. Combination sealing/insulating techniques include electrical tape, shrink tubing, and junction boxes. Terminations which could not be insulated due to design configuration, or which provided a shock hazard after a supplemental insulating/sealing step, were rated 1; an example is the hand-soldered termination. Terminations that provided some degree of insulation/sealing and safety received 2 or 3 ratings, depending on level. A termination judged excellent in both sealing and insulation is the plug/receptacle type, primarily due to its rubber-like shroud.

. Module Ground Provision - Since a ground connection is expected to be necessary due to code requirements, the capability of a termination to carry multiple contacts within a single termination becomes important. Terminations with this capability (such as screw terminal block) were rated 4. Terminations that would require an additional termination for the ground connection were rated 1 (e.g. the crimp type).

. Heat Dissipation - The ability of a termination mounted on the back of a module to dissipate heat is a demonstrated factor in its performance. Heat dissipation is enhanced by exposed surface area of current-conducting parts of the termination. Generally speaking, those terminations rated high in seal and insulation levels were rated low in heat dissipation. Ideally, some balance is desirable. An example of a poorly-rated termination is the plug/receptacle with its high level of insulation and sealing. An example of a highly-rated termination is the screw terminal block with its exposed terminals.

. Disconnect Cycles - the ability of a termination to be disconnected quickly and easily with a minimum of labor was considered to be an advantage. Terminations not designed to be disconnected, such as the hand-soldered types, were rated 1, while terminations capable of greater than 10 mating/de-matings, such as the plug/receptacle, were rated 4.

. Contact Resistance and Pressure - Contact resistance is obviously very important since increasing resistance reduces current flow. Contact resistance and contact pressure are inversely related in that generally the higher the contact pressure the lower the contact resistance. It is understood that contact base metals and plating materials are factors also; it is assumed the manufacturer has chosen the best combinations. Terminations that are disconnectable generally utilize low contact pressures to reduce the forces needed for mating and demating. An example of this type, the plug/receptacle, was rated 2. Terminations with very high contact pressure, such as the crimp type, were rated 4.

. Reliability (MTBF) - This criterion, perhaps one of the most important, was also the most difficult to gather data for since very little empirical evidence existed that could be compared on an equal basis. For this reason, the expertise of ITT Cannon was utilized for guidance in determining a relative "order of reliability". Basically, those terminations expected to perform reliably in the environment were rated 4 (e.g. welded), and terminations expected to have a lower MTBF (like the spring clip) were rated 2. No termination type received a rating lower than 2. MTBF's are discussed in greater detail in Section 4.0.

2.5.2 MANUFACTURING CATEGORY

. Preparation Time - The importance of this criterion is based on labor costs, and refers to the amount of labor involved in preparing the conductor/module for attachment of the termination. Low scores are recorded for termination types, such as hand soldering, which require a high degree of preparation, while a high score is given to insulation displacement which requires no conductor prepapration.

. Producibility - This criterion's importance is based in labor costs, and refers to the expected ease of production and ability to automate facilities in the actual termination attachment. The plug/receptacle scored high due to automated machinery ability. Hand-solder scored low because of the manual requirements of the termination.

. Repairability - The importance of this criterion will become apparent as failures begin to occur in a system. Ease of repair in the event of termination failure, and subsequent replacement, will no doubt prove to be cost-effective. Easily repaired/replaced terminations such as the crimp type are rated high, while the welded termination receives a low rating due to equipment needed, set-up, and skill level.

. Labor Skill Level - The importance of labor skill level (and special tools) is reflected in costs. Labor skill level refers to the degree of skill and training required by personnel to make a satisfactory and reliable termination. A high rating was given to the crimp type termination since the skill level is relatively low, and crimp tools are available that will not release until the crimp is completed. On the other hand, a low socre is given to the hand-soldered termination due to the high skill level required for a satisfactory connection, and the large human factor.

. Special Tools - The importance of this criterion is associated with extra cost considerations. A special tool is defined as any tool or piece of equipment not generally found in a common tool kit, and requiring some training for proper use. The requirement of special tools is associated with a low score, e.g. the welded connection which requires very specialized equipment. The screw terminal block, which requires a common screw-driver as equipment, received a high rating.

. Safety - Safety's importance is necessary to guard against personnel injury. The rating of this criterion reflects the shock hazards associated with actually making the electrical connection of the termination. This attribute is directly related to the insulation level of the termination. Terminations which pose no shock hazard in connection, such as the plug/receptacle (which is completely shrouded), are rated high. Termination types with conductor exposure, such as the spring clip, are rated low.

2.3.3 ENVIRONMENTAL DURABILITY

. Moisture - The ability of a termination to withstand exposure to moisture is important since the majority of environments contain moisture in one form or another. This criterion is directly related to the termination's seal level. A well-sealed termination will resist any admission of moisture which can initiate corrosion or shunting. The well-sealed, environmentally-stable termination received the highest score (e.g. the plug/receptacle). Terminations with low to moderate contact pressures, such as the spring clip, are particularly susceptable to moisture admission and are rated low.

. Temperature Cycling - The ability of a termination to withstand temperature cycling is important because this characteristic of the environment is responsible for many termination failures. Daily temperature fluctuations of 40 and 50 degrees F are common in many parts of the world. Termination types which provide constant pressure on the conductor, which compensates for the expansion and contraction of metallic contacts and conductors, are rated high (e.g., the spring clip). Terminations that do not allow for this change generally are scored lower (e.g. the hand-soldered, which can separate as a result of fatigue in the solder).

. Corrosive Atmosphere and Contamination - These criteria are important because each causes increased contact resistance, which leads to lower current flow. Generally, the less exposed the termination, particularly the contacts or metallic portions of the termination, the higher the rating (as with termination types whose sealing technique includes utilization of a junction box, or insulation displacement). The crimp-type is rated lower due to its lesser seal level.

. Vandalism - This criterion includes not only voluntary destruction and tampering by man, but also unintentional vandalism by insects and vermin. It is important because the problem is so common. Generally, the more isolated and inaccessible the termination, the safer it is from vandalism. Therefore those terminations secured inside a junction box, as the wire wrap type would box, receive high ratings, while those most easily tampered with and exposed, such as twist-on, are rated lower.

. Ultra-Violet Radiation - This criterion is important since it will be so prevalent. Even though terminations may not be subjected to direct sunlight, reflected light (continuing UV radiation) will be surround every PV system. Once again, those terminations which are isolated in a junction box or fabricated of UV-stable materials will perform best and are rated highest. An example of a highly-rated termination is the screw terminal block whose phenolic material is stable in ultraviolet, and would most likely be contained in a junction box. A lower-rated termination would be the crimp, due to its more limited and less stable insulation.

. Vibration and Strain Relief - These criteria are important because they are facets of the environment. Wind loading and panel flexing cannot be avoided so the termination and panel must be able to function with them. It is assumed that engineering provisions are made for vibration and strain relief. However, those terminations that display the best mechanical strength are rated high, as in the case of the crimp seal. Those with relatively low mechanical strength, as the twist-on, are rated low.

2.5.4 UTILITY CATEGORY

. Series and Parallel Connections - Photovoltaic systems will use series, parallel, and combinations of these to deliver the needed voltage/current levels. All termination types were capable of both series and parallel connections and were all rated high.

. Wire-to-Wire and Panel-to-Wire Connections - This criterion was totally dependent upon module and module output configurations. Ratings were assigned according to the termination's ability to be utilized in wire-to-wire and panel-to-wire configurations. All terminations were applicable in wire-to-wire;

are all rated high. In panel-to-wire, certain terminations cannot be attached to (or through) a panel (bulkhead), like the crimp type which was rated low.

2.3.5 CODE (NEC)

Approval or disapproval of electrical terminations and interconnections are very dependent on precedence and the discretion (and code interpretation) of individual inspectors. Therefore, presented here is generally an inspector concensus-type rating. The higher scores went to termination types such as crimp and screw terminal block, and lower scores were assigned to spring clip and wire wrap.

2.4 APPLICATION CLASSES AND ASSOCIATED CONSTRAINTS

The four application classes, remote, residential, intermediate and industrial, differ enough to make certain selection criteria more important in one application than in another. For this reason, each application class is associated with a unique set of weighting factors which emphasize those criteria considered most important.

Each application class is discussed in this section, with attention to criteria considered most important.

2.4.1 REMOTE

Due to the general inaccessibility of this type of application and the associated higher costs of required maintenance and repair, any criteria which would contribute to the termination's reliability were weighted high. Criteria included: all those under the heading of "environmental durability"; all criteria under "functional" with the exception of "ground provision" and "disconnect cycles" which were not applicable in the remote class; "safety" in installation; and "parallel connections" and "wire-to-wire" under "utility" due to low voltages and small array sizes expected .

2.4.2 RESIDENTIAL

Due to the close proximity of the system to the homeowner and personal property, all criteria under "functional" except "heat dissipation", "disconnect cycles", and "contact resistance" were considered most important. Also "safety" and "code approval" were weighted high. "Heat dissipation", "disconnect cycles" and "contact resistance" were not considered instrumental in this application because of the accessibility of the application.

2.4.3 INTERMEDIATE

Due to the increased reliability needed over the residential application class, the highly weighted factors in this class are all those included in the "residential class" plus the key factors under "durability"; including "moisture", "temperature cycling", and "Ultraviolet Radiation" which would enhance the reliability of a termination in the intermediate class.

2.4.4 INDUSTRIAL

Criteria weighted heavily in this application class includes: "corrosive atmosphere" due to the system possibility being located within an industrial area where corrosive atmospheres are expected; all criteria under "functional" except "disconnect cycles", which was deleted due to the fact that modules were not expected to be individually removed in the event of failure. "Safety" was weighted high as in all other applications. "Series connections" and "panel-to-wire" connections were also weighted significantly because of the larger panel sizes expected to be utilized in this application class.

3.0 RANKING

3.1 INTRODUCTION

Presented in this section are the tables utilized in determining the ranking of candidate electrical terminations.

The attribute value found in Table 2 for a particular termination criterion is multiplied by the weighting factor found under the same criterion, in the application desired, in Table 3. For example, to find the value of a twist-on termination's seal level in the residential application, the value "3" is found in Table 2 and the weighting factor "4" is found in Table 3. These values are multiplied for a product of "12" which can be found on the ranking table for the residential class, Table 5. These calculated values for each criterion are then added together for each termination type for the total numerical value found in Table 8. Table 9 lists the same information in numerical order.

3.2 ATTRIBUTE RANKING TABLES

Termination attributes are listed in Table 2, and application attribute weighting factors are shown in Table 3. Termination rankings for the 4 classes of application are given in Tables 4 - 7.

TABLE 2
TERMINATION ATTRIBUTES*

TERMINATION TYPE	FUNCTIONAL									MANUFACTURING					
	VOLTAGE RATING	CURRENT RATING	INSUL. LEVEL	SEAL LEVEL	GND PROVIS.	HEAT DISS.	DISCON. CYCLES	CONTACT RES.	RELIAB. (MTBF)	PREP TIME	PRODUC-IBILITY	REPAIR-ABILITY	LABOR SKILL LEVEL	[illegible]C. [illegible]OLS	SAFET
CRIMP	4	4	3	3	1	3	1	4	4	3	3	4	4	3	3
HAND-SOLDERED	4	4	1	4	1	3	1	4	2	2	2	3	1	2	1
INSUL. DISP.	2	2	2	4	1	2	2	3	4	4	3	2	3	3	2
PLUG/ RECEPTACLE	4	4	4	4	4	1	4	2	3	2	4	3	2	2	4
SCREW	4	4	1	4	4	4	4	4	2	2	3	4	2	4	2
SPRING CLIP	1	1	1	2	1	3	4	4	2	2	3	4	4	4	1
TWIST-ON	3	3	4	3	1	3	4	3	3	3	3	4	4	4	2
WELDED	4	4	1	4	1	3	1	4	4	2	2	1	2	1	1
WIRE WRAP	1	1	2	4	1	3	1	3	4	3	3	2	4	3	2

* - All termination types considered sealed in some manner

1 = poor, unacceptable; 2 = fair, average; 3 = good, above average; 4 = excellent

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TABLE 2 (Continued)

TERMINATION ATTRIBUTES*

TERMINATION TYPE	DURABILITY									UTILITY			CODE		
	MOIST.	TEMP. CYCLE	CORROS ATM.	CONTAM	VANDAL	UV RAD.	VIB. (JOINT STR)	STRAIN RELIEF	SERIES CONN.	PARA. CONN.	WIRE TO WIRE	PANEL TO PANEL	NEC		
CRIMP	3	3	3	3	4	3	4	4	4	4	4	1	4		
HAND-SOLDERED	4	2	3	3	4	3	3	3	4	4	4	4	2		
INSUL. DISP.	4	4	4	4	4	4	2	4	4	4	4	4	3		
PLUG/ RECEPTACLE	4	4	4	4	2	4	4	4	4	4	4	4	3		
SCREW	3	3	3	4	3	4	3	4	4	4	4	4	4		
STRING CLIP	2	4	3	4	3	4	3	4	4	4	4	4	1		
TWIST-ON	3	3	3	3	2	3	2	1	4	4	4	1	3		
WELDED	3	4	3	3	4	3	4	3	4	4	4	1	3		
WIRE WRAP	3	3	3	4	4	4	4	3	4	4	4	4	1		

* - All termination types considered <u>sealed</u> in some manner
1 = poor, unacceptable; 2 = fair, average; 3 = good, above average; 4 = excellent

TABLE 3

APPLICATION ATTRIBUTE WEIGHTING FACTORS*

ATTRIBUTES / APPLICATIONS	DURABILITY								FUNCTIONAL									MANUFACTURING						UTILITY				CODE		
	MOISTURE	TEMP. CYCLING	CORROS. ATM.	CONTAMINATION	VANDALISM	UV RADIATION	VIBRATION	STRAIN RELIEF	VOLTAGE RATING	CURRENT RATING	INSUL. LEVEL	SEAL LEVEL	GND. PROVISION	HEAT DISS.	DISCONN. CYCLES	CONTACT RES.	RELIABILITY (MTBF	PREPARATION	PRODUCIBILITY	REPAIRABILITY	LABOR SKILL LEVEL	SPECIAL TOOLS	SAFETY	SERIES CONN.	PARALLEL CONN.	WIRE-TO-WIRE	PANEL-TO-WIRE	NEC		
REMOTE	4	4	4	4	4	4	4	4	4	4	4	4	1	4	1	4	4	2	2	3	2	2	4	1	4	4	1	2		
RESIDENTIAL	3	2	1	2	2	3	2	2	4	4	4	4	4	1	1	1	2	2	2	3	2	2	4	2	3	3	2	4		
INTERMEDIATE	4	4	3	2	2	4	2	2	4	4	4	4	4	2	1	2	3	2	2	3	2	2	4	3	2	2	3	4		
INDUSTRIAL	3	2	4	3	2	3	2	3	4	4	4	4	4	4	1	4	4	2	2	3	2	2	4	4	1	1	4	4		

* - These factors to be multiplied by termination attribute ratings in Table 2 for final ranking.

TABLE 4

TERMINATION RANKING FOR REMOTE APPLICATION

TERMINATION TYPE	FUNCTIONAL									MANUFACTURING					
	VOLTAGE RATING	CURRENT RATING	INSUL. LEVEL	SEAL LEVEL	GND PROVIS.	HEAT DISS.	DISCON. CYCLES	CONTACT RES.	RELIAB. (MTBF)	PREP TIME	PRODUC-IBILITY	REPAIR-ABILITY	LABOR SKILL LEVEL	SPEC. TOOLS	SAFETY
CRIMP	16	16	12	12	1	12	1	16	16	6	6	12	8	6	12
HAND-SOLDERED	16	16	4	16	1	12	1	16	8	4	4	9	2	4	4
INSUL. DISP.	8	8	8	16	1	8	1	12	16	8	4	6	6	6	8
PLUG/RECEPTACLE	16	16	16	16	4	4	4	8	12	4	8	9	4	4	16
SCREW	16	16	4	16	4	16	4	16	8	4	4	12	4	8	8
STRING CLIP	4	4	4	8	1	12	4	16	8	4	4	12	8	8	4
TWIST-ON	12	12	16	12	1	12	3	12	12	6	6	12	8	8	8
WELDED	16	16	4	16	1	12	1	16	16	4	6	3	4	2	4
WIRE WRAP	4	4	8	16	1	12	1	12	16	6	6	6	8	6	8

TABLE 4 (Continued)

TERMINATION RANKING FOR REMOTE APPLICATION

TERMINATION TYPE	DURABILITY									UTILITY					
	MOIST.	TEMP. CYCLE	CORROS ATM.	CONTAM	VANDAL	UV RAD.	VIB. (JOINT STR)	STRAIN RELIEF	SERIES CONN.	PARA. CONN.	[illegible]	[illegible]	NEC		
CRIMP	12	12	12	12	4	12	16	16	4	16	16	1	8		
HAND-SOLDERED	16	8	12	12	4	12	12	12	4	16	16	4	4		
INSUL. DISP.	16	16	16	16	4	12	8	12	4	16	16	4	6		
PLUG/ RECEPTACLE	16	16	16	16	2	16	16	16	4	16	16	4	6		
SCREW	12	12	12	16	3	16	12	16	4	16	16	4	8		
STRING CLIP	8	16	12	16	3	16	12	16	4	16	16	4	2		
TWIST-ON	12	12	12	16	2	16	8	4	4	16	16	2	6		
WELDED	12	16	12	16	4	12	16	12	6	16	16	1	6		
WIRE WRAP	12	12	12	16	4	16	16	12	4	16	16	4	2		

TABLE 5

TERMINATION RANKING FOR RESIDENTIAL APPLICATION

TERMINATION TYPE	FUNCTIONAL									MANUFACTURING					
	VOLTAGE RATING	CURRENT RATING	INSUL. LEVEL	SEAL LEVEL	GND PROVIS.	HEAT DISS.	DISCON. CYCLES	CONTACT RES.	RELIAB. (MTBF)	PREP TIME	PRODUC-IBILITY	REPAIR-ABILITY	LABOR SKILL LEVEL	SPEC. TOOLS	SAFETY
CRIMP	16	16	12	12	4	3	1	4	8	6	6	12	8	12	12
HAND-SOLDERED	16	16	4	16	4	3	1	4	4	4	4	9	2	4	4
INSUL. DISP.	8	8	8	16	4	2	2	3	8	8	4	6	6	6	8
PLUG/ RECEPTACLE	16	16	16	16	16	1	4	2	6	4	8	9	4	4	16
SCREW	16	16	4	16	16	4	4	4	4	4	4	12	4	8	8
STRING CLIP	4	4	4	8	4	3	4	4	4	4	4	12	4	8	4
TWIST-ON	12	12	16	12	4	3	4	3	6	6	6	12	8	8	8
WELDED	16	16	4	16	4	3	1	4	8	4	6	3	4	2	4
WIRE WRAP	4	4	8	16	4	3	1	3	8	6	6	6	8	6	8

TABLE 5 (Continued)

TERMINATION RANKING FOR RESIDENTIAL APPLICATION

TERMINATION TYPE	DURABILITY									[illegible]				CODE	
	MOIST.	TEMP. CYCLE	CORROS ATM.	CONTAM	VANDAL	UV RAD.	VIB. (JOINT STR)	STRAIN RELIEF	SERIES CONN.	PARA. CONN.	WIRE TO WIRE	PANEL TO PANEL	NEC		
CRIMP	9	6	3	6	8	9	8	8	8	12	12	2	16		
HAND-SOLDERED	12	4	3	6	8	9	6	6	8	12	12	8	8		
INSUL. DISP.	12	8	4	8	8	12	4	8	8	12	12	8	12		
PLUG/RECEPTACLE	12	8	4	8	4	12	8	8	8	12	12	8	12		
SCREW	9	6	3	8	6	12	6	8	8	12	12	8	16		
SPRING CLIP	6	8	3	8	6	12	6	8	8	12	12	8	4		
TWIST-ON	9	6	3	6	4	9	4	2	8	12	12	2	12		
WELDED	9	8	3	6	8	9	8	6	8	12	12	2	12		
WIRE WRAP	9	6	3	8	8	12	8	6	8	12	12	8	4		

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TABLE 6

TERMINATION RANKING FOR INTERMEDIATE APPLICATION

TERMINATION TYPE	FUNCTIONAL									MANUFACTURING					
	VOLTAGE RATING	CURRENT RATING	INSUL. LEVEL	SEAL LEVEL	GND PROVIS.	HEAT DISS.	DISCON. CYCLES	CONTACT RES.	RELIAB. (MTBF)	PREP TIME	PRODUC-IBILITY	REPAIR-ABILITY	LABOR SKILL LEVEL	SPEC. TOOLS	SAFETY
CRIMP	16	16	12	12	4	6	2	8	12	6	6	12	8	6	12
HAND-SOLDERED	16	16	4	16	4	6	4	8	6	4	4	9	2	4	4
INSUL. DISP.	8	8	8	16	4	4	2	6	12	8	4	6	6	6	8
PLUG/ RECEPTACLE 2	16	16	16	16	16	2	4	4	9	4	8	9	4	4	16
SCREW	16	16	4	16	16	8	4	8	6	4	4	12	4	8	8
STRING CLIP	4	4	4	8	4	6	4	8	6	4	4	12	8	8	4
TWIST-ON	12	12	16	12	4	6	4	6	9	4	6	12	8	8	8
WELDED	16	16	4	16	4	6	1	8	12	4	6	3	4	2	4
WIRE WRAP	4	4	8	16	4	6	1	6	12	6	6	6	8	6	8

TABLE 6 (CONTINUED)

TERMINATION RANKING FOR INTERMEDIATE APPLICATION

TERMINATION TYPE	DURABILITY									UTILITY				CODE	
	MOIST.	TEMP. CYCLE	CORROS ATM.	CONTAM	VANDAL	UV RAD.	VIB. (JOINT STR)	STRAIN RELIEF	SERIES CONN.	PARA. CONN.	WIRE TO WIRE	PANEL TO PANEL	NEC		
CRIMP	12	12	9	6	8	12	8	8	12	8	8	3	16		
HAND-SOLDERED	16	8	9	6	8	12	6	6	12	8	8	12	8		
INSUL. DISP.	16	16	12	8	8	16	4	8	12	8	8	12	12		
PLUG/ RECEPTACLE	16	16	12	8	4	16	8	8	12	8	8	12	12		
SCREW	12	12	9	8	6	16	6	6	12	8	8	12	16		
SPRING CLIP	8	16	9	8	6	16	6	8	12	8	8	12	4		
TWIST-ON	12	12	9	6	4	12	4	2	12	8	8	3	12		
WELDED	12	16	9	6	8	12	8	6	12	8	8	3	12		
WIRE WRAP	12	12	9	8	8	16	8	6	12	8	8	12	4		

TABLE 7
TERMINATION RANKING FOR INDUSTRIAL APPLICATION

TERMINATION TYPE	FUNCTIONAL									MANUFACTURING					
	VOLTAGE RATING	CURRENT RATING	INSUL. LEVEL	SEAL LEVEL	GND PROVIS.	HEAT DISS.	DISCON. CYCLES	CONTACT RES.	RELIAB. (MTBF)	PREP TIME	PRODUC-IBILITY	REPAIR-ABILITY	LABOR SKILL LEVEL	SPEC. TOOLS	SAFETY
CRIMP	16	16	12	12	4	12	1	16	16	6	1	12	8	6	12
HAND-SOLDERED	16	16	4	16	4	12	1	16	8	4	4	9	2	4	4
INSUL. DISP.	8	8	8	16	4	8	2	12	16	8	4	6	6	6	8
PLUG/RECEPTACLE	16	16	16	16	16	4	4	8	12	4	8	9	4	4	16
SCREW	16	16	4	16	16	16	4	16	8	4	4	12	4	8	8
STRING CLIP	4	4	4	8	4	12	4	16	8	4	4	12	8	8	4
TWIST-ON	12	12	16	12	4	12	4	12	12	6	6	12	8	8	8
WELDED	16	16	4	16	4	12	1	16	16	4	6	3	4	2	4
WIRE WRAP	4	4	8	16	4	12	1	12	16	6	6	6	8	6	8

TABLE 7 (CONTINUED)

TERMINATION RANKING FOR INDUSTRIAL APPLICATION

TERMINATION TYPE	DURABILITY									UTILITY			CODE		
	MOIST.	TEMP. CYCLE	CORROS ATM.	CONTAM	VANDAL	UV RAD.	VIB. (JOINT STR)	STRAIN RELIEF	SERIES CONN.	PARA. CONN.	WIRE TO WIRE	PANEL TO PANEL	NEC		
CRIMP	9	6	12	9	8	9	8	12	16	4	4	4	16		
HAND-SOLDERED	12	4	12	9	8	9	6	9	16	4	4	16	8		
INSUL. DISP.	12	8	16	12	8	12	8	12	16	4	4	16	12		
PLUG/ RECEPTACLE	12	8	16	12	4	12	8	12	16	4	4	16	12		
SCREW	9	6	12	12	6	12	6	12	16	4	4	16	16		
STRING CLIP	6	8	12	12	6	12	6	12	16	4	4	16	4		
TWIST-ON	9	6	12	9	4	9	4	3	16	4	4	4	12		
WELDED	9	8	12	9	8	9	8	9	16	4	4	4	12		
WIRE WRAP	9	6	12	12	8	12	8	9	16	4	4	16	4		

TERMINATION TYPE	APPLICATION CLASS			
	REMOTE	RESIDENTIAL	INTERMEDIATE	INDUSTRIAL
CRIMP	293	239	260	272
HAND-SOLDERED	249	197	223	237
INSUL. DISP.	271	213	244	256
PLUG/RECEPTACLE	301	254	284	289
SCREW	287	238	267	283
SPRING CLIP	242	180	209	222
TWIST-ON	259	209	231	240
WELDED	260	198	226	236
WIRE WRAP	256	195	224	237

TABLE [illegible] RANKING NOT INCLUDING COST CONSIDERATIONS

TABLE 9
RANKING BY NUMERICAL ORDER

RANK \ APP'L	REMOTE	RESIDENTIAL	INTERMEDIATE	INDUSTRIAL
1	PLUG/RECPT (301)	PLUG/RECPT (254)	PLUG/RECPT (284)	PLUG/RECPT (289)
2	CRIMP (293)	CRIMP (239)	SCREW (267)	SCREW (283)
3	SCREW (287)	SCREW (238)	CRIMP (260)	CRIMP (272)
4	INSL. DISP. (271)	INSL. DISP. (213)	INSL. DISP. (244)	INSL. DISP. (256)
5	WELDED (260)	TWIST-ON (209)	TWIST-ON (231)	TW ST-ON (240)
6	TWIST-ON (259)	HAND-SOLDER (197)	WELDED (226)	HAND-SOLDER (237)
7	WIRE-WRAP (256)	WELDED (198)	WIRE-WRAP (224)	WIRE-WRAP (237)
8	HAND-SOLDER (249)	WIRE-WRAP (195)	HAND-SOLDER (223)	WELDED (236)
9	SPRING CLIP (242)	SPRING CLIP (180)	SPRING CLIP (209)	SPRING CLIP (222)

4.0 RESULTS/CONCLUSIONS

4.1 BEST-SUITED TERMINATIONS

Results of the evaluation show the plug/receptacle and crimp-type terminations to be the most appropriate existing electrical termination for use in all four application classes based on attribute score and cost. It is interesting to note that the three top-rated termination types (plug/receptacle, crimp, and screw type) are top-rated in all four application classes although not in the same order. Generally speaking, the three top-rated termination types were very close in numerical values except for cost.

Of the three top-rated termination types, the least expensive connection is the crimp type with a total cost of $0.69 per connection. Next is the plug/receptacle type with total cost of $0.90, and last is the screw type with total cost of $4.78, incidentally the most expensive of all termination types considered.

Costs were not integrated into the selection criteria due to fluctuations of actual costs with respect to application class, differences in module manufacturer facilities, module design, locale, and personnel utilized. For these same reasons, it was impossible to provide any correlation between specific modules manufactured and the ideal termination to be used. It is the intention that the attribute chart values be modified (if necessary) by the electrical termination selector, to more closely conform to the requirements of a specific module or a particular unique application.

The two termination types found to be unacceptable in voltage and current ratings (spring clip and insulation displacement) were nevertheless evaluated fully. It is interesting to note here that the insulation displacement method of termination was rated fourth in each application class. This would indicate that the termination would be an appropriate choice in any application if the voltage and current ratings, presently limited by conductor wire size, could be increased.

4.2 DESIGN IMPROVEMENTS/COST DRIVERS

The factors which affect termination costs are: manufacturing material, equipment, and labor; installation labor, skill and equipment; and sealing material and labor.

Comparing cost data for the three top-rated terminations, the first striking difference is in initial cost, with crimp at $0.08, plug, receptacle as $0.32 and screw type at $0.98. The crimp and screw type terminations are quite simple and have been in production for a considerable length of time. Also, they are both manufactured in large quantities. It is therefore unlikely that any manufacturing cost could be greatly reduced. The plug/receptacle termination type however, is relatively new on the market and perhaps could benefit by some manufacturing cost reduction in the future.

The major cost drivers in the screw-type of termination, besides initial cost, are material cost and factory and field labor costs associated with the use of a junction box for satisfactory environmental sealing. There are ways to reduce junction box-associated costs, such as an elastomeric junction box with screw terminals (terminal block) molded into it, or having the junction box be part of the module or support frame (which would eliminate attachment labor). Another possible way to reduce cost while addressing the "sealing" problem is to manufacture a boot or shroud that slipped-over (or otherwise attached to) a standard terminal block, effectively isolating the terminals from the environment, and eliminating the need for a junction box. Such a cover is not currently manufactured, but if available, would be considerably less expensive than a junction box.

Field labor is high due to the considerable amount of time involved in making the electrical connections and re-attaching the lid of the junction box.

The major cost driver that could be feasibly reduced in the crimp type of termination is the labor involved in sealing the termination. This could be resolved by re-designing the crimp termination to include some sort of tight-fitting collar at the conductor entry end(s) of the crimp termination. A butt splice termination utilizing this type of sealing might look like the following, figure 1.

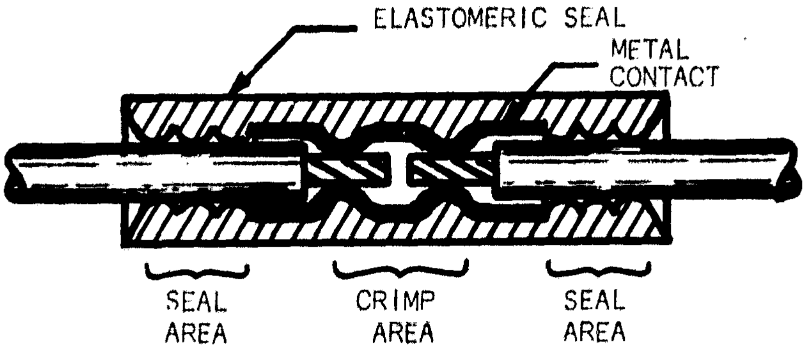

FIGURE 1: SUGGESTED CRIMP TERMINATION SEAL

The cost drivers identified in the plug/receptacle type of termination are the high initial cost and high factory labor content (installation). These cost drivers seem to be inherent in the plug/receptacle type of termination.

5.0 MINI-APPENDICES

5.1 TERMINATION CONSIDERATIONS RELATIVE TO INTERCONNECTS, MODULE CONSTRUCTION, AND SUPPORT STRUCTURES

5.1.1 MODULE INTERCONNECT

Modules are provided with terminations for interconnect to 1) the rest of the system, if a single module is used, 2) other modules, if the system uses more than one, and 3) system ground. The location and number of positive and negative terminations depends on several factors: 1) will the module be used alone or interconnected to other modules, 2) relative cost and reliability factors of multi-terminations per module vs. single terminations per module with complex, long wiring runs, and 3) is the ground lead included in the termination. The ground termination deserves special consideration because, in general, electrical interconnects between modules will be in series whereas ground connections will always be in parallel. If the array support structure is insulating (e.g., concrete, wood) then a separate ground bus system will be needed.

5.1.2 PANEL INTERCONNECT

Since a panel is composed of a multiplicity of modules, factory assembled and interconnected, it needs to be provided with terminations for interconnection to other panels. It would be desirable to use terminations of the end modules in a panel for connection into an array; however, the panel terminations may require higher current capability than those on a module due to higher voltages that may be generated. A convenient (and unobstructive) place for mounting them on the panel will need to be delineated. There is also the question of grounding a panel: a common ground connection to which all the module grounds are connected may be desirable.

5.1.3 ARRAY INTERCONNECT

It is assumed that interconnection between arrays to form larger elements of a solar photovoltaic power system will be done at distributed (or centrally located) places, and is not a part of this study. Panels (or modules) in an array will be field interconnected; however, the array must be provided with one or more terminations so that cables can be connected to form the larger power units. Array terminations, particularly for series-connected panels, may be the same as (or similar to) panel terminations.

Positioning of terminations on modules and panels cannot be standardized without consideration of the mounting support structure. Various potential array support systems attach to a module (or panel) at different points, and some of them make accessibility to the backs of modules (or panels) difficult. Standardization of module output locations and/or support structures would be advantageous and is one solution.

5.1.4 MODULE STRUCTURES

Various types of module structures are in current production or are being studied for future market introduction. Figures 2* and 3** represent schematically, most of the possible module structures. These do not, however, deal with the question of electrical terminations. There are several types of module structures:

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*Investigation of Test Methods, Material Properties and Processes for Solar Cell Encapsulatns, JPL Contract 954527, Springborn Laboratories, Inc., June, 1978.

**Evaluation of Available Encapsulation Materials for Low-Cost Long-Life Silicon Photovoltaic Arrays, JPL Contract No. 954328, Battelle Columbus Laboratories, June 30, 1978.

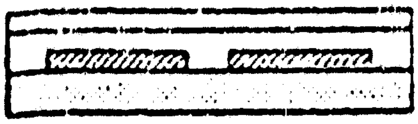
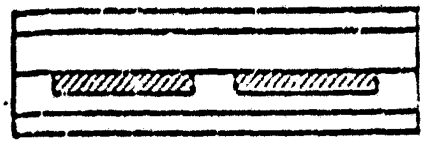
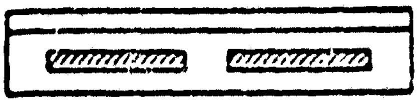
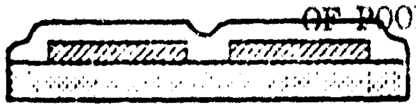
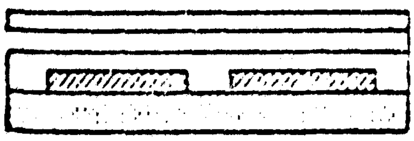
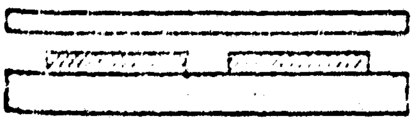
Design	No.	Description
	1.	Cells bonded to rigid substrate; transparent encapsulant, top cover.
	2.	Cells bonded to underside of transparent superstrate/top cover; encapsulant; back cover.
	3.	Rigid single transparent encapsulant; top cover.
	4.	Flexible single transparent encapsulant; rigid clear superstrate.
	5.	Flexible single transparent encapsulant; rigid substrate.
	6.	Cells bonded to rigid substrate; clear conformal top coat.
	7.	Cells bonded to clear superstrate/top cover; conformal under coat.
	8.	Cells bonded to rigid substrate; clear encapsulant; air gap; top cover.
	9.	Cells bonded to rigid substrate; air gap; top cover.

FIGURE 2: FLAT-PLATE SOLAR MODULE DESIGN

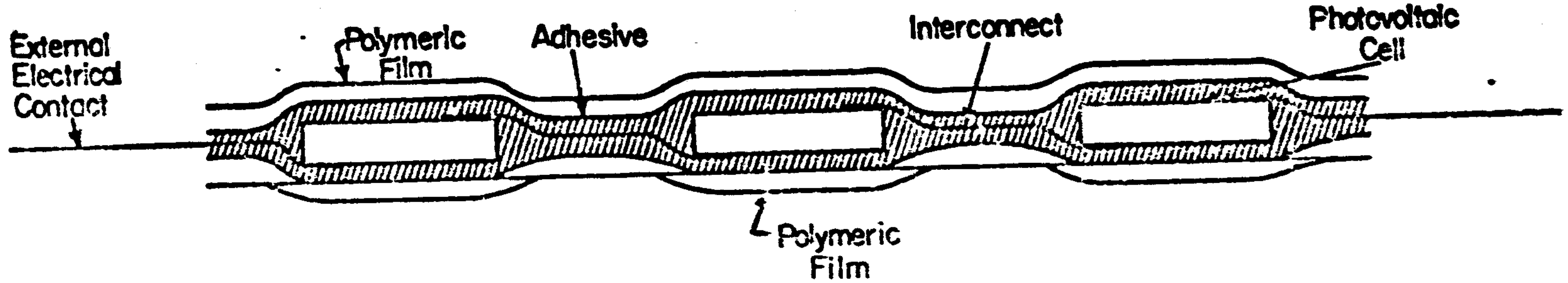


FIGURE 3: FILM LAMINATE MODULE

1. Modules utilizing a rigid substrate to which a termination may be attached.

2. Modules without rigid substrates, but employing a rigid (transparent) superstrate to which a termination may be attached.

3. Flexible modules requiring a frame for termination attachment.

4. Modules employing a rigid substrate and/or rigid superstrate and also a frame.

The mechanical aspects of attaching a termination will vary considerably depending not only on the module design, but also on the material characteristics of a particular design (e.g., a rigid substrate may be bare metal, coated metal, glass, plastic, or wood).

Figure 4 illustrates an exploded view of a potential module termination. Points of importance are:

1. Mechanical attachment of termination to frame (A) or solar cell encapsulation system (B).
2. Sealing of leads leaving solar cell encapsulant system (C).
3. Sealing of leads entering termination (D).
4. Isolation of leads from frame (E).
5. Sealing of interconnect wires at termination connections (F) or (G).

If the leads running from solar cells to termination are exposed, they must be adequately protected from weathering. Note that moisture (with contaminants) can readily travel between the wire and insulating coat of a lead.

It is essential that all of these items be accomplished in a cost-effective, reliable manner that does not degrade performance of the module. In addition, terminations must be rugged to permit rough handling during connect/disconnect in the field without damage to the termination or the module to which it is attached.

5.1.5 REQUIREMENTS IMPOSED BY THE ARRAY SUPPORT STRUCTURE

The panel and/or array support structure is a major source of requirements (and constraints) on the interconnect system, both geometric and electrical. It is necessary to consider a broad range of support structure configurations, sufficient to represent all important support structure constraints. Support configurations are categorized* by structure, including truss, frame, and thin and thick shell (i.e., semi and full monocoque).

*Low Cost Structures for Photovoltaic Arrays, Motorola Inc., Sandia Contract #07-6948, Final Report.

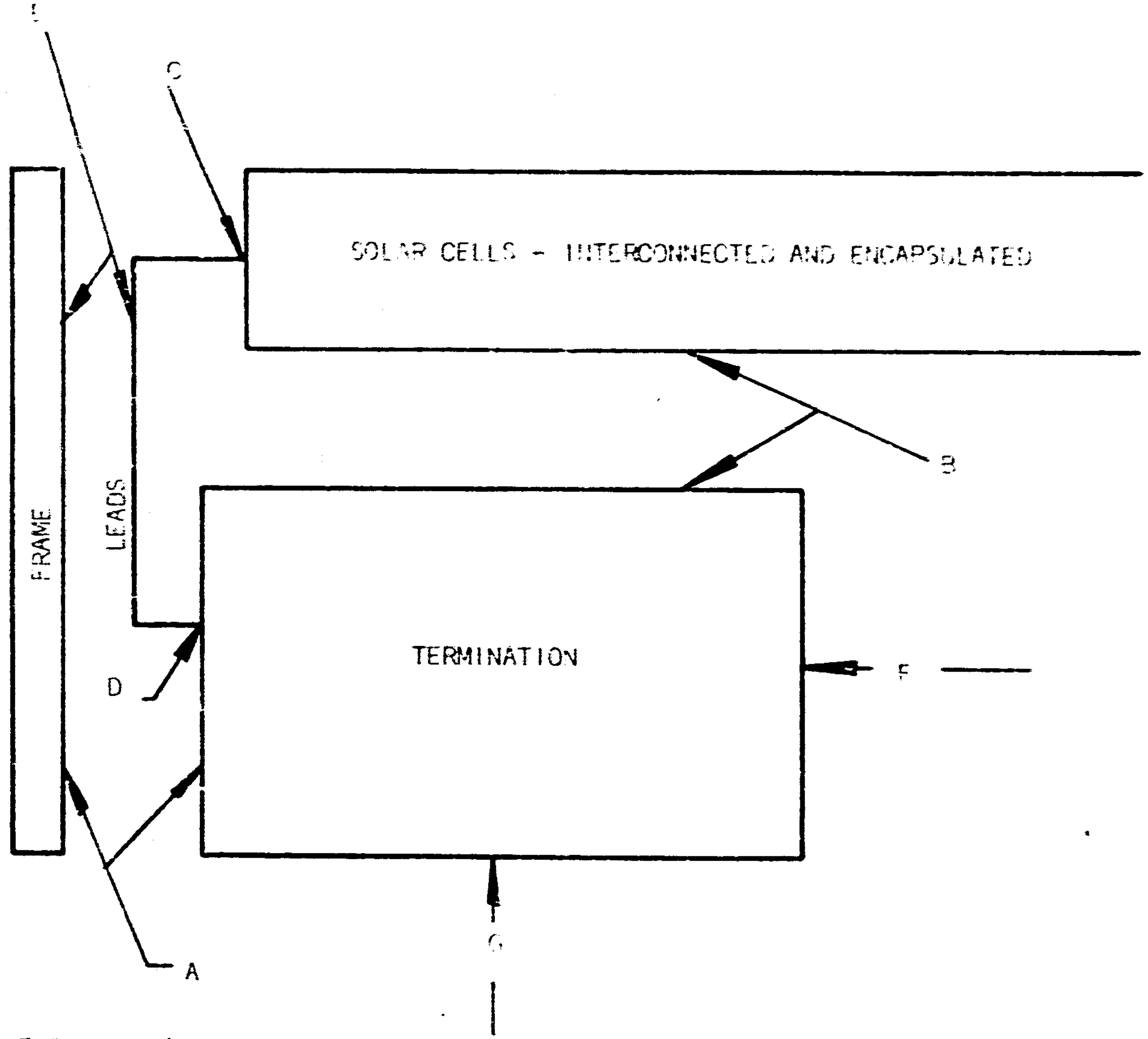


FIGURE 4: EXPLODED VIEW OF TERMINATION ATTACHMENT
A: TERMINATION - FRAME, IF PRESENT
B: TERMINATION - SOLAR CELL ENCAPSULATION
C: WIRE - SOLAR CELL ENCAPSULATION
D: WIRE - TERMINATION
E: WIRE - FRAME
F,G: TERMINATION - CONNECTOR

The module can be supported by the panel/array support structure in several ways. The module support structural interface will be point, line, or area, and usually one of the first two. This support is generally imposed on the back of the module, but may be on the side. Various combinations of these factors have an effect on connector requirements. Additionally, modules may be arranged so that their sides are immediately adjacent to other modules.

Typical constraints imposed by the various types of support structures are:

Restricted access to back of the panel/module.

Restricted access to the side of the panel/module.

Restrictions on cable routing.

Opportunity to combine functions such as structure and cable support.

Grounding requirements will depend on which parts of the structure are electrically conductive.

The wide variety of support structures utilized makes detailed interconnect system requirements imposed by support structures, impossible. This study makes the following assumptions of the support structure:

- Free access to module output(s).
- No restrictions on cable routing

5.2 CIRCUIT, SYSTEM GROUND, DIODE CONSIDERATIONS

5.2.1 SERIES AND/OR PARALLEL CONNECTION IN PANEL OR ARRAY

Consider an array comprising a multitude of modules. If the modules are all connected in series, the amount of interconnect wire can be greatly reduced if positive and negative terminals are separated and placed adjacent to opposite edges of a module. This, however, requires two terminations per module. With the large area solar cells expected by some to be in production by 1986, connection of cells within a module will tend to be in series, giving a tendency for positive and negative terminals to be on opposite sides of a module. Thus, providing separated module terminations will also avoid some additional wiring within a module.

5.2.2 EQUIPMENT GROUND TERMINATION

The purpose of equipment grounding conductors is to provide personal safety by creating a virtual ground for non-current-carrying conductive parts of the equipment. The requirement for an equipment ground is determined by the materials used in the construction of the module.

A system ground, or means to limit maximum voltage with respect to ground, necessitates preventing insulation breakdown within the module. Consistent with module insulation breakdown level, the insulation breakdown rating of the connector must be equal to or greater than the insulation breakdown within the module. Consistent with module insulation breakdown level, the insulation breakdown rating of the connector must be equal to or greater than the insulation breakdown rating of the module to ensure the same level of safety.

Until photovoltaic modules and systems become commonplace, or until the codes and standards are revised to specifically address photovoltaics, the approval/disapproval of the use of certain electrical terminations and interconnections will be left to the discretion and code interpretation of individual code inspectors with the result that innovative termination design configurations may be totally rejected. To minimize this impact the following activities should be undertaken: 1) work with the NEC subcommittee on photovoltaics to draft requirements for PV module terminations; 2) use termination components which have been tested and approved by nationally recognized testing laboratories and have the entire module tested and approved.

5.2.3 PROTECTIVE DIODE CONNECTION

Solar cells may be connected in a series-parallel arrangement to minimize the effects on performance resulting from cell shadowing or from breakage of a cell without redundant contacts. Bypass diodes are often used to prevent back-biasing of series strings of solar cells in such cases. Module termination selection is affected if placement of the diodes is external to the module; external diodes are usually located across the module output terminals. Results to date indicate that appropriate series/paralleling coupled with internally mounted diodes would greatly enhance module performance and minimize extra requirements for terminal selection.

5.3 CODE REQUIREMENTS

Code requirements for photovoltaic module termination hardware are dependent on:

1) Applications:
   a) Small Remote
   b) Residential
   c) Intermediate
   d) Large Industrial and Utility
2) Code Interpretation

The National Electrical (NEC) is the most widely accepted code for all applications with the exception of small remote installations and large utility plants. Small remote installations with less than 30VDC are not addressed by the NEC. The generation portion of utility plants are presently governed by utility company practices made up of industry standards (e.g., IEEE, ANSI, NEMA) as well as their own standards.

In the following paragraphs, the candidate connection hardware for residential and intermediate applications are examined relative to the governing code requirements.

The basic requirements are as follows:

1) Readily accessible parts above 30VDC must be guarded against accidental contact.

2) Non-current carrying metal parts must be properly grounded.

3) The connection must be suitable for code approved conductors.

Photovoltaic systems are intended for widespread use in a variety of geographical climates as well as in areas of heavy pollution. The long-term effects of environmental conditions upon termination performance are not adequately documented, and attempts at correlating accelerated aging test data with real-time results have met with limited success. For this reason, until enviornmental durability is demonstrated, it is recommended that photovoltaic terminations be sealed to enhance reliability and aid in termination protection. Consistant with this recommendation is that materials should be prudently selected for use in outdoor environments.

The IEEE standards listed in Section 6, References, were obtained and reviewed. Applicable information obtained from these standards is as follows.

- Standard ANSI/IEEE 386-1977 was developed cooperatively by IEEE and NEMA for separable insulated connectors (also called dead front connectors) for use in underground electrical distribution systems. The Forward Section of this standard states that vast numbers of these separable insulated connectors are in use with an enviable safety record. The purpose of this standard is to establish definitions, electrical ratings, tests, and interchangeable construction features for load-break separable insulated connectors used at 601 volts and above, and 600 amps and below. Separable connectors which meet the requirements of this standard could possibly be used for higher voltage photovoltaic applications.

- Safety of life and preservation of property are the two most important factors in design of electrical equipment. Personal safety may be divided into safety of maintenance and operating personnel, and safety for the general public.
- The use of UL or other laboratory-approved equipment is recommended.
- High voltage equipment should be manufactured in accordance with NEMA, ANSI, and IEEE standards.
- Installations should be designed so that most maintenance can be accomplished with a minimum need for specialized services.
- Flexibility of electrical systems is important for adaptability to development and expansion, as well as to changes in requirements during system life.
- Electrical connectors for industrial plants are designed to meet the requirements of NEC; they are evaluated on UL standards. When used in power generation systems, they must also have current carrying capability such that temperature rise in the connector is no more than in an equal length of conductor. They must also be capable of withstanding momentary overloads or short circuits to the same degree as the conductor.
- Terminators of armor cable must be capable of grounding the metal armor.

5.3.1 CODE RESEARCH

5.3.1.1 AGENCIES CONTACTED

The following agencies were contacted to define code requirements:

1) Underwriters Laboratory (UL).

2) American Society of Testing Materials (ASTM).

3) National Fire Protection Association (Sponsor of the National Electrical Code).

4) County of Orange, Building and Safety Department.

5) County of Los Angeles, Building and Safety Department.

6) City of Los Angeles, Building and Safety Department.

7) Burt Hill Kosar Rittelman Associates.

The Burt Hill Kosar Rittelman Associates Study of Code Requirements for PV modules for residential applications was reviewed. Some of the major results of their study (relative to this project) are:

1. The National Electrical Code (NEC) will be the major governing electrical code for residential applications.

2. Future design and development should not be limited completely by presently approved wiring methods. New methods will be accepted provided they are engineered with safety in mind.

3. The quickest and easiest method of obtaining code approval would be to maximize factory assembly utilizing nationally recognized laboratory-approved test components and obtain laboratory test approval.

Telephone calls were made to Orange County Building and Safety Department, the Public Utility Commission for California, Southern California Edison, California OSHA, and Bechtel to determine whether utility plants were governed by a regulatory agency or codes. The results of these conversations were that:

> The only codes which govern the design of a utility plant are the utilities' own specifications. These are made up of specific specifications written by them as well as Industry Standards (e.g. IEEE, NEMA, ASA, ANSI, ASTM, etc.).

5.3.1.2 CODE CHARACTERISTICS OF EACH TERMINATION TYPE

BUTT SPLICE (CRIMPED)

Butt Splice (crimped) connections are acceptable. All splices must be covered and insulated. (NEC ART 110-14).

INSULATION DISPLACEMENT

Insulation displacement is also presently being used in the UL approved prewired systems. Regular piercing type are good up to 24 volts.

PLUG/RECEPTACLE

Plug/receptacle connections are acceptable in UL approved prewired systems. They are also acceptable in temporary connections. An effort should be made to gain NEC approval under the special equipment section for sealed quick disconnects composed of pin and socket contacts. Quick disconnects would provide a good inexpensive method of interconnecting photovoltaic modules if definite code approval could be gained. An ANSI/IEEE STD 386-1977 "Separable Insulated Connectors For Power Distribution System Above 600 V", indicates that high voltage separable connectors are being used for interconnecting underground electrical distribution equipment. This standard also states in the forward section that these separable connectors have an enviable safety record.

SCREW

Screw type connections are acceptable methods of terminating and interconnecting electrical conductors.

SOLDERED CONNECTIONS

Soldered connections are acceptable for UL approved prewired systems. They are not generally approved for field wiring because of the lack of control and inspectability. Solder is acceptable if used in conjunction with a method which makes a mechanically and electrically sound connection without the solder (NEC ART 230-81).

SPRING CLIP

Would be acceptable in UL approved systems. However, this type of connection is not normally used in the power industry because of small contact area. Therefore, its acceptance would be very much at the discretion of the inspector.

TWIST-ON

Twist-on connections are acceptable up to a #6 copper wire by NEC.

WELDED TERMINATION

Welded terminations are accepted in UL prewired systems. They are also generally accepted by the code (NEC ART 110-14B). However, a conversation with an inspector indicated that weld connections may sometimes not be accepted. This is because of the difficulty in determining the quality of a weld, after it has been completed, without a destructive type test.

WIRE WRAP

Wire wrap connections without some positive mechanical holding method (e.g., nut on threaded post) are presently not approved in the NEC, but are approved as a part of a prewired system with UL approval. Since NEC requires #14 AWG or larger and since #18 AWG wire is the largest wire being used for wire wrap, it would be difficult to obtain approval for this termination method. A development, testing and approval program would be required for the #14 AWG gage and larger wire. Also, since this method requires single strand solid wire, wire flexibility may be a problem. This may be used in small remote applications if contained in a sealed J-Box.

5.3.1.3 GENERAL CODE CONSIDERATIONS

- All live parts of electrical equipment shall be guarded against accidental contact (NEC ART 110-17)
- Equipment operating in damp or wet locations or exposed to other vapor with a deteriorating effect must be approved for that environment (NEC ART 110-11).
- Approval or disapproval of electrical termination and interconnection can be very dependent on the discretion and code interpretation of individual inspectors. Therefore, it is apparent that an effort should be made to insure that the optimum termination method or methods to be used in the photovoltaic industry shall be clearly specified and documented, and not left to the discretion of individual inspectors.

5.4 CRITIQUE AND EXPANSION OF EXHIBIT I

5.4.1 COPY OF EXHIBIT I

A copy of Exhibit 1 of RFP BQ-2-1320-131 is included in this report in the following pages as Attachment 1.

ATTACHMENT 1

June 16, 1978

Exhibit 1

Projected 1986 Photovoltaic Module

Engineering and Performance Characteristics

GENERAL

In support of the U.S. Department of Energy, National Photovoltaic Program, the goal of the Low-cost Solar Array (LSA) Project is by 1986 to reduce the price of photovoltaic (solar cell) modules to $0.50 per peak Watt (expressed in constant 1975 dollars) when produced in annual quantities of 500 MW. Additional 1986 module goals are an efficiency of 10 percent or greater and a life of 20 years. An important and necessary step in meeting these objectives is the study of electrical termination hardware for modules and arrays.

The objective of the Photovoltaic Module Electrical Termination Requirements Study is to develop information which will facilitate the selection of electrical termination hardware for terrestrial solar cell modules and arrays. The base of information which this study is to draw on is the vast quantity of existing electrical termination hardware used outdoors. To be of most value to the photovoltaic community, information coming from this study should be specific and to the fullest extent possible parametric. Expected output from this study include:

- Termination hardware requirements, including environmental, system interface, and design requirements; and test procedures
- Catalog of existing termination hardware and their attributes
- Summary of the attrubute cost dependencies and cost driver sensitivities
- Candidate electrical termination hardware for solar cell modules and arrays
- Areas for cost improvement

In conducting this study, cost is an important selection factor. With an allocation of $0.50 per peak Watt for the whole module, termination hardware cost should not be a significant fraction of that amount. One emphasis of the study is to seek out and describe the cost dependencies of each attribute or property important to the selection of electrical termination hardware for solar cell modules and arrays. By doing so, it is anticipated that cost drivers can be identified.

The cost to be used throughout the study is the life cycle cost (LCC). Included in the life cycle cost are the costs of installation and maintenance, as well as the first cost of the hardware. Only by using the LCC method can the impact of termination choices be truly expressed.

Termination hardware selection is influenced by a variety of factors, some system (i.e., application) oriented and others, such as code and cost requirements, oriented toward design constraints. Whenever possible, this Exhibit quantizes these factors based on present knowledge and projected 1986 module requirements and characteristics. The following sections of this Exhibit describe environmental requirements and concerns (parameters to be addressed in the study); module production quantities and current and voltage levels; safety, treated as a parameter for study and alluded to in the form of the module characteristic of operating voltage; reliability/lifetime, a parameter for study; demating frequency (low); and other parameters needed or to be determined in the conduct of the study.

SYSTEMS TERMINOLOGY

The following presents the definition of terminology used to describe photovoltaic systems. Amplification is provided when felt necessary for clarification. The terminology are of a general nature, reflecting the diversity of power system designs. Some terminology may not be applicable to small scale applications, whereas for large scale applications all terminology is applicable.

- SOLAR CELL - The basic photovoltaic device which generates electricity when exposed to sunlight.

Photovoltaic ("solar") cells generate electricity in the presence of sunlight. Present cells are round, ranging from 5 to 10 cm (2.0 to 4 in) in diameter, and are sawn from long single polycrystalline silicon crystals, called ingots, into wafers approximately 0.4 mm (0.015 in) thick. Future methods of cell production include ribbon sheet, wherein a cell is grown in a continuous long strip of silicon. There is no clear indication of which technology will be utilized in 1986, and both ribbon and ingot technologies are being actively investigated. Whichever technology is eventually used, it is clear that the cell will be a shape, such as square or hexagonal, that yields a high cell packing density within a module.

- MODULE - The smallest complete, environmentally protected assembly of solar cells, optics, and other components (exclusive of tracking), designed to generate dc power under unconcentrated terrestrial sunlight.

Individually, solar cells are fragile and difficult to handle in large quantities. With their nominal ½ volt output, individually connecting cells in the field to form a power system is uneconomical. Coupled with their susceptibility for degradation in the terrestrial environment, primarily the effects of moisture and airborne contaminants, it is not desirable to use unprotected solar cells. However, electrically connecting solar cells in series and parallel and then encapsulating this assembly to form a module provides environmental protection for the cells and interconnects while making a handleable unit with less electrical field connections. This unit then serves as a building block for solar electric power systems.

- PANEL - A collection of modules fastened together, preassembled and wired, designed to provide a field-installable unit.

Panels provide structural support for one or more modules. In large applications, panels can be utilized as a means of minimizing the total number of field-installed units thus helping lower installation costs. If the application is sufficiently large, panels will be preassembled and prewired in the module factory.

- ARRAY - A mechanically integrated assembly of modules or panels together with support structure (exclusive of foundation), tracking, thermal control, and other components, as required, to form a dc power producing unit.

Panels or, if panels are not used, modules, are mechanically integrated with support structure to form a free-standing unit.

- BRANCH CIRCUIT - A number of modules or paralleled modules connected in a series to provide dc power at the system voltage.

The system voltage levels may vary from 15 to 2000 Vdc, depending on application. When used, panels may be prewired to minimize the number of field electrical connections.

- ARRAY SUBFIELD - A group of solar photovoltaic arrays associated by a distinguishing feature such as field geometry, electrical interconnection, or power conditioning.

Applications requiring limited quantities of energy may have photovoltaic power systems ending at the array/branch circuit level, its energy requirements being met by at most several branch circuits. However, applications requiring a large amount of energy will necessitate the use of a greater number of branch circuits/arrays. When combining branch circuits, there is a natural grouping that takes place, usually, dictated by the physical size constraints of the array or the requirements of the power conditioning unit, and this grouping is termed an array subfield.

- ARRAY FIELD - The aggregate of all solar photovoltaic arrays generating power within a given system.

If the application energy requirement is very large, several array subfields may be required.

SOLAR CELL MODULE CHARACTERISTICS

It is anticipated that by 1986 there will be a product line of solar cell modules whose characteristics of size, construction, and performance differ because of their intended applications. Table 1 identifies the application classes, the approximate size of each application within an application class, and the estimated annual production.

Table 1. 1986 Application Classes, Sizes, and Estimated Annual Production

Application Class	Application Size (peak Watts)	Estimated Annual Production
Small Remote	<1 kWp	10 MWp/year
Residential	1-10 kWp	50 MWp/year
Intermediate	10-500 kWp	220 MWp/year
Large Industrial	>500 kWp	220 MWp/year

Table 2 identifies projected 1986 solar cell module characteristics for each application class, including installation and repair considerations. The average output of the modules will meet or exceed 100 W/m^2 of module area (10% efficiency) when the module is at its nominal operating cell temperature; large industrial class modules are anticipated to have a higher average output of 140 W/m^2 of module area (14% efficiency) at NOCT. NOCT is the average cell temperature within a module when it is operating open-circuited in the following ambient conditions: insolation of 80 mW/cm^2, 20 C air temperature, and 1 m/sec wind velocity.

Table 3 elaborates on the projected 1986 solar cell module electrical characteristics as related to module size.

Application Class	Module Size	Module Current	Module Voltage[3]	System Voltage
1. Small Remote (<1KW)	0.3 x 0.3m (1 x 1 ft) 0.3 x 0.6m (1 x 2 ft) 0.6 x 0.6m (2 x 2 ft) 0.6 x 1.2m (2 x 4 ft)	Normal: 0.5-12 amp Maximum Continuous: 1-15 amp	7.5-60 Vdc	15-40 Vdc @ NOCT
2. Residential (1-10KW)	0.3 x 0.3m (1 x 1 ft) 0.3 x 0.6m (1 x 2 ft) 0.6 x 0.6m (2 x 2 ft) 0.6 x 1.2m (2 x 4 ft) 1.2 x 1.2m (4 x 4 ft)	Normal: 1-24 amp Maximum Continuous: 2-28 amp	7.5-60 Vdc	40-300 Vdc @ NOCT
3. Intermediate (10KW-500KW)	0.6 x 1.2m (2 x 4 ft) 1.2 x 1.2m (4 x 4 ft) 1.2 x 2.4m (4 x 8 ft)	Normal: 2-24 amp Maximum Continuous: 3-28 amp	7.5-60 Vdc	100-500 Vdc @ NOCT
4. Large Industrial (>500KW)	1.2 x 2.4m (4 x 8 ft) 2.4 x 4.8m (8 x 16 ft)	Normal: 6-215 amp Maximum Continuous: 8-240 amp	7.5-60 Vdc	500-2000 Vdc @ NOCT

TABLE 2: PROJECTED 1986 PHOTOVOLTAIC MODULE APPLICATION CLASSES, CHARACTERISTICS AND INSTALLATION CONSIDERATIONS.

NOTES:

1. Nominal Operating Cell Temperature (NOCT) is the average cell temperature within a photovoltaic module when it is operating open-circuited in the following ambient conditions: insolation of 80 mW/cm^2, $20^{o}C$ air temperature, and 1 m/sec wind velocity.

2. Manufacturing facility assembly considerations are: (a) degree of shop assembly operations: moderate to high (semi-automated to fully automated); (b) degree of termination prefabrication: low to moderate; (c) termination repair capability: high (special tool or machine would be available).

Application Class	Module Power (Maximum)	Field Installation Considerations[2]	Typical Applications
1. Small Remote (<1KW)	9 - 70 W @ NOCT[1]	No. of installers: 1-2 men Degree of termination prefabrication: moderate Degree of field assembly operations: low to moderate (simple and quick assembly with minimal tools) Termination repair capability: simple to repair in the field	• Battery charging • Remote weather stations • Microwave repeater stations
2. Residential (1-10KW)	9-140 W @ NOCT	No. of installers: 1-2 men Degree of termination prefabrication: low to moderate Degree of field assembly operations: high Termination repair capability: simple to repair in the field	• Personal residences • Condominiums, townhouses
3. Intermediate (10KW-500KW)	70-290 W @ NOCT	No. of installers: 2-4 men Degree of termination prefabrication: moderate Degree of field assembly operations: moderate (some field assembly) Termination repair capability: moderate field repair capability; may require special tool or machine in field	• Apartment complexes • Water pumping • Shopping centers • Small industrial facilities
4. Large Industrial (>500KW)	290-1615 W @ NOCT	No. of installers: 3-4 men Degree of termination prefabrication: high Degree of field assembly operations: low (minimal field assembly) Termination Repair capability: moderate field repair capability; requires special tool or machine & may require skilled operator	• Cogeneration facilities • Large industrial and process industries • Utility power stations

TABLE 2: Continued

NOTES: (continued) 3. Module voltages are 7.5, 15, 30, and 60 Vdc, which are the nominal voltages at NOCT to charge 6, 12, 24, and 48 Vdc battery systems, respectively. See Table 3.

Table 3. Estimated 1986 photovoltaic module electrical characteristics versus module size

Module Size	Module Current (amps) for Module Voltage[1]				Module Power (Maximum)
	7.5 Vdc	15 Vdc	30 Vdc	60 Vdc	
0.3 x 0.3m (1 x 1 ft)	1.5	0.75	-	-	9 W
0.3 x 0.6m (1 x 2 ft)	3	1.5	0.75	-	18 W
0.6 x 0.6m (2 x 2 ft)	6	3	1.5	0.75	36 W
0.6 x 1.2m (2 x 4 ft)	12	6	3	1.5	72 W
1.2 x 1.2m (4 x 4 ft)	24	12	6	3	144 W
1.2 x 2.4m (4 x 8 ft)	48	24	12	6	288 W
2.4 x 4.8m (8 x 16 ft)	215	108	53.8	26.9	1613 W

Notes:

1. Module voltages are nominal voltages at NOCT which will charge 6, 12 24, and 48 Vdc battery systems, respectively.

2. The 2.4 x 4.8m (8 x 16 ft) "module" is a Large Industrial class panel probably composed of four 1.2 x 2.4m (4 x 8 ft) fourteen percent efficient modules.

ENVIRONMENTAL REQUIREMENTS

Electrical termination hardware will be outdoors like the modules and arrays they interconnect. If very severe environmental conditions exist, devices such as J-boxes can be utilized to protect the electrical terminations. A question to be addressed by the study is whether, in fact, protective devices are cost effective. In the study, environments to be considered in evaluating termination hardware include: solar exposure (particularly ultraviolet (UV)); thermal conditions, including freezing and thawing; effects of wind, snow, ice, humidity, hail, salt mist, and atmospheric oxidants; dust and debris accumulation, expecially nonremovable stains or contamination; dynamic loading effects of wind, snow, and hail; fungus; and insects and vermin. General environmental conditions modules and arrays can experience include:

- Temperature: -40°C to +90°C
- Humidity: 10 to 100% RH
- Wind loading: ±2.4 kPa (± 50 psf)
- Twisted mounting surface ("racking"): 2 cm/m (¼ inch/foot)

TERMINATION HARDWARE SELECTION CONCERNS

In conducting this study, a list of selection criteria factors applicable to solar cell modules and arrays is to be developed for use in the survey and summary of existing electrical termination hardware. The following is a strawman listing of factors that when used in the conduct of the survey/summary could yield important information relevant to requirements for solar cell modules and array termination hardware:

1. Application Special Requirements, for example, reliability and cost requirements, and special service environments (salt, acid, etc.)

2. Electrical Operating Parameters, nominal, minimum, maximum, and transient values of, for example, current, voltage, and power.

3. Environmental Parameters, (see previous section), those environmental conditions experienced by the hardware when in its stored condition, as well as in its installed operating and off conditions. Important parameters include: nominal, minimum, maximum, and transient values of temperature and humidity; solar irradiance, particularly UV; atmospheric contaminants (type and concentration); shock and vibration (plane, amplitude, and duration); degree of sealing and the need for hermeticity; life -- design life versus maximum anticipated; and degree of weather protection.

4. Approvals and Approval Specifications, "code" requirements may be more stringent than any other application parameter or requirement. Identification of these requirements should include: the approval organization, the specifications met by the hardware/apparatus, and a listing of the stringent design requirements contained in the specifications.

5. Termination Configuration and Orientation, location requirements bear upon the selection of termination hardware and include: location of terminations with respect to internal circuitry (modules); location of terminations with respect to series and/or parallel connection with other system components (modules); proximity of terminations; presence of voltage barriers; and the mechanical support and accessibility provisions with regard to system component (module) structural members and mounting interfaces.

6. Termination Design Approach, including connectors, terminal blocks, studs, and cable pigtails.

7. Insulation, materials, thickness, and properties.

8. Contacts, base and plating materials.

9. Method of Conductor Attachment.

10. Installation and Removal, frequency and ease.

11. Operator Safety, including voltage isolation and grounding provisions.

12. Preventative Maintenance, requirements and frequency.

In actual practice, demating frequency is considered low. Once installed, there is no operational reason to break the electrical connection unless there is a problem.

5.4.2 CRITIQUE AND EXPANSION OF THE MODULE, PANEL AND ARRAY REQUIREMENTS CONTAINED IN EXHIBIT I OF RFP BQ-2-1320-131.

5.4.2.1 GENERAL

Page 1: Although the original efficiency goal was > 10%, current objectives of the industry are higher, i.e. 14% at NOCT.

Page 3: "single polycrystalline silicon" should read "single crystalline silicon".

"square or hexagonal" would better be written "square, rectangular, or hexagonal" since current industry emphasis is on square and rectangular cells.

Pages 3/4: It would help the reader to grasp the different systems if examples were given of array, branch circuit, array subfield, and array field connections.

Page 5: Table 1 is designed for potential U.S. applications.

It is probable that the market in underdeveloped countries will become large first. In such a case, small village units would predominate. Table 1 would then read

Small Remote and Village	< kW_p	200 MW_p/year
Residential and Village	1 - 10 kW_p	200 MW_p/year
Intermediate	10 - 500 W_p	80 MW_p/year
Large Industrial	> 500 W_p	20 MW_p/year

5.4.2.1.1 DEFINITION OF MODULE, PANEL, AND ARRAY REQUIREMENTS

Second last paragraph: it is not obvious why module efficiency will be only 10% except for the large industrial class modules. It is probable that all modules will be 14%, except smaller ones (at about 13%) because of a larger percent of peripheral area.

Page 6: Table 7. Module currents are given in terms of "Normal" and "Maximum Continuous". These terms need to be defined.

3.4.2.1.1.1 MODULE CHARACTERISTICS

The module characteristics listed in Table 3 of Appendix 1 are to apply in terms of potential production realization by 1986. While the smaller sizes, which are in production today, will continue into the future for low power applications, it has not yet been established to what size modules may be economically and reliably produced. It is expected that -- the area of each silicon solar cell will be as large as possible; this is necessary for the required economy in processing and assembly. As a result, only the smaller modules will use small area solar cells, their size dictated by the maximum current necessary for the particular application (e.g., 0.57 amps as shown in Table 3, Appendix 1). This raises a particular question concerning several of the proposed modules sizes. For example, the 36 watt module has currents ranging from 0.65 to 6 amps. By 1986, it is probable that individual solar cells delivering more than 6 amps will be in large scale production. To make the proposed higher voltage, lower current versions of the 36 watt module would then be required utilizing an additional 3 different (smaller) sizes of solar cells. This may not be the most economical solution; it could be to use a multiplicity of smaller modules which would be manufactured only using smaller silicon solar cells.

The size categorization in Table 3 (Exhibit 1) is a good first approximation to a standard family of modules and, for the larger sizes, the study may have to consider alternates (e.g. a 4 x 8 ft. module or a panel composed of two 4 x 4 ft. modules). It is also highly probable that by 1986 solar cells will be densely-packed in modules by virtue of their square, rectangular, or hexagonal shapes. As a result, the power outputs listed in Table 3, Exhibit 1, are low, and the electric current levels must be revised upwards, probably requiring the production of additional small modules for low current applications.

This will be further motivated by the expected improvement in solar cell efficiency, so that (combined with dense packing) module efficiency will increase from the 9% listed in Table 3 (Exhibit 1) up to the range of 14% for the larger modules, somewhat less (e.g. 13%) for the smaller modules.

Table 3 also does not consider the inherent structural strength advantages of rectangular modules over square modules. Accordingly, Table 3 should include some additional rectangular forms.

The last row in Table 3 (1613W) does not take into account fill factor (current is at maximum power, rather than short circuit, as is the case for the other rows in table 3).

The need for very high current modules at low voltage is also very questionable.

All these factors considered, Table 3 of Exhibit I could appear as follows.

Table 3 of Exhibit I:
Estimated 1986 photovoltaic module electrical characteristics
versus module size

MODULE SIZE	Module Current (amps for Module voltage[1])						Module power (maximum)
	7.5 Vdc	15 Vdc	30 Vdc	60 Vdc	120 V	240V	
0.15x0.3m (.5x1 ft)	1						[illegible]
0.3x0.3m (1x1 ft)	2						12 W
0.3x0.6m (1x2 ft)	4.2						25 W
0.6x0.6m (2x2 ft)	8.3	4.2					50 W
0.3x1.2m (1x4 ft)	8.3	4.2					50 W
0.6x1.2m (2x4 ft)		8.3					[illegible]
1.2x1.2m (4x4 ft)		16.7	8.3				200 W
0.6x2.4m (2x8 ft)		16.7	8.3				200 W
1.2x2.4m (4x8 ft)			16.7	8.3			400 W
2.4x4.8m (8x16 ft)				33.3	16.7	8.3	1600 W

Notes:

1. Module voltages are nominal voltages at NOCT which will charge 6, 12, 24, and [illegible] Vdc battery systems, respectively.

2. The 2.4 x 4.8 m (8 x 16 ft) "module" is a Large Industrial Class panel probably composed of four 1.2 x 2.4M (4 x 8 ft) fourteen percent efficient modules.

5.4.2.1.1.2 PANEL CHARACTERISTICS

The only panel listed in Table 3 is 8 x 16 ft., composed of four 4 x 8 ft. modules. It is not likely that larger panels will be manufactured. It is not certain, however, whether the 4 x 8 ft. module will become a reality by 1986; if it is not, then 4 x 8 ft. panels will be made, and the 8 x 16 ft. panel will be constructed of eight 4 x 4 ft. modules. (The appearance of a 4 x 4 ft. module is probable). As a result of dense packing and high solar cell efficiency, output of the 4 x 8 ft. panel will be appreciably higher than listed in Table 3 of Exhibit 1. (Output of the Large Industrial Glass array, 8 x 16 ft., will be 140 W/M^2 at an insolation level of 100 mw/cm^2, not 80 mw/cm^2 as indicated in the second last paragraph on page 5 of Appendix 1.)

5.4.2.1.1.3 ARRAY CHARACTERISTICS

Solar photovoltaic arrays will cover a large variety of sizes, depending on the type of system and the array support structure utilized. High currents and/or voltages will be encountered. The definition of an array will need alteration to include those structures (gunite sprayed on embankments) where the foundation is the support structure.

5.5 RESEARCH AND SURVEYS

5.5.1 INTRODUCTION

Any interconnection scheme must be able to satisfy the following requirements:

1. Continuous operation at normal system currents and voltages, and be able to withstand short circuits and transients for short periods.
2. Connection insulation dielectric breakdown rating should be equal to or greater than the maximum module voltage level above earth ground to be encountered in service.

3. Termination scheme should be inexpensive and should require a minimum amount of field labor during initial installation.

4. It is desirable to have a scheme which can be easily disconnected.

5. Terminations (interconnects) must be reasonably long-lived with series and/or contact resistance held to a minimum throughout the life of the system.

Connector criteria are evaluated not only in terms of the minimum necessary to do the job, but also those required to satisfy the requirements of the National Electrical Code (NEC).

The NEC defines a "pressure connector" (solderless) as follows:

"A device that establishes a connection between two or more conductors or between one or more conductors and a terminal by means of mechanical pressure and without the use of solder."

The use of connectors is certainly allowed by the NEC if the requirements of Section 110-14 (Electrical Connections) are satisfied:

1. A thoroughly good electrical connection is achieved

2. Conductors are not damaged

3. Conductors are mechanically secure such that there is no stress on the connection.

4. Insulation of the connection is equivalent to that of the conductors.

5. Conductors of dissimilar metals shall not be intermixed in a connector where physical contact occurs between dissimilar conductors unless the device is suitable for the purpose and conditions of use.

Everyone of these conditions imposed by the NEC are reasonable and desirable for solar module terminations for any application. It should be noted however, that the NEC assumes that all connections will either be in "dry" locations or will be weather-proofed. To satisfy this requirement, a connector of the weather-proof variety would definitely be needed.

Additional connector criteria lie in the areas of lifetime (and minimizing contact resistance power losses during lifetime) as well as in the areas of ease of installation and repair.

5.5.1.1 PRELIMINARY ESTIMATES OF REQUIREMENTS

Contained in the following pages are four basic graphs which were used to generate early estimations of requirements. Included is the graph of module quantity vs module size (Figure 5) for each application class. This graph was used to determine termination quantitites to be expected. Next is Figure 6, module power in watts vs. module area for various efficiencies. This graph was used to project power levels from expected modules. Figures 7 and 8 are module current vs module size for 10% and 14% area efficiencies respectively. These were used to determine requirements for current levels of terminations.

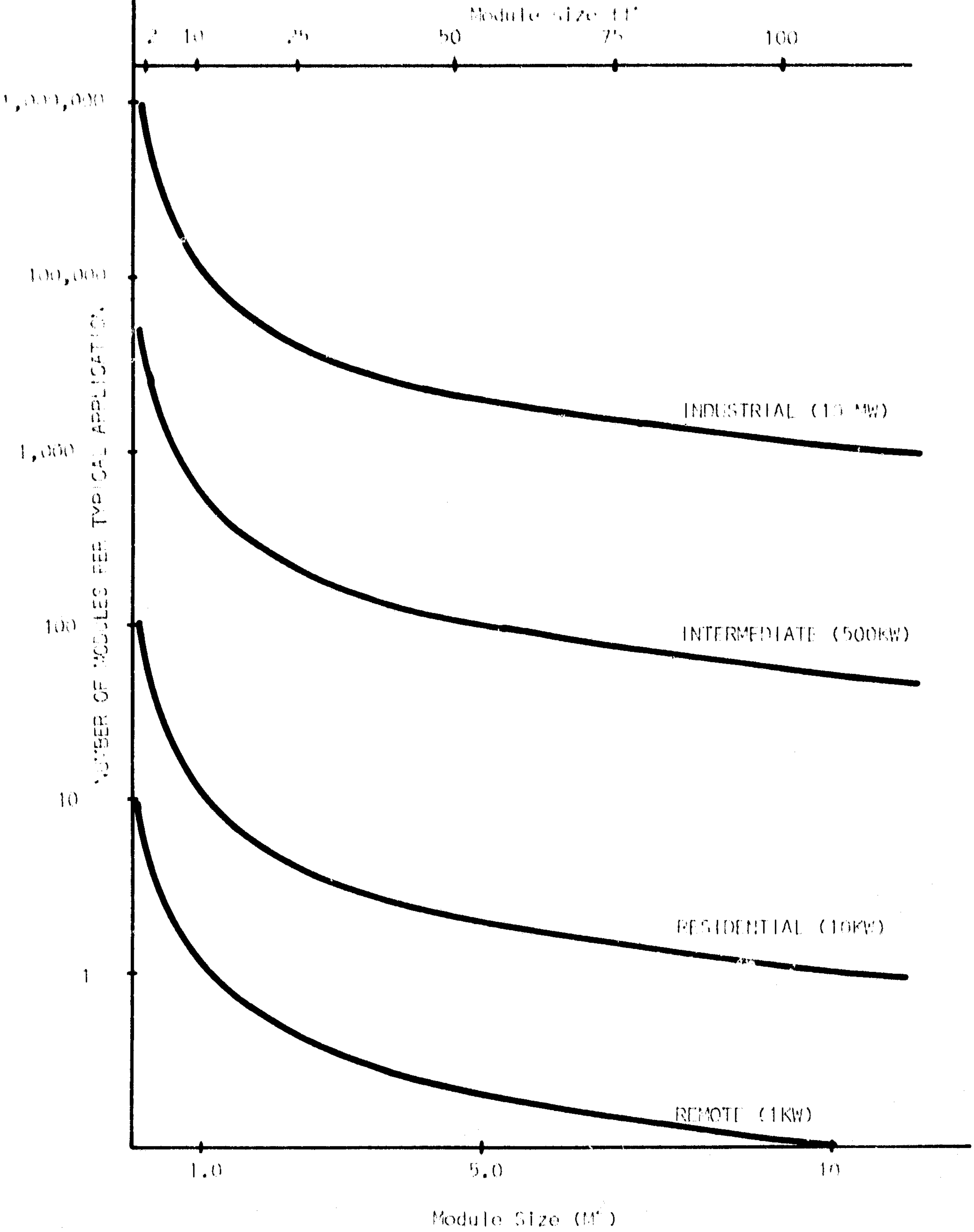
5.5.2 SURVEYS AND RESULTS

The questionaire sent to termination manufacturers produced little tangible data for use in the project. The majority of manufacturers surveyed did respond with catalogs and brochures of their products, but none made any attempt to recommend any particular termination in their product line.

Listed in attachment 2 are the termination manufacturers from which was drawn all information on existing hardware. Attachment 3 is a facsimile of the inquiry and questionaire sent to each manufacturer.

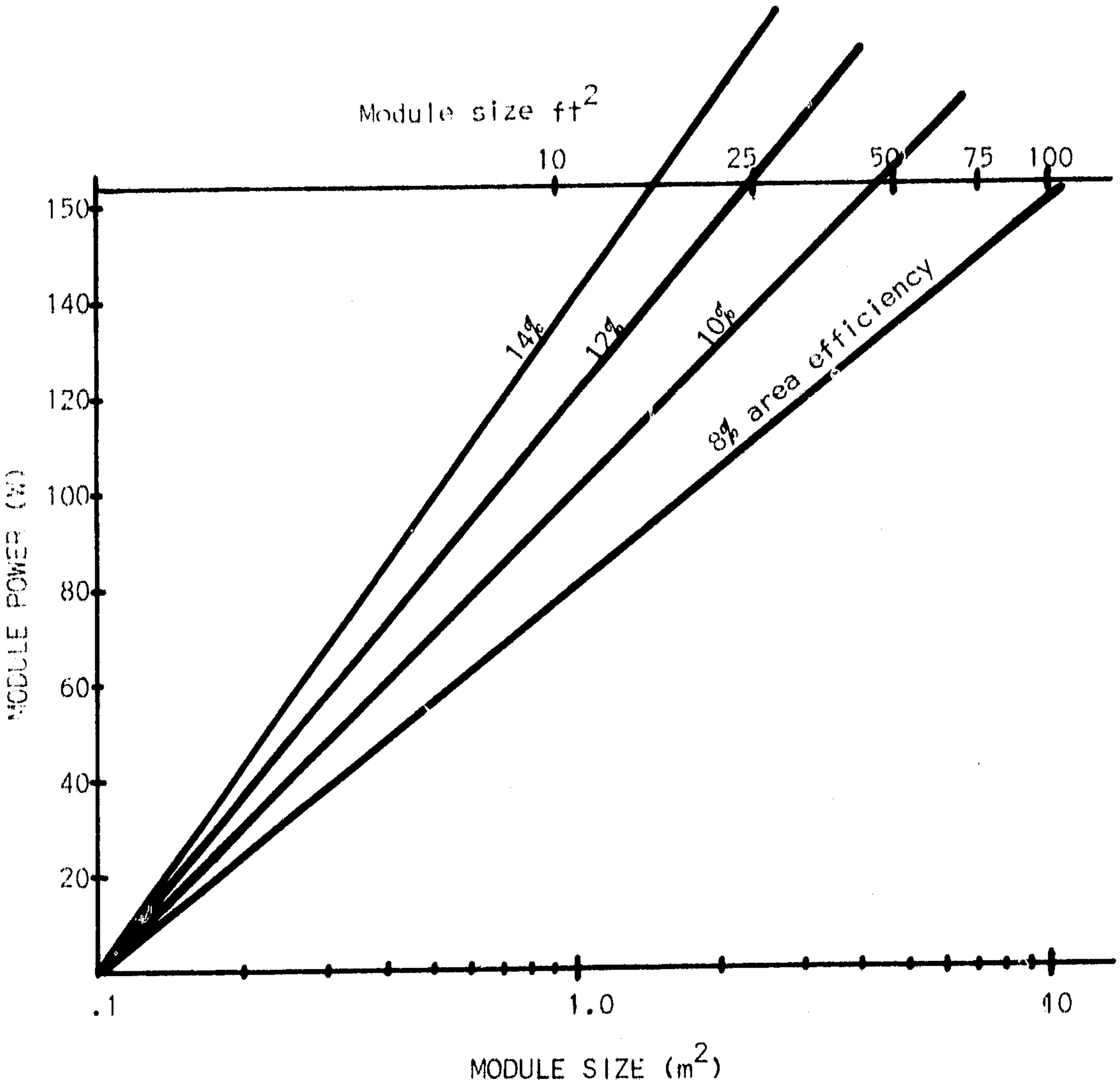
A list of module manufacturers and users is shown in Attachment 4; they were sent the questionaire shown in Attachment 5. Current module configurations and termination types are presented in Attachment 6. The chart shows that the majority of modules currently manufactured use lead wires rather than any sort of built-in termination. Two manufacturers utilize a junction box on the module, and three utilize screw terminals for module outputs. All modules except one have module outputs located at the back of the module.

MODULE QUANTITY VS MODULE SIZE
FOR SELECTED APPLICATIONS, 10% AREA EFFICIENCY
FIGURE 5



MODULE POWER VS AREA

FIGURE 6



MODULE CURRENT VS AREA
(10% AREA EFFICIENCY)

FIGURE 7

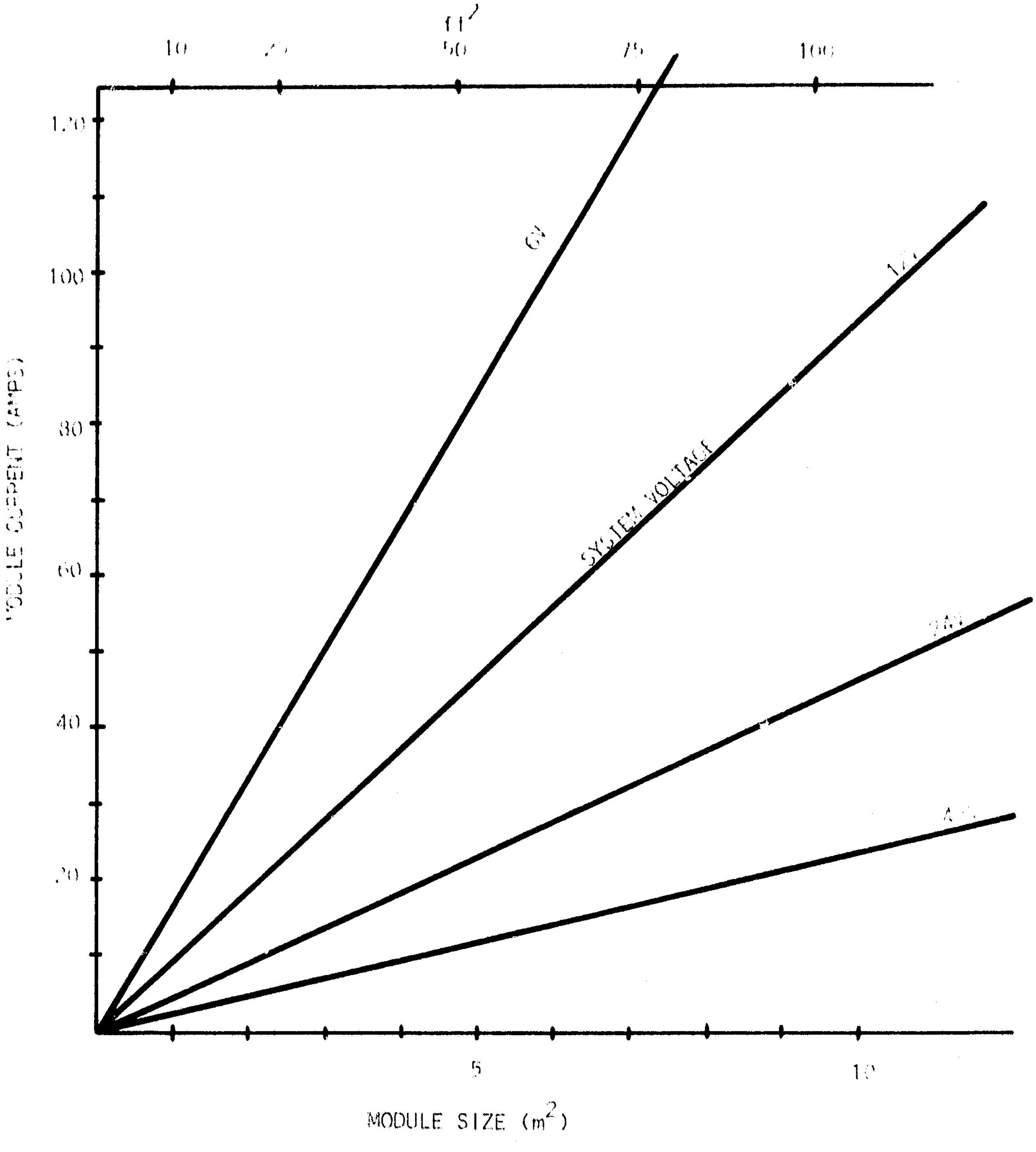
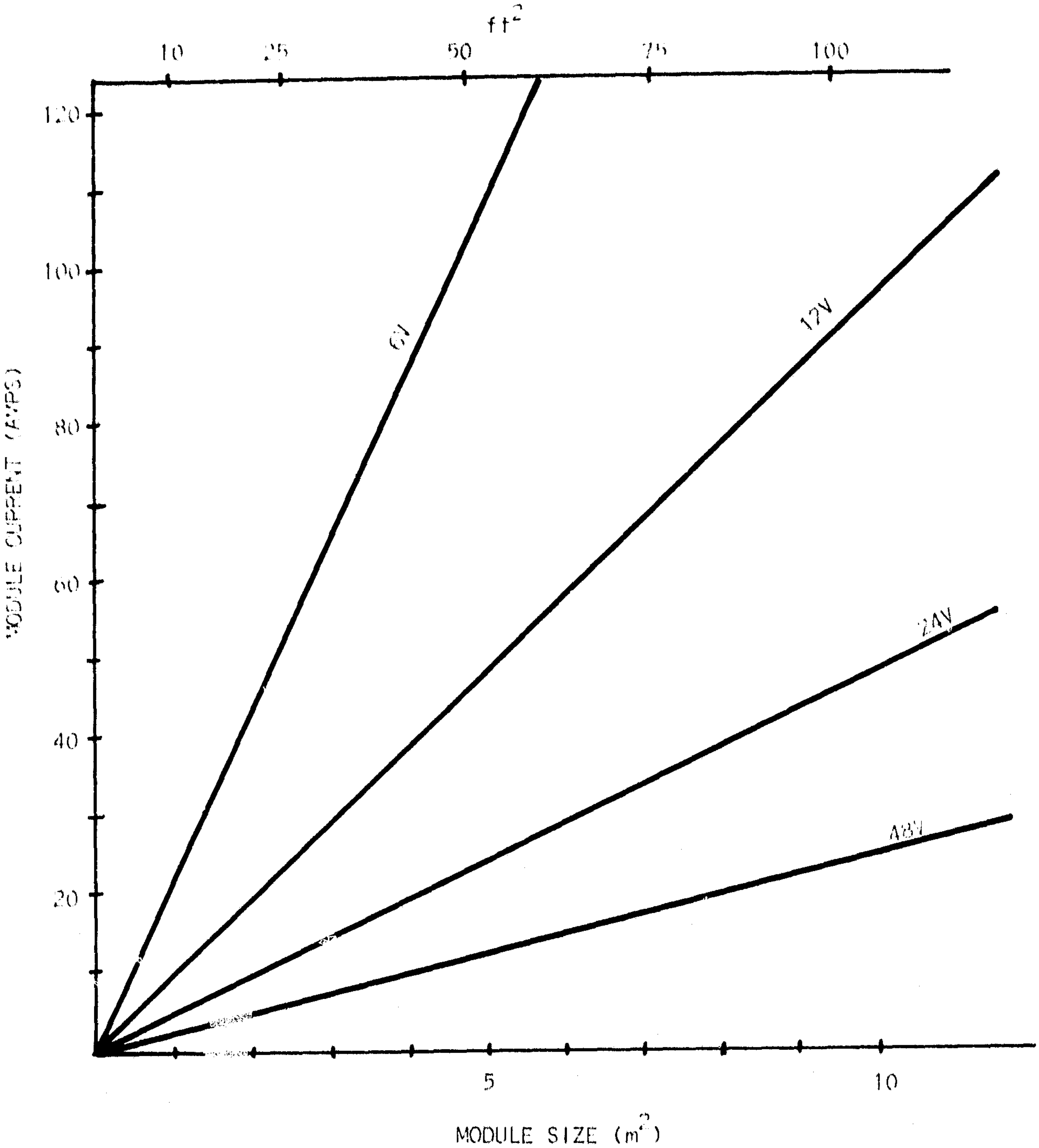


FIGURE 8

MODULE CURRENT VS AREA
(14% AREA EFFICIENCY)



ATTACHMENT 2

SUGGESTED LIST OF TERMINATION MANUFACTURERS

MANUFACTURER	HARDWARE C - Connectors T - Terminal Block/Strips W - Wire/Cable	RATING 1 - Should have applicable hardware 2 - May have applicable hardware 3 - Contact if time	PERSON TO CONTACT
AMP, Inc. Dept. EBH Harrisburg, PA 17105 717/564-0100	C, T, W	1	Russell Knerr Director-Marketing
AMPHENOL North [illegible] Div. Bunker Ramo Corp. Dept. EBH 900 Commerce Dr. Oak Brook, IL 60521 312/986-2700	C, T	1	Bob Ploudre V.P. Marketing (Comm'l,
BELDEN CORP. Electronic Div. Dept. EBH P.O. Box 1327 Richmond, IN 47374 317/966-6661	W	1	Clyde J. Schultz Director-Interconnect Sys 2000 S. Batavia Ave Geneva, IL 60134
BUCHANAN Distributor: East Side Electric Supply Phoenix, AZ 602/273-1415	T	1	
BURNDY CORP. Dept. EBH Richards Ave. Norwalk, CT 06856 203/838-4444	C, T	1	Joe Bradley V.P. Marketing
CONTROL PRODUCTS DIV. Amerace Corp. Dept. EBH 2330 Vauxhall Rd. Union, NJ 07083 201/964-4400	T	2	

MANUFACTURER	HARDWARE C - Connectors T - Terminal Block/Strips W - Wire/Cable	RATING 1 - Should have applicable hardware 2 - May have applicable hardware 3 - Contact if time	PERSON TO CONTACT
CROUSE HINDS Suite 1290 5670 Wilshire Blvd. Los Angeles, CA 90036 213/936-5134	C	2	
CURTIS INDUSTRIES, Inc. Dept. EBH 8000 W. Tower Avenue Milwaukee, WI 53012 414/354-1500	T	2	
HOLLINGSWORTH SOLDERLESS TERMINAL CORP. Dept. EBH Box 499 Pottstown, PA 19464 215/326-9900	T	2	
HUBBELL WIRING State Street & Bostwick Ave. Bridgeport, CT 06602 203/333-1181	C, W	1	
KULKA ELECTRIC CORP. A North American Philips Co. Dept. EBH 520 S. Fulton Ave. Mt. Vernon, NY 10551 914/664-4024	T	1	
MOLEX, Inc. Dept. EBH 2222 Wellington Court Lisle, IL 60532 312/969-4550	T	1	Bill Hickey Engineering

ATTACHMENT 2 (continued)

MANUFACTURER	HARDWARE C - Connectors T - Terminal Block/Strips W - Wire/Cable	RATING 1 - Should have applicable hardware 2 - May have applicable hardware 3 - Contact if time	PERSON TO CONTACT
NATIONAL WIRE & CABLE Dept. EBH 136 San Fernando Rd. Los Angeles, CA 90031 213/225-5611	W	3	Ray Miller Engineering
PASS & SEYMOUR, Inc. 50 Boyd Ave. P.O. Box 5000 Syracuse, NY 13201 315/468-6211	C	3	
PYLE-NATIONAL CO. 1334 N. Kostner Ave. Chicago, IL 60651 312/342-6300	C	1	
RAYCHEM 300 Constitution Drive Menlo Park, CA 94025 415/329-3905	C, W, T	1	Roger Ellis Engineering
SPECTRA-STRIP An Eltra Co. Dept. EBH 7100 Lampson Ave. Garden Grove, CA 92642 714/892-3361	W	3	
T&B/Thomas & Betts Dept. EBH 36 Butler St. Elizabeth, NJ 07207 201/354-4321	T	1	

ATTACHMENT 2 (continued)

MANUFACTURER	HARDWARE C - Connectors T - Terminal Block/Strips W - Wire/Cable	RATING 1 - Should have applicable hardware 2 - May have applicable hardware 3 - Contact if time	PERSON TO CONTACT
TRW CINCH CONNECTORS Dept. EBH 1501 Morse Aven Elk Grove Village, IL 60007 312/439-8800	C, T	2	Ed Rowland Engineering
VIKING INDUSTRIES, Inc. Dept. EBH 9324 Topanga Canyon Blvd. Chatsworth, CA 91311 213/882-6275	C	3	Gerald Louder Corp. Marketing Mgr.
WEIDMULLER 4326 Eubank Road Richmond, VA 23231 804/226-2877	T	3	
WINCHESTER ELECTRONICS Litton Systems Dept. EBH Main & Hillside Aves. Oakville, CT 06779 203/274-8891	C	2	Dennis Kohonik Engineering
DANIEL WOODHEAD CO. 3411 Woodhead Drive Northbrook, IL 60062 312/272-7990	C	2	

ATTACHMENT [illegible]

SURVEY OF POTENTIAL TERMINATION SUPPLIERS
DIRECTOR OF MARKETING

Dear Sir:

We are writing to survey your company's interest in providing low cost electrical termintion hardware for solar photovoltaic modules in both current and future production. This survey is being conducted for the Jet Propulsion Laboratory with funding by the U.S. Department of Energy. The names of all respondents and their areas of interest will be tabulated in our final report. This same data will be given to the Solar Energy Research Institute (SERI) for inclusion in their computer data bank thus giving potential customers of your company two sources of information on your interest and products.

Typical examples of types of termination (given for illustration and not to indicate limits of our interest) and of applicable conditions are summarized on enclosure 1.

If your company is interested in providing such electrical termination hardware, your cooperation in completing the enclosed questionaire will be greatly appreciated.

Sincerely,

Paul S. Masser
(602)244-3847

Enclosure 2

QUESTIONAIRE FOR ELECTRICAL TERMINATION MANUFACTURERS

Company____________________________

Address____________________________

Contact for additional information (Person and/or Title)__________________

1. What type of electrical terminations in your product line would you recommend be considered for solar photovoltaic arrays? A brochure will be appreciated, if available.

2. What is the approximate cost per mated line pair (lots of 100,000 to 1,000,000.)

3. Are you interested and able to provide special modified hardware in production quantities (i.e., special mountings, etc.)?

4. Are your electrical termination products currently being used outdoors?

   ____

5. What range of electrical variables are covered by your products?

   AC_________, DC_________, Voltage__________, Current_________.

ATTACHMENT 4

SOLAR MODULE MANUFACTURERS/USERS

1. ARCO Solar, Inc.
   20554 Plummer St.
   Chatsworth, CA 15069

   Peter Zanibas

2. OCLI Optical Coating Laboratory, Inc.
   15251 East Don Julian Rd.
   City of Industry, CA 91746

   Dick Sharman, Gen. Manager

3. Photon Power, Inc.
   1820 Mills Ave.
   El Paso, TX 79901

   Guy Roderick, Pres.

4. Sensor Technology, Inc.
   21012 Lassen St.
   Chatsworth, CA 91311
   (213) 882-4100

   Sanja Chitre Project Supervisor
   Irwin Rubin, Pres.

5. SES/Shell Oil Co.
   Tralle Industrial Park
   Newark, Del. 19711
   (302) 731-0990

   Robert Johnson, V.P. Marketing

6. Solar Power Corp.
   20 Cabot Rd.
   Woburn, Mass. 01801
   (617) 935-4600

   Paul Caruso

7. Solarex Corporation
   1335 Piccard Drive
   Rocheville, MD 20850
   (301) 948-0202

   Anthony Clifford
   Dr. Joseph Lindmayer, Pres.

8. Spectrolab
   12500 Gladstone Ave.
   Sylmar, CA 91342
   (213) 365-4611

   Robert Oliver
   Gene Ralph, V.P.

ATTACHMENT 4 (continued)

9. Spire Corporation
Patriots Park
Bedford, Mass.

Roger G. Little

10. Motorola

Photon Power, Inc.	-	El Paso, Texas
SES/Shell Oil Co.	-	Newark, Del.
Fort Belvoir	-	Virginia
MIT, Lincoln Lab.	-	Massachusetts
Far West Corrosion	-	Gardena, California
DOE	-	Washington, D.C.
NASA Lewis	-	Cleveland, Ohio
Tideland Signal Corporation	-	Houston Texas
California Edison	-	Rosemead, California
Arizona Public Service	-	Phoenix, Arizona

ATTACHMENT 5

ITT

International Telephone and Telegraph Corporation

Cannon Electric Division

World Headquarters
666 East Dyer Road, M.S. #75
Santa Ana, California 92702
(714) 557-4700

ORI
OF

March 28, 1979

Chief Engineer
xxxxxxxxxxxxxxx
xxxxxxxxxxxxxx
xxxxxxxxxxxxx
xxxxxxxxxxxxxx

Dear Sir:

We would appreciate your assistance in obtaining pertinent information on the electrical termination and interconnection for photovoltaic power generation.

ITT Cannon Electric manufactures electrical interconnect hardware. We are presently involved in a study of electrical termination hardware for photovoltaic modules, panels and array. This study is being done in conjunction with Motorola, Inc. for Jet Propulsion Laboratories and is being funded by the Department of Energy and N.A.S.A.

Your cooperation in filling out the attached questionaire would be greatly appreciated. Thank you for your assistance.

Sincerely,

Joseph M. Dondlinger
Engineering Development Specialist
Advanced Development

JMD/bl

Attachment

CANNON® PLUGS

QUESTIONAIRE FOR SOLAR PANEL MANUFACTURERS AND USERS

Date____________

Name____ Title____________________

Company______________________________ Address________________________

ORI
OF

1. What type of electrical termination and interconnection is presently being used (manufacturer and description).____________________

2. What is the approximate cost per mated line:____________________

3. What has been your experience with the presently used electrical termination hardware and interconnections (problems, reliability, ease of installation, higher production capability).____________________

4. What improvements do you recommend to the present hardware?____________________

5. What are the requirements for electrical termination and interconnection as you see them?____________________

6. Types of applications for which your photovoltaic modules are presently being used and will be used in the future (remote, residential, commercial, etc.). Please describe:____________________

7. Factors which influenced your selection of termination and interconnection hardware (current, voltage, environmental conditions, materials, etc.).

8. Are you working to any code requirement (National Electrical Code, Underwriters Laboratory, etc.)? ______________________

____

Which codes do you see as applicable? ______________________

____

Any problems meeting code requirements? ______________________

____

9. Please supply a list of users for your equipment so we can obtain user experience with electrical termination hardware and interconnects:

USER'S NAME (APPLICATION)	ADDRESS	PHONE NO.

10. Do you have any brochures or pictures of your photovoltaic modules, interconnect and termination hardware which we could obtain? ______________________

____

11. Other comments: ______________________

____

____

____

____

ATTACHMENT 6

CURRENT MODULE CONFIGURATIONS

MFG.	MODULE OUTPUTS			LOCATION	
	LEADWIRES	J-BOX	SCREWTERM.	BACK	EDGE
Sensor Tech	✓			✓	
Solarex 435	✓	✓		✓	
Arco			✓	✓	
Tideland Sig.			✓	✓	
Phillips	✓				✓
Solar Power	✓	✓		✓	
Solarex 1480	✓			✓	
Motorola 1			✓	✓	
Motorola LCM	✓			✓	

A summary of comments made concerning electrical termination is as follows:

- Would like a universal type termination system for which required tools and materials were easily available for installation and maintenance.
- Field repairable with minimum of tools.
- Inexpensive.
- Easy to install or plug together.
- Maximize factory installation.
- Safety of installation is a major concern.
- If a lug type terminal is used, prefer the spade type, so complete removal of the screw is not necessary.
- Tamper-proof interconnection.
- Prefer to have connectors in the back of module to maximize solar cell area by minimizing spacing between modules.
- Connectors should be sealed to prevent corrosion build up.
- Should be fool-proof so less skilled personnel can make connections.
- Should be capable of shipping panels without electrical termination loosening.
- Temperature cycling appears to be a major cause of termination failure.
- Several manufacturers would like to have a connector which would make contact with the flat wire encased in the module or some type of bus tab coming out of the sealed module.
- Initially intend to use lug type compression terminals as widely used in outdoor utility stations. (Generally enclosed).

A survey of environmental conditions was conducted. In summary the environmental conditions which the photovoltaic hardware will encounter will be the full gamut of outdoor environments including:

1) Moisture in all forms, (hail, snow, rain).

2) Temperature - cycling and extremes.

3) Corrosive Atmospheres - salt spray, smog, ultraviolet smog.

4) Dynamic and Static Loading - from wind, earthquake, maintenance.

5) Vandalism - from man, animals, birds.

6) Vegetation - trees, vines, fungus.

7) Lighting strikes-resulting in voltage transients.

From discussions, it would appear that a screw-lug-type termination enclosed in a sealed junction box is the current preferred method of terminating for small remote applications. This method is reliable with a minimum of tools and special equipment required. Quick connects are preferred for the larger government funded projects for ease of installation and testing, due to the bigger quantities involved.

Telephone conversation with the Southern Pacific Railroad Company signal department and communication department revealed that all their environmentally exposed electrical connections are housed in sealed junction boxes.

Several key areas for project success became evident as a result of the survey:

1. The electrical termination manufacturers surveyed were asked for their product line recommendations to be considered for use on solar photovoltaic arrays (question 1, attachment 3 "Questionaire for Electrical Termination Manufacturers"). No manufacturers responded with specific products. Manufacturer literature and catalogs were studied and the most suitable termination(s) chosen, based on information available.

   Most manufacturers either did not have price sheets or would not supply them and were reluctant to quote accurate prices at the requested quantities. This appeared to be because of the lack of a firm purchase order. Cost is discussed further in Section 5.9.

2. The interface between the module and its electrical termination, the panel and array circuit (including lightning protection), and code requirements (particularly for conduit, etc.) were key areas in evaluating candidate terminations.

3. Another key area was categorizing the candidate terminations by generic types so that they could be evaluated more easily against the chosen selection criteria. Some of these evaluations are subjective since data was not available. Others are quantitative, such as the range of electrical current rating of available terminations of a certain generic type. In all cases, objectivity was the goal. Subjective evaluations were based on surveys of knowledgeable personnel with results averaged.

5.6 GENERIC TERMINATION TYPES

Nine generic types of electrical terminations were found to be applicable in photovoltaic module interconnection. These types are:

I. Crimp

a) Butt splice

b) Parallel splice

c) Closed end

II. Hand-soldered

III. Insulation Displacement

IV. Plug/Receptacle

a) Pin and socket

V. Screw

VI. Spring Clip

VII. Twist-on

VIII Welded

IX. Wire Wrap

The nine generic termination types are examined in the following section. Each type is discussed with a brief description of basic attributes, connector technique, current capabilities, limitations, and expected (or demonstrated) environmental durability. Pictorial examples of current products illustrating many of the termination types are given.

1. CRIMP

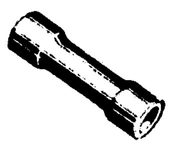
Butt splice, parallel splice, and closed and wire joint are grouped together because of a similarity of construction, function, and assembly technique.

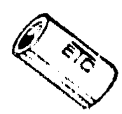
The crimp method of making electrical connections consists of compressing the crimp barrell of the terminal onto the wire very tightly so that intimate metal-to-metal contact is made. Crimped connections have extremely low electrical resistance because of being true metal-to-metal connections. A crimping tool is necessary if the process is to be controlled, and the crimp easily and correctly made, and reliably reproduced. Contact pressure is high, and the joint is mechanically strong. Crimp connections are used to splice wires together or to attach terminals to the ends of wires.

Current capabilities coincide with the size conductor used; the termination is available through #1/0 AWG.

Environmental durability is moderate, as the completed connection is rain proof at best. Subsequent sealing with tape or shrink-tubing would be required. The terminal is available insulated.

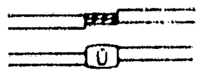

Nylon connector


Butt connector



Parallel connector


(a) Butt connector (2 crimps)


(b) Parallel connector (1 crimp)


(c) Pigtail connector (1 crimp)

II. HAND-SOLDERED

Hand-soldered connections are made by first mechanically joining two or more conductors together, applying a flux to chemically clean and prepare the conductors, heating the joint to solder flow temperatures, and applying solder. The solder serves as both a bonding agent and as the link in metallic continuity.

Current capabilities coincide with conductor size and are limited only by conductor current capacities.

Environmental durability is moderate, with long life when the connection is adequately sealed. Sealing could be accomplished utilizing shrink tubing and/or tape, within a junction box.

Connection assembly times are slow, and a high degree of operator skill is required.

III. INSULATION DISPLACEMENT

This connection technique is accomplished by using a special tool to push a non-stripped wire down between tapered tangs mounted on an insulated board, which strips off the wire insulation and makes conductor contact with the tangs in one motion. It is a very rapid and reliable method of wire connection whose main application now is in communications and computer hardware.

Current capabilities are low due to limitations on wire size of #18 AWG.

Environmental durability is untested and would be expected to be poor. Sealing would be essential and could be accomplished by utilizing a junction box.

IV. PLUG/RECEPTACLE

Plug/receptacle connectors are disconnectable and involve use of a male contact crimped to a conductor which in turn mates to a female contact also crimped to a conductor. (The other configurations are tab/receptacle and bullet/receptacle). See Figure 9. Pin and socket types are available in multiple contact versions. Contact pressure is kept low to allow ease of disconnection. They are primarily used in applications where rapid connection is required and where eventual disassembly is anticipated.

Current capability coincides with conductor size, and is available up to #0 AWG.

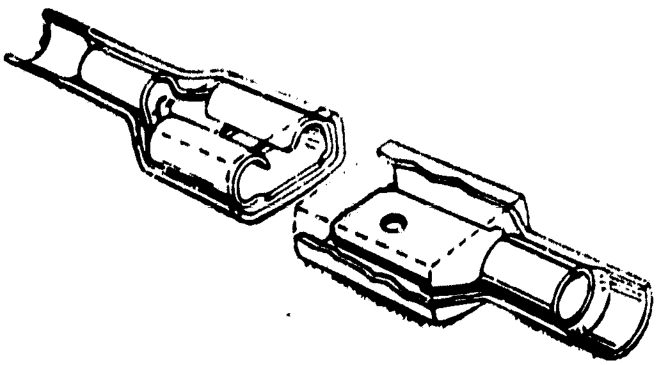
Environmental durability is moderate to excellent. All are available insulated, with the pin and socket type available sealed as well.

V. SCREW TYPE

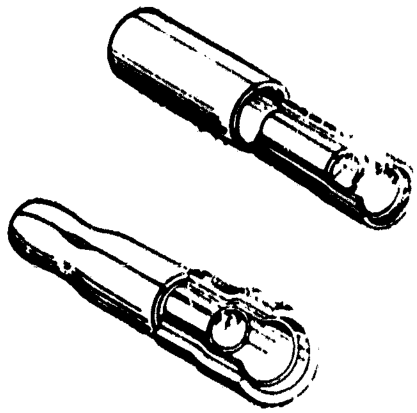
A screw connection is probably the oldest type of mechanical connection. It consists simply of screwing down a metal bolt to the wire compressed under it. The joint is a pure pressure joint. A more modern version of the screw connection uses ring-tongue or fork-tongue terminals to which the wire is crimped. The screw is tightened down on the terminal instead of the bare wire.

Current capabilities conform to wire sizes used and are generally available throughout the wire size range.

Environmental durability is poor and would require the use of a sealed junction box. Connections have a record of loosening under conditions of vibration or corrosion.

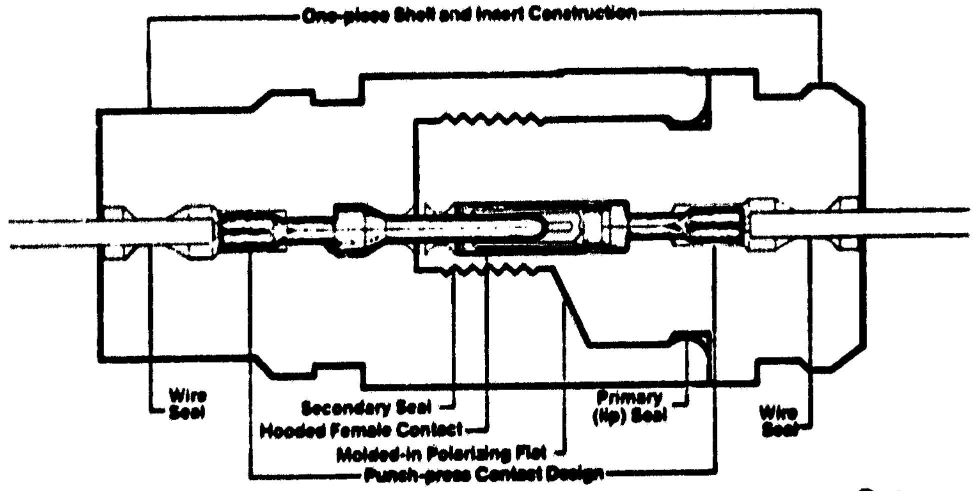


TAB/RECEPTACLE

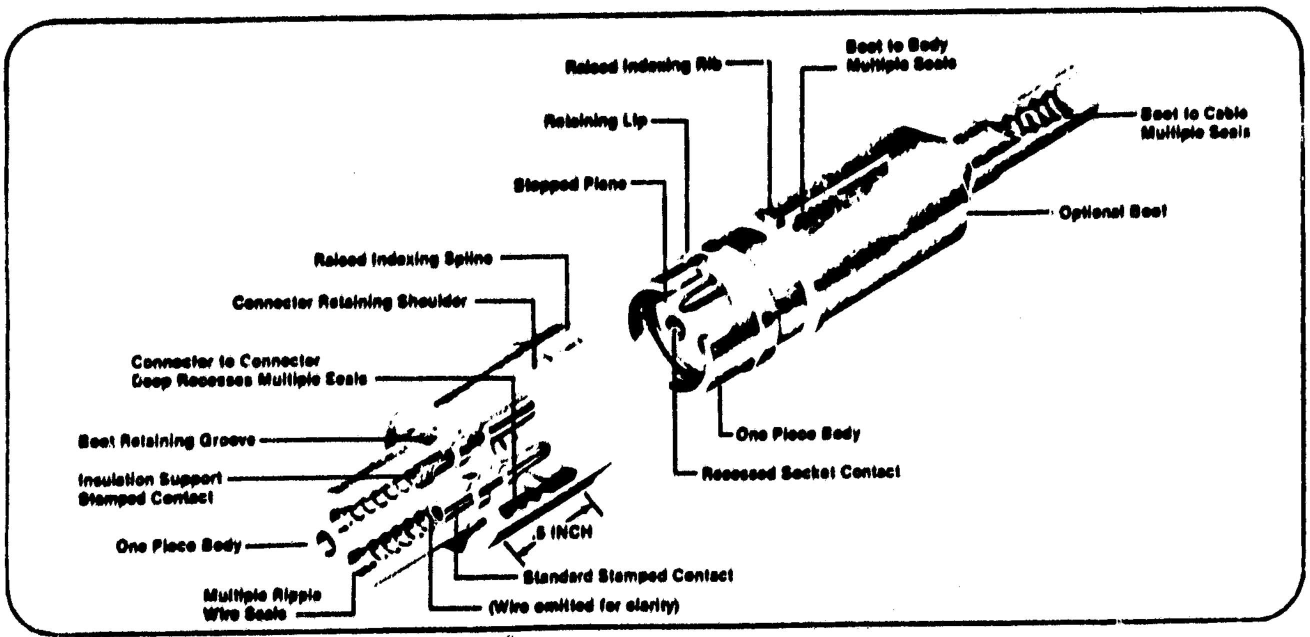


BULLET/RECEPTACLE

FIGURE 9



AMPHENOL 44 SERIES



ITT CANNON ELECTRIC SURE-SEAL 3

FIGURE 9 (continued)

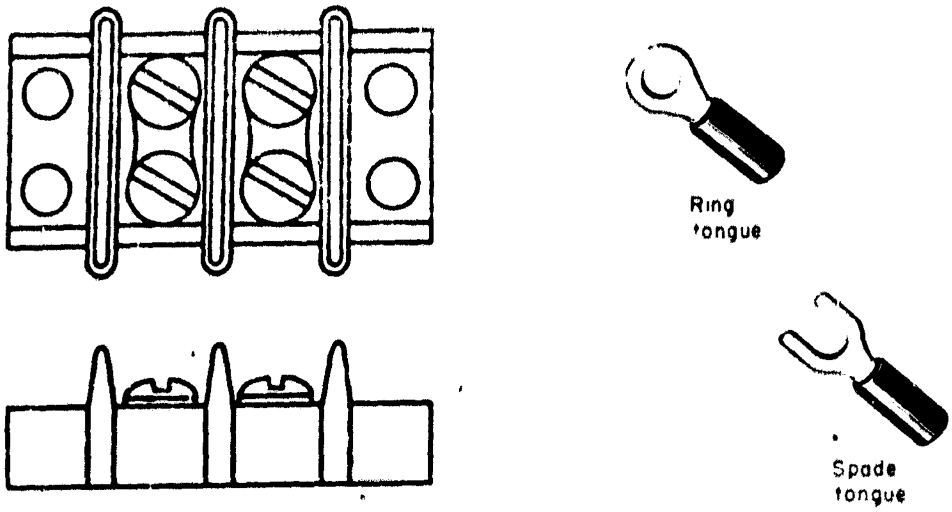


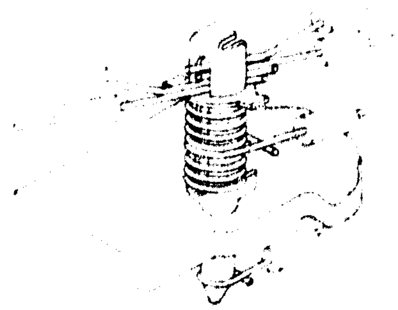
FIGURE 10: SCREW TYPE CONNECTORS

VI. SPRING CLIP

Spring clip terminals provide a means for quickly connecting or disconnecting wires without need for soldering, crimping, or bending of wires. Terminals have a slotted post into which wires may be pushed when the spring is depressed. Contact pressures are moderate.

Current capabilities coincide with the size of conductor used, which is limited to #18 AWG and smaller.

Environmental durability is poor as the terminal has no insulation or seal, and would require sealing and insulation through utilization of a junction box.



Spring-clip terminal (*Vector Electronics Co.*

VII. TWIST-ON

Twist connectors are similar to closed-end wire joints (crimp type) in appearance, but differ in the method of attachment. Twist connectors provide a quick means for connecting and disconnecting wires without the need for soldering or crimping. An insulated barrel contains a tapered metallic spring which is twisted by hand over two or more wire ends to keep them in close contact. Contact pressure is dependent upon force exerted.

Current capabilities conform to conductor sizes used, generally limited to #10 AWG.

Environmental durability is moderate, with the completed connector requiring addition sealing and insulating with shrink tubing or tape.

SECTION OF TWIST-ON CONNECTOR

VIII. WELDED

The point-to-point technique of welded connections involves bringing electrodes in contact with either side of the electrical joint, and energizing the electrodes. The heat generated fuses the metal of each conductor together to form the welded joint.

Current capabilities coincide with current ratings of the conductors joined.

Environmental durability is excellent as properly welded joints are reliable without protection from moisture (sealing). Mechanical strength of the joint is also excellent.

C - 2

The completed connection would require insulation in the form of shrink tubing and/or tape to prevent short circuits. This type of connection is limited to the use of solid wire. A high degree of operator skill is required.

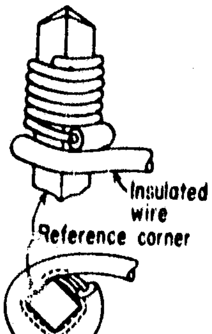
Most evidence indicates that the welded joint is a more reliable electrical connection than a soldered joint.

IX. WIRE WRAP

This connection technique involves use of a machine to wrap the conductor around a square post very tightly. Contact pressures are high; a proper joint is a metal-to-metal connection. Major applications include communications and computer hardware, which have displayed reliable performance over extended periods in dry locations.

Current capabilities coincide with conductors, which are limited to #18 AWG solid wire.

Environmental durability is untested as all applications to date have been in dry (i.e. protected) locations. Sealing could be accomplished with a junction box.



(a) Gardener Denver's
Wire Wrap

5.7 SEALING CONSIDERATIONS

Since it has been determined from surveys and experience that it would be advantageous for photovoltaic electrical terminations to be sealed for purposes of reliability and environmental durability, and since some termination types are not available in a sealed fashion, all terminations were considered to be sealed in some manner for the evaluation. This put ranking comparisons on a more equal basis. In cases where the termination was not available sealed, a supplemental seal utilizing electrical tape, shrink tubing, junction box, or a combination thereof, is used. In all cost considerations as well, terminations are considered sealed unless otherwise noted.

The supplemental sealing/insulating methods considered and utilized for the terminations requiring them are illustrated in Figure 11.

Figure 12 presents data on current capabilities of each termination type studied. Only four terminations, spring clip, twist-on, insulation displacement, and wire wrap were found to be of insufficient current capacity for all application classes. The current capabilities shown in Figure 12 are data received from the manufacturers (as listed in catalogs). The current capabilities shown on Figure 12 have no relation to any supplemental sealing that might be considered necessary for environmental durability.

5.8 COST

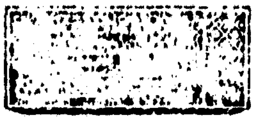
5.8.1 INTRODUCTION

Presented within this section are MTBF;s for each termination type, and termination costs. The raw cost data compiled are initial cost at purchase quantities of 10^4 and 10^7. The termination initial cost data gathered probably do not represent actual purchase prices as originally intended. However, the cost data is accurate in a relative sense, as when used in comparing the generic termination types in this study. Representative termination types were chosen for each type, suitable for use in photovoltaic systems. The terminations selected

FIGURE 11

SUPPLEMENTAL SEALING/INSULATING METHODS AVAILABLE:

SCOTCHCAST ELECTRICAL SPLICING KITS



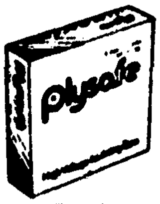
[illegible] insulation [illegible] moisture sealing splices [illegible] shielded [illegible] cables rated up to 5KV (multi-conductor cables up to 600 volts).

[illegible] transparent mold [illegible] No. 4 [illegible] the insula[illegible] sealing compound.

SCOTCH "IVI-SPRAY" SEALER

An electrical grade enamel paint and sealer, formulated to give protection against weather, moisture [illegible] and [illegible]. Use for [illegible] repair, [illegible] spray [illegible] treatment for additional thickness build-up and sealing, seal breakout leads.

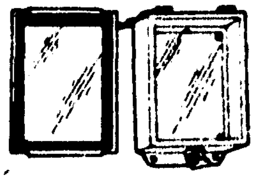
PLYMOUTH PLYSAFE HIGH VOLTAGE INSULATING TAPE



A self fusing high voltage tape for applications up to 138kV and 130°C. Weather and sunlight resistant. Can be used alone for emergency temporary repairs. Use with Plyshield Tape for high voltage splices and terminations.

SCOTCHKOTE ELECTRICAL COATING

An electrical grade, fast-drying sealing agent in a brush-top can. It is compounded to be compatible with "Scotch" brand plastic electrical tapes and provides extra moisture and corrosive protection.



JIC pull boxes are designed for use as instrument enclosures as well as pull boxes and terminal wiring boxes. For use where wiring must be protected against oil, water, dust, dirt, etc. Recommended for machine tool wiring. The cover permanently chained to the box is equipped with a neoprene gasket to assure a liquid-tight seal. Standard finish is gray enamel.

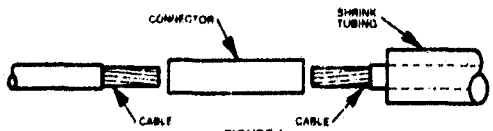


FIGURE 1

1. Connector and Heat Shrinkable Tubing prior to installation.

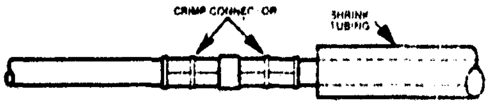


FIGURE 2

2. Crimp connector installed.

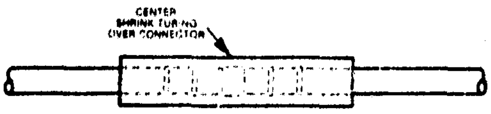


FIGURE 3

3. Heat Shrinkable tube in position.

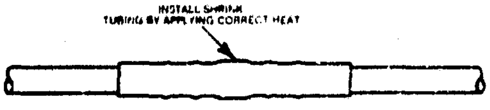
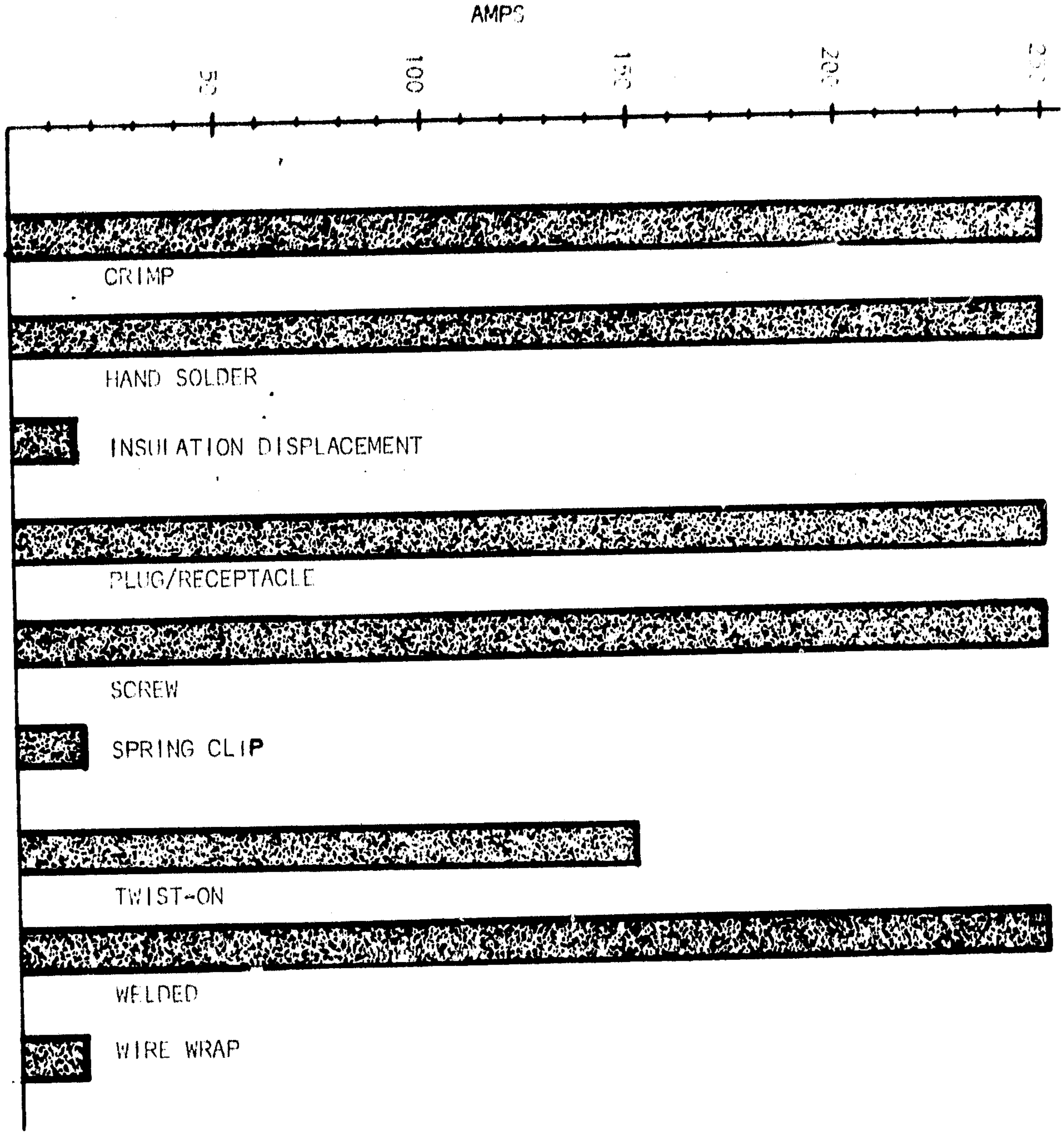


FIGURE 4

4. Heat Shrinkable tube after heat application.



TERMINATION CURRENT CAPABILITIES VS TYPE
FIGURE 12

are sealed and insulated where possible, or where not available supplemental sealing and/or insulation was added and the cost and labor recorded. Therefore, each termination type was made as similar as possible in sealing and insulation characteristics. The sealing materials cost include the use of such materials as electrical tape, shrink tubing, junction box, or a combination thereof, to bring all termination types up to a similar level of seal and insulation.

Sealing techniques utilized for each termination type are listed below:

Crimp - Requires additional sealing with UV-stabilized electrical tape or shrink tubing.

Hand Solder - Requires additional sealing and insulation with UV-stabilized electrical tape or shrink tubing.

Insul. Disp. - Requires additional sealing accomplished by enclosure within a junction box.

Plug/Receptacle - Found to be satisfactorily sealed and insulated as purchased.

Screw Terminal - Requires additional sealing accomplished by enclosure within a junction box.

Spring Clip - Requires mounting on an insulated surface and within a junction box for sealing.

Twist-On - Requires additional sealing with UV-stabilized electrical tape or shrink tubing.

Welded - Requires additional insulation with UV-stabilized electrical tape or shrink tubing.

Wire Wrap - Requires additional sealing accomplished by enclosure within a junction box.

5.8.2 COST ESTIMATIONS

The factory labor rate used in the study was \$9.70/hr., based on Building Construction Cost Data 1978. It was expected that all operations necessary in the installation of the termination on the module would be performed at the factory level. The field labor rate used in the study was \$19.15/hr. This labor rate was used for all installation labor required on-site.

5.8.3 COST DATA FOR EACH TERMINATION TYPE

Spring Clip - Initial costs in quantities of 10^4 and 10^7, including insulated mounting board, were \$0.962 and \$0.812 respectively. Factory labor, which would include attachment of insulating board and spring clip to junction box and junction box to module, is calculated to be \$1.19. The field labor involved for the connection to the adjacent module, requiring only insertion of the already stripped wire, is \$0.38, including sealing the junction box. The sealing material (which is the cost of the junction box) is \$1.73. Sealing labor is included in the factory labor cost. The total cost for this termination type in quantities of 10^4 is \$4.26.

Crimp - Initial costs in quantities of 10^4 and 10^7 were \$0.0763 and \$0.90 respectively. Factory labor, which would include stripping of module output wires and crimping-on the termination (either butt-splice or quick-disconnect type), is determined to be \$0.20. The field labor involved for connection to an adjacent module, requiring either insertion of wire and crimp or connection of quick-disconnect plus supplemental application of either UV-stabilized electrical tape or shrink tubing (approximately equal in cost) is \$0.38. The cost of the sealing material, either tape or tubing, is \$0.02. The labor involved in the sealing operation is \$0.12 for a total termination cost in quantities of 10^4 of \$.69.

Twist-On - The initial costs, in quantities of 10^4 and 10^7 respectively, are $0.0776 and $0.0700. Factory labor is $0.10; it consists of stripping each module output wire. Field labor which involves twisting the termination over the two (or more) output wires, is $0.29. Sealing material cost for the application of electrical tape or shrink tubing, is $0.02, and the sealing labor is determined to be $0.12. The total termination cost in quantities of 10^4 is $0.60.

Plug/Receptacle - The initial costs in quantities of 10^4 and 10^7 are $0.322 and $0.232 respectively per mated pair. Factory labor is $0.39, and includes stripping and crimping-on a pin and socket and inserting each into its respective shroud. Field labor is minimal at $0.09, and requires insertion of the plug into the receptacle. No supplemental sealing material or labor is required. Total cost of this termination in quantities of 10^4 is $0.80.

Insulation Displacement - The initial costs of this termination in quantities of 10^4 and 10^7 respectively, are $0.823 and $0.658. Factory labor which would include attachment of the termination within a junction box, is $1.09. Field labor is $0.38, which involves inserting the output wires to be connected into the termination strip and attaching the junction box lid. The sealing material is the junction box at a cost of $1.73, and the sealing labor is included in the factory labor cost. The total termination cost in quantities of 10^4 is $4.02.

Hand Soldered - Initial costs in this termination method consists of equipment and materials which are included in the cost data for factory and field labor. Factory labor is $0.10 and includes stripping and tinning module output wires. Field labor, which includes making the solder joint and the sealing and insulation application, is $0.952. The sealing material cost is $0.02 for the application of electrical tape or shrink tubing. The sealing labor cost is $0.12, for a total termination cost in quantities of 10^4 of $1.19.

Screw Terminal - Initial costs in quantities of 10^4 and 10^7 are, respectively, \$0.985 and \$0.788 including two ring tongue terminals. Factory labor is \$1.12; it includes attachment of ring tongue terminals to module output wires, and installation of terminal block and junction box onto the module. Field labor, which involves attaching terminals onto the terminal block and re-fitting the junction box lid, is \$0.95. Sealing material cost is \$1.73. The cost of the junction box, and sealing labor, are included in factory labor. The total cost for this termination type is \$4.78 in quantities of 10^4.

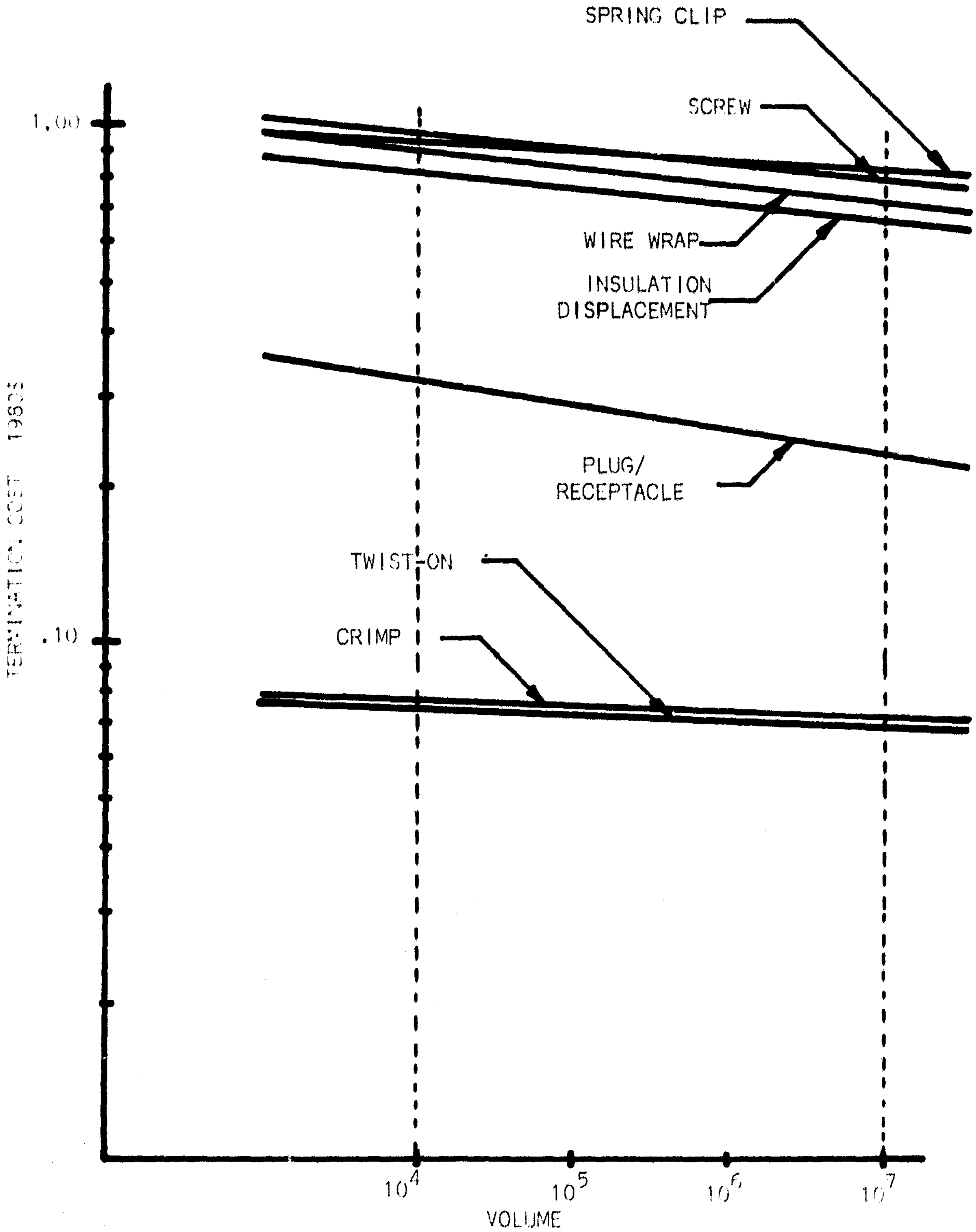
Welded - The initial costs in this termination method consist of equipment and supplies, which are inlcuded in the cost data for factory and field labor. Factory labor is \$0.10 and includes stripping and preparation. Field labor is \$1.047 due to the rather sophisticated equipment needed, and supplemental insulation. Insulation materials cost is \$0.02, either tape or tubing, and the sealing labor cost is \$0.12. The total cost of this termination method is estimated to be \$1.28 in quantities of 10^4.

Wire Wrap - Initial costs in 10^4 and 10^7 quantities are \$0.942 and \$0.745 respectively. Factory labor, which involves attachment of the wire-wrap block within a junction box and subsequent box attachment to the module, is \$1.09. Field labor cost of making the connection to the adjacent module and re-attaching the junction box lid is \$0.38. Sealing material cost (junction box) is \$1.73, with sealing labor included in the factory labor cost. Total termination cost in quantities of 10^4 is \$4.14.

Initial termination component cost as a function of volume is presented in Figure 13. Notice that sealing is not inherently provided by all termination types.

FIGURE 14

TYPICAL INITIAL COSTS OF GENERIC TERMINATION TYPES
(wire size #12AWG, maximum current: 40 amps)



Costs vs. current levels were plotted for each termination type and are found in Figures 14 a - 14 g. As expected, the higher current ratings were associated with higher initial costs.

The normalized cost of adding a module ground provision for each termination type is found on Figure 15. The types displaying 100% cost require an additional termination. The types displaying less than 100% generally require an additional pin or space available for use as a ground provision.

Factory and Field assembly costs are illustrated in Figure 16, and include initial cost, factory labor, field labor, and sealing materials and labor to represent termination installation costs. These costs do not include travel time, set-up or any other ancillary activities.

Termination replacements in the field due to failure are shown in Figure 17, but costs illustrated do not include travel time, fault detection time, or preparation time for replacement.

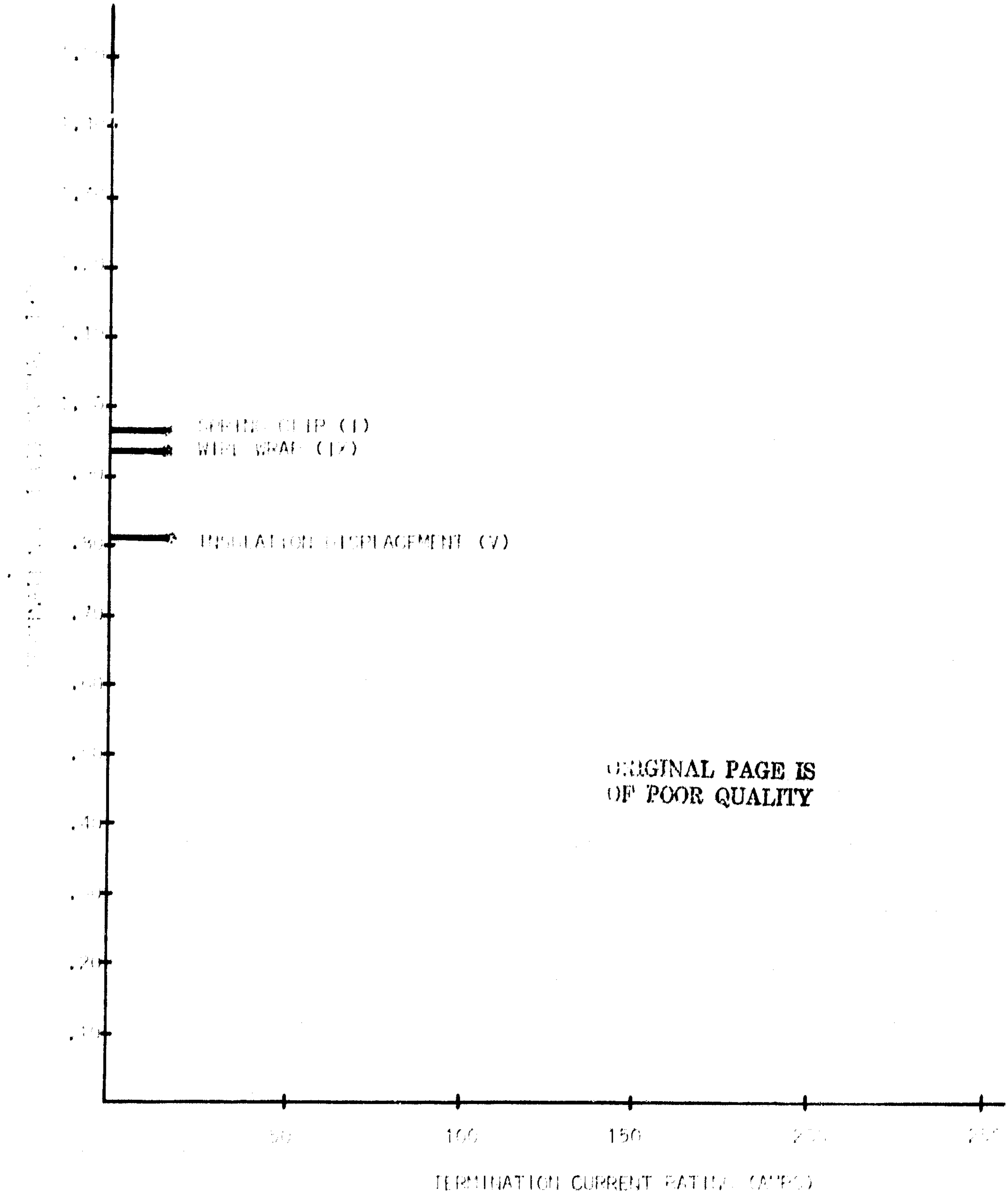
All appropriate labor costs in this project are based on an itemization of necessary activities, for which a time-motion study was performed by the Motorola Industrial Engineering Group.

Clearly, the necessity of a junction box for sealing makes certain termination types unattractive on a cost basis. There is an alternative to the use of a junction box to seal the spring clip, insulation displacement, screw terminal, and wire-wrap types of termination; this would be application of silicone-type sealant over exposed metallic parts. This method was judged inadequate and costly, and also likely to be unsatisfactory unless done in a competent manner. Currently, the four termination types listed above enjoy a long service life when utilized in a "dry" (i.e. protected in junction box) location.

Cost vs. MTBF data for each termination type are presented in Figure 18.

FIGURE 14a

TERMINATION COST ($) VS. TERMINATION CURRENT RATING
QUANTITIES OF 10^4



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 14b

TERMINATION COST ($) VS. TERMINATION CURRENT RATING
QUANTITIES OF 10[4]

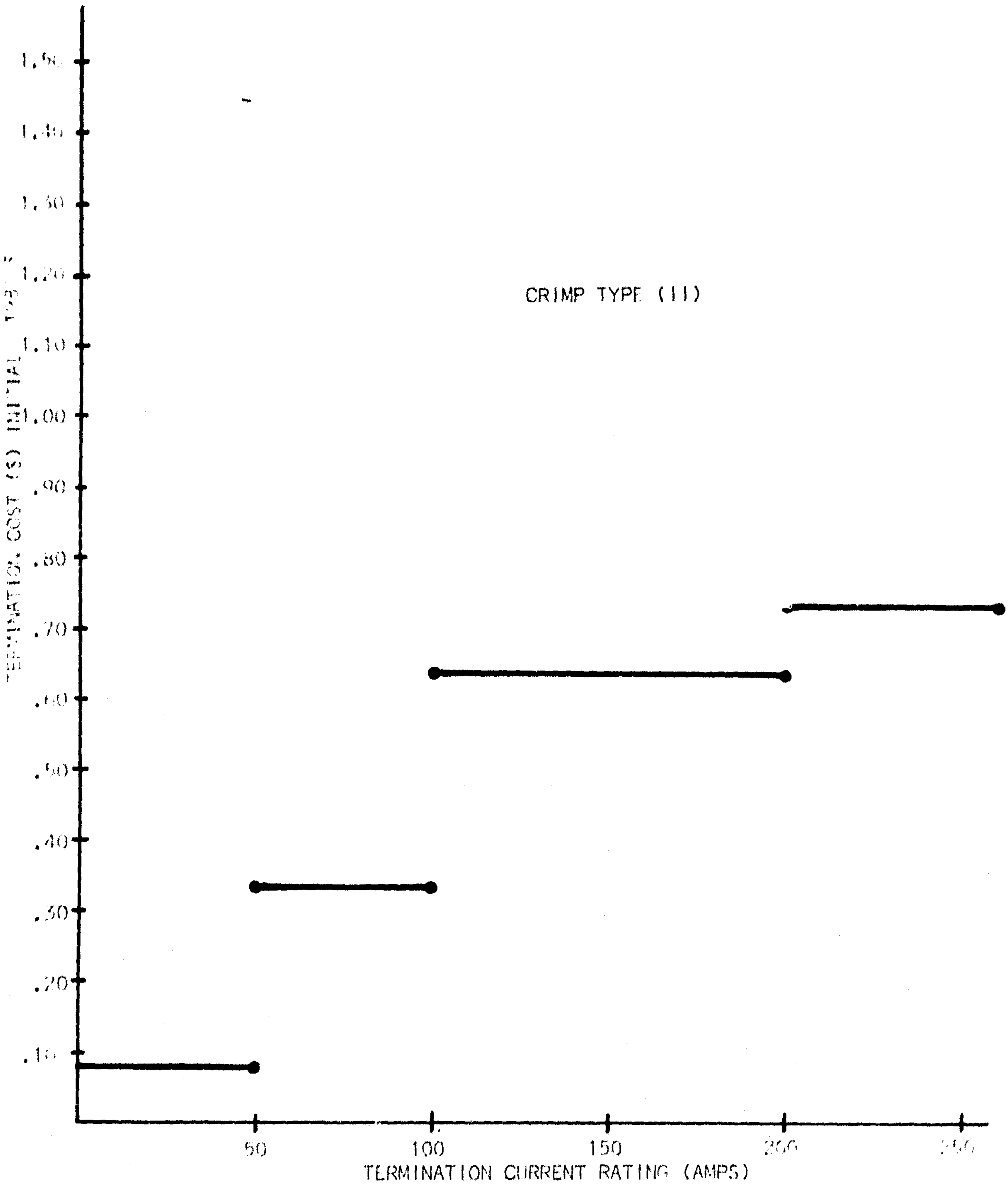


FIGURE 14c

TERMINATION COST ($) VS. TERMINATION CURRENT RATING
QUANTITIES OF 10^4

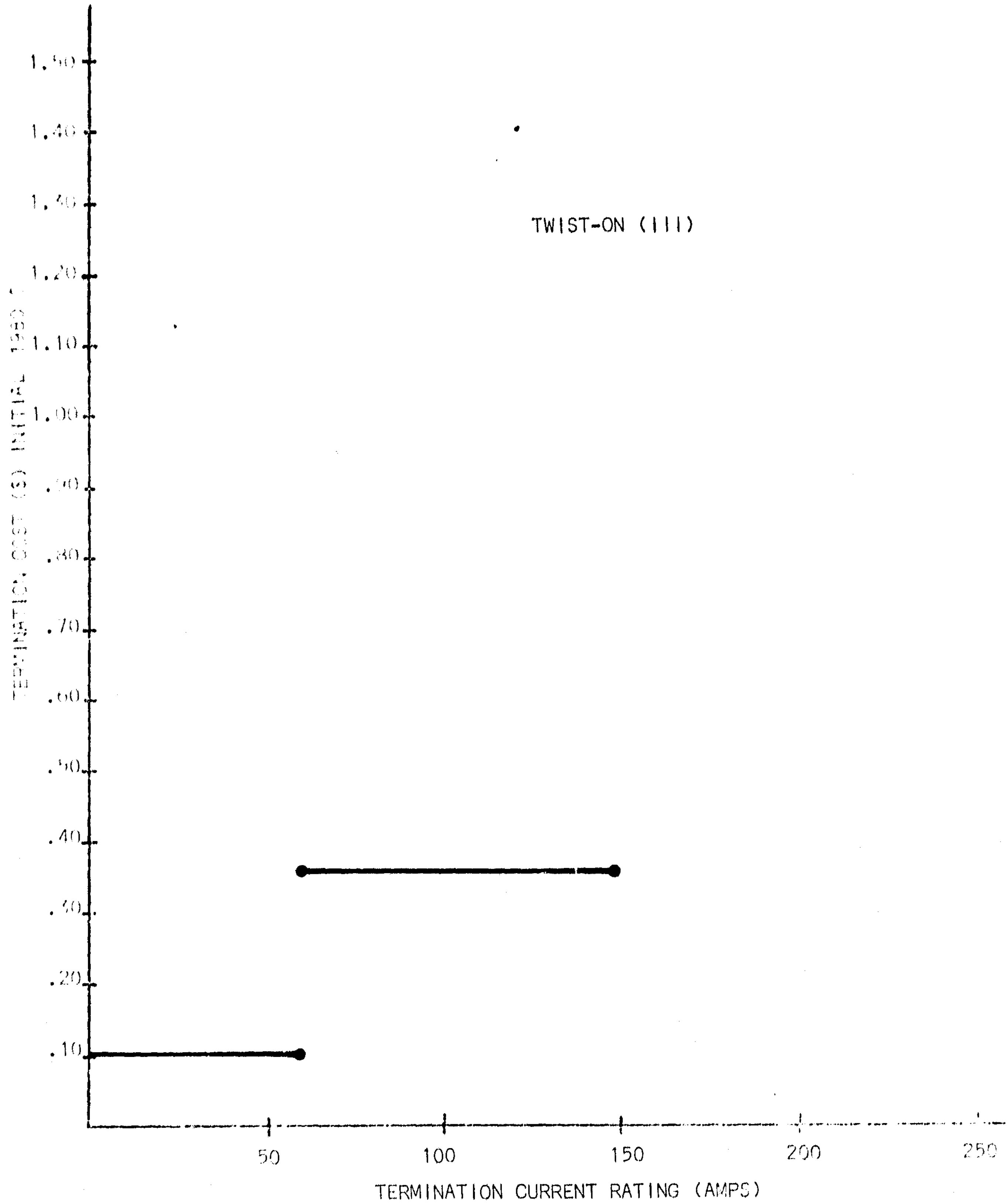


FIGURE 14d

TERMINATION COST ($) VS. TERMINATION CURRENT RATING
QUANTITIES OF 10^4

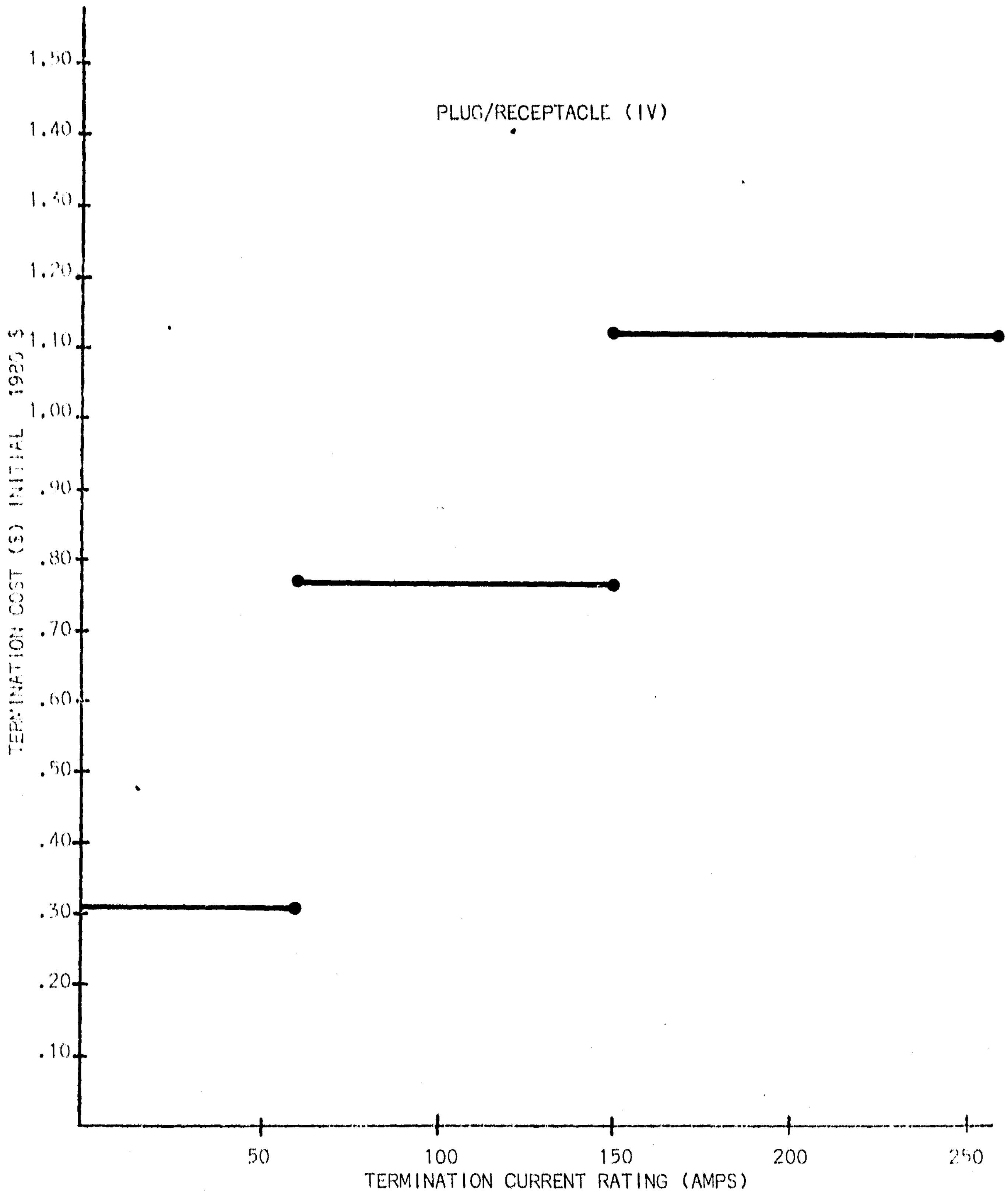


FIGURE 14c

TERMINATION COST ($) VS. TERMINATION CURRENT RATING
QUANTITIES OF 10^4

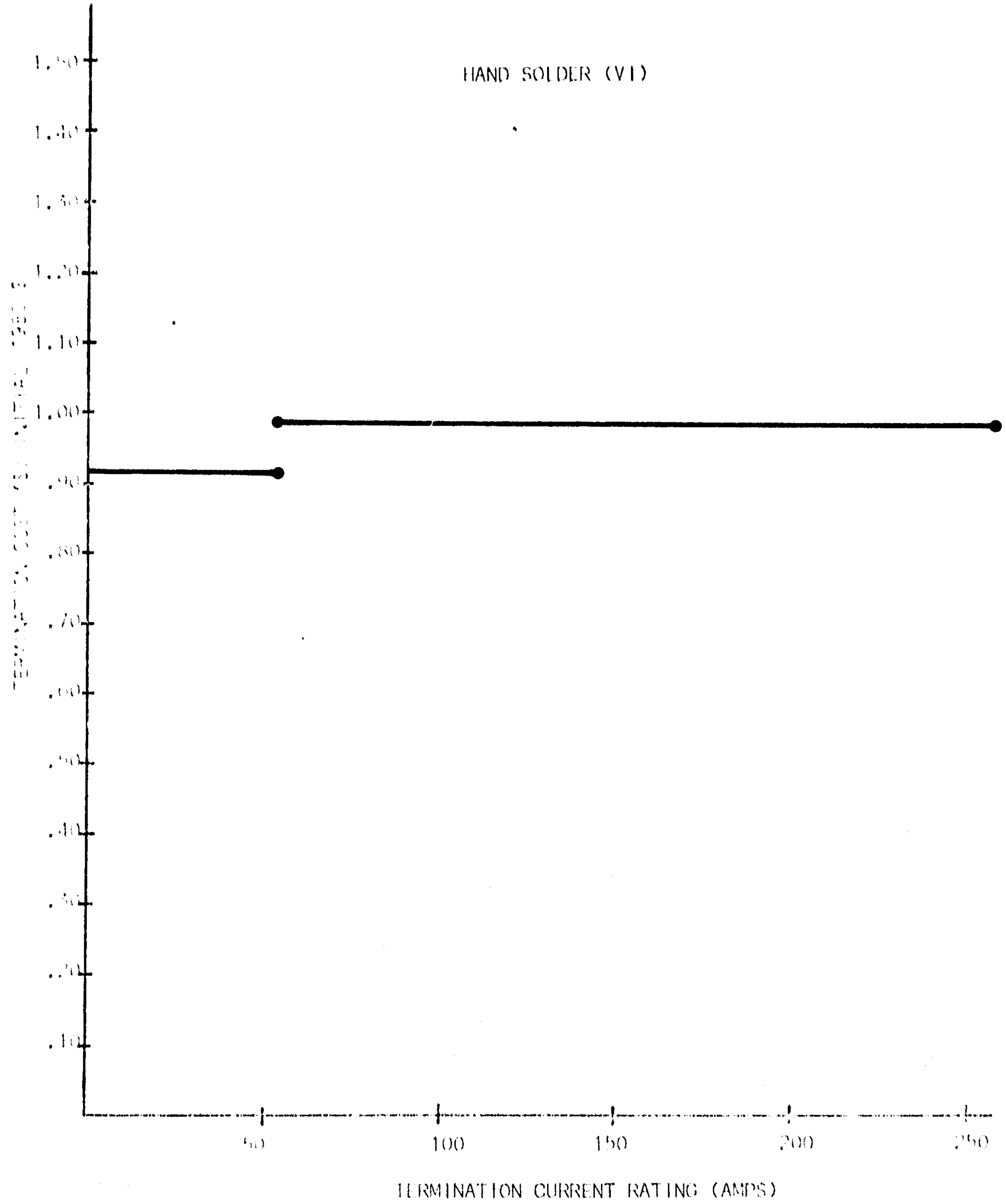


FIGURE 14f

TERMINATION COST ($) VS. TERMINATION CURRENT RATING
QUANTITIES OF 10^4

SCREW (VII)

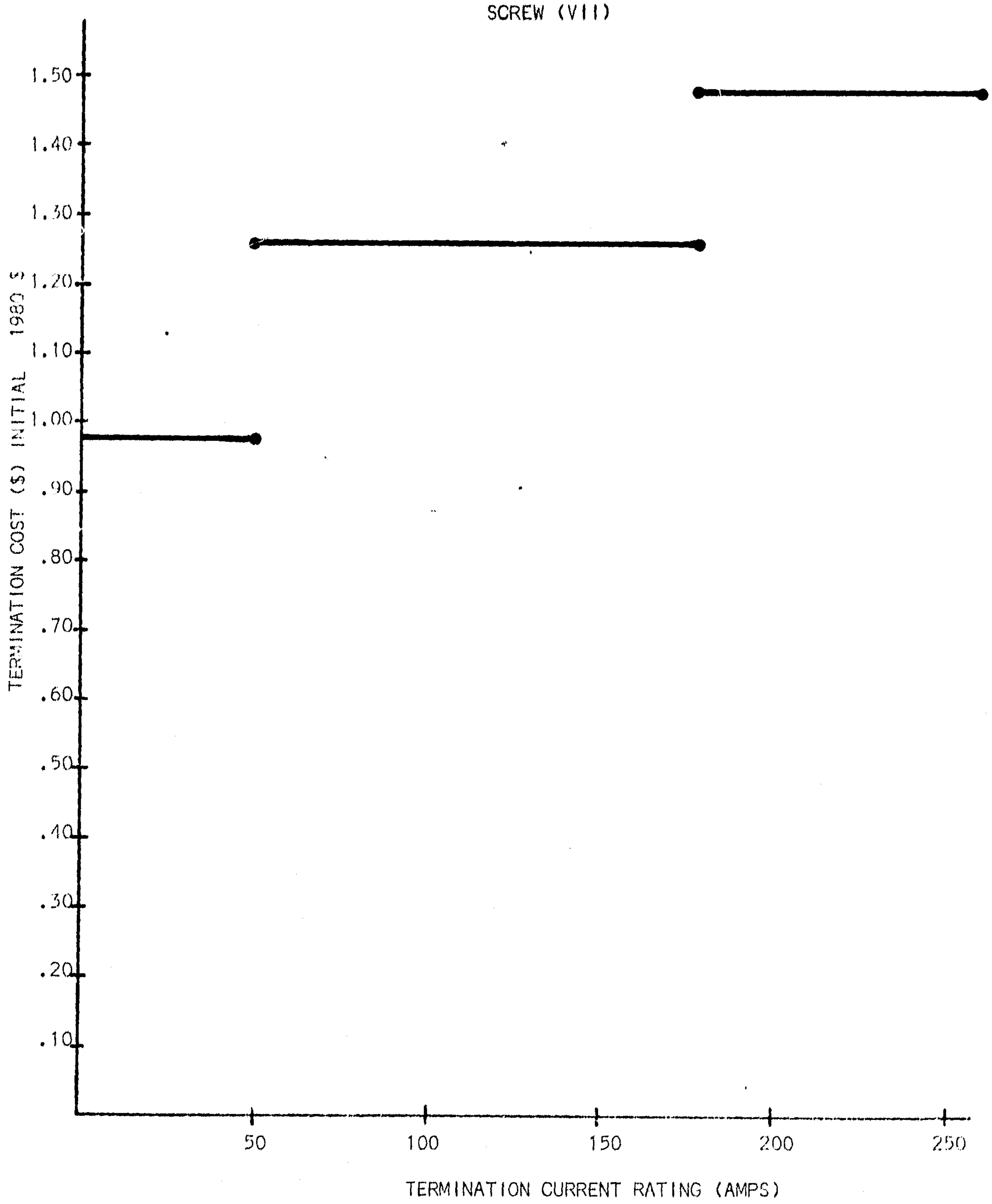
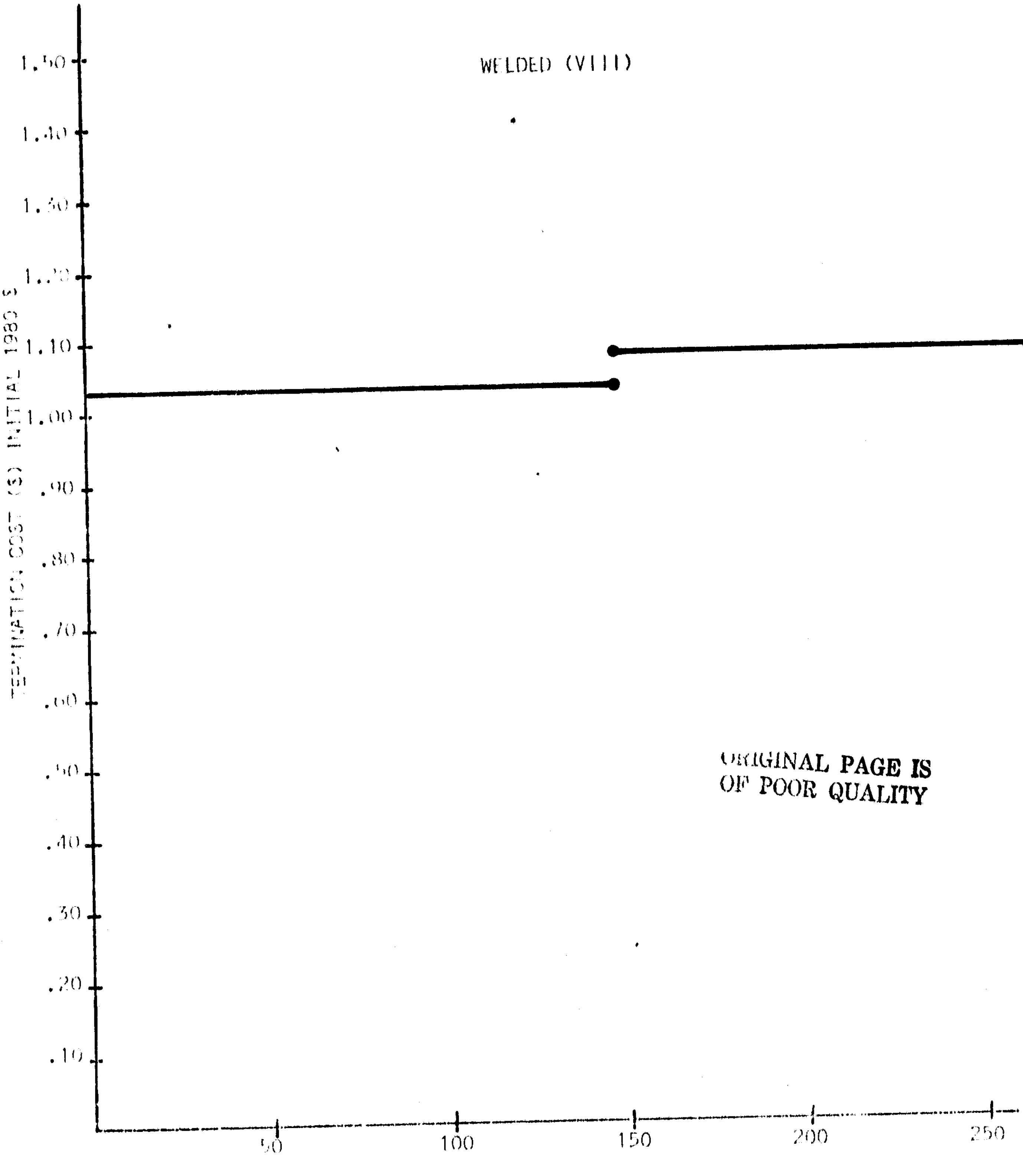


FIGURE 14a

TERMINATION COST ($) VS. TERMINATION CURRENT RATING
QUANTITIES OF 10^4



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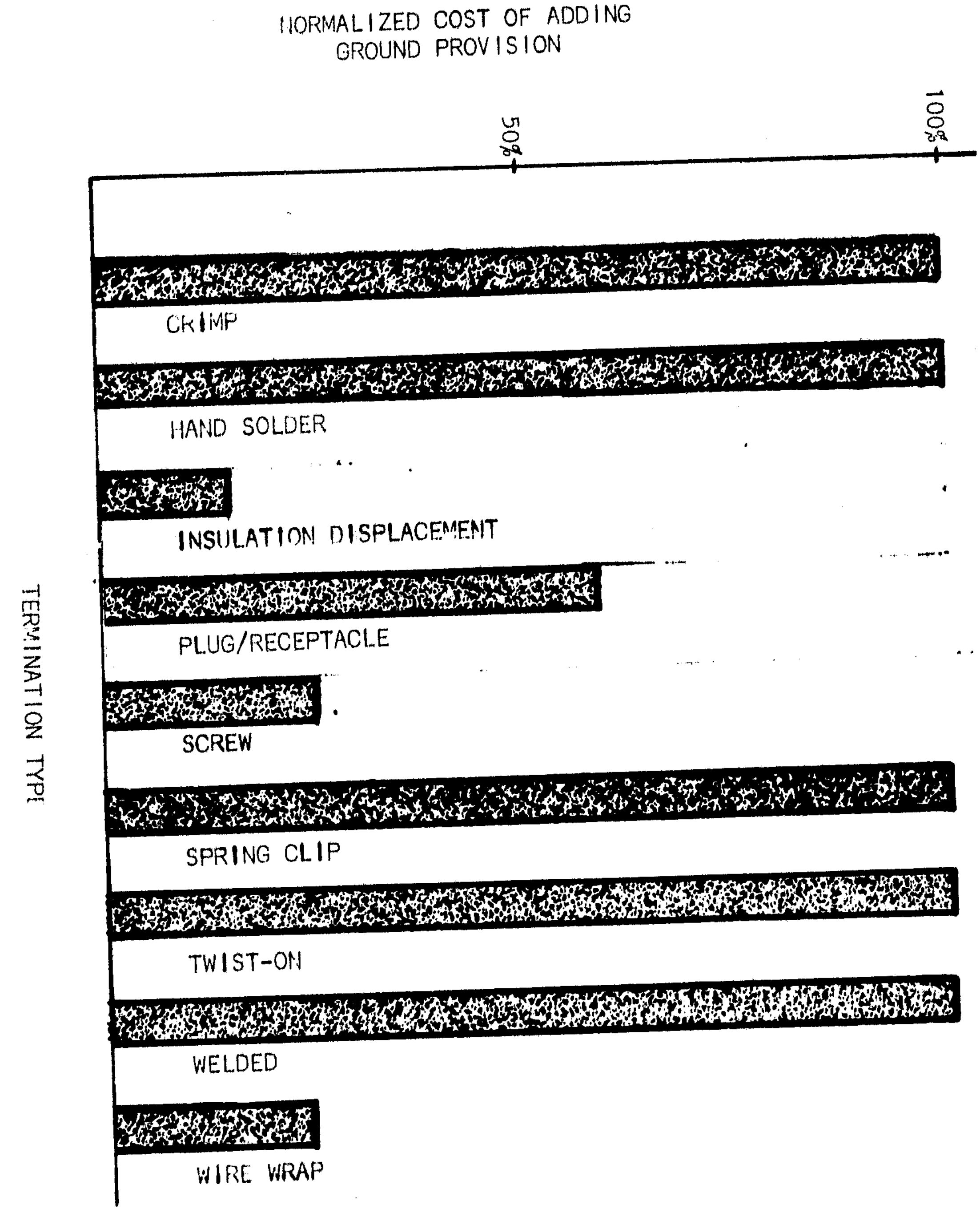


FIGURE 15
COST OF ADDITION OF GROUND PROVISION VS. TYPE

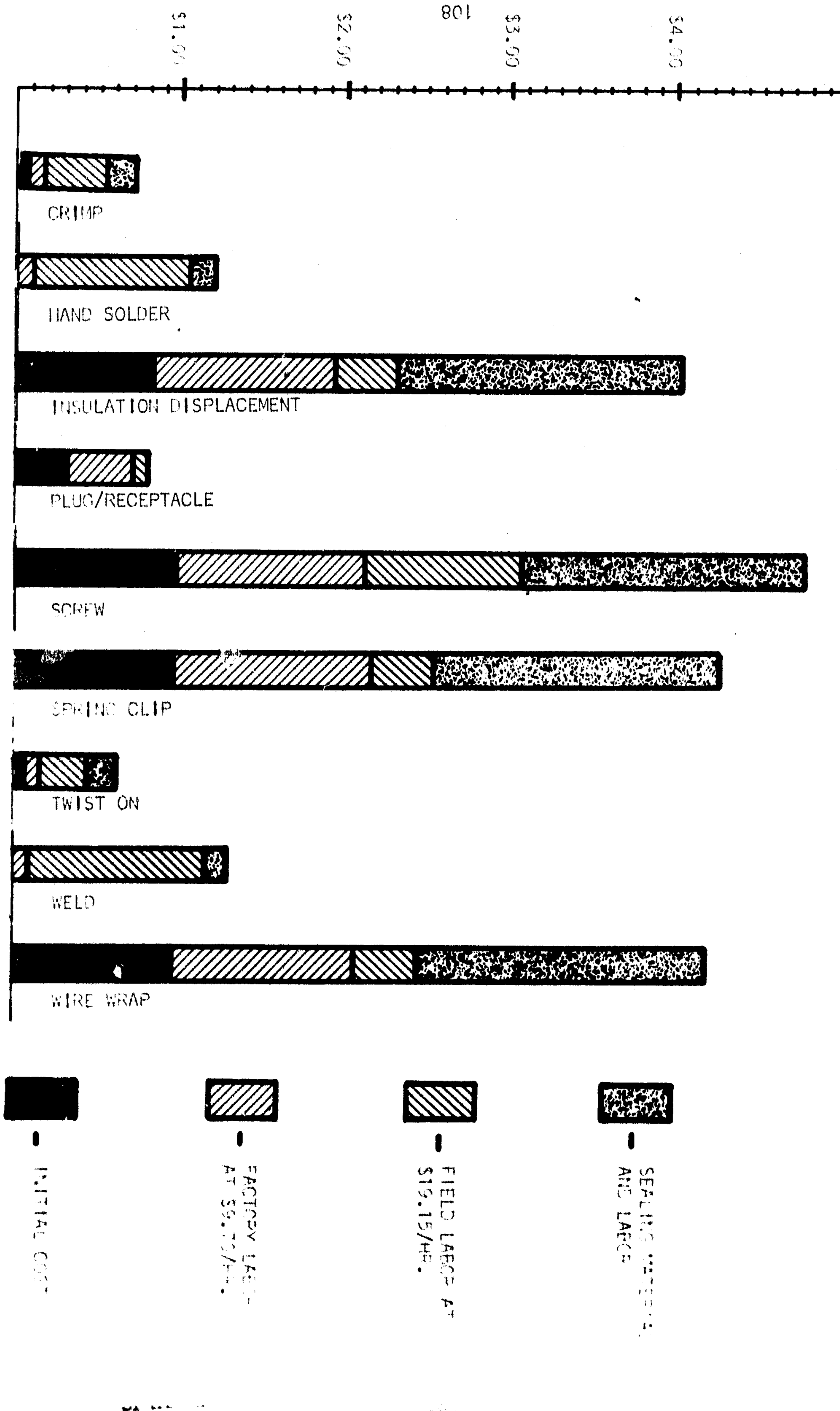
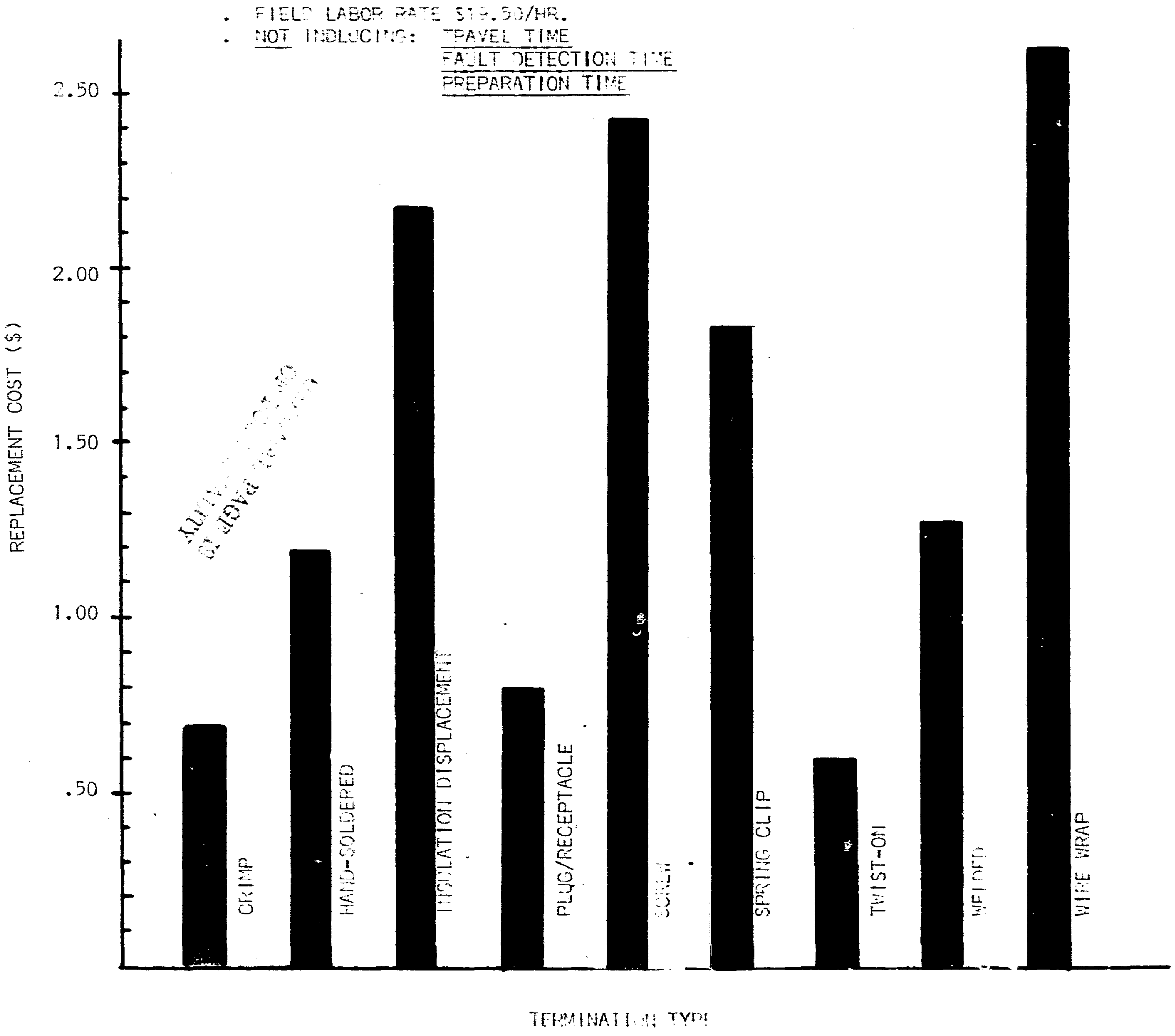


FIGURE 16

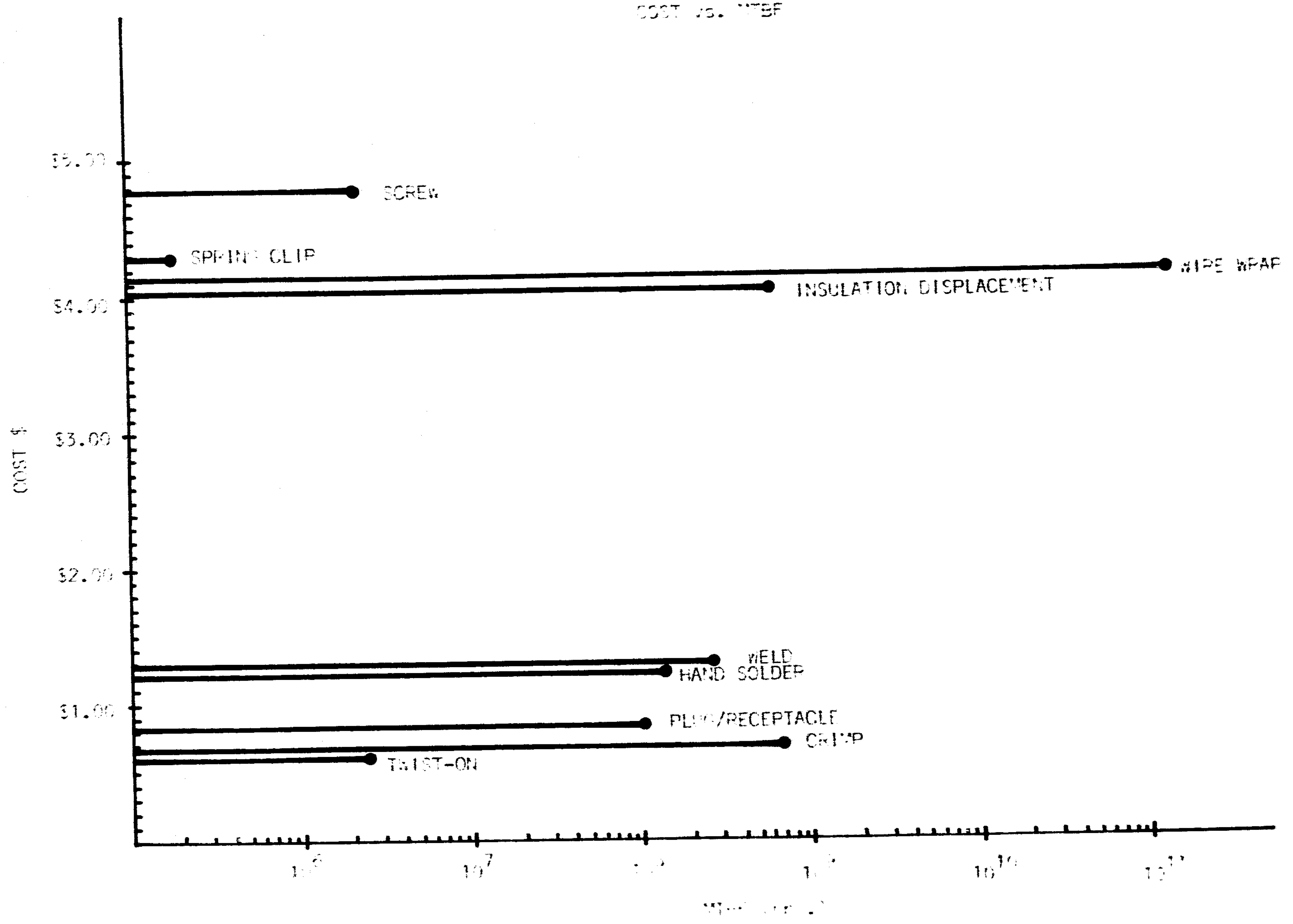
FACTORY AND FIELD ASSEMBLY COSTS FOR TERMINATION TYPE

FIGURE 17

FIELD TERMINATION REPLACEMENT DUE TO TERMINATION FAILURE



COST vs. MTBF



$5.00
$4.00
$3.00
$2.00
$1.00
COST $
SCREW
WIRE WRAP
INSULATION DISPLACEMENT
WELD
HAND SOLDER
CRIMP
TWIST-ON
10^7
10^{10}

5.9 MTBF ESTIMATIONS

Failure rates were calculated for the five termination types listed in MIL-HDBK-217C. Manufacturer inputs were utilized to establish the remaining termination failure rates. These failure rates were then converted to MTBF's, for each type, and are found in Table 10. It is interesting to note that all termination types have MTBF's greater than the system design life of 20 years. This demonstrates that concern over the termination useful life need not be considered. This also reduces the life cycle costing to strictly initial costs, on a single connector (termination) basis.

The following portion of MIL-HDBK 217C is reproduced for reference.

TABLE 10

TERMINATION TYPE	SINGLE TERMINATION MTBF (hrs)
Wire Wrap[1]	1.33×10^{11}
Crimp[1]	6.41×10^{8}
Insulation Displacement	6.22×10^{8}
Welded[1]	2.56×10^{8}
Hand Solder[1]	1.28×10^{8}
Plug/Receptacle[1]	1.00×10^{8}
Twist-On	2.28×10^{6}
Screw	2.24×10^{6}
Spring Clip	1.96×10^{5}

[1] - MTBF based on failure rates determined from MIL-HDBK 217C, all others determined by parametric data.

A PORTION OF MIL-HDBK 217C

RELATING TO FAILURE RATES OF CONNECTORS

2.11 CONNECTOR

2.11.1 Connector, general (except printed circuit board types)

TABLE 2.11.1-1. Prediction Procedure for Connectors

PART SPECIFICATIONS COVERED (Table 2.11-2 shows connector configurations)

Type	MIL-C-SPEC	Type	MIL-C-SPEC
Rack and panel	24308 28748 83733	Coaxial, RF	3607 3643 3650 3655 25516 39012
Circular	5015 26482 38999 81511 83723	Power	3767

Part Failure Rate Model (λ_p)

The failure rate model (λ_p) is for a mated pair of connectors. For a single connector, divide λ_p by two.

$$\lambda_p = \lambda_b (\pi_E \times \pi_P \times \pi_K) \text{ failures}/10^6 \text{ hours}$$

where:

π_E - Table 2.11.1-6

π_P - Table 2.11.1-7

π_K - Table 2.11.1-8

OR
OF

Table 2.11.1-1. Prediction Procedure for Connectors (Cont)

Base Failure Rate Model (λ_b)

$$\lambda_b = Ae^x$$

where $x = \frac{N_T}{T+273} + \left(\frac{T+273}{T_o}\right)^P$

e = 2.718, natural logarithm base
T = operating temperature (°C)
= ambient + temperature rise(Table 2.11.1-4)

Constants	Insert Material			
	A	B	C	D
A	0.02	0.431	0.19	0.77
T_o	473	423	373	358
N_T	-1592	-2073.6	-1298	-1528.8
P	5.36	4.66	4.25	4.72

Calculated values of λ_b for selected operating temperatures are shown in Table 2.11.1-5

Table 2.11.1-2. Configuration, Applicable Specification, and Insert Material for Connectors

Configuration	Specification	Insert Material (Table 2.11.1-3) A	B	C	D
Rack and panel	MIL-C-28748		X		
	MIL-C-83733		X		
	MIL-C-24308	X	X		
Circular	MIL-C-5015		X		X
	MIL-C-26482	X	X		X
	MIL-C-38999	X	X		
	MIL-C-81511		X		
	MIL-C-83723		X		
Power	MIL-C-3767		X		X
Coaxial	MIL-C-3607			X	
	MIL-C-3643			X	
	MIL-C-3650			X	
	MIL-C-3655			X	
	MIL-C-25516			X	
	MIL-C-39012			X	

Table 2.11.1-3. Temperature Ranges of Insert Materials

Type	Common Insert Materials	Temperature Range (°C)*
A	Vitreous glass, alumina ceramic, polyimide	-55 to 250
B	Diallyl phthalate, melamine, fluorosilicone, silicone rubber, polysulfone, epoxy resin	-55 to 200
C	Polytetrafluoroethylene (teflon) chlorotrifluoroethylene (kel-f)	-55 to 125
D	Polyamide (nylon), polychloroprene (neoprene), polyethylene	-55 to 125

*These temperature ranges indicate maximum capability of the insert material only. Connectors using these materials generally have a reduced temperature range caused by other considerations of connector design. Applicable connector specifications contain connector operating temperature range.

Table 2.11.1-4. **Insert Temperature Rise (°C) versus Contact Current**

Amperes Per Contact	Contact Size			
	22 GA	20 GA	16 GA	12 GA
2	3.7	2.4	1.0	0.4
3	7.7	5.0	2.2	0.8
4	13.0	8.5	3.7	1.4
5	20.0	13.0	5.5	2.0
6	27.0	18.0	7.7	2.8
7	36.0	24.0	10.0	3.7
8	46.0	30.0	13.0	4.8
9	58.0	37.0	16.0	5.9
10	70.0	45.0	20.0	7.2
15		95.0	41.0	15.0
20			70.0	25.0
25			105.0	38.0
30				53.0
35				71.0
40				91.0

$\Delta T = 0.989\ (i)^{1.85}$ for 22 gauge contacts

$\Delta T = 0.64\ (i)^{1.85}$ for 20 gauge contacts

$\Delta T = 0.274\ (i)^{1.85}$ for 16 gauge contacts

$\Delta T = 0.1\ (i)^{1.85}$ for 12 gauge contacts

ΔT = °C insert temperature rise

i = amperes per contact

NOTE: Operating temperature of the connector is usually assumed to be the sum of the ambient temperature surrounding the connector plus the temperature rise generated in the contact. If the connector is mounted on a suitable heat sink, the heat sink temperature is usually taken as ambient. For those circuit design conditions which generate a contact hot spot, this hot spot temperature rise is added to the ambient to obtain the operating temperature.

For RF coaxial connectors, assume ΔT = 5°C.

Table 2.11.1-7. **Values of Failure Rate Multiplier, π_P, for Number of Active Contacts (Pins) in a Connector**

Number Of Active Contacts	π_P	Number Of Active Contacts	π_P
1	1.00	65	13.20
2	1.36	70	14.60
3	1.55	75	16.10
4	1.72	80	17.69
5	1.87	85	19.39
6	2.02	90	21.19
7	2.16	95	23.10
8	2.30	100	25.13
9	2.44	105	27.28
10	2.58	110	29.5[illegible]
11	2.72	115	31.98
12	2.86	120	34.53
13	3.00	125	37.22
14	3.14	130	40.02
15	3.28	135	43.08
16	3.42	140	46.25
17	3.57	145	49.60
18	3.71	150	53.12
19	3.86	155	56.83
20	4.00	160	60.74
25	4.78	165	64.85
30	5.60	170	69.17
35	6.46	175	73.70
40	7.42	180	78.47
45	8.42	185	83.4[illegible]
50	9.50	190	88.72
55	10.65	195	94.23
60	11.89	200	100.00

For coaxial and triaxial connectors, the shield contact is counted as an active pin.

π_P is a function of the number of active pins:

$$\pi_P = e^{\left(\frac{N-1}{N_o}\right)^q}$$

where $N_o = 10$

$q = 0.51064$

N = number of active pins

2.11.1-8

Table 2.11.1-8. π_K Mating/ Unmating Factor

Mating/Unmating Cycles (per 1000 hours)	π_K
0-0.05	1.0
>0.05-0.5	1.5
>0.5-5	2.0
>5-50	3.0
>50	4.0

One cycle includes both connect and disconnect.

2.11.2 PRINTED CIRCUIT BOARD CONNECTOR

Table 2.11.2-1 Prediction Procedure for PCB Connectors

Specification	Description
MIL-C-21097	One-Piece Connector
MIL-C-55302	Two-Piece Connector

Part Failure Rate Model (λ_p)

The failure rate, λ_p, is for a mating pair of connectors and is:

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_P \times \Pi_K) \text{ failures}/10^6 \text{ hours}$$

where the factors are:

Π_E	Table 2.11.2-4
Π_P	Table 2.11.2-5
Π_K	Table 2.11.2-6

Base Failure Rate (λ_b)

$$\lambda_b = Ae^x$$

where $x = \left(\frac{N_T}{T+273}\right) + \left(\frac{T+273}{T_o}\right)^P$

e = 2.718, natural logarithm base
T = operating temperature (°C)
T = ambient + temperature rise (Table 2.11.2-2)

A = 0.216
T_o = 423
P = 4.66
N_T = -2073.6

λ_b values are shown in Table 2.11.2-3.

Table 2.11.2-2. Connector Temperature Rise (^{o}C) Versus Contact Current and Contact Size

Amperes/Contact	26 GA	22 GA	20 GA
1	1.4	0.99	0.6
2	5.0	3.6	2.3
3	10.5	7.6	4.9
4	17.9	12.9	8.31
5	27.1	19.4	12.6

$\Delta T = 1.38\ (i)^{1.85}$ for 26 GA

$\Delta T = 0.989\ (i)^{1.85}$ for 22 GA

$\Delta T = 0.64\ (i)^{1.85}$ for 20 GA

Note 1: ΔT = ^{o}C temperature rise
i = amperes per contact

Note 2: The operating temperature of the connector is usually assumed to be the sum of the ambient temperature surrounding the connector plus the temperature rise generated in the contact.

Table 2.11.2-3. Operating Temperature Versus Base Failure Rate (λ_b) in Failures/Million Hours

Temperature (°C)	λ_b
0	0.00013
10	0.00016
20	0.00021
30	0.00028
40	0.00037
50	0.00047
60	0.0006
70	0.0008
80	0.0009
90	0.0011
100	0.0014
110	0.0018
120	0.0022
130	0.0028
140	0.0035
150	0.0043
160	0.0055
170	0.007
180	0.0088
190	0.011
200	0.014

Table 2.11.2-4. π_E Based on Environmental Service

Environment	π_E	
	MIL SPEC	Lower Quality
G_B	1.0	1.5
S_F	1.0	1.5
G_F	4.0	8.0
N_S	4.0	8.0
A_{IT}	5.0	10.0
A_{UT}	5.0	10.0
G_M	5.0	10.0
N_U	9.0	19.0
A_{IF}	10.0	20.0
A_{UF}	10.0	20.0
M_L	15.0	30.0

Table 2.11.2-5. Values of Failure Rate Modifier, π_P, for Number of Active Pins in a Connector

N	π_P	N	π_P
1	1.00	65	13.20
2	1.36	70	14.60
3	1.55	75	16.10
4	1.72	80	17.69
5	1.87	85	19.39
6	2.02	90	21.19
7	2.16	95	23.10
8	2.30	100	25.13
9	2.44	105	27.28
10	2.58	110	29.56
11	2.72	115	31.98
12	2.86	120	34.53
13	3.00	125	37.22
14	3.14	130	40.07
15	3.28	135	43.08
16	3.42	140	46.25
17	3.57	145	49.60
18	3.71	150	53.12
19	3.86	155	56.83
20	4.00	160	60.74
25	4.78	165	64.65
30	5.60	170	69.17
35	6.46	175	73.70
40	7.42	180	78.47
45	8.42	185	83.47
50	9.50	190	88.72
55	10.65	195	94.23
60	11.89	200	100.00

π_P is a function of the number of active pins

$$\pi_P = e^{\left(\frac{N-1}{N_o}\right)^q}$$

where $N_o = 10$

$q = 0.51064$

N = number of active pins

2.11.2-5

OR
OF

Table 2.11.2-6. Cycling Rate Factor π_K

Cycling Frequency (Matings/1000 Hours)	π_K
0 - 0.05	1.0
>0.05 - 0.5	1.5
>0.5 - 5.0	2.0
>5.0 - 50.0	3.0
>50.0	4.0

A cycle is defined as the mating and unmating of a connector.

2.11.3 Example Failure Rate Calculations

EXAMPLE 1.

Given: A MIL-SPEC connector, with with 20 GA pins, uses insert material, type B. The connector has 20 active pins and is installed in a ground fixed environment with an ambient temperature of 25°C. The load current is expected to be 5 amperes, and the connector is expected to be connected and disconnected once every 200 operating hours.

Find: The failure rate of the connector.

Step 1. The insert temperature rise is determined to be 13°C, derived from Table 2.11.1-4 for size 20 GA pins at 5 amperes.

The operating temperature is determined from:

Operating temperature = ambient temperature + insert temperature rise.
Operating temperature = 25°C + 13°C = 38°C

Step 2. The insert material is type B. Utilizing Table 2.11.1-5, the base failure rate for type B insert material at 38°C is 0.00073 failures/10^6 hours.

Step 3. The environmental factor for ground fixed (π_E) is 2.0, as shown in Table 2.11.1-6. The pin density factor (π_P) is 4.0, as shown in Table 2.11.1-7 for 20 active pins. The π_K factor is 2.0, as determined from Table 2.11.1-8, for mating/unmating cycles of 5/1000 hours.

Step 4. The failure rate of the connector is found by substituting the values of λ_b, π_E, π_P, and π_K into the part failure rate model:

$$\lambda_p = \lambda_b (\pi_E \times \pi_P \times \pi_K)$$

$$\lambda_p = 0.00073 (2.0 \times 4.0 \times 2.0)$$

$\lambda_p = 0.0117$ failures/10^6 hours for a mated pair.

For a single connector, per Table 2.11.1-1:

$\lambda_p = .0117/2 = 0.0054$ failures/10^6 hours.

2.11.3-1

EXAMPLE 2.

Given: A lower quality connector, with 16 GA pins, uses insert material, type D. The connector has 10 active pins and is installed in an airborne inhabited, transport environment with an ambient temperature of 40°C. The load current is expected to be 5.0 amperes, and the connector is expected to be connected and disconnected once every 20 hours.

Find: The failure rate of the connector.

Step 1. The insert temperature rise is determined to be 5.5°C, derived from Table 2.11.1-4, for size 16 GA pins at 5.0 amperes.

The operating temperature is determined from:

Operating temperature = ambient temperature + insert temperature rise.
Operating temperature = 40°C + 5.5°C = 45.5°C.

Step 2. The insert material is type D. Utilizing Table 2.11.1-5, the base failure rate for type D insert material at 45.5°C is 0.0113 failures/10^6 hours.

Step 3. The environmental factor for airborne inhabited, transport, lower quality is 15.0, as shown in Table 2.11.1-6. The pin density factor (π_P) is 2.58, as shown in Table 2.11.1-7, for 10 active pins. The π_K factor is 3.0, as determined from Table 2.11.1-8 for 50 mating/unmating cycles per 1000 hours.

Step 4. The failure rate of the connector is determined by substituting the values of λ_b, π_E, π_P, and π_K into the part failure rate model:

$$\lambda_p = \lambda_b (\pi_E \times \pi_P \times \pi_K)$$

$$\lambda_p = 0.0113 (15.0 \times 2.58 \times 3.0)$$

$$\lambda_p = 1.31 \text{ failures}/10^6 \text{ hours for a mated pair.}$$

For a single connector, per Table 2.11.1-1:

$$\lambda_p = 1.31/2 = .66 \text{ failures}/10^6 \text{ hours.}$$

EXAMPLE 3.

Given: A two-piece printed circuit board connector (MIL-C-55302) with 50 active pins will be utilized in a ground fixed environment in which the connector is expected to be connected and disconnected once every 300 hours of operation. Pin size is 22 gage. Ambient temperature will be 25°C, and the expected load current will be 2.0 amperes.

Find: The failure rate of the connector.

Step 1. Calculate the operating temperature by adding the temperature rise in the connector to the ambient temperature, 25°C.

From Table 2.11.2-2, ΔT for 22 gage when 2.0 amperes are flowing = 3.6°C.

Operating temperature = ambient + heat rise.
Operating temperature = 25°C + 3.6°C = 28.6°C.

Step 2. From Table 2.11.2-3, λ_b is determined to be 0.00027 for 28.6°.

Step 3. From Table 2.11.2-4, π_E for ground environment and MIL-SPEC quality is 4.

Step 4. From Table 2.11.2-5, π_P for 50 pins is determined to be 9.5.

Step 5. From Table 2.11.2-6, π_K for 3.33 matings/1000 hours is determined to be 2.0.

Step 6. The failure rate of the connector is determined by substituting the values determined into the failure rate equation:

$$\lambda_P = \lambda_b (\pi_E \times \pi_P \times \pi_K)$$

$$\lambda_P = 0.00027 (4 \times 9.5 \times 2)$$

$$\lambda_P = 0.02 \text{ failures}/10^6 \text{ hours.}$$

2.12 PRINTED WIRING BOARDS

The specifications applicable to printed wiring boards are:

MIL-P-55110 Printed Wiring Boards

The failure rate model for printed wiring boards is:

$$\lambda_p = \lambda_b N \pi_E$$

where: λ_p = board failure rate in f./10^6 hr.

λ_b = $6(10)^{-6}$ failures/10^6 hr. for two-sided boards

= $5(10)^{-4}$ failures/10^6 hr. for multi-layer boards

N = number of plated-through holes

π_E = (see below)

Environment	G_B	S_F	G_F	N_S	G_M	A_{IT}	A_{IF}	N_U	A_{UT}	A_{UF}	M_L
π_E	1	1	2	4	4	4.2	6.4	10	10	20	[illegible]

The above model is applicable only to high quality boards that have received screening and burn-in and that use G-10 or equivalent epoxy materials.

2.13 CONNECTIONS

The part failure rate model (λ_p) is:

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_T \times \Pi_Q) \text{ failures}/10^6 \text{ hours}$$

where:

λ_b = base failure rate (Table 2.13-1)

Π_E = environmental factor (Table 2.13-2)

Π_T = tool type factor (Table 2.13-3 for crimp type)

= 1 for all types except crimp

Π_Q = quality factor (Table 2.13-4 for crimp type)

= 1 for all types except crimp

TABLE 2.13-1 BASE FAILURE RATE, λ_b

CONNECTION TYPE	λ_b (F/10^6 HR.)	
Wirewrap	.0000025	2.5×10^{-6}
Solder, reflow lap to P.W. boards	.00008	8.0×10^{-5}
Solder, wave to P.W. boards	.00029	2.9×10^{-4}
Hand solder	.0026	2.6×10^{-3}
Crimp	.00026	2.6×10^{-4}
Weld	.0013	1.3×10^{-3}

TABLE 2.13-2. ENVIRONMENTAL FACTORS (π_E)

EQUIPMENT	π_E
S_F	1.0
G_B	1.0
G_F	1.5
N_S	1.5
N_U	3.0
A_{IT}	3.0
A_{IF}	6.0
G_M	3.0
A_{UT}	4.0
A_{UF}	8.0
M_L	7.0

TABLE 2.13-3. TOOL TYPE FACTORS (π_T) FOR CRIMP CONNECTIONS

TOOL TYPE	π_T
Automated	1
Manual	2

Notes: 1 Automated encompasses all powered tools not hand-held.

2 Manual includes all hand-held tools.

TABLE 2.13-4. QUALITY FACTORS (π_Q) FOR CRIMP CONNECTIONS

QUALITY GRADE	π_Q	COMMENTS
Automated Tools	1.0	Daily pull tests recommended.
Manual Tools:		
Upper	0.5	Only MIL-SPEC or approved equivalent tools and terminals, pull test at beginning and end of each shift, color coded tools and terminations.
Standard	1.0	Only MIL-SPEC tools, pull test at beginning of each shift.
Lower	[illegible]	Anything less than standard criteria.

only to have the equipment production procedures damage the parts or introduce latent defects. Total equipment program descriptions as they might vary with different part quality mixes is beyond the scope of this Handbook. Reliability management and quality control procedures are described in other DOD standards and publications. Nevertheless, when a proposed equipment development is pushing the state-of-the-art and has a high reliability requirement necessitating high quality parts, the total equipment program should be given careful scrutiny and not just the parts quality. Otherwise, the low failure rates as predicted by the models for high quality parts will not be valid.

c. Use Environment.

All part reliability models include the effects of environmental stresses through the factor, π_E. The definitions of these environments are shown in Table 2-3. The π_E factor is quantified within each part failure rate model. These environments encompass the major areas of equipment use. Some equipment may experience more than one environment during its normal use, e.g., equipment in spacecraft. In such a case, the reliability analysis should be segmented, namely, missile launch (M_L) conditions during boost and return from orbit, and space flight (S_F) while in orbit.

TABLE 2-3
ENVIRONMENTAL SYMBOL IDENTIFICATION AND DESCRIPTION

ENVIRONMENT	π_E SYMBOL	NOMINAL ENVIRONMENTAL CONDITIONS
Ground, Benign	G_B	Nearly zero environmental stress with optimum engineering operation and maintenance.
Space, Flight	S_F	Earth orbital. Approaches Ground, Benign conditions without access for maintenance. Vehicle neither under powered flight nor in atmospheric re-entry.
Ground, Fixed	G_F	Conditions less than ideal to include installation in permanent racks with adequate cooling air, maintenance by military personnel and possible installation in unheated buildings.
Ground, Mobile	G_M	Conditions more severe than those for G_F, mostly for vibration and shock. Cooling air supply may also be more limited, and maintenance less uniform.

ENVIRONMENT	π_E SYMBOL	NOMINAL ENVIRONMENTAL CONDITIONS
Naval, Sheltered	N_S	Surface ship conditions similar to G_F but subject to occasional high shock and vibration.
Naval, Unsheltered	N_U	Nominal surface shipborne conditions but with repetitive high levels of shock and vibration.
Airborne, Inhabited, Transport	A_{IT}	Typical conditions in transport or bomber compartments occupied by aircrew without environmental extremes of pressure, temperature, shock and vibration, and installed on long mission aircraft such as transports and bombers.
Airborne, Inhabited Fighter	A_{IF}	Same as A_{IT} but installed on high performance aircraft such as fighters and intercepters.
Airborne, Uninhabited, Transport	A_{UT}	Bomb bay, equipment bay, tail, or wing installations where extreme pressure, vibration, and temperature cycling may be aggravated by contamination from oil, hydraulic fluid and engine exhaust. Installed on long mission aircraft such as transports and bombers.
Airborne, Uninhabited, Fighter	A_{UF}	Same as A_{UT} but installed on high performance aircraft such as fighters and intercepters.
Missile, Launch	M_L	Severe conditions of noise, vibration, and other environments related to missile launch, and space vehicle boost into orbit, vehicle re-entry and landing by parachute. Conditions may also apply to installation near main rocket engines during launch operations.

d. Part Failure Rate Models.

Part failure rate models for microelectronic parts are significantly different form those for other parts and are presented entirely in Section 2.1. Another type of model is used on most other parts; a typical example is the following one for discrete semiconductors:

CALCULATIONS

Part failure rate model (λ_p) is:

$$\lambda_p = \lambda_b (\pi_E \times \pi_T \times \pi_Q) \text{ failures}/10^6 \text{ hrs.}$$

λ_p = part failure rate ($F/10^6$ hr.)

λ_b = base failure rate (table 2.13-1)

π_E = environmental factor (table 2.13-2) = 3.0

G_M (ground, mobile) selected as most similar to photovoltaic environmental factor)

π_T = tool type factor (table 2.13-3 for crimp type) = 1 for others

π_Q = quality factor (table 2.13-4 for crimp type) = 1 for others

WIRE WRAP

$$\lambda_p = 0.0000025 \ (3.0 \times 1 \times 1.0) = 7.5 \times 10^{-6}$$

$$\text{MTBF: } \frac{1}{7.5 \times 10^{-6}} \times 10^6 = 1.33 \times 10^{11} \text{ MTBF}$$

CRIMP

$$\lambda_p = .00026 \ (3.0 \times 2 \times 10.0) = 0.0156 \times 10^{-6}$$

$$\text{MTBF} = \frac{1}{0.0156 \times 10^{-6}} \times 10^6 = 6.41 \times 10^8$$

WELDED

$$\lambda_p = .0013 \ (3.0 \times 1 \times 1.0) = 0.0039 \times 10^{-6}$$

$$\text{MTBF} = \frac{1}{0.0039 \times 10^{-6}} \times 10^6 = 2.56 \times 10^8$$

HAND SOLDER

$$\lambda_p = .0026 \ (3.0 \times 1 \times 1.0) = 0.0078 \times 10^{-6}$$

$$\text{MTBF} = \frac{1}{0.0078 \times 10^{-6}} \times 10^6 = 1.28 \times 10^8$$

PLUG/RECEPTACLE

Part failure rate model (λ_p) is:

$$\lambda_p = \lambda_b (\pi_E \times \pi_p \times \pi_K) \text{ failures}/10^6 \text{ hours (mated pair)}$$

λ_b = base failure rate = 0.00094 (table 2.11.1-5)

π_E = environmental service condition = 5.0 (table 2.11.1-6)

π_p = failure rate multiplier = 1.00 (table 2.11.1-7)

π_K = mating/unmating factor = 2.0 (table 2.11.1-8)

$$\lambda_p = 0.0009 (5.0 \times 1.00 \times 2.0) = 0.009 \times 10^{-6}$$

$$\text{MTBF} = \frac{1}{0.009 \times 10^{-6}} \times 10^6 = 1.1 \times 10^8$$

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