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RESEARCH AND DEVELOPMENT TECHNIQUES FOR FABRICATION OF LIGHTWEIGHT SOLAR CONCENTRATORS

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COMPLETE 5-FOOT-DIAMETER ELECTROFORMED CONCENTRATOR WITH BACK MOUNTED TORUS STRUCTURE BEFORE COATING

FOREWORD

This report was prepared by Electro-Optical Systems, Inc. (EOS), Pasadena, California for the National Aeronautics and Space Administration, Western Operations Office, under contract NAS 7-86 with the Jet Propulsion Laboratory designated as Technical Monitor. Mr. Lee Leventhal was Contract Monitor for the Laboratory, and Mr. Walter Scott, for the National Aeronautics and Space Administration.

The investigation presented began in November 1961 and will be concluded in November 1962. A supplement will be issued to this report that will cover the work done after 15 October 1962. The work was performed within the Advanced Power Systems Division of EOS under the supervision of Mr. Marlowe A. Pichel.

ABSTRACT

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This report relates to research, development, and fabrication of high performance, lightweight solar concentrators.

The first phase of the work was concerned chiefly with small-scale studies leading to improved structural design of one-piece concentrators. Appropriate tooling was designed and fabricated to permit the adaptation of the new structural approaches to the fabrication of 5-foot-diameter mirrors. Experimental studies to evaluate the effects of various plating parameters on the physical properties of electroformed nickel and copper were also conducted. During this phase of effort the reflectivity of various vacuum and chemically deposited coatings was examined.

In the second phase of the program the new mirror design and tooling concepts were used in the fabrication of several 5-foot-diameter concentrators. The results of the studies of physical properties and coatings were used in establishing the plating and coating procedures for the 5-foot concentrators.

The program has resulted in an improved backing structure design for the large concentrators. The studies of physical properties have defined trends in the effects produced by plating parameters on the strength and modulus of elasticity of the electroforms. Plating procedures have been improved and formalized, and vacuum coating approaches have been systematized. Completed concentrators have been delivered to the Jet Propulsion Laboratory for structural testing.

Author

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1. INTRODUCTION

During the last 5 years Electro-Optical Systems, Inc. has conducted several study and developmental programs related to solar energy collectors. Since detailed information has already been described in the reports resulting from these prior activities, an extensive review will not be included here. However, the programs, resultant reports, and a brief description of the area of activity, are listed in the following paragraphs. A familiarity with the information contained in these past reports will be beneficial in the understanding and evaluation of the work conducted under the present program.

Definitions of terminology and descriptive phrases used in this report are contained in paragraph 1.5.

1.1 Review of Prior Concentrator Development at Electro-Optical Systems, Inc.

An extensive 1-year effort, both analytical and experimental, concerned with the design and development of solar concentrators and their integration into space power systems, was performed by EOS for the Army Ballistic Missile Agency, Huntsville, Alabama, under Contract DA-04-495-506-ORD-1790. The program involved a comprehensive study covering a wide range of subjects including details of system design requirements and design data, basic concentrator design considerations, thermal energy converters, concentrator size requirements, and estimates of some component weights and dimensions. Concentrator structural and fabrication techniques were discussed and included elements of concentrator structure, concentrator design considerations, fabrication techniques, and materials. The experimental development phases of the program included fabrication of small-scale sample concentrators. A wide variety of fabrication processes were investigated to study the advantages and disadvantages of each.

Explosive forming, spin forming, stretch forming, matched-die forming, and other similar processes that were evaluated involved actual

deformation and stretching of the skin material to conform with the forming die, tool, or mandrel used in the fabrication process. In addition to this deformation and stretching of the material itself, the part was required to come in physical contact with the face of the mandrel or tool during the course of forming. As a result, it was found to be impossible to maintain the surface accuracy and polish required for high efficiency concentrator performance without repolishing after the forming process was completed. Subsequent polishing operations were found to be difficult, if not impossible, to carry out on the thin-skin structures that were required for achievement of very low specific weight (pounds per square foot of surface area). For these as well as other considerations, the formation of the concentrator reflector face skins by these more conventional methods was considered far from optimum; consequently, a better fabrication process was desired.

To eliminate the need for reforming or repolishing the concentrator reflective-face material, various techniques for producing a structurally sound, lightweight, highly reflective face skin by replicating an accurate master were considered. One of the most extensively developed techniques for such replication involves the use of plastic materials, both filled and unfilled, which obtain their structural integrity through the use of backing structures such as glass laminates and honeycombs. Unfilled plastic materials, both in the polyester and epoxy categories, were found to have the ability to reproduce surface characteristics very accurately and, with proper coatings, could exhibit reflectivities very nearly approaching those obtainable with coated glass. Unfilled plastic materials were found to be relatively unstable, however, and highly accurate geometries could not be maintained. These materials were also found to have very little strength in themselves and, as a consequence, proper backing structures were required for adequate support. Moreover, these materials may be subject to degradation due to ultraviolet radiation and other space factors. Filled plastic resins were relatively more stable,

istics. The surfaces very often developed a minute "orange peel" effect that resulted in a definite loss of reflectivity.

During the course of extensive experimental evaluation of replicated plastic surfaces, rigidized by various means, a definite showthrough of the backing structure was experienced. Samples were prepared both by EOS and outside vendors employing various types of honeycombs, both metallic and nonmetallic. Foams of varying densities and formulations were also evaluated. In all cases where thicknesses needed to produce structures with reasonably low weights were used, showthrough and distortion were evident. In the case of honeycomb-backed structures, this showthrough appeared in the form of the cell structure of the honeycomb, and was caused by residual stress and shrink of the materials used to bond the backing structure to the reflective surface. In the case of foam backing, the distortion was not so clearly defined but progressed with time in the form of an exaggerated and nonuniform "orange peel" effect. This condition was accelerated with large temperature changes and resulted in considerable loss in mirror efficiency.

The ability of plastic resins and related materials to withstand space environment has not at this time been satisfactorily demonstrated. The combinations of these various materials required to develop a suitable structure can result in heat transfer and other thermal characteristics that, in turn, can adversely influence the geometry of the structure. Although being unquestionably useful for some applications, these methods of fabrication (as was the case with methods involving reforming of metallic skins) were considered to have serious drawbacks for high-efficiency, long-life concentrators.

During the course of these investigations the process of replication by electroforming was also evaluated. This process appeared to offer solutions to many of the important problems inherent in other methods and made possible very accurate surface

replication of the master. Comparative tests on electroforms replicated from optically ground and polished glass masters demonstrated reflectivity characteristics essentially identical with those of the master from which they were replicated. Moreover, it appeared possible to achieve, through further development and refinement of the process, reflective face skins and structural parts that would have low internal or residual stress. As a result, the geometry of the master should be reproduced accurately.

In order to fully evaluate the possibilities that the electroforming process seemed to offer, a number of electroformed reflective skins and structures were produced by outside vendors for evaluation. From these structures the ability of the electroforming process to produce reflective surfaces comparable to glass mirrors was verified. Problems existed, however, in two basic areas: (1) improvement and refinement of the state of the art of electroforming were needed to gain greater control over stress characteristics and the physical properties of the electrodeposited material; (2) development of specific designs and fabrication techniques was required to allow the advantages offered by electroforming to be used to the fullest in concentrator fabrication. New techniques were required, along with an extremely high degree of process control. As experience showed, these were not available in shops where practices have been formalized for many years.

As a consequence, EOS undertook the development of its own special capabilities and facilities for precision electroforming. Electroforming studies, coupled with advanced and novel designs and applications for the electroforming technique, resulted in the development of small-scale and 60-inch-diameter concentrators having efficiencies approaching 90 percent, based on the concentration ratios required for high-temperature, high-performance systems such as solar thermionic power systems. The resultant structures proved the feasibility of fabricating solar concentrators by the electroforming process. The reflecting face skin, supporting and rigidizing structure, brackets, points of attachment, etc., could all

be produced from one common material as an integral structure without the need for adhesives, welds, brazes, or the like. With proper controls over the fabrication process, high reflectivity and accurate control of geometry could be expected. Other advantages would be gained, including improved thermal characteristics and dimensional stability in space environment.

Details of these investigations and the related experimental developments are recorded in the first phase technical summary report, EOS Report 410-Final, dated 16 May 1960, and in the final report, EOS Report 410-Final II, dated 11 December 1960. Both of these reports were produced as a result of the work performed under Contract DA-04-495-506-ORD-1790.

In order to continue the development work undertaken initially for the Army Ballistic Missile Agency, a research and development program was undertaken by EOS for the National Aeronautics and Space Administration under Contract NAS 7-10. This work was performed over a period of 1 year, commencing 1 November 1960 and ending 31 October 1961. Specific investigations and supporting experimental developments were undertaken in a number of related areas with the goal of developing the necessary supporting knowledge, techniques, and related equipment to produce and evaluate lightweight, high efficiency solar concentrators.

Basic electroforming studies were continued to investigate parameters affecting stress and physical properties. The examination of these factors in relation to actual fabrication processes was initiated. Areas of investigation included the development of necessary instrumentation to determine the existence and magnitude of inherent stress in the electroforms, methods of determining and controlling variations in current density, effects of additives and contaminants on the characteristics of the solution and resulting electroforms, and methods of determining effects produced by variations in agitation, temperature, etc. In addition to this main area of developmental work

[illegible] to nickel electroforming, the use of copper having improved structural properties was also evaluated and the deviations from nickel techniques were examined. Investigations were also performed relative to the use of various master materials, the choice and use of sensitizing and reflective coatings for nonmetallic masters, and their effect on parting of the replica from the master itself.

Master fabrication techniques were investigated for use in conjunction with electroformed concentrators. This phase of the program also included an investigation of scaling problems. Master surfacing materials were evaluated and tested experimentally to determine the reflectivity and the stability of geometry that could be expected. A model master was developed to demonstrate feasibility of the design and fabrication technique that would be used to generate desired geometry and surface conditions. Methods used in the fabrication of the model master demonstrated necessary tooling and equipment, fabrication, grinding and polishing processes. A test plating of a replica was made from the model master to check surface polish and determine if any parting problems existed.

Concentrator design concepts were evaluated relative to their compatibility with the electroforming process. Designs considered included reflective skins rigidized by a peripheral torus, as well as other structural concepts and those which would be applicable to segmented as well as one-piece concentrators. Small-scale experimental fabrication was undertaken to determine the feasibility of employing particular design concepts in actual production, and to determine the problem areas related to tooling, electroforming, and other practical fabrication problems. In conjunction with the small-scale concentrator development, techniques were developed for fabricating various substructures such as ribs, struts, and brackets.

In order to adapt these techniques to concentrator sizes that would be representative of those sizes that might be employed in

space power systems, the more feasible of the small-scale models was scaled and made in a 60-inch-diameter size so that problems associated with parting, handling, surface coating, etc., could be evaluated directly. A number of 60-inch units were produced experimentally and sectioned to determine uniformity of plating and integrity of structure, etc. Two additional 60-inch units made entirely of electroformed nickel and representing the finalized design and fabrication concepts were produced for delivery to JPL for further evaluation.

Although the development of techniques for producing electroformed copper having improved physical characteristics was not as advanced as for nickel electroforming, an all-copper, torus-rigidized 60-inch diameter concentrator was produced to determine the problems associated with working with this material in the larger sizes. The same design concepts and tooling that were employed to produce the 60-inch nickel concentrators were used in production of the copper unit.

In order to adequately evaluate the concentrators produced under the program, a series of testing procedures was developed and the necessary supporting equipment and testing techniques were established. These included development of tests to determine and evaluate both qualitatively and quantitatively, if possible, the accuracy of geometry and the quality of the reflective surface. One of the most critical areas of testing involved the use of calorimetry. Consequently, equipment and techniques were developed to permit calorimetric testing of concentrators. Each concentrator produced under the contract was evaluated using the techniques developed.

The first all-electroformed nickel 60-inch concentrator achieved efficiencies (with cold-wall calorimeter; cf. Sect. 5.5) ranging from 55.6 percent at a 1/2-inch calorimeter aperature diameter to 88.3 percent at a 1-inch aperture diameter. This concentrator underwent a rather extensive shake and vibration survey at JPL and the resultant information was fed back to produce modifications and improvements in subsequent models. The second nickel concentrator produced efficiencies that ranged from an average of 64 percent at the 1/2-inch

copper concentrator, which had a badly degraded reflective surface due to oxidation of the copper reflective face prior to application of the reflective coating, produced efficiencies averaging approximately 60 percent at 1/2-inch orifice size and 77.5 percent at 2-inch aperture size.

Results of these performance tests indicated that performance levels could be achieved using this method of construction that were far higher than those demonstrated by any other fabrication techniques.

Extensive details of these investigations and related experimental developments were recorded in the final technical summary report, EOS Report 1587-Final, dated 27 December 1961.

1.2 Summary of Program Goals

The developmental work performed during the course of the prior programs demonstrated the feasibility of producing solar concentrators entirely by the electroforming process. It became apparent that to achieve the desired goals the electroforming process must be carried out under a high degree of control. In addition, specific areas of development were required. To achieve more rapid improvement in practical electroformed concentrator fabrication techniques, a number of specific problem areas were identified for evaluation and experimental development during the course of the present program. These areas were as follows:

1.2.1 Backing Structure Studies

Backing structure studies would be undertaken to establish various concepts for backing or support structures for 5-foot-diameter mirrors. The various parameters would be analyzed relative to their application to larger sizes of concentrators. In conjunction with this, small-scale experimental studies of support structures were to be conducted to include an evaluation of backing masters, support structure and attachment methods, application of the more promising design concepts,

on the characteristics of the concentrator reflector face and backing structure.

In the course of the experimental development a number of representative mirrors approximately 17 to 18 inches in diameter would be fabricated. In addition, at least two 5-foot-diameter mirrors would be fabricated using nickel electroforming techniques that would demonstrate the most promising methods developed in the smaller experimental sizes. These mirrors, or major portions thereof, would be sectioned to evaluate the soundness of fabrication techniques and ultimate strength capabilities.

In addition, two 5-foot-diameter mirrors would be fabricated, using the nickel electroforming process, to demonstrate the most promising design and fabrication techniques. Necessary special tools and fixtures required for fabrication of the more advanced structures would be designed and fabricated. These would include a rotator capable of handling 5-foot diameter and larger masters, necessary handling fixtures, specially shaped anodes and masks, special mandrels, master extensions, and other devices associated with more sophisticated design concepts.

The two final 60-inch nickel concentrators would be subjected to optical and performance tests prior to delivery to the Jet Propulsion Laboratory for further optical and performance testing as well as for shake and vibration evaluations.

Upon conclusion of the experimental and design phases of the program the various parameters would be summarized and recommendations made regarding backing structure designs.

1.2.2 Plating Techniques

Development of plating techniques for the fabrication of electroformed nickel and copper mirrors and mirror structures would be continued. These investigations would include small-scale studies to seek an improvement

the structural properties of nickel and copper electroforms, reduction and control of plating stress in nickel and copper mirrors, development of techniques for monitoring and determining additive concentrations in plating solutions and the possible use of chromium for improvement of structural and, more particularly, surface properties of nickel and copper mirrors.

Physical testing of various plated samples would be accomplished and would include, if necessary, the development and construction of special testing devices to measure important physical properties. A major objective of this work is to increase the knowledge of copper-plating techniques to a level approaching that of nickel.

At the conclusion of this developmental phase at least one 5-foot-diameter concentrator would be fabricated using the electroformed-copper techniques that would demonstrate the most promising design and fabrication concepts associated with use of this material. Optical and performance tests would be made on this mirror before delivery to JPL for further testing and evaluation.

At the conclusion of the program the various parameters affecting electroforming of the various materials would be summarized and recommendations made regarding these techniques and processes.

1.2.3 Advanced Coating Studies

Advanced coating studies would be made and would include small-scale evaluations of problems related to substrate and master characteristics, the development of surface coatings for maximum reflectivity, an evaluation of coating durability, including development of devices for measuring coating adherence, if possible, and for mirror handling and cleaning. The mechanics of coating deposition would also be demonstrated and these techniques applied to the coating of the small and large mirrors to be fabricated during the course of this contract. In addition, at the conclusion of the experimental phase of the program, recommendations concerning facilities for coating large concentrators would be made.

The first 5-month period of the program was involved with design concepts and small-scale experimental studies, as reported in the Interim Summary Report EOS 2100-IR-1 of 10 May 1962. Fabrication of the various 5-foot-diameter concentrators, continuation of the supporting studies, application of the most desirable reflective and protective coatings, and testing of the concentrators were accomplished during the second phase of the program.

1.4 Summary of Report

This report covers all phases of work performed during the 11½-month period ending 15 October 1962 and includes information relating to the fabrication of all deliverable items except certain portions of final fabrication of the all-copper concentrator. The plating parameter information together with calorimetric test results on this unit will appear in an addendum to this report. It is expected to be published soon after the issuing date of this report.

During the course of the program, considerable interaction occurred between the different areas of work. For clarity, however, in this report the four basic areas of activity are presented separately as follows:

Section 2 contains information on the basic backing structure studies and techniques. As a background to the developmental work during the program and as an aid to those who are not familiar with the electroforming process as it is used in the fabrication of lightweight concentrators, prior electroforming activities at EOS are reviewed briefly. New information reported includes facts on work involving backing structure engineering, methods of attaching the backing structure to the mirror skin, and fabrication techniques required to implement the most promising designs. The experimental plating and fabrication problems are discussed.

Section 3 covers the advanced plating studies. Its primary content is a presentation of physical properties data derived from the test programs in both nickel and copper.

[illegible] the information derived from the advanced coating studies. A summary contains recommendations for coatings to be considered in certain possible future applications. A brief facilities review is also presented.

Section 5 discusses in considerable detail the making of the several 5-foot-diameter solar concentrators delivered under the provisions of this program. Fabrication problems and solutions are defined, the making of test skins is explained. All applicable parametric values and process materials used are recorded. The section concludes with a discussion of the various testing and evaluation methods that are applicable and those selected for specific use in testing concentrators produced on this program. The performance test results are listed and discussed in detail.

1.5 Definitions

During the course of this and prior programs, the use of new techniques, processes, and designs has necessitated the development of a new terminology and descriptive phrases. To clarify the reading of this report for those who are not familiar with the terminology, the following set of definitions is presented and will be used throughout:

1. Concentrator (or mirror)

   The reflecting device used to concentrate solar radiation into a focal zone.

2. Concentrator face (or face skin)

   The reflective face of the concentrator.

3. Backing (or rigidizing structure)

   That part which supports and holds the reflective face skin, to preserve the as-formed geometry of the reflective face skin.

4. Monocoque structure

   A type of single structure or shell which forms and includes the reflective face and the rigidizing or backing structure as one unit. This structure may be either a mirror segment or a complete mirror.

5. Back-mounted torus

A type of rigidizing structure that consists of a thin-shelled torus fastened to the reflective skin on its back side so as not to obscure any of the reflective surface. It is fastened to the skin near or at the rim.

6. Original mirror

A concave mirror from which masters or replications may be formed.

7. Mirror master

A fixture, normally convex, having the required degree of surface quality and finish, together with necessary geometrical accuracy, from which the concentrator face skin may be formed by a replication process. Masters may represent an entire mirror surface, or a segment, or section of the entire surface, and may be fabricated separately (original masters) to specification, or produced by replicating (replicated masters) the surface and geometry of an original mirror or mirror segment.

8. Replica mirror

Mirrors formed by the replication process using electroforming or other techniques. These can be formed either from original masters or replicated masters.

9. Mandrel (or molds)

Structures produced by a variety of methods on which material is electrodeposited to produce a finished electroform to the predetermined and desired shape. A mirror master, for instance, is a mandrel.

10. Anode array

A term used in electroforming referring to the exact configuration of the anodes, type of materials used, and existence of auxiliary provisions, such as wrapping the anodes for isolating contamination.

[illegible] referring to the number of amperes per square foot of area being electroformed. Usually an average value is quoted.

12. Inherent stress

Electroforming terminology referring to the stresses developed in the electrodeposited material during the plating process. These stresses may be either tensile or compressive in nature.

13. Concentrator specific weight

The total weight of concentrator divided by projected surface area. In this report the specific weight will be expressed in pounds per square foot.

14. Specular reflectivity

That portion of the incident energy which is reflected at an angle equal to the angle of incidence.

15. Concentration efficiency

The ratio of the total power (solar radiation) delivered to a given absorber orifice to the total power incident on the mirror. The concentration efficiency is a function of mirror geometry, surface characteristics, and magnitude of specular reflectivity.

16. Concentration ratio

The ratio of the projected area of the mirror surface to the area of the focal zone into which the energy incident on the mirror is focused.

17. Parting layer

A coating (either vacuum or chemically deposited) that is applied to the master before electroforming to facilitate removal of the plated mirror from the master.

18. Sensitizing layer

A coating that is applied to any nonconductive master to provide sufficient conductivity to commence electrodeposition.

The sensitizing layer is usually, but not always, the parting layer.

19. Antidiffusion layer

A vacuum-deposited coating, usually silicon monoxide, that is used to prevent substrate material from diffusing through upper coating layers (such as the reflective layer).

20. Rim angle

The angle between the optical axis of the mirror and the rim of the mirror as projected from the focal point.

2. BACKING STRUCTURE STUDIES

2.1 Background

There is very little engineering information available that is applicable to backing the extremely thin metallic skins required for solar concentrator reflector faces in a manner that produces no showthrough or optical distortion. A considerable amount of survey and experimental evaluation has been conducted in the past to determine the best possible methods for such backing or rigidizing.

High quality solar concentrators are required to withstand both the launch and space environment and to have no detrimental thermoelastic characteristics, and yet to be lightweight and reasonably immune from storage and preflight sterilization degradation. They also must maintain a high degree of specular reflectivity throughout their operational life, which, in some applications being planned at the present time, may be on the order of two or three years.

Constructural concepts associated with the above operational characteristics have been exhaustively contemplated and, the first approach, the monocoque structural concept evolved. Principally the monocoque design was inspired by the problem that any small stress input to the reflective skin is a source of degradation to the entire system. The simplicity of the monocoque concept also relieved the backing structure master complexity.

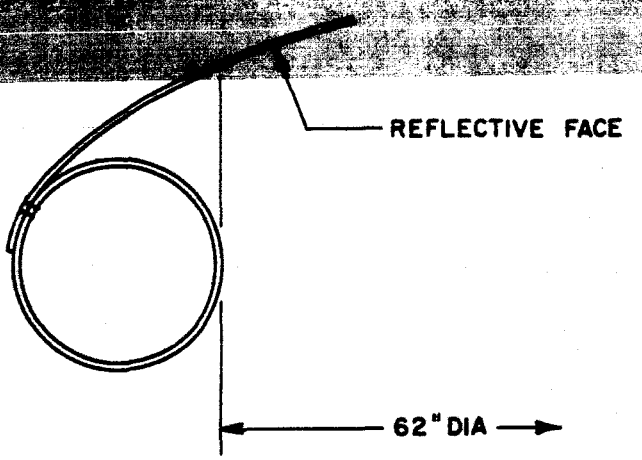
The basic concept of a monocoque structure is joining one or more structural elements of entirely double-curved sheets together at, as nearly as possible, right angle junctions. In other words, the double-curved sheets mutually reinforce each other at their envelope termini. An exception to the general rule is at lightening holes in the double-curved skins. In that case, the curvature of the skin is increased so that the double-curved sheet, in itself, is a stiffened member.

[illegible] at [illegible] during the previous 2 years had [illegible] structures. However, prior to that period many types of configurations had been fabricated and tested, on at least small-scale mirrors. Inflatables, rigidized inflatables, plastic backed, both plastic and metallic honeycomb units, welded metallic truss-supported structures and foam-backed replicas in both metal and plastic all had been tried with various degrees of success. The majority of them did not approach the monocoque replication accuracy or structural stiffness when taking into account the equivalent weight.

Since the current program had as its objective the development of all-electroformed structures that do not incorporate welds, adhesives, or other such joining techniques, the types of backings to be considered were further limited to those that can be produced by electroforming or by a compatible process, after which attachment to the reflective skin could be accomplished by electroforming.

In the months immediately preceding this program, increasing attention had been given to the torus-type structure for rigidizing concentrator skins. It was apparent that the torus, with its high strength-to-weight ratio, possessed a shape particularly suited to direct electroforming as a method of joining the structure. Several acceptable representative mirrors were produced with the torus rigidizing structure mounted on the front face of the reflecting skin, as shown in Fig. 1. In their size range, (20 ft^2 reflective area) these units were the lightest high performance solar concentrators produced to date. They possessed efficiencies exceeding 85 percent with a weight of less than 19 pounds.

A question arose, however, in regard to the ratio of outside diameter to reflective surface diameter. This ratio exceeded unity when a front-mounted torus was used. The diametral clearance of payload stages of present launch vehicles is sufficiently critical to necessitate a reduction in outside diameter. Such a reduction should be achieved without lowering the rigidizing efficiency of the front torus structure. The new design should not interfere with the front face which should have a reflective surface close to 60 inches in diameter on a 60-inch overall diameter concentrator.



FRONT MOUNTED TORUS STRUCTURE
PRODUCED ON PREVIOUS CONTRACTS

FIG. 1 ATTACHMENT METHODS - FRONT TORUS RIDGIDIZED STRUCTURE

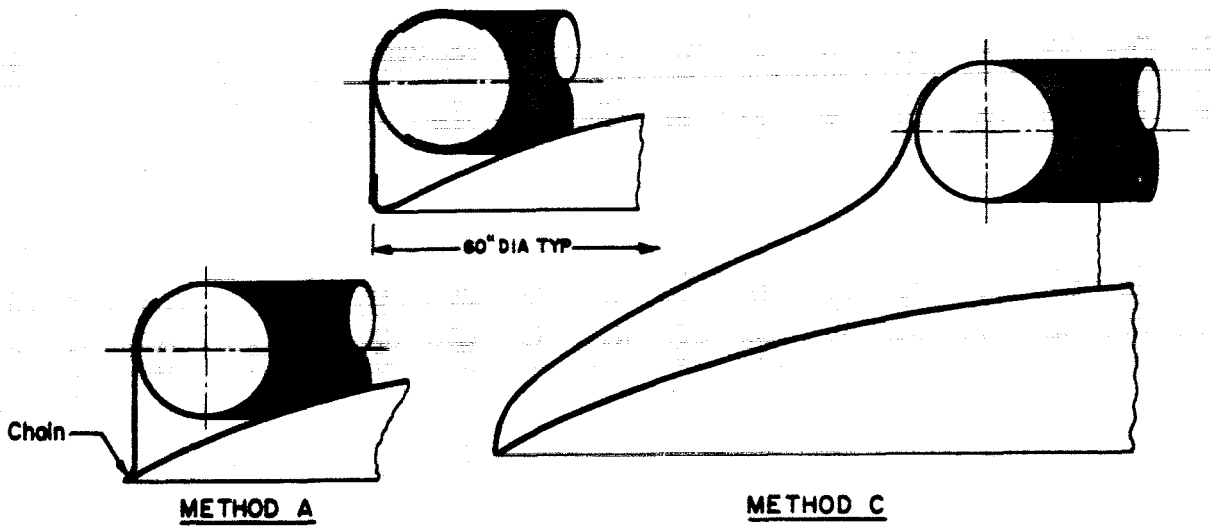


FIG. 2 ATTACHMENT METHODS - REAR TORUS RIGIDIZED MIRROR

Techniques that appear applicable are most easily demonstrated in medium-sized samples in the 2- to 3-foot-diameter range and can be fully evaluated in larger units, such as 5-foot-diameter concentrators. These sizes permit the application of fabrication and joining techniques that cannot be performed on extremely small samples. In a given curvature, a ratio of skin thickness-to-total-diameter can actually be varied, and from this variation information can be obtained that will be useful for scaling to still larger sizes. The main area of activity related to backing structures during the course of this program was concerned with 5-foot-diameter sizes, although other variations or novel approaches were investigated experimentally on a small scale. The application of the resultant techniques to concentrators larger than 5 feet in diameter was also examined.

Preliminary studies had shown that the rim, or outside support, is considerably more desirable than center support for a number of reasons. Comparisons indicate that maximum support and rigidity can be gained with minimum structural weight when peripheral support is used. The development of structural techniques and designs of concentrators should not, and cannot, ignore the fact that in application an absorber, cavity, or device of some sort, will be positioned and supported at the focal zone. For high performance systems the support must provide accurate and stable positioning of the absorber or cavity within a very few thousandths of an inch.

Absorber supports that are positioned from the center of the concentrator will necessarily intercept the reflected solar flux between the mirror and the absorber. In this position the converging cone of light is extremely concentrated as compared to the solar flux falling on the mirror surface. The total amount of energy lost through obscuration of the struts or absorber supports is far greater per unit area than that which would be lost due to the same obscurity in the unconcentrated state. It appears difficult to design the necessary absorber supports to allow sufficient minimization of

obscuration and still provide the necessary structural stability and strength required for adequate mounting.

In comparison with this condition, collector or cavity support by a tripod or similar design that is attached to the periphery or rim of the concentrator provides maximum accuracy and structural support for the absorber at the focal point. Such supports also provide minimum possible obscuration since they intercept the solar flux prior to concentration. Positioning of the absorber supports at the periphery or rim necessitates that this portion of the concentrator be structurally sound and stable.

When a peripherally supported concentrator design is employed in which the points of attachment to the vehicle or the mounts are at the rim, preferably in the same location as the absorber supports (as demonstrated in prior concentrators produced by EOS), maximum stability and support are gained without the need for the remainder of the concentrator structure to support any more than its own weight. It is obvious that if the concentrator was center supported by the vehicle and the more desirable rim-mounted absorber support method was used, the load would have to be transferred from the rim to the center of the mirror by relatively heavy structural members. This configuration, although acceptable, would be considerably heavier than the totally rim-supported configuration.

Based on these considerations, the peripheral torus design incorporating mounting points for both vehicle attachment and absorber support structures appears to be most desirable.

2.3 Small-Scale Experimental Studies

A number of small-scale experimental studies were carried on during the first 5-month period of the program. Experimental work employed 18-inch-diameter glass convex masters that had approximately the same focal length-to-diameter relationship as the 5-foot concentrators to be produced later in the program.

A variety of backing concepts were considered during the early stages of the program for backing or rigidizing electroformed face skins. As previously mentioned, the center supported configurations were discarded because of their inherent limitations. This eliminated the concept of the fully enclosed monocoque-type structure for one-piece mirrors. An important objective of the present program has been to provide backing and support structures in a configuration that will provide maximum usable reflective surface of the mirror.

Since the complete monocoque was eliminated, it appeared that rear-mounted variations of the torus or modified monocoque-type configuration would be capable of providing the necessary structural rigidity and points of attachment. A number of variations were considered and applied experimentally on a small scale. Since the torus technique was chosen for evaluation, full area backing masters as such were not required. Special tooling and mandrels that were required for application of the torus to the rear of the concentrator reflective skin in actual fabrication of the 5-foot-diameter concentrators are reviewed separately. (cf. Section 2.4)

2.3.2 Support Structure Attachment Methods

Various methods of attaching the rear-mounted torus to the reflector-face skin were considered. A number of variations exist, but the most desirable from the standpoint of applicability to the electroforming process are shown in Fig. 2. Among the proven attachment methods, an encapsulation lock provided by the chain or wire technique, and secondary plating using the electroformed riveting technique, appear to be the most promising. In application, the convex master is modified at the rim in accordance with the method chosen, and the reflective-face skin electroformed with the necessary rim or encapsulation locking devices. The torus, which for experimental purposes is merely a formed tube, is positioned in back of the reflective-face skin and the necessary mandrels for attachment are

hand formed of wax or other removable materials. Secondary plating is then accomplished, which provides structural attachment and bonding of the torus to the reflective-face skin.

2.3.3 Evaluation of Various Concepts - Experimental Fabrication

A number of experimental fabrications were accomplished using an 18-inch-diameter glass master. Although the basic techniques had been demonstrated before, a number of minor problems existed relative to their use. If secondary plating was to be used, provisions for controlling differences in thermal expansion between the glass master and the electroformed parts had to be made. This was necessary for the retention of the mirror skin on the master during its formation, through removal from the plating tank, and during the stages of secondary preparation for attachment of the rigidizing members. Stresses had to be accurately controlled and special provisions made to prevent leakage or entrance of the plating solution between the reflective face and the master during subsequent plating operations. Anode positioning, agitation techniques, and control of the various parameters associated with the electroforming process itself were required in addition to the special tooling necessary to produce the configurations.

Figure 3 shows an 18-inch-diameter mirror skin with chain attached and illustrates one of the methods with which secondary attachment of the rear-mounted torus can be achieved. Figure 4 is a close-up of the chain lock showing in detail the method of obtaining encapsulation or lock-on of the secondary parts. Figure 5 shows a close-up of the torus attachment method.

Although the encapsulation method that uses the chain or wire locking techniques provides very strong mechanical attachment for secondary structures, certain problems exist relative to the application of the technique, particularly for larger concentrators. The chain or locking device must be in contact with the master at all points or the electroformed bond may not be structurally sound. Agitation is sometimes difficult and stress concentrations result from the

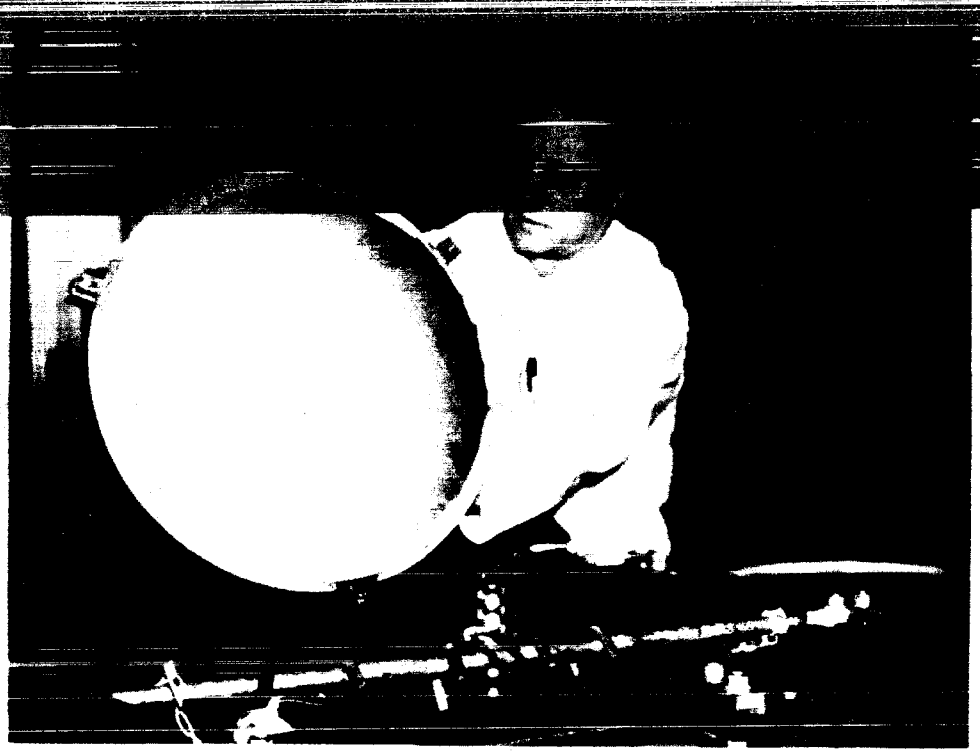


FIG. 3 18-INCH-DIAMETER MIRROR SKIN WITH CHAIN ATTACHED

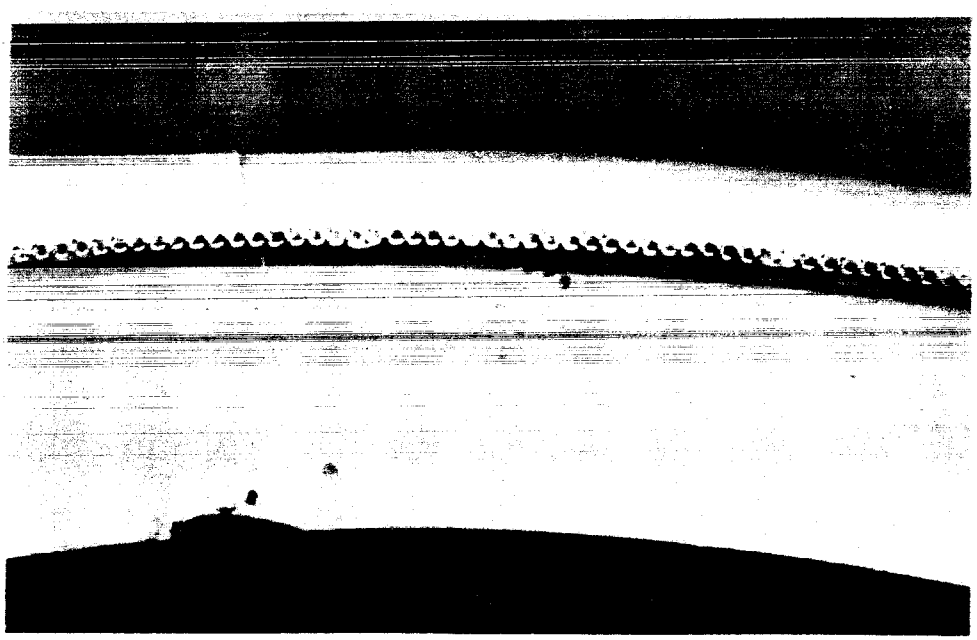


FIG. 4 CLOSE-UP OF CHAIN LOCK DETAIL

[illegible] density conditions that exist at this point. An alternative to the lock-on on the back of the mirror skin itself is the formation at the outer edge of the reflective skin of a reverse-rolled edge or rim. In this technique, an edge form is attached to the master and provides a master extension, so the formation of the reflective skin results in a rim extending to the rear of the mirror. Preparation of the master for this edge-bond method is shown in Fig. 6. The configuration is particularly desirable since, because of the tooling required, a seal is formed at the edge of the reflective skin that helps to prevent entrance of plating solution during subsequent operations.

On all the techniques mentioned, plating was done using the inverse rotating fixture and anode arrangement shown in Figs. 7 and 8. After formation of the skin, the torus was positioned to the rear of the mirror and necessary filleting or auxiliary mandrels were prepared for the subsequent growth of the structural element that locked the torus to the reflective skin. Preparation of the small-scale sample demonstrating attachment of the torus is shown in Fig. 9. In the experimental studies the second technique, that of providing an edge band on the reflective face so that all attachments can be made on areas not affecting the figure or surface of the mirror, was most successful. Figure 10 shows an 18-inch-diameter mirror rigidized with rear-mounted torus in which the lack of edge roll is evident from the reflected images in the picture. The staining that was evident around the edge of the mirror was corrected, and a number of test skins have been produced in which no leakage occurred and a structurally sound edge band was achieved.

The values of the plating parameters of bath temperature, current density and agitation used on the representative small mirrors are presented in Table I.

2.3.4 Effects of Plating Stresses

The present knowledge of the electroforming processes and controls that are available make it possible to accurately control

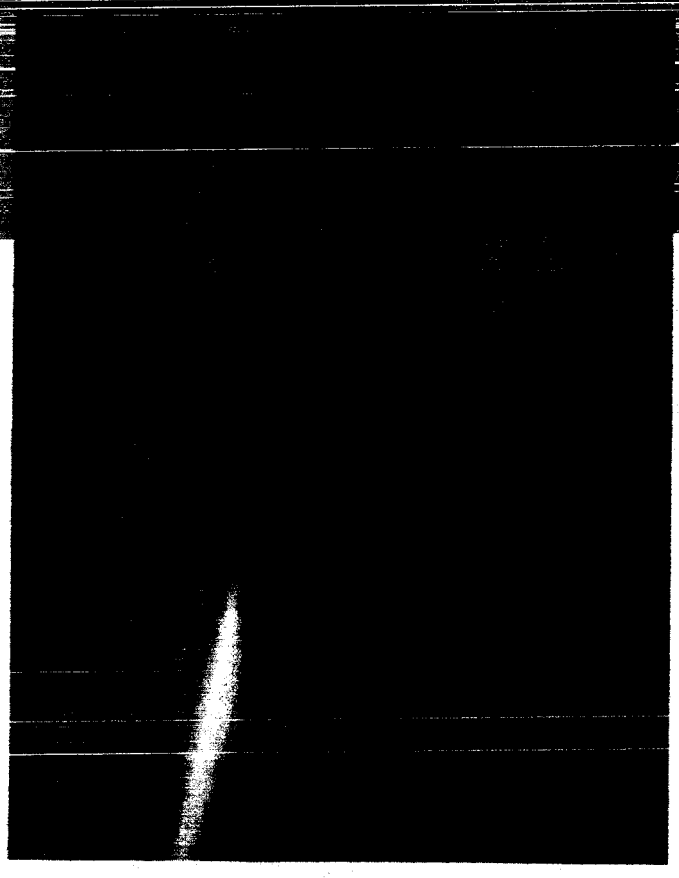


FIG. 5
CLOSE-UP OF TORUS ATTACHMENT

FIG. 6 PREPARATION OF MASTER FOR EDGE-BOND METHOD

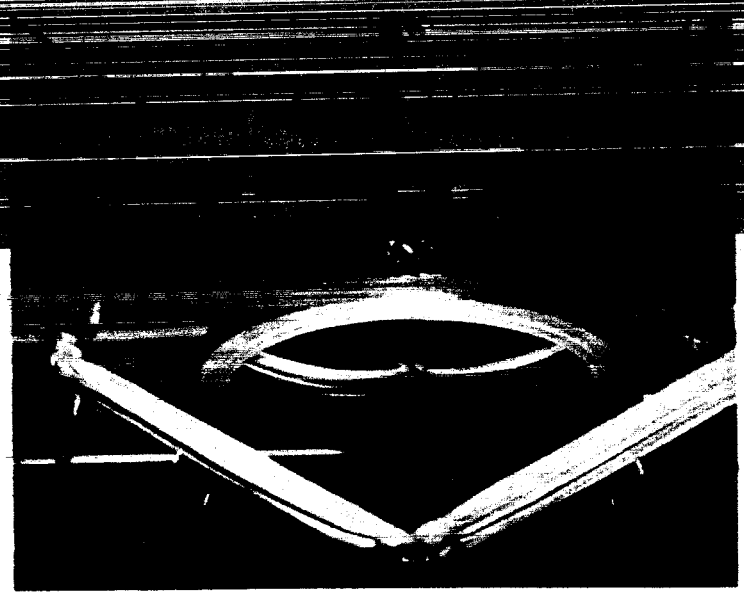


FIG. 7 INVERSE ROTATING ASSEMBLY AND ANODE ARRAY WITH 18-INCH-DIAMETER MIRROR MASTER IN PLACE

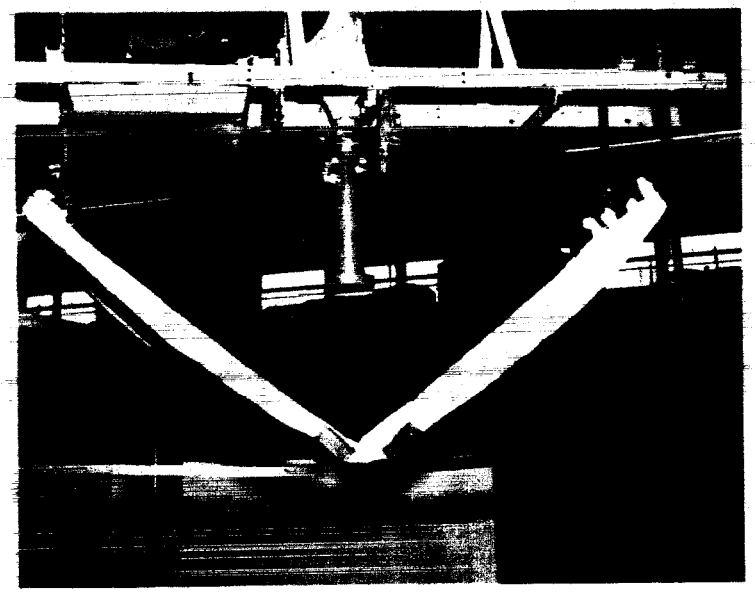


FIG. 8 INVERSE ROTATING ASSEMBLY AND ANODE ARRAY USED FOR SMALL-SCALE MIRROR PLATING

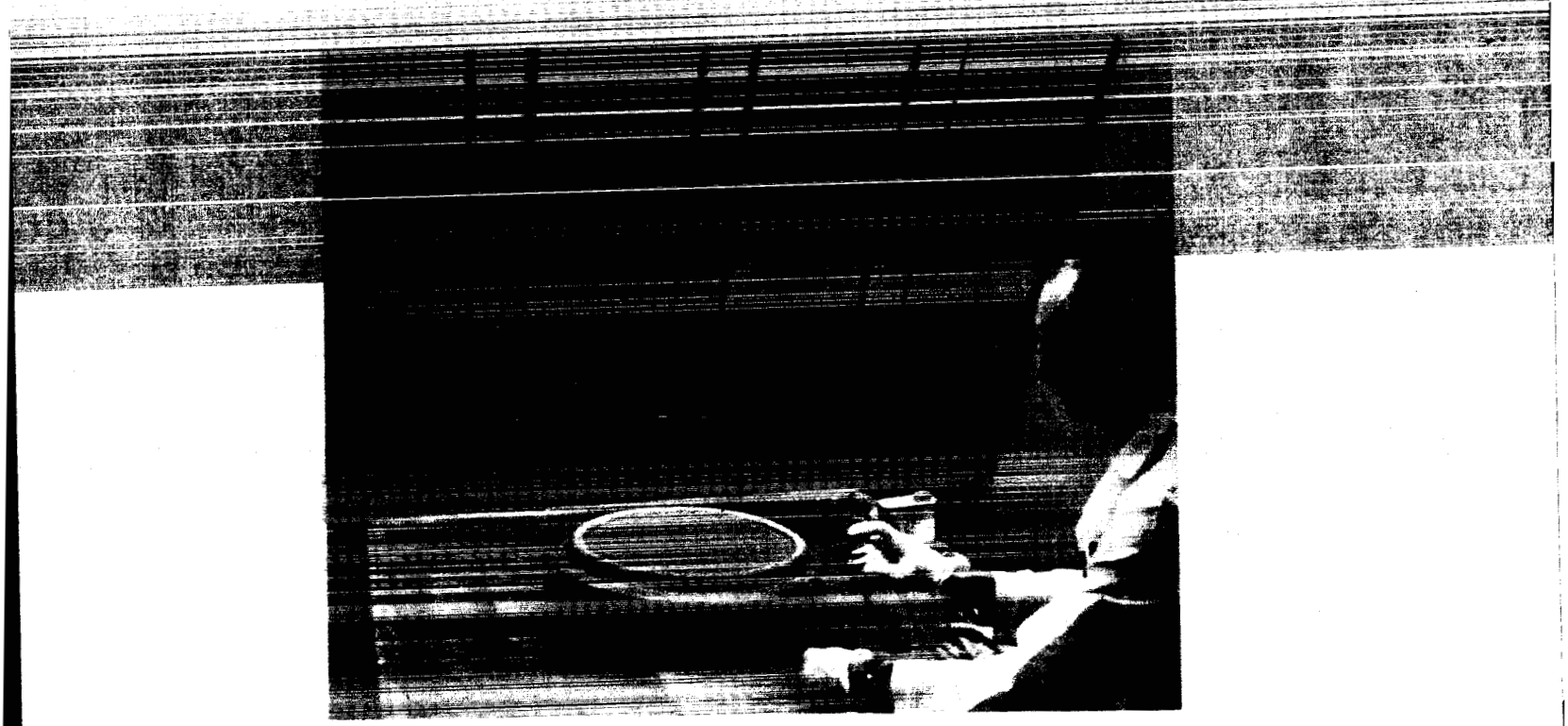


FIG. 9 PREPARATION FOR ATTACHMENT OF TORUS

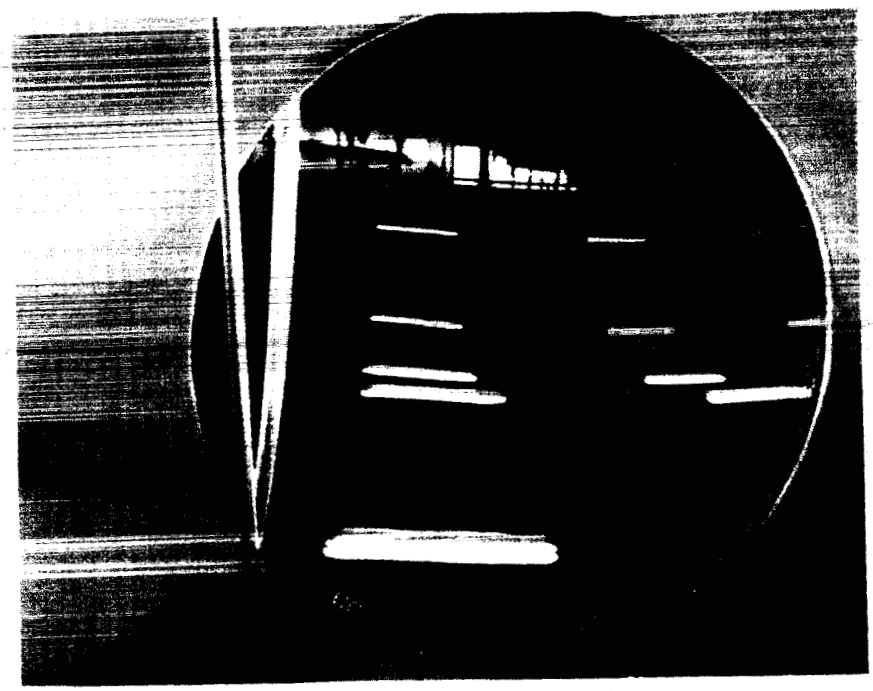


FIG. 10 18-INCH-DIAMETER MIRROR RIGIDIZED WITH REAR-MOUNTED TORUS SHOWING LACK OF EDGE ROLL

TABLE I PLATING PARAMETERS - SMALL-SCALE STUDIES

Replica No.	Type of Backing Structure	Bath * Temperature (°F)	Current Density (amp/ft^2)	Method of Agitation	Skin Thickne (inches
19-POM7: R3	No structure added because of flange thinness.	96	15	Rotation	0.009
19-POM7: R4	No structure added because of pitted mirror.	98	15	Rotation	0.009
19-POM7: R5	No structure added because of burns on edges.	100	12.5	Rotation and gusher	0.010
19-POM7: R6	Back mounted torus using chain.	100	11.1	Rotation	0.010
19-POM7: R7	Back mounted torus using chain.	100	8.7	Rotation	0.010
19-POM7: R8	No structure added because of burns on edges	100	15.0	Rotation	0.008
19-POM7: R9	Back mounted torus using chain.	100	10.0	Rotation	0.012
19-POM7: R10	Back mounted torus using secondary rivet plating.	100	10.0	Rotation and side gusher	0.010

* All were plated in a sulfamate nickel bath. (Typical analysis, Section 3.1.1.1, item 8.e.)

[illegible] during the formation of the required reflective face skins and additional structural elements. Plating stresses can be controlled to produce either tensile or compressive stress in the resultant electroforms and, in some instances, these effects can be used to advantage during the fabrication of the various components. It has been established experimentally that the highest accuracy of geometry of reflective-face skins is obtained when a near zero inherent stress condition is achieved during plating. This results in a part that has little or no tendency to deviate from the geometry of the master; a slightly tensile but near zero-stress condition prevents leakage of solution between master and reflective skin. Such leakage often results in staining, blushing, or other degradation of the reflective surface if stresses are not carefully controlled. Unfortunately, when low or zero stress is achieved during the formation of the reflective skin, parting from the master is more difficult since there is no tendency of the mirror skin to part itself due to internal stress conditions. For highly accurate concentrators, however, it appears imperative that near zero-stress conditions be achieved during the formation of the reflective face itself.

Tensile or compressive stresses are intentionally used in some instances where joining or attachment encapsulation can be improved by their use. When internal-electroformed rivets are formed, for instance, low-current-density conditions that exist within the hole in the mandrel, or part, produce a characteristic that expands the electroformed rivet material in the hole, tightening the lock to a greater degree than could be achieved by other conditions. When a torus or part is encapsulated from the outside, tensile stresses in the electroformed deposit can increase the encapsulation bond beyond the level that could be achieved through zero-stress plating.

If small heat-transfer or thermal-conductivity variations are expected in different portions of a structure, some compensation can be achieved during formation of the various parts by balancing the resultant thermal stresses against the inherent or plated-in stresses.

It is of utmost importance that new design concepts utilize the various conditions that can be achieved through the use of controlled electroforming techniques. Present knowledge of the controls possible has provided a basis for certain design concepts, and it is evident that as more knowledge is gained, maximum advantage can be taken to produce concentrators of the lowest possible specific weight consistent with design or environmental requirements.

Eight small-scale mirrors were fabricated. The back-mounted torus configuration with an essentially cylindrical flange joining the torus to the skin in a secondary plating appeared the most promising. The specific weight of the mirror was the lowest observed, edge roll distortion was confined to the extreme edge, which left almost the entire frontal area of the concentrator with an accurate reflective surface, and the techniques developed seemed feasible for direct application to the 5-foot-diameter experiments to follow.

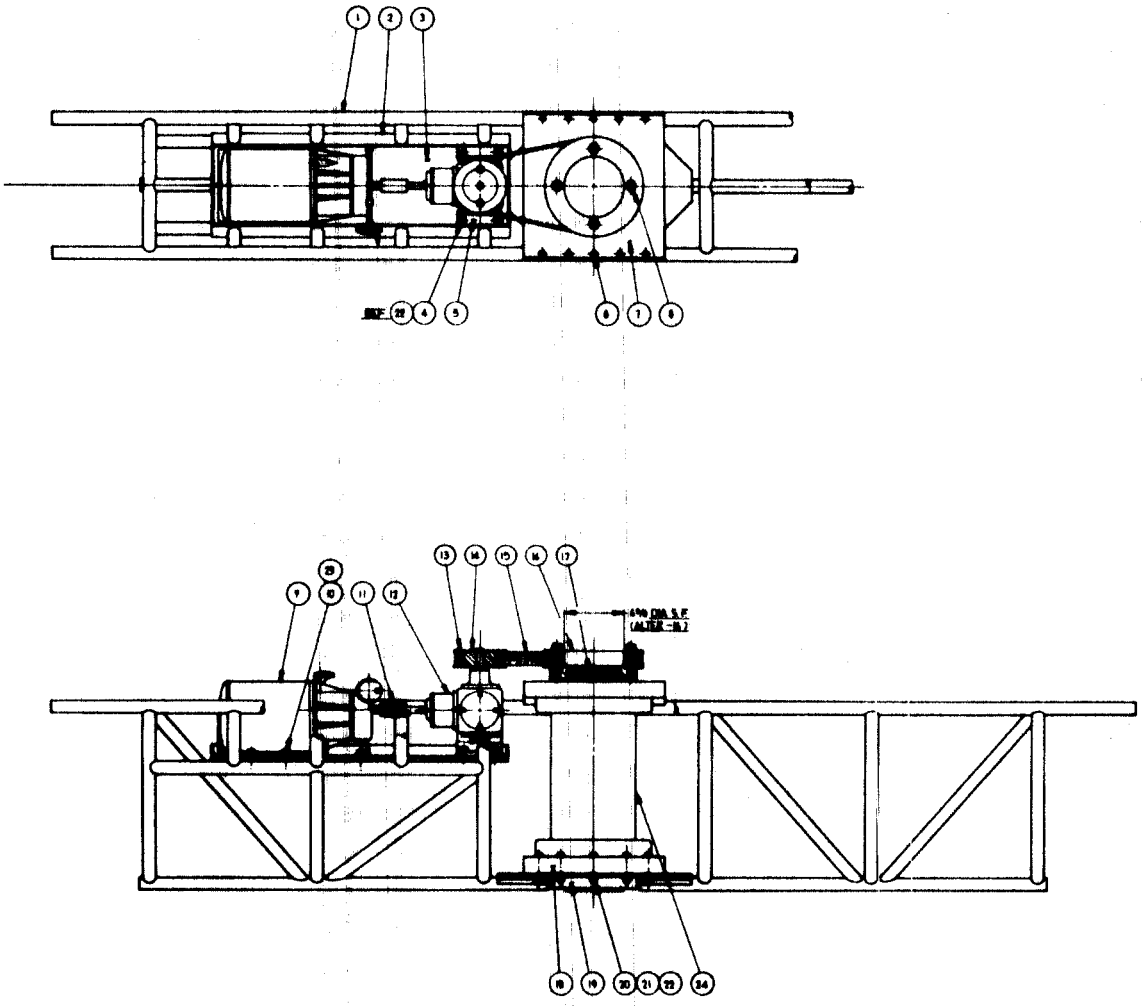
2.4 Development of Special Equipment

It was determined during prior programs that certain special tooling and fixtures were required to produce some of the components of the larger size concentrators in a practical and uniform manner. Earlier shake and vibration tests, accompanied by sectioning and measurement of the reflective concentrator face skins, showed that uniformity and control of face skin thickness were extremely important for structural stability. Small-scale studies showed that the required uniformity and control of thickness could be achieved by rotating the master in relation to the anodes during formation of the reflective skin. The process of rotation also provides other desirable effects. Agitation is improved uniformly over the skin surface. When the part is mounted horizontally, with the mirror surface of the master facing downward, the resultant part is entirely free from inclusions, which are present when the part is formed face up in a stationary position.

diameter master and related equipment, new rotational equipment had to be designed and fabricated. Basic designs for the rotating equipment are shown in Figs. 11 through 15. Figure 11 shows the main rotational assembly that includes the central spindle made in a tubular fashion so that, if necessary, plating solution can be pumped through the spindle during operation to provide additional agitation at points where required. The commutator assembly (including slip rings, brushes, etc.) is a separate unit underneath the spindle assembly. This unit provides two isolated circuits so that, in addition to supplying cathode power to the master, auxiliary anodes can be placed where required on the rotating assembly and powered by this contactor. For copper plating where high current is required the two slip rings and brush assemblies can be run in parallel, providing current-carrying capacities over 2000 amperes.

A master-holding fixture attaches directly to the lower flange of the commutator assembly. Figure 12 shows a detail of the rotator and spindle housing assembly. Figure 13 shows the support assembly for the rotating fixture, which is essentially a truss section on which is mounted a reversible motor and speed reduction unit. Figure 14 shows the support fixture extensions that are used to adapt the unit to the 12- by 12-foot plating tank, which would be used if masters larger than 5 feet in diameter were to be rotated. Figure 15 shows the completed rotating bridge. The entire assembly is shown in use in Fig. 16.

A swivel fixture was designed and fabricated to serve as a versatile mirror handling support. Problems have been experienced in the past relative to supporting or holding the finished concentrator in the various positions required for processing or fabrication in such a manner that possiblities of damage would be minimized. This fixture is capable of handling and holding the mirror in all positions from horizontal to vertical (or slightly past vertical, for cleaning operations). The center shaft is mounted in a bearing so the part can be rotated to, and locked in, any desired position. The design



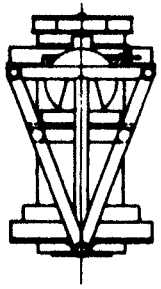


FIG. 11 ROTATING FIXTURE ASSEMBLY

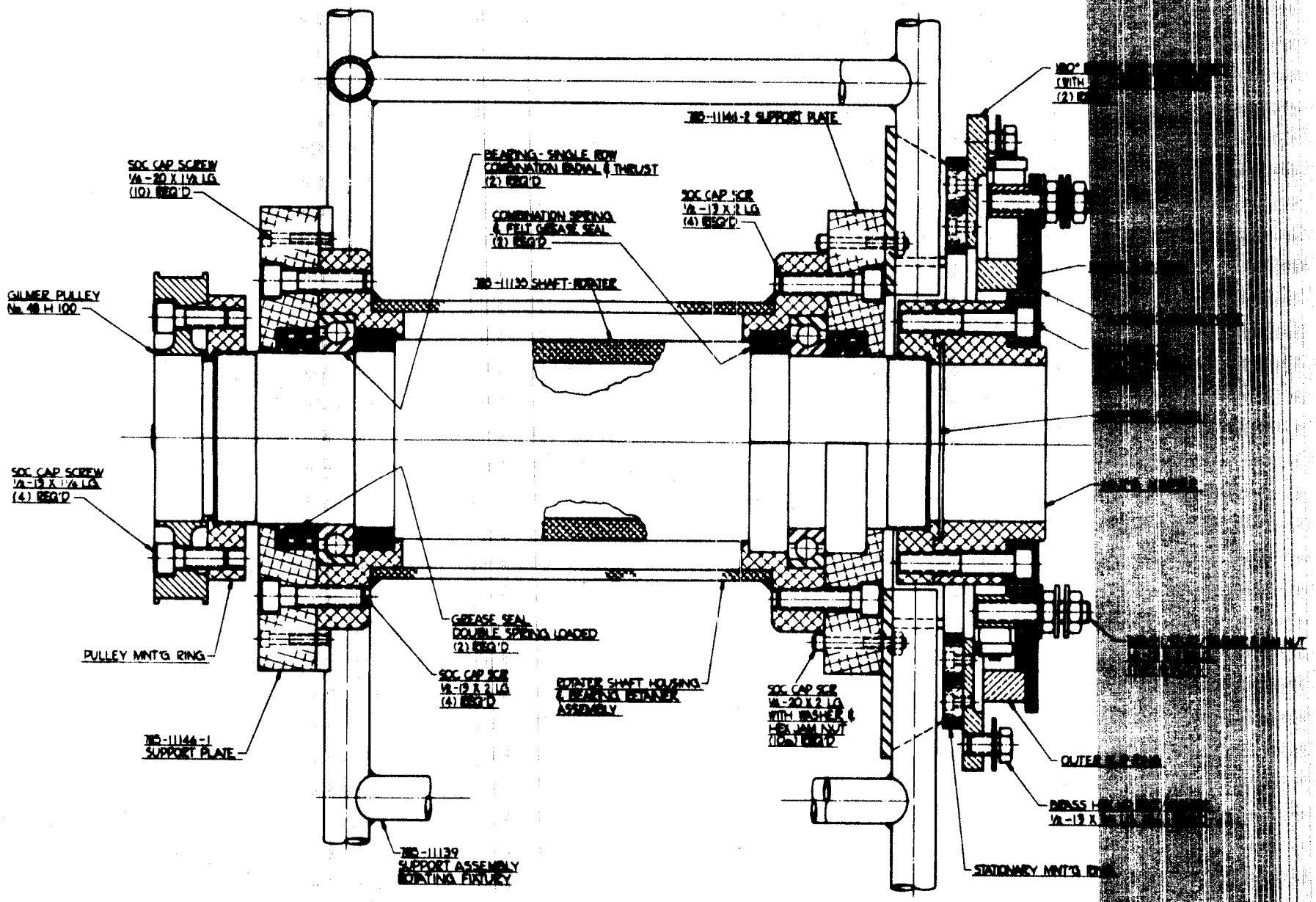


FIG. 12 ROTATOR HOUSING ASSEMBLY

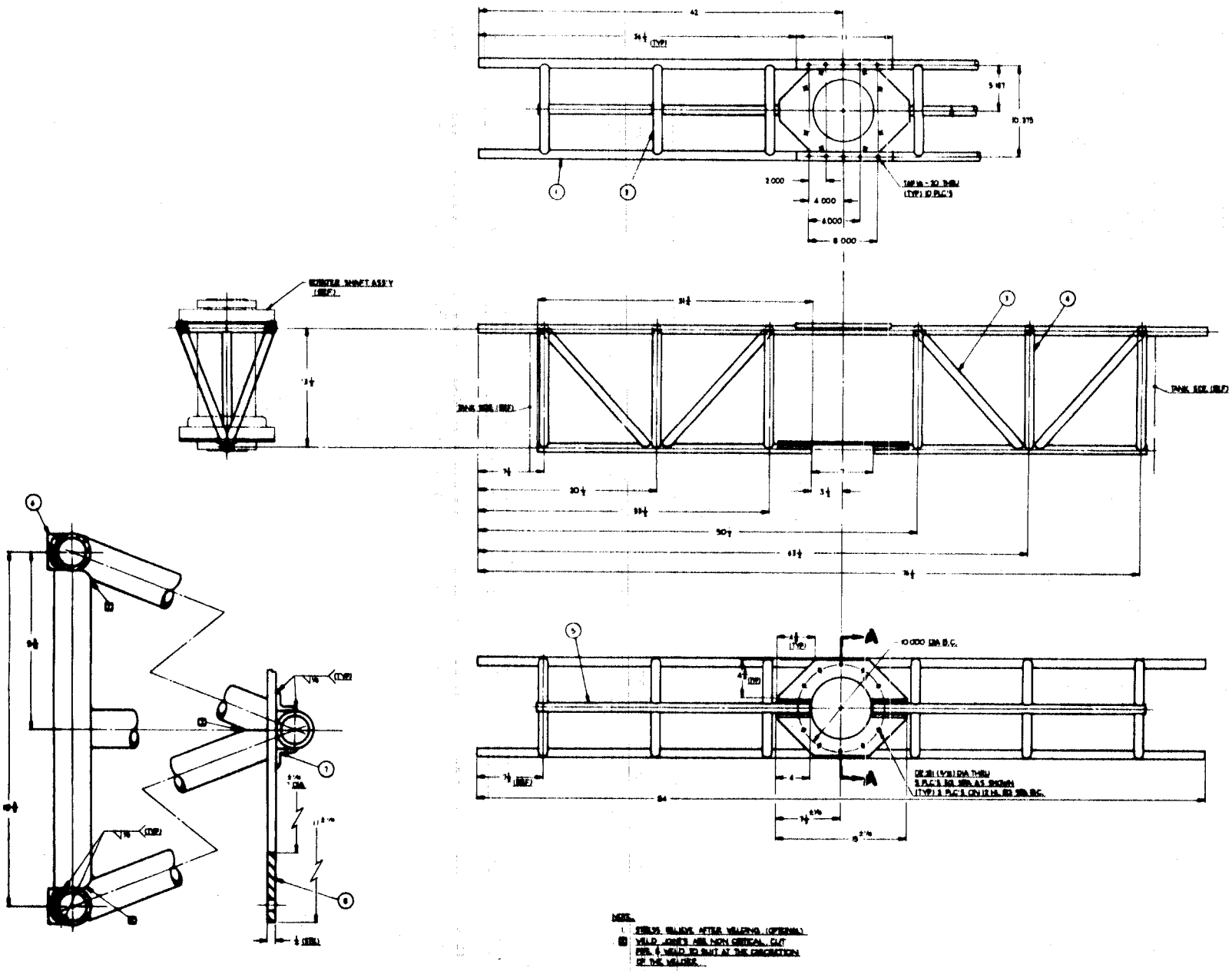
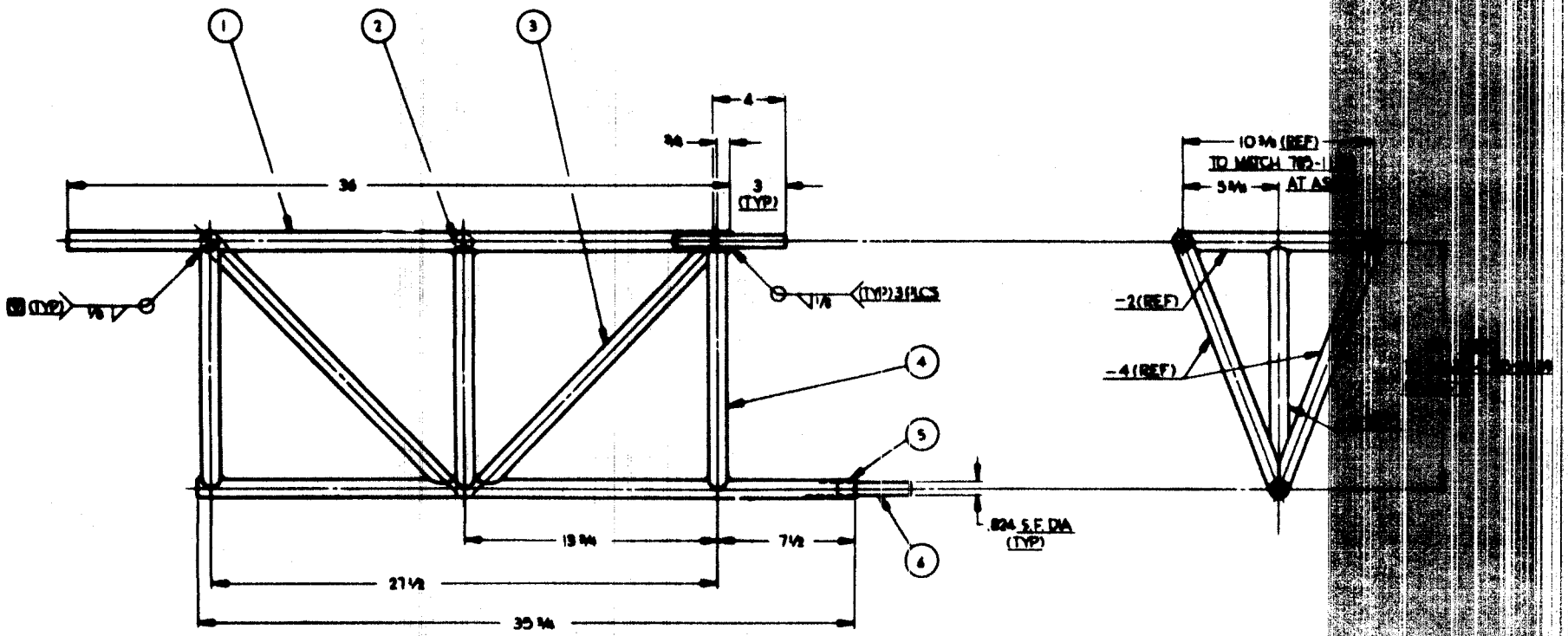


FIG. 13 SUPPORT ASSEMBLY - ROTATING FIXTURE



3	6		DOWEL	1/2 DIA X 4 LG	1/2 DIA STD ST'L
1	5		BRACE	3/4 DIA X 35 3/4	3/4 DIA STD ST'L
6	4		SUPPORT	3/4 DIA X 14 1/2	
2	3		GUSSET	3/4 DIA X 18 1/2	
3	2		CROSS ARM	3/4 DIA X 10 3/8	
2	1		BAR	3/4 DIA X 36.5	3/4 DIA STD ST'L

LIST OF MATERIALS

UNLESS OTHERWISE NOTED

ARNOLD

ELECTRO-OPTICAL SYSTEMS

Pasadena, California

SUPPORT FIXTURE EXTENSION

D 795

1/4

FIG. 14 SUPPORT FIXTURE ASSEMBLY

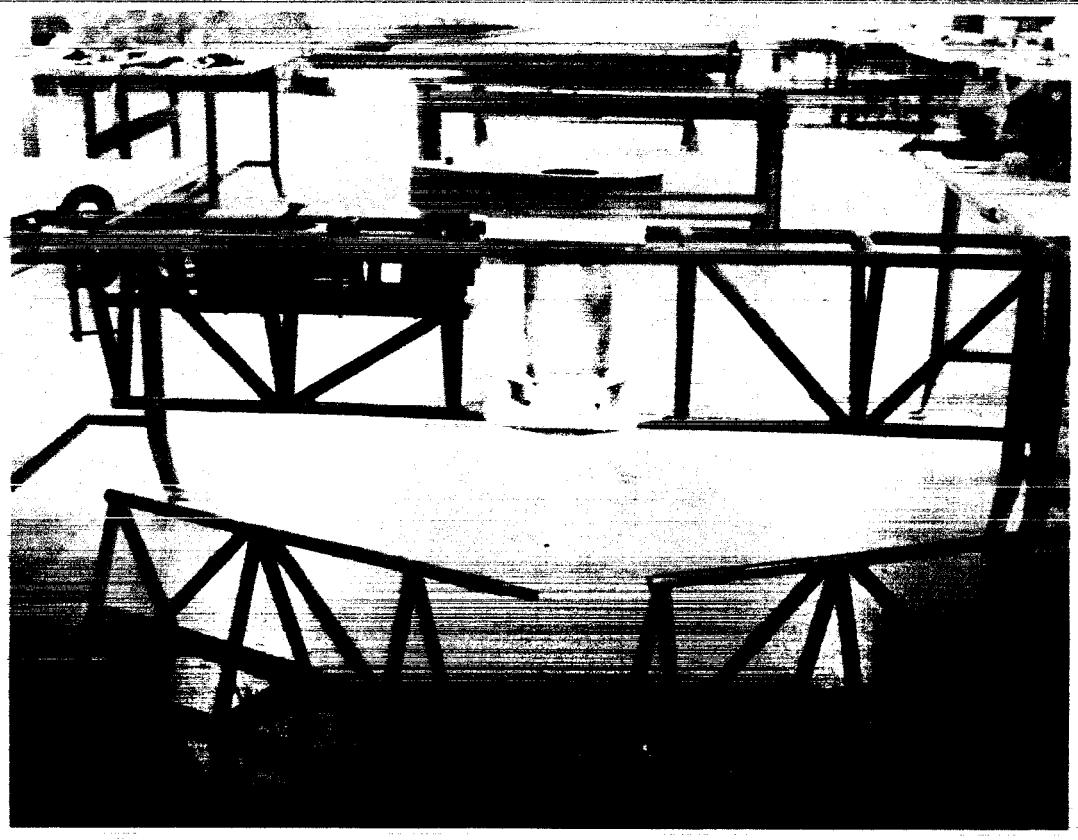


FIG. 15 ROTATOR ASSEMBLY AND EXTENSIONS

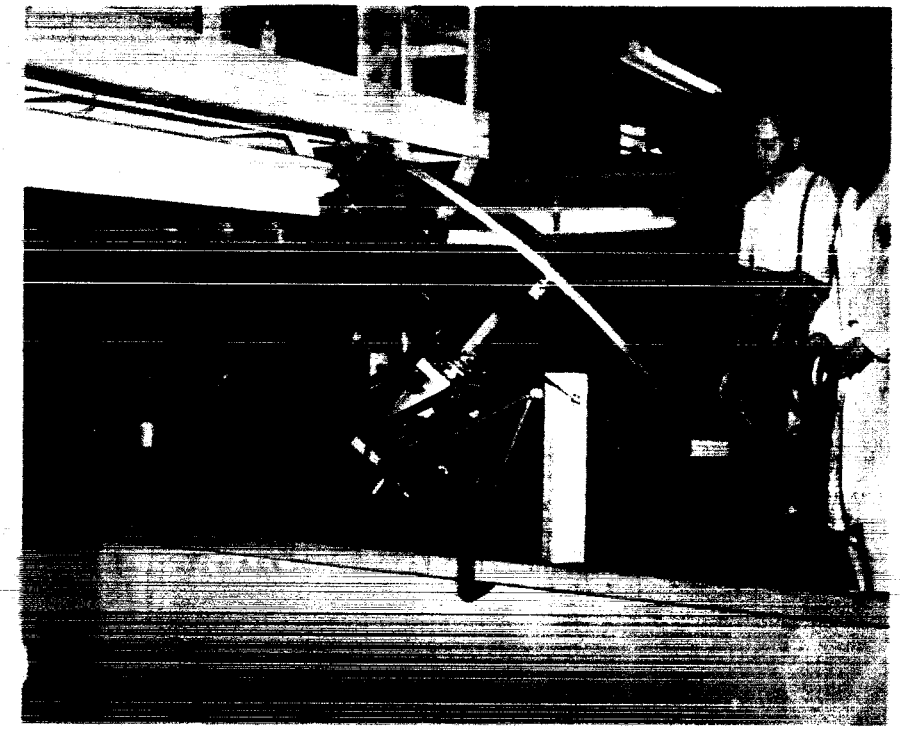


FIG. 16 ENTIRE ROTATING ASSEMBLY INCLUDING MOTORIZED ROTATING BRIDGE UNIT AND SPECIAL MASTER RIM RING SUPPORT MEMBERS

[illegible] a motor drive for subsequent cleaning operations where [illegible] rotation may be required. The prototype unit, however, has been fabricated without the motor drive. If rotation is required for wax removal or other cleaning processes, the power unit may be added at a later date. Figure 17 shows the basic swivel fixture and assembly. Figure 18 shows the completed handling fixture on the shaft of which is mounted a support assembly holding a 5-foot-diameter concentrator in a tilted position. This fixture is capable of holding and handling lightweight mirrors up to 10 feet in diameter.

A considerable number of additional fixtures and special devices were required during the various stages of preparation for electroforming the 5-foot-diameter concentrators, using rotational techniques. A master holding fixture was designed for the rotational equipment (Fig. 16). Of all-aluminum, welded construction, the main frame of this fixture was designed to absorb static loads imposed by the weight of the glass master in all attitudes and also the accelerations resulting from starting and stopping the motor drive on the rotation assembly. A special aluminum ring was developed for the rim of the master. The ring is potted onto the master with sealing compound, and its threaded studs afford adjustments between the two structures for alignment of the rim plane of the glass master prior to plating.

Plating and cleaning tanks in the laboratories were modified as required for the new equipment. Figure 16 shows a set of brackets prepared for holding the entire rotation assembly in various attitudes convenient for cleaning, applying sensitizing materials and parting the completed concentrators form the master. Various masking and damming devices were fabricated for use in the preparation stages of work.

Unique anode arrays were produced in successive stages during the experimental plating, both for the nickel and copper concentrators. One arrangement of anodes, the array used in the plating of 60-POM3: R12 (the skin of the second nickel concentrator), is shown in Fig. 19. An auxiliary anode attachment was developed as illustrated in Fig. 20. It incorporates a titanium strip closely contoured to the rim groove area of the mirror skin in which it operated for the purpose of augmenting the throwing power or the main anode array.

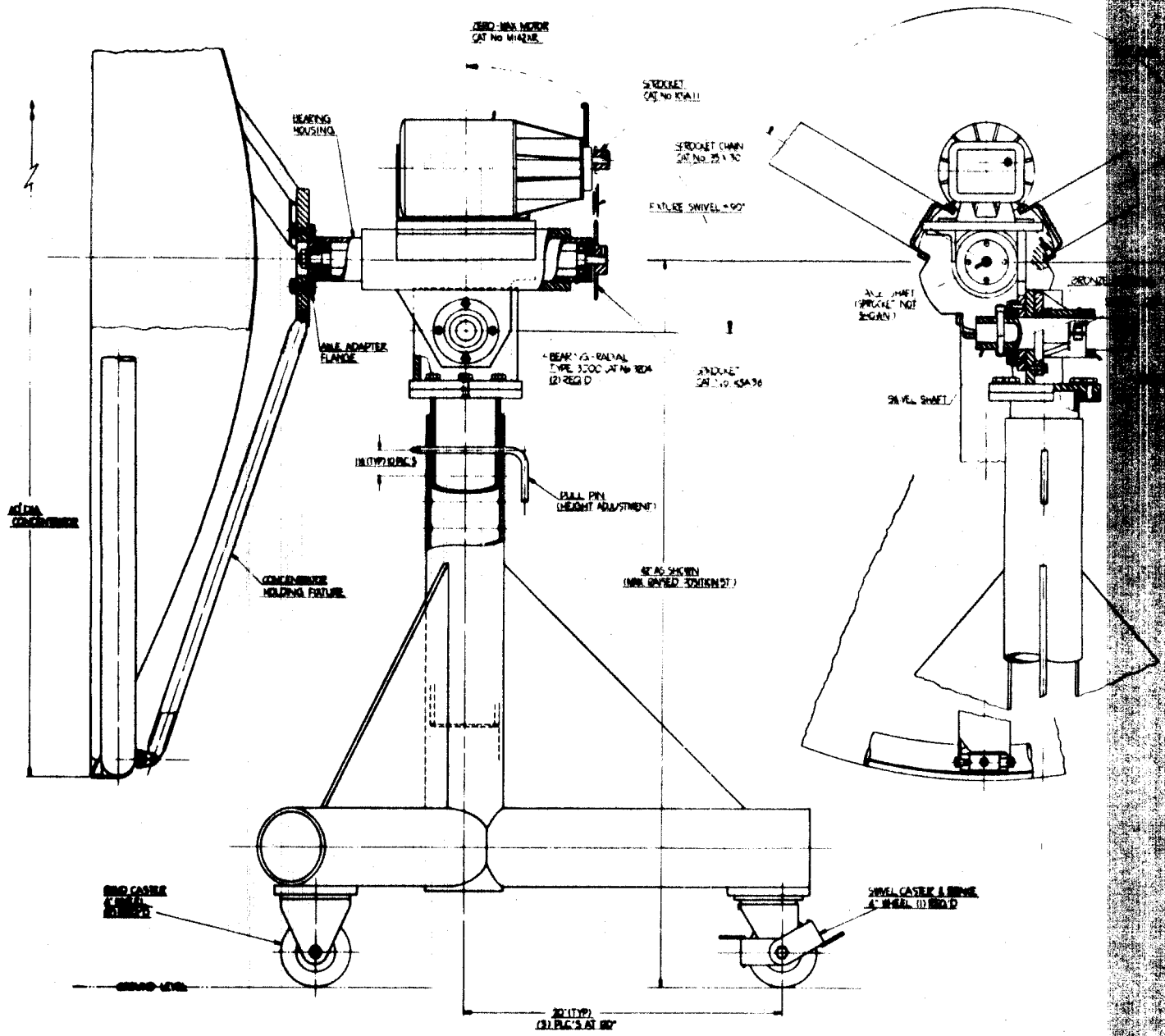


FIG. 17 SWIVEL FIXTURE - MIRROR HANDLING EQUIPMENT

FIG. 18 SWIVEL FIXTURE - MIRROR HANDLING EQUIPMENT

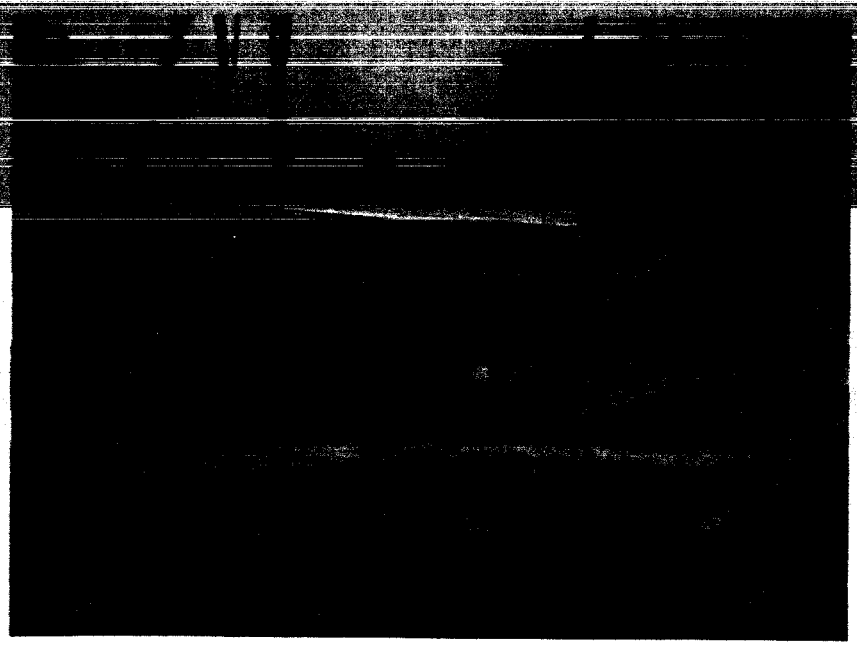


FIG. 19 MAIN ANODE ARRAY

FIG. 20 AUXILIARY TITANIUM ANODE AND ATTENDANT SOLUTION AGITATION PROVISION

3. DEVELOPMENT OF PLATING TECHNIQUES

A key factor in the successful fabrication of efficient concentrators by electroforming techniques is an understanding of, and the ability to control, the various parameters associated with the electroforming process.

3.1 Small-Scale Studies

Small-scale plating studies were initiated at the beginning of the program and continued throughout the first eight months of work to obtain as much information as possible about the various parameters affecting or controlling the electroforming processes. To isolate the more basic research from the applied plating techniques, a separate clean room and analytical laboratory were established adjacent to the production plating operation. Figure 21 shows a portion of this research plating and analysis laboratory.

3.1.1 Solution Analysis and Controls

In addition to the techniques previously reported, more detailed analytical procedures were established, and the plating solutions were constantly monitored to provide greater control over the resultant electroformed parts.

Nickel electroforming techniques and related parameters and bath requirements are now more firmly established. Procedures were definitized, and the experimental baths were analyzed on a regular basis. In addition to stress tests, which were made periodically at various bath temperatures, analyses were made for sulfate, boric acid, chloride, and total nickel content. Variations in the techniques produced changes in the method of analysis, which in turn resulted in a greater degree of accuracy and reduction in required analysis time. It is felt that this is an important factor, since prior to and during the

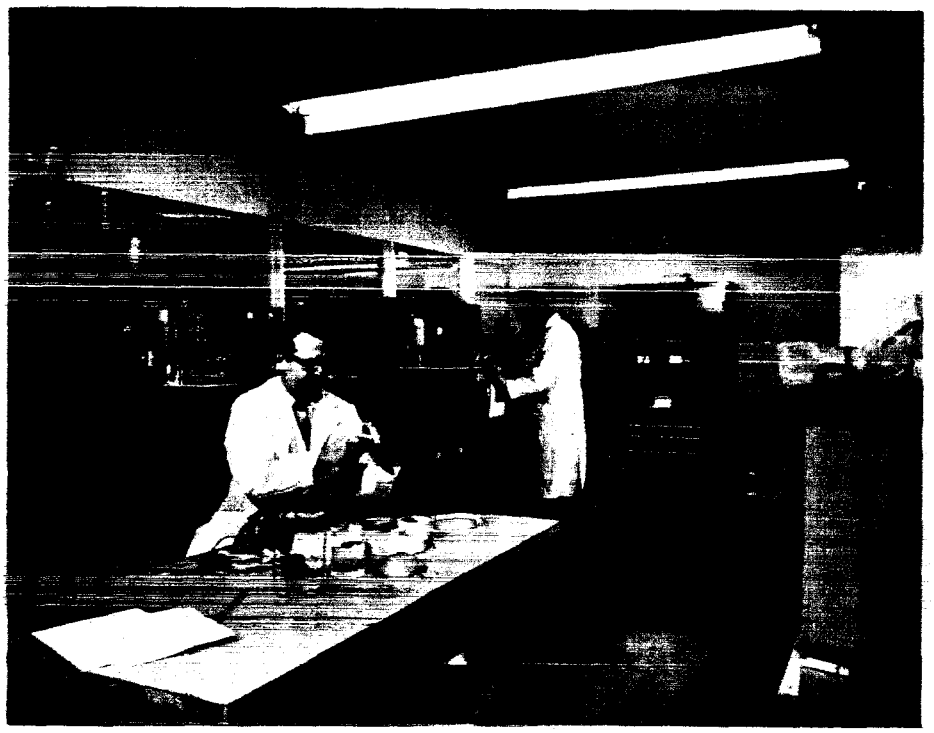


FIG. 21 PLATING RESEARCH AND ANALYSIS LABORATORY

[illegible] the electroforming process a high degree [illegible] is required if stress levels and [illegible] physical properties are to be closely controlled. Details of the current analytical processes for both nickel sulfamate and copper sulphate solutions for both the preparation of a new bath and for maintenance of an existing one are described below.

3.1.1.1 New Bath

Basically, the Barrett nickel sulfamate procedure is used. The double nickel concentrate (Barrett Co.), which has been buffered to an approximate pH of 4.0, is procured. The following procedure is followed in the makeup of the new bath. The solution is always made up in a transfer tank, so as not to subject the plating tank to the contaminants that usually exist in commercial grade chemicals.

1. Distilled water is placed in the tank in the amount of approximately one-third the calculated volume of the solution.
2. Double nickel concentrate is added to the distilled water, which brings the volume of the solution to approximately three-fourths of the desired solution level.
3. Heaters are installed and the temperature raised to approximately 140°F.
4. Boric acid content is adjusted within the range of 4.0 to 4.5 oz/gal.
5. The pH factor is adjusted upward with sulfamic acid.
6. The concentration of chloride ions, which are always present in the nickel concentrate, is checked. (Approximate content 0.6 oz/gal.)
7. The solution is brought to the desired level with the addition of more distilled water.
8. Purification of the bath proceeds as follows:
   a. Five pounds of carbon powder (Darco Co.) per 100 gallons of solution are added.
   b. Using at least 2 impellers that will give adequate circulation, thoroughly mix the carbon into the solution for 4 hours at 140°F.

flock is sifted atop the solution, and the flocculent material settles the carbon to the bottom of the tank.

d. The solution is allowed to stand for approximately two hours.

e. An analysis is completed and adjustments are made to bring the balance of the solution to the desired operating conditions, which are as follows:

(1) pH - 4.7 ±0.2

(2) Nickel (metal) - 12.5 -0 +0.5 oz/gal

(3) Chloride - 0.6 ±0.1 oz/gal

(4) Boric acid - 4.7 ±0.2 oz/gal @ 120°F

(5) Additives (after the solution has been purified):

Sulfamate nickel anti-pitter as required

Sulfamate stress reducer as required

f. The purified solution is filtered into the clean plating tank.

9. After transfer to the plating tank is completed, a 2½-gallon sample of the solution is taken and strip tested for inherent stress to determine the crossover point. The usual points included in the testing are 10, 15, 20, 25, 30, 40, 50, 60, and 70 amps/ft^2. The test results are plotted graphically as in Fig. 22.

If the crossover or zero-stress point at a certain value is too great, or if there is a relatively steep curve resulting from the strip-test data, stress reducer (S.N.S.R., Barrett Co.) is added to the 2½-gallon sample. Further strip tests are conducted to check the adjusting of the crossover point to the desired value. No additions are made to the main plating solution until the sample solution checks are completed, after which the larger tank is treated and then retested to determine the crossover point.

STRIP TEST - NICKEL

DATE 4/11/62 TANK NO. 6 TEMP. 100° 120° SOLUTION Normal + .005 oz/gal. SpGr 1.270 pH 4.6

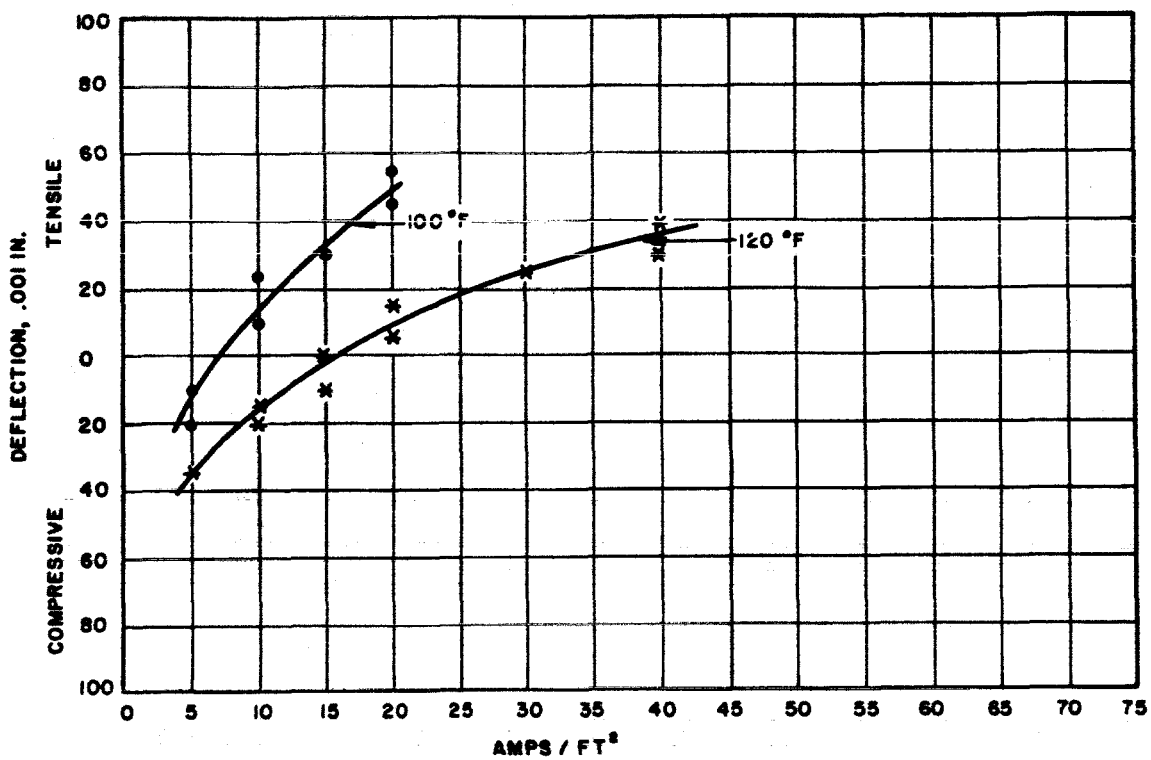


FIG. 22 STRESS VS CURRENT DENSITY FOR TYPICAL NICKEL SOLUTION

10. The surfamate antipitting agent (S.N.A.P., Barrett Co.) is added directly to the plating sample.

a. A stock solution is prepared as follows:

(1) S.N.A.P. - 100 grams

(2) H_2O (distilled) - 1 liter

b. The amount of antipitting agent to be added is determined as follows:

(1) A 3-inch metal hoop is placed into the sample and gently removed. It should remain wetted.

(2) A 5-inch metal hoop is immersed into the plating solution and removed gently. The 5-inch wetted hoop has to be enticed out of the solution and remain wetted for at least 2 to 3 seconds.

(3) The amount of S.N.A.P. added to the solution also depends upon the amount of agitation that is present in the plating, both from impeller turbulence and from exhaust through the manifold from the filter.

3.1.1.2 Existing Bath

The analysis of an existing plating bath is as follows:

1. Checks are made frequently during a period of active electroforming for:

a. Nickel metal - concentration

b. Chloride ion - concentration

c. Boric acid - concentration

d. pH value

e. Specific gravity

f. Surface tension

Adjustments are made, as required, following the chemical analysis.

2. Strip tests for determining levels of inherent stress are conducted before each plating.

plated at approximately 3 amp/ft^2 for the removal of metallic ions and other foreign contamination that the filter fails to pick up. Iron, zinc, copper, magnesium, zinc, etc., are plated out at the lower current density to give a greater purity to the deposited nickel.

3.1.1.3 Copper Solution

Copper solution analysis and controls have been established as follows:

1. Analysis and Parameters
   a. $CuSO_4$ - 33.5 ± 0.4 oz/gal
   b. H_2SO_4 - 11.5 ± 0.5 oz/gal
   c. Additives (products of Dayton-Bright Co., Dayton, Ohio)
      (1) DB-41 (the brightener) - 5 grams/gal
      (2) Dextum (the grain refiner) - 25 grams/gal
   d. Bath temperature - 96° ± 2°F
   e. Continuous filtration
   f. Current density - normally 60 to 75 amp/ft^2 (or depending on the crossover point that is established by strip-testing the desired inherent stress and/or the desired physical properties)
2. Strip Testing
   a. A 2½-gallon sample of the plating solution is placed in a beaker. Tests are conducted at 40, 50, 60, 70, and 80 amps/ft^2 to establish the crossover point.
   b. Adjustment of the solution is made by adding small increments of the additives, which are placed into the 2½-gallon sample solution.
   c. The main solution is then modified according to the results of the testing.

In addition to analyses for solution composition and stress determination, Hull cell testing has been employed to spot check the various solution compositions. With this device, cathode and anode are mounted at an angle to one another in a fixed volume of solution. During plating on the cathode, a complete range of current densities is produced as a result of the physical relationships of anode and cathode. Visual observations can be made of the surface condition and quality of plating that result from the variations from high to low current density. The quality of the resultant electroform, grain structure, appearance, etc., can be analyzed rapidly in this manner. Figure 23 shows the Hull cell test device.

Figure 24 shows some of the additional monitoring and control equipment that has been incorporated in the analytical lab. This equipment includes devices for periodic reversal of current during plating, and detailed recording of plating time in ampere hours or ampere minutes. Both current and voltage are recorded on strip-chart recorders to aid in the evaluation of certain effects, such as changes in additive agent caused by plating conditions and decay rate of additives.

3.1.2 Stress Determination and Control

Continued emphasis has been placed on determination and control of stress in the electroforming of solar concentrators. A number of devices have been employed for stress measurement, including the Spiral Contractometer, which was described in earlier reports, and various strip-testing methods.

The strip-testing technique continues to be the most versatile method for day-to-day evaluation of the various conditions. Modifications to this technique have involved the use of various masking methods in conjunction with the strip test in an effort to balance current density to produce more uniform test characteristics over the surface of the stress-test strip itself. A definite reduction in current density, and therefore stress level, has been

FIG. 23 HULL CELL TESTING

[illegible] and [illegible] by using this new method. Only slight differences were noticed in test-strip deflection when tests were made under identical conditions using the old and new configurations. Both methods appear to offer a reproducible means of making direct comparisons between various plating conditions. A modified strip-test fixture is shown in Fig. 25.

A more sophisticated device for the determination of stress has recently been devised, and Electro-Optical Systems has obtained one of these units for comparison to other stress measuring devices. This unit, known as a stressometer, is shown in Fig. 26. With this device a thin metal diaphragm is used as the end closure for a shallow plastic cylinder. The diaphragm becomes the cathode of the test circuit and a conforming anode is used and positioned directly above the cathode diaphragm. The cavity behind the diaphragm contains a fluid, and is connected to a small capillary tube. The unit must be carefully calibrated, and temperatures maintained very accurately. Because the unit is sensitive to both temperature and pressure fluctuations, as well as to stresses occurring on the test cathode, its use is rather involved. If the outside factors are carefully controlled, however, the instrument is capable of measuring a very small amount of stress occurring in the material that is being electrodeposited on the diaphragm (cathode). Since its calibration and use are so involved, it is not practical as a working tool, but is valuable for determination of near-zero stress conditions.

All the aforementioned stress-measuring devices are acceptable for use in the solutions with which this program is concerned, and a considerable amount of information is being obtained on the various plating baths being used on current developmental efforts.

A typical stress versus current density curve obtained with the strip-test technique at various temperatures is shown for a basic nickel solution in Fig. 22. Stress versus current density for

FIG. 24 MONITORING AND CONTROL EQUIPMENT

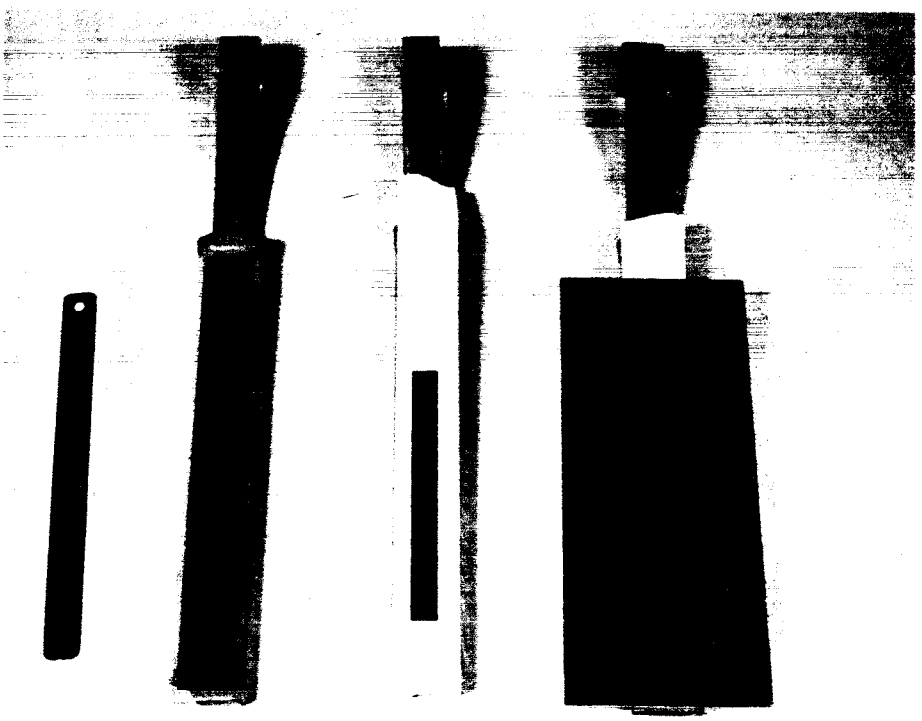


FIG. 25 MODIFIED STRIP-TEST FIXTURE

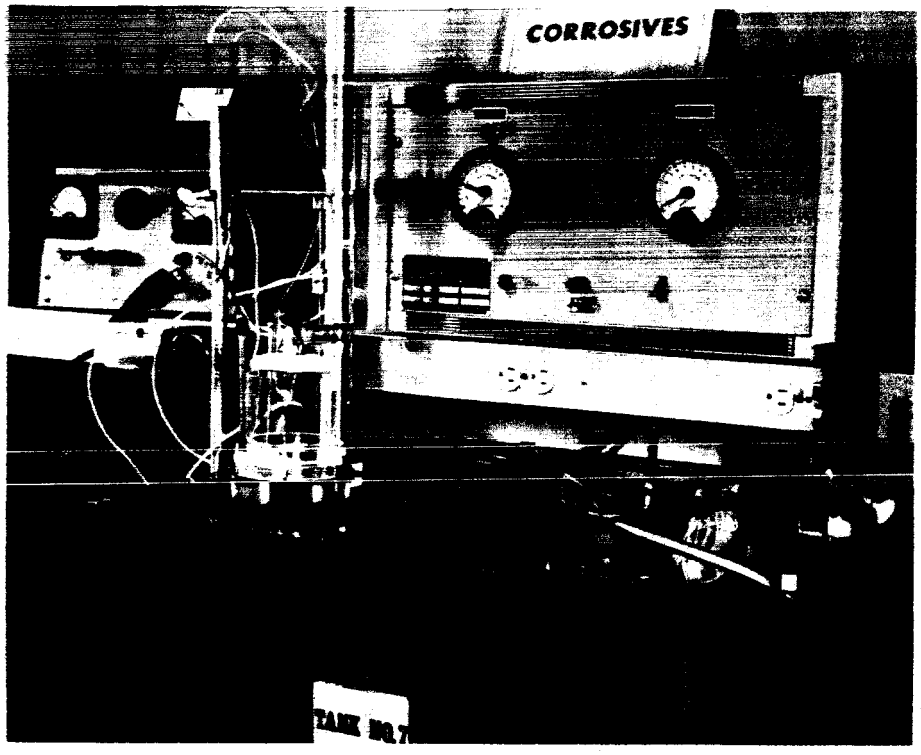


FIG. 26 STRESSOMETER

[illegible] modified copper solution is shown in Fig. 27.

Variation in current density is one of the key factors producing variations in stress in the resultant electroform. Additionally, current density or the distribution of current density over a typical part is one of the most difficult parameters to control.

Conditions where the stress versus current density curve is flat are highly desirable, inasmuch as wide fluctuations of current density over the various portions of the part will not result in appreciable variations in stress. This condition can be approached through the use of elevated bath temperatures. However, the use of elevated temperatures is often accompanied by other undesirable effects such as greater variations caused by nonuniform thermal expansion of various components and other related factors. It can be seen from the graphs in Figs. 22 and 27 that for any given configuration, if the current density at a point is known, the stress that will result in the electroform can be determined. It is possible to adjust conditions to produce either compressive or tensile stress or, as is quite often more desirable, near-zero stress conditions. The copper electroforming solution that yielded the graph shown in Fig. 27 appears to hold promise of maintaining low or near-zero stress conditions over a wide range of current densities under certain temperature and agitation conditions.

It was found during the experimental plating of 5-foot-diameter mirror skins that bath analyses can change sufficiently from day to day to require that strip tests be run immediately before every plating, and the test results taken into account in the selection of current density for the plating. This is now considered standard practice in the laboratories. Figure 28 illustrates the strip test conducted the morning of the day on which the second nickel concentrator skin 60-POM3: R12 was plated. The crossover point (zero inherent stress) was at a current density of 13 amps/ft^2. With this information the decision was made to plate at an average current density of 15 amp/ft^2 to ensure a condition of zero or slight tensile stress.

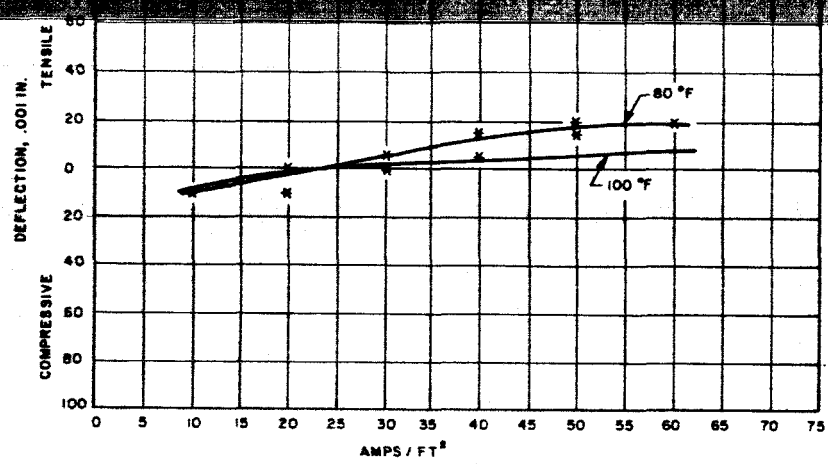


FIG. 27 STRESS VS CURRENT DENSITY FOR MODIFIED COPPER SOLUTION

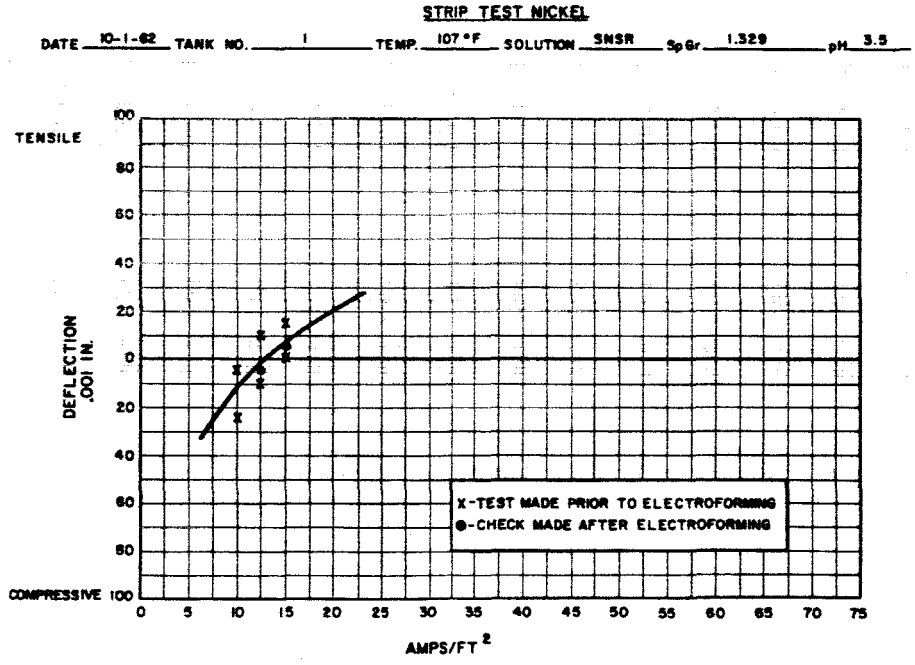


FIG. 28 STRIP TEST TAKEN PRIOR TO THE PLATING OF 60-POM 3: R12

3.1.3.1 Chromium as a Surfacing Material

Chromium and other bright, hard deposits have been considered desirable as surfacing materials for providing protection to the reflective-face skin. A number of studies have been undertaken employing various bath compositions and plating techniques in an effort to produce a highly reflective, hard, durable surface condition. An effective chromium plating solution has been achieved that provides a highly reflective chromium overcoat. The following two methods were considered for the application of chromium:

1. Direct deposition of the chromium on the mirror master with subsequent electrodeposition of the structural material.
2. Electroforming of the reflective face in the usual manner with a secondary flash protective overcoating of chromium.

Little success has been achieved with the first method, since subsequent adhesion of the structural units is difficult. A number of electroformed nickel samples have been overcoated successfully with chromium, however. These samples have been tested together with electroformed nickel reflective surfaces that were overcoated with a flash of rhodium metal. The samples have been included with other reflectivity samples for testing, and the results are reported in a later section of this report. The appearance of the chromium and rhodium-plated parts is quite good visually, and the abrasive resistance as observed in simple comparative tests appears to be excellent.

At first, considerable difficulty was experienced in determining the best range of current densities and general configurations to provide maximum brightness of the chromium or rhodium flash without the need for any subsequent polishing. It appears, however, that a reasonably broad range of conditions can be achieved that will permit plating to the necessary degree of brightness.

The most promising bath analyses and parameters were as follows:

[illegible] chromic acid, and

0.55 oz/gal sulphuric acid at 112°F with no agitation, with 0.02 oz/gal zero-mist (Udylite Corp.)

3.1.3.2 Experimental Plating of Brass

Midway in the program a small amount of work was done on electroforming another nonmagnetic material--brass. A small 6-inch-diameter mirror was produced by the electrodeposition of brass. No physical properties tests of the material were conducted; however, upon visual inspection the mirror appears to confirm the feasibility of electroforming in a two-element bath.

The bath analysis was as follows:

Cuprous cyanide	3.75 oz/gal
Sodium cyanide	7.5 oz/gal
Zinc cyanide	1.2 oz/gal
Sodium carbonate	4.0 oz/gal

Plating parameters were the following:

Temperature	95°F
Anodes	Lead-free brass
Agitation	Stirrer only
Current density	20 amp/ft^2

3.2 Determination of Physical Properties of Electroformed Material

A wide variation in the appearance of grain structure, stiffness, brittleness, and other characteristics in the electroformed samples of various materials has been observed. To determine the variations in physical properties that exist for different electroformed materials, a series of tests was outlined in which all the possible parameters were varied to make test specimens that were subjected to the usual tests for ultimate tensile strength, yield strength, elongation, and modulus of elasticity. Hardness was also evaluated.

3.2.1 Testing of Variations in Physical Properties

A large number of test specimens were produced for physical property measurements. In nickel, the first group of specimens

gested certain trends that additional tests might confirm. Therefore, a second lot of nickel specimens was produced during the eighth month. The various parameters affecting or influencing the resultant electroforms have been varied independently, where possible, to determine their influence on the resultant structure. Test coupons were prepared by electroforming to approximately 0.010 inches or less in thickness, on a flat rectangular mandrel. In most instances a glass plate has been used for the mandrel, but, to determine the effects (if any) of the substrate, other materials have also been used. The same technique has been used to produce electroformed samples for the reflectivity tests. The geometry and relationship of anodes to cathode were balanced in such a way that the center of the test plate was uniform in thickness. The test coupons were then cut from the center of the test sheet in such a manner that three coupons were obtained from each panel. These were then machined to the dimensions required for testing, and supplied to the testing laboratory. Test coupons and reflectivity samples obtained from these electroformed test panels are shown in Fig. 29.

As previously stated, some parameters can be varied independently while others produce interrelated effects, or can be varied only in conjunction with other parameters. Initial tests involved a standard solution and controlled conditions of agitation, current density and geometry while bath temperature was varied. In other instances, agitation, current density, and other factors were independently varied while the remaining parameters were maintained in a constant condition. Conditions that have been evaluated are as follows:

3.2.1.1 Nickel Tests

Tensile tests were performed on samples plated in the Barrett sulfamate nickel solution. The pH, specific gravity, nickel content, boric acid, and anti-pit agent were kept to the manufacturer's specifications. Specimens 11 by 16 inches were plated on plate glass sensitized with chemical silver or on nickel sheet stock. From

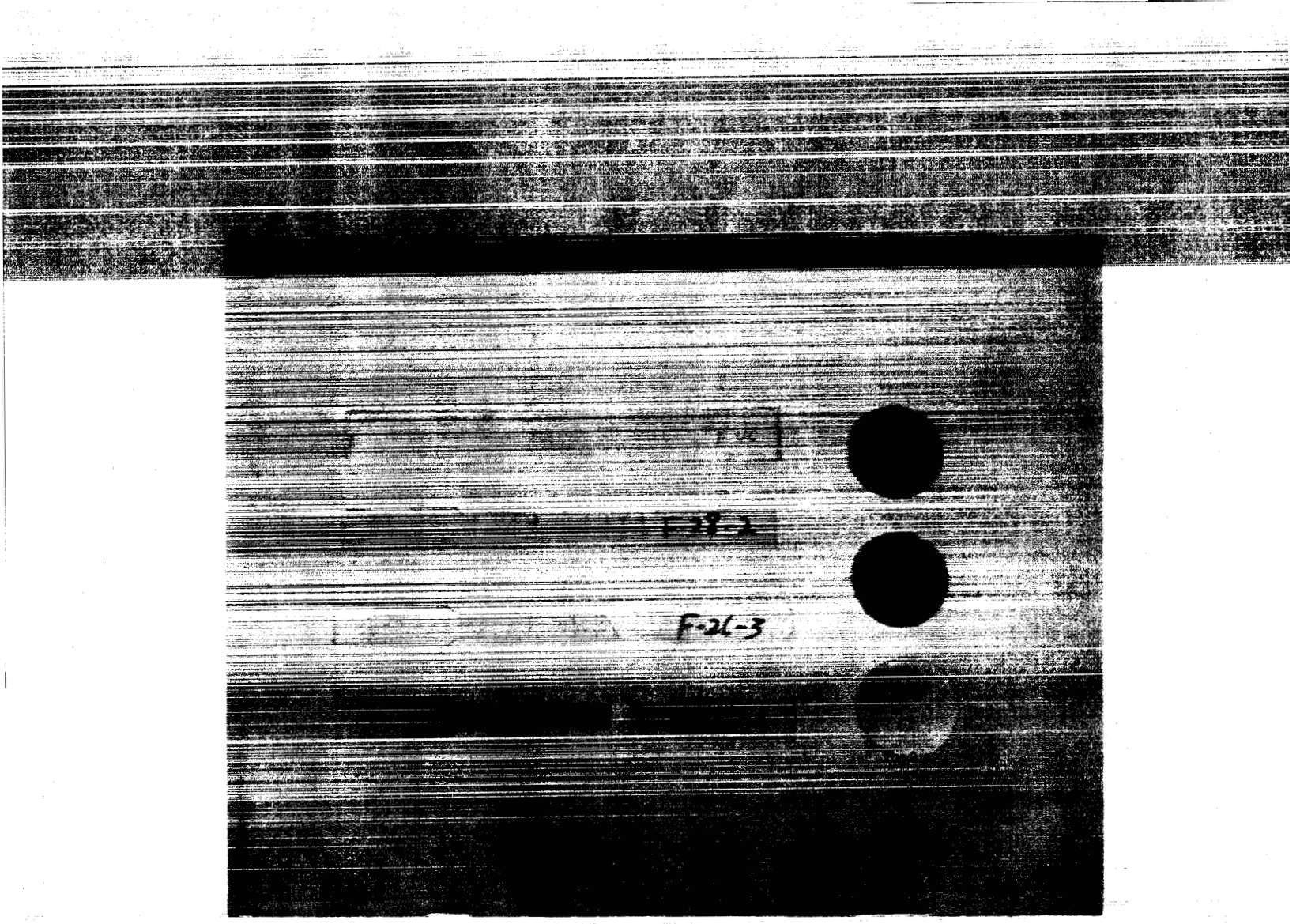


FIG. 29 ELECTROFORMED TEST COUPONS AND REFLECTIVITY SAMPLES

[illegible] due to ASTM physical test coupon size with a 2-inch gauge length. The parameters varied were temperature, current density, agitation, and substrate. Also, different solutions were compared.

The following chart will serve as a reference to the test data. Asterisks indicate that the specimen was produced in a second lot, approximately 6 weeks after the others.

PHYSICAL TEST REFERENCE CHART - NICKEL

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	Substrate Material	Thickness (mils)	Tank No.
1.			Temperature Change Without Agitation			
F-18	85	15	No	Glass	10	5
F-17	100	15	No	Glass	10	5
*F-62	110	15	No	Glass	10	5
F-15	120	15	No	Glass	10	5
F-26	140	15	No	Glass	10	5
*F-64	160	15	No	Glass	10	5
2.			Temperature Change With Agitation			
F-23	85	15	Yes	Glass	10	5
F-22	100	15	Yes	Glass	10	5
*F-68	110	15	Yes	Glass	10	5
*F-60	120	15	Yes	Glass	10	5
F-25	140	15	Yes	Glass	10	5
*F-65	160	15	Yes	Glass	10	5
3.			Current Density Change at 100°F			
F-37	100	5	No	Glass	10	5
F-3	100	10	No	Glass	10	5
F-17	100	15	No	Glass	10	5
F-39	100	40	No	Glass	10	5

No.	T	Amps/ft²	Yes - No	Material	(mils)	No.
4.		Current Density Change at 110° F				
*F-68	110	15	Yes	Glass	10	5
*F-66	110	22	Yes	Glass	10	5
*F-59	110	60	Yes	Glass	10	5
5.		Current Density Change at 140° F				
F-32	140	5	No	Glass	10	5
F-26	140	15	No	Glass	10	5
F-29	140	22	No	Glass	10	5
F-33	140	40	No	Glass	10	5
*F-63	140	60	No	Glass	10	5
6.		Agitation Added at 85° F				
F-18	85	15	No	Glass	10	5
F-23	85	15	Yes	Glass	10	5
7.		Agitation Added at 100° F				
F-17	100	15	No	Glass	10	5
F-22	100	15	Yes	Glass	10	5
8.		Agitation Added at 110° F 15 amp/ft²				
*F-62	110	15	No	Glass	10	5
*F-68	110	15	Yes	Glass	10	5
9.		Agitation Added at 110° F 22 amp/ft²				
*F-67	110	22	No	Glass	10	5
*F-66	110	22	Yes	Glass	10	5
10.		Agitation Added at 140° F				
F-26	140	15	No	Glass	10	5
F-25	140	15	Yes	Glass	10	5

		Amps/ft²	Yes - No	Material	(mils)	No.
11.			Agitation Added at 160° F			
*F-64	160	15	No	Glass	10	5
*F-65	160	15	Yes	Glass	10	5
12.			Substrate Change			
F-21	100	15	No	Nickel	10	5
F-17	100	15	No	Glass	10	5
13.			Substrate Change			
F-46	80	5	No	Nickel	10	5
F-27	80	5	No	Glass	10	5
14.			Solution Change (both Norm Sn Sol.)			
F-36	100	5	No	Glass	10	5
F-37	100	5	No	Glass	10	5
			Other Specimens Not Grouped Above			
F-43	80	40	No	Glass	10	5
*F-61	110	60	No	Glass	10	5

3.2.1.2 Copper Tests

Tensile tests were performed on samples plated in a copper sulphate solution with varied amounts of hardening additives as indicated in some of the groups below. As in the case of nickel, the specimens were plated in a panel size of 11 by 16 inches on plate glass sensitized with chemical silver. From each panel three samples were cut to ASTM coupon size.

The following chart groups the tested specimens:

PHYSICAL TEST REFERENCE CHART - COPPER

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	Hardening Agent	Tank No.
15.			Temperature Change		
F-48	90	40	No	1.2 oz/gal molasses	7
F-45	120	45	No	1.2 oz/gal molasses	7
16.			Current Density Change		
F-55	90	50	Yes	0.3 oz/gal triisopropanolamine	3
F-56	90	75	Yes	0.3 oz/gal triisopropanolamine	3
17.			Hardening Agent Concentration Change		
F-52	90	15	Yes	0.1 oz/gal triisopropanolamine	3
F-53	90	15	Yes	0.2 oz/gal triisopropanolamine	3
F-55	90	15	Yes	0.3 oz/gal triisopropanolamine	3
F-57	90	15	Yes	0.4 oz/gal triisopropanolamine	3
18.			Hardening Agent Change		
F-44	90	45	No	1.2 oz/gal molasses	7
F-49	98	33-1/2	No	1 oz/gal triethanoline	3
F-56	90	75	Yes	0.3 oz/gal triisopropanolamine	3
*F-71	90	75	No	Dayton-Bright System	3
			Other Specimens Not Grouped Above		
F-50	90	50	No	1 oz/gal triethanoline	7
F-51	90	20	No	1 oz/gal triethanoline	3

The last two exhibited very inferior grain structure with extreme brittleness.

3.2.2 Results of Tests and Interpretation

Discussion of the test results is separated into the groups defined in the previous tables. For each group results in terms of tensile yield strength and modulus of elasticity are given in tabular form. The figures are derived from the testing laboratory report and the modulus values are reduced on EOS data sheets. One representative sample of each is included in this section (pages 72 through 74). In the Appendix* are resultant curves representing data of individual samples indicating the characteristics of modulus versus stress, giving a definition of the approximate proportional limit of the samples. The more important trends that have been established with this data are discussed with their respective groups and are graphically portrayed in this section.

3.2.2.1 Nickel

The most thorough testing was done on nickel specimens. One undesirable variable apparently influenced some of the results. The variable is a bath change (same sulfamate nickel formula) that took place just prior to the plating of specimen F-37 near the end of the first series of samples. F-39, F-43, F-46, and all specimens in the second series (marked *) were electroformed in the newer solution, as noted below the control tests. A comparison of F-36 and F-37 indicates some drop in strength values. This also seemed apparent in other specimens in the second series. The more pronounced trends were only somewhat clouded by this change; however, for a close examination of the effect of parameter changes on physical property values, a detailed study within the narrower ranges established by the present work may be indicated for clearer definition of the results.

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*Appendix data issued to contract distribution list; additional copies on request.

[illegible] Temperature Change Without Agitation

It is readily apparent that the tested physical [illegible] improved with the elevation of temperature up to about 140°F, with moderate improvement above that point. The tests were conducted at a current density of 15 amps/ft^2. The results appear graphically in Fig. 30 for ultimate strength (F_{tu}), in Fig. 31 for yield point (F_{ty}), and in Fig. 32 for modulus of elasticity (E). The steep slope of improvement in the range from 100°F to 120°F suggests that in a solution with little or no agitation, emphasis in that range should be placed on increasing the temperature.

TEST RESULTS - AVERAGE OF 3 SPECIMENS OF EACH NUMBER

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-18	85	15	No	75.5	50.5	20.2
F-17	100	15	No	75.0	49.5	20.8
F-62	110	15	No	108.0	74.0	15.5
F-26	140	15	No	132.6	87.8	26.5
F-64	160	15	No	113.0	77.5	19.5

Group 2: Temperature Change with Agitation

The data indicate that the strength of the deposited material is improved considerably by agitation at lower temperatures. Starting at the relatively high base, the values go up slowly with bath temperature to near 140°F, and then fall off sharply by 160°F. The modulus remains quite even within a range of 20 to 26 million.

TEST RESULTS - AVERAGE OF 3 SPECIMENS OF EACH NUMBER

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-23	85	15	Yes	117.5	82.3	26.0
F-22	100	15	Yes	126.0	92.0	23.0
F-68	110	15	Yes	109.0	75.8	23.0
F-60	120	15	Yes	194.0	97.0	21.0
F-75	140	15	Yes	145.0	101.0	23.8
F-65	160	15	Yes	98.0	68.8	20.5

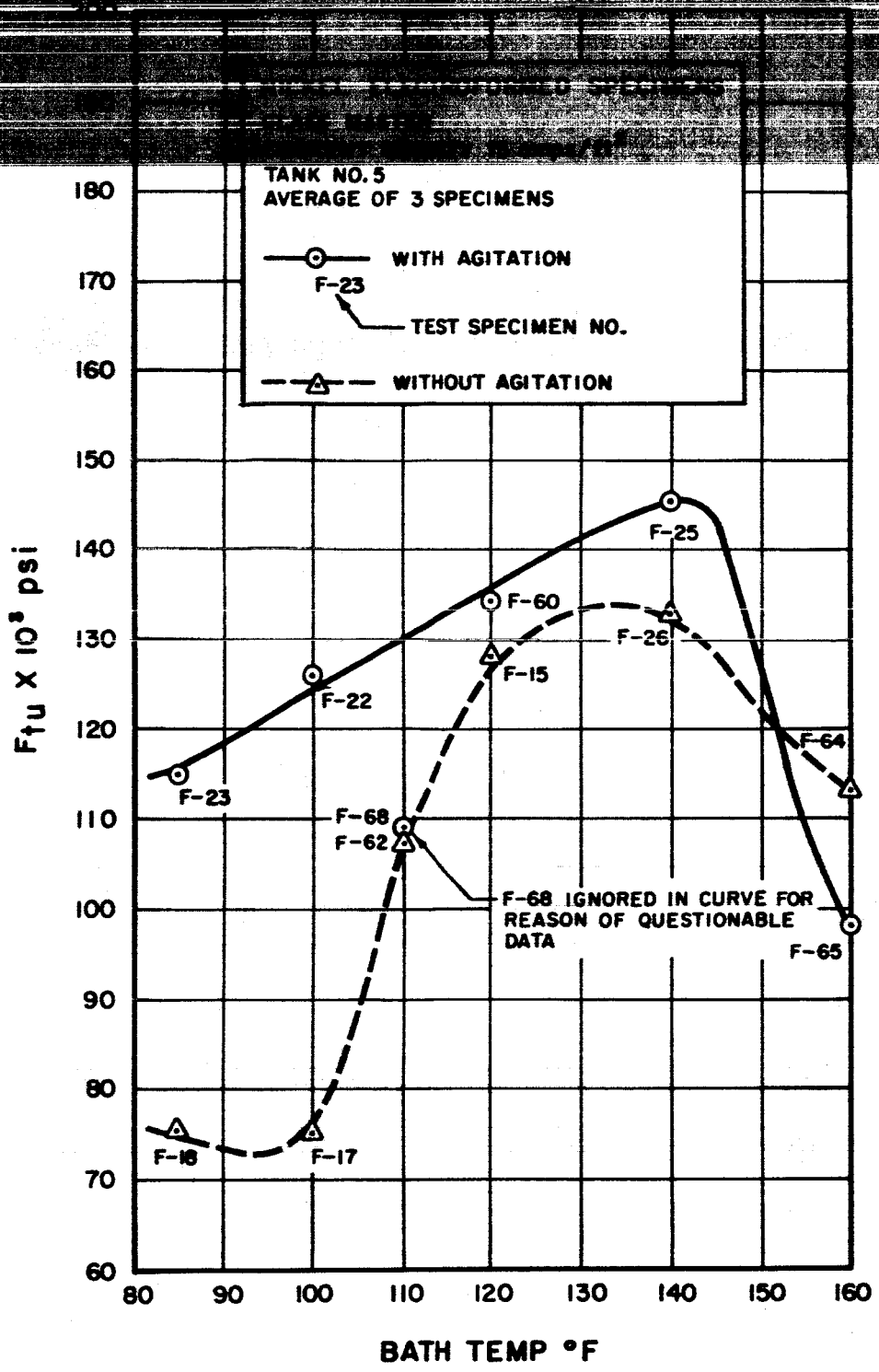

FIG. 30 RELATION OF ULTIMATE TENSILE STRENGTH (F_{tu}) TO CURRENT DENSITY

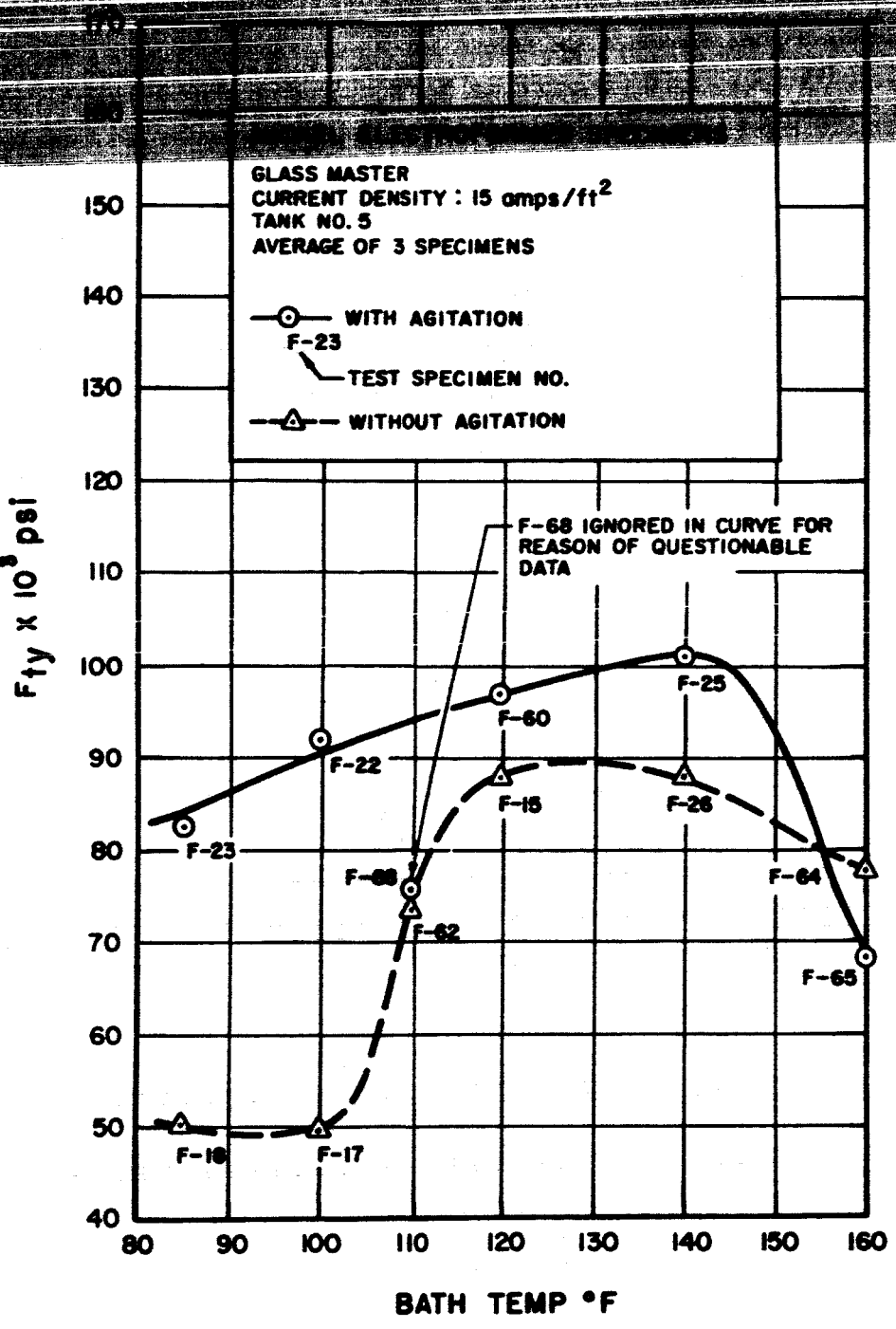

FIG. 31 RELATION OF YIELD POINT (F_{ty}) TO BATH TEMPERATURE

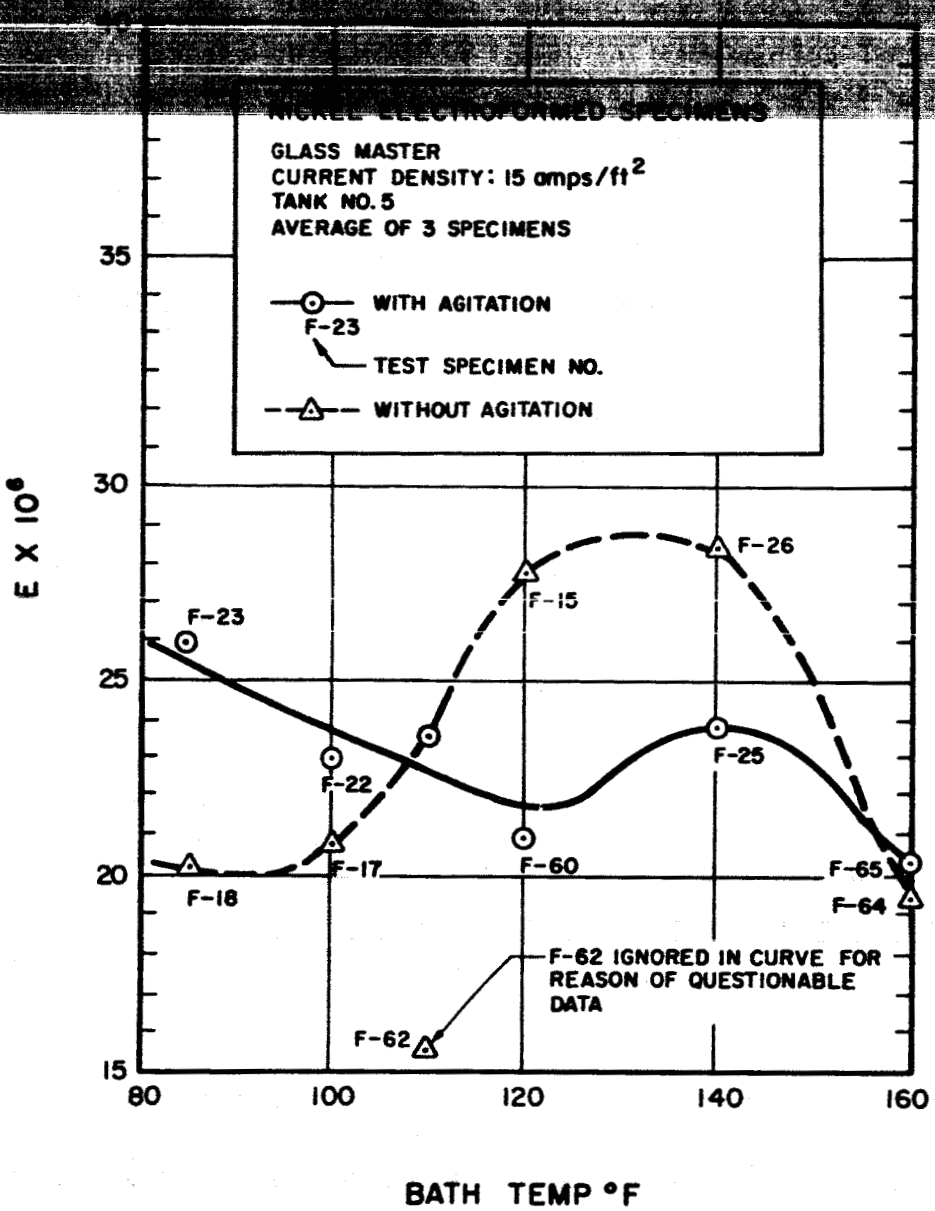

FIG. 32 RELATION OF MODULUS OF ELASTICITY (E) TO BATH TEMPERATURE

Group 3: Current Density Change at 100°F

The relatively low values in this group are typical of samples of electroforming without agitation and at a temperature of only 100°F. Within the group the only sharply defined trend resulting from current density at this temperature is a higher value at the very low rate of 5 amps/ft^2. Although only one point was tested with agitation, it is expected that more data would result in a rather flat curve for the current density versus strength when under agitation, as shown in Fig. 33a.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-37	100	5	No	110.0	72.5	25.0
F-3	100	10	No	81.7	53.0	21.5
F-17	100	15	No	75.7	49.0	20.8
F-39	100	40	No	83.7	58.0	15.0

Group 4: Current Density Change at 110°F

Current density change without agitation at 110°F seems to exhibit results quite similar to those at 100°F (Group 3), except that the fall off slope is displaced higher in the scale at the 15 to 20 amp/ft^2 area instead of at very low current density as in Group 3 with agitation. The resultant curve is quite flat. Both appear in Fig. 33b. The lack of points at 40 amp/ft^2 minimizes the validity of the precise shape of these curves at this time.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-68	110	15	Yes	109.0	75.8	15.5
F-66	110	22	Yes	196.7	65.5	23.0
F-59	110	60	Yes	100.7	74.8	22.0

[redacted]

HUNTINGTON PARK, CALIF.
LUDLOW 8-4161

CERTIFIED REPORT OF PHYSICAL TEST

FOR ACCOUNT OF: ELECTRO-OPTICAL SYSTEMS

DATE 3-21-62

YOUR P. O. NO. 18193, Shipper C-239

FILE NO.

MANUFACTURED BY:

SECTION NO.

PRIME CONTRACTOR:

MATERIAL Electro-Plated Nickel Specimens

SUBCONTRACTOR:

SPECIFICATION

ATTN: Mr. W. D. McCrary

PHYSICAL PROPERTIES

				YIELD POINT:		TENSILE STRENGTH:							
HEAT NUMBER	ACTUAL SIZE	ACTUAL AREA	ACTUAL LOAD IN LBS.	POUNDS PER SQ. IN.	ACTUAL LOAD IN LBS.	POUNDS PER SQ. IN.	ELONGATION IN 2 IN.	ELONGATION PER CENT	REDUCED DIMENSION	REDUCTION OF AREA PER CENT	CODE	LAB NO.
ROOM TEMPERATURE TENSILE TEST												
#15 1	.502 / .0133	.006677	582	87200	846	127000	0.18	9			g	32-765P
2	.502 / .0132	.006626	586	88400	850	128000	0.17	8.5			g	
3	.502 / .0130	.006526	584	89500	848	130000	0.18	9			g	
#17 1	.502 / .0110	.005522	268	48500	418	75700	0.30	15			g	
2	.502 / .0110	.005522*	275	49800	418	75700	0.31	16			g	
3	.502 / .0110	.005522	271	49100	418	75700	0.28	14			g	
#18 1	.0092 / .502	.004618	249	53900	366	79300	0.24	12			G	
2	.0095 / .502	.004769	238	49900	358	75100	0.24	12			G	
3	.0095 / .502	.004769	233	48900	349	73200	0.26	13			g	
MAXIMUM REQUIREMENTS												
MINIMUM REQUIREMENTS												

YIELD STRENGTH BY EXTENSOMETER AT 0.2% Offset IN 2".

Code:
(F) Indicates flaw
(G) " broke outside gauge mark
(g) " broke at gauge mark

* Yield approximate
All specimens had .0003-.0007 taper in thickness near end of reduced section.

WITNESSED BY:
☐ NAVY INSPECTOR
☐ ARMY INSPECTOR
☐

RESPECTFULLY SUBMITTED
Paul J. Petrus
METAL CONTROL LABORATORIES
CHEMISTS - METALLURGISTS - ENGINEERS - INSPECTORS

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Load/lbs	Stress/psi	Strain/in.	E x Y10^6	
25	3,745			
50	7,500	.00027	27.8	
75	11,220			
100	15,000	.00054	27.8	
125	18,720			
150	22,420			
175	26,220			
200	29,900	.00109	27.5	
225	33,700			
250	37,420			
275	41,200			
300	45,000	.00175	25.70	
325	48,700	.0019	25.60	
350	52,400	.00215	24.38	
375	56,200	.00235	23.90	
400	59,800	.0026	23.02	
425	63,700	.0029	21.94	
450	67,400	.0032	21.08	
475	71,200	.0035	20.32	
500	74.900	.0038	19.70	
525	78,600	.0042	18.70	
550	82,400	.0046	17.90	
575	86,100	.0050	17.20	
600	89,900	.0055	16.35	
625				
650				
675				
700				
725				
750				
775				
800				

NOTE:

1) $\text{Stress} = \frac{\text{load lb}}{\text{area in}^2}$

2) $Y = \frac{\text{stress}}{\text{strain}}$

3) $\frac{2.5 \times 10}{6.677 \times 10^{-3}} = 3.745 \times 10^{-3}$

DATA SHEET

Date

Sample

Test No.

By

ELECTRO-OPTICAL SYSTEMS, INC.

W.A. _____

S

Load/lbs	Stress/psi	Strain/in.	E x Y10^6	
25	3,778			
50	7,540	.00026	28.7	
75	11,320			
100	15,080	.00053	28.5	
125	18,850			
150	22,600			
175	26,400			
200	30,150	.0011	27.4	
225	33,980			
250	37,700			
275	41,600			
300	45,200	.00178	25.4	
325	49,000			
350	52,800			
375	56,600			
400	60,250	.00262	23.15	
425	64,100	.0029	22.05	
450	68,000	.0032	21.22	
475	71,700	.0035	20.45	
500	75,400	.0039	19.35	
525	79,200	.0042	18.85	
550	82,900	.0046	18.05	
575	86,500	.0050	17.30	
600	90,500	.0055	16.45	
625				
650				
675				
700				
725				
750				
775				
800				

DATA SHEET

Page of

Date

Test No.

By

ELECTRO-OPTICAL SYSTEMS, INC.

W.A.

S

Load/lbs	Stress/psi	Strain/in.	E x Y10^6	
25	3,450			
50	7,660	.00029	26.4	
75	11,490			
100	15,320	.00058	26.4	
125	19,110			
150	22,950			
175	26,800			
200	30,600	.0012	25.50	
225	34,450			
250	38,300	.00155	24.70	
275	42,200	.0017	24.70	
300	45,900	.0019	24.20	
325	49,800	.0021	23.70	
350	53,500	.0023	23.30	
375	57,400	.0026	22.05	
400	61,250	.0028	21.85	
425	65,00	.0031	20.95	
450	68,900	.0034	20.25	
475	72,800	.0037	19.65	
500	76,400	.0041	18.62	
525	80,400	.0044	18.25	
550	84,200	.0049	17.18	
575	88,000	.0053	16.62	
600	91,700	.0059	15.55	
625				
650				
675				
700				
725				
750				
775				
800				

EOS FORM 247 (REV.)

tially higher than at lower temperatures. The drop in value in the low end of the current density scale is still definable, but is less pronounced than at 100° or 110°F, as seen in Fig. 33c. Again, only one point was tested with agitation and an approximate estimated slope of a curve is shown.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-32	140	5	No	120.0	98.2	23.0
F-26	140	15	No	132.6	87.8	26.5
F-29	140	22	No	120.0	78.0	15.5
F-33	140	40	No	120.0	76.0	27.2
F-63	140	60	No	90.2	66.0	21.6

Group 6: Agitation Added at 85°F

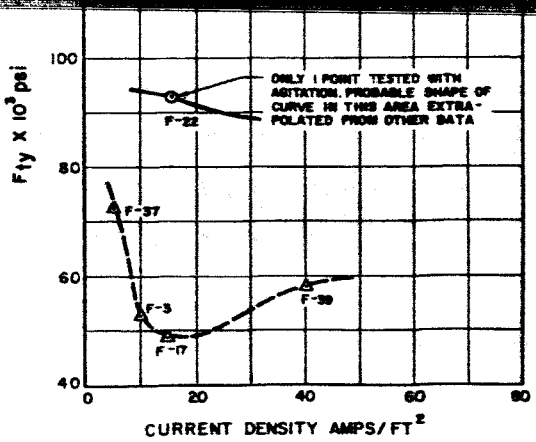
Agitation apparently makes a very substantial difference at this lower temperature, The extent is graphically illustrated in Figs. 30, 31, and 32.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-18	85	15	No	75.5	50.5	20.2
F-23	85	15	Yes	117.5	87.3	26.0

Group 7: Agitation Added at 100°F

The maximum spread in strength created by agitation is noted at the 100°F level (a temperature frequently used in the subject of solar concentrator electroforming). Results can be seen in Figs. 30 and 31.



RELATION OF YIELD POINT (F_{ty}) TO CURRENT DENSITY AT 100° F

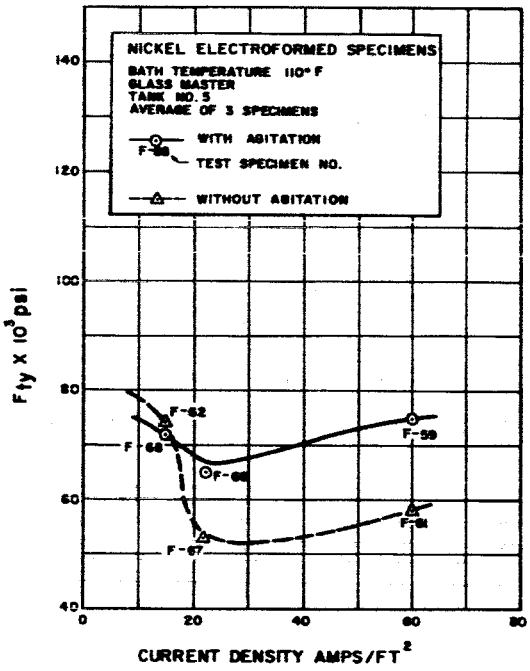


FIG. 33b

RELATION OF YIELD POINT (F_{ty}) TO CURRENT DENSITY AT 110° F

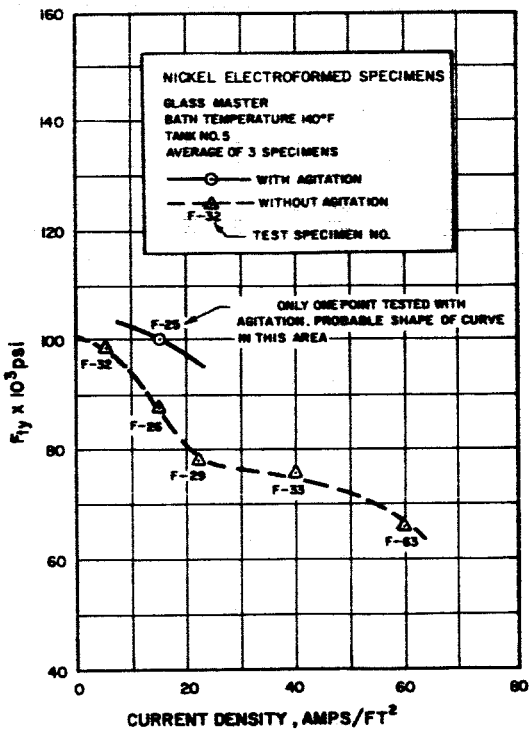


FIG. 33c

RELATION OF YIELD POINT (F_{ty}) TO CURRENT DENSITY AT 140° F

No.	°F	Amps/ft^2	Yes - No	x 10^3	x 10^3	x 10^6
F-17	100	15	No	75.0	49.5	20.8
F-22	100	15	Yes	126.0	97.0	23.0

Groups 8 and 9: Agitation Added at 110° F at Two Current Densities

The improvement from agitation alone decreases with temperature, as is shown by the following data for 110° F. However, the difference still amounts to approximately 10 to 25 percent in both strength and modulus. Group 8 points (F-62 and F-68) are illustrated in Figs. 30, 31, and 32.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-62	110	15	No	108.0	74.0	15.5
F-68	110	15	Yes	109.0	75.8	23.0
F-67	110	22	No	79.2	53.2	19.8
F-66	110	22	Yes	96.7	65.5	23.0

Groups 10 and 11: Agitation Added at 140° and 160° F

At elevated temperature the improvement given by bath agitation diminishes, and disappears at approximately 155°F. Results appear in Figs. 30, 31, and 32.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-26	140	15	No	132.6	87.8	26.5
F-25	140	15	Yes	145.0	101.0	23.8
F-64	160	15	No	113.0	77.5	19.5
F-65	160	15	Yes	98 .0	68.8	20.5

Groups 12 and 13: Substrate Changes

In both groups polished nickel was substituted for glass as the plating mandrel, or substrate, in the first sample. Results are inconclusive in the case of Group 13 because of the very low temperature of 80°F, which caused poor grain structure. In the more typical case in Group 10, however, it is apparent that the change makes little difference.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6	Substrate
F-21	100	15	No	79.8	52.5	21.2	Nickel
F-17	100	15	No	75.0	49.5	20.8	Glass
F-46	80	5	No	65.0	42.0	22.2	Nickel
F-27	80	5	No	83.0	57.0	22.0	Glass

Group 14: Solution Change

The bath was completely changed but with the same formula: nickel sulfamate (Barrett Co.). The moderate decrease in strength properties remains unexplained, since all measured parameters were the same. The modulus was apparently unaffected. The chloride ion, nickel, acid, and borate concentrations were checked and found close to equal. Unknown impurities, variables in agitation and/or tank vibration may have contributed to the change, which was as follows.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6	Tank
F-36	100	5	No	120.0	81.8	15.2	Old 5
F-37	100	5	No	110.0	77.5	15.0	New 6

3.2.2.2 Copper

A series of twelve experimental platings was completed in hardened copper baths. All but one bath was modified with a variation of the molasses additive. The twelfth was hardened with the Dayton Bright System, which now is being used almost exclusively in EOS laboratories for mirror plating. As in the case of nickel, above, the reporting of results is by groups.

Group 15: Temperature Change

Very little plating of copper has been done outside the 90° to 98°F range, but the few examples of electroforming at elevated temperatures always exhibit poor physical properties, as in the case of F-45. F-48, plated at 90°F, was moderately acceptable at 37,000 psi yield point and modulus at 13.2 x 10^6. F-45, the sample plated at 120°F, was so pulpy in grain structure that it was unacceptable for physical properties testing.

Group 16: Current Density Change

A sharp falloff in yield and ultimate tensile strength was observed when the current density decreased from 75 down to 50 amps/ft^2. Results of this test are illustrated in Fig. 34a and b. Also shown is a curve generated by two cases without agitation, in which the samples were plated in baths with different hardening agents. A lack of intermediate points limits the validity of the shape of the curves. The curves are only suggested approximations.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No..	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6
F-55	90	50	Yes	41.0	27.2	14.8
F-56	90	75	Yes	60.0	41.8	13.5

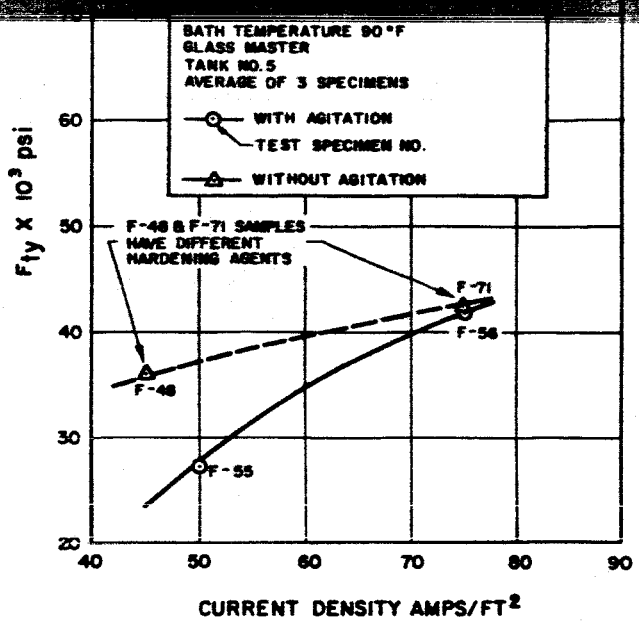


FIG. 34a

RELATION OF YIELD POINT (F_{ty}) TO CURRENT DENSITY

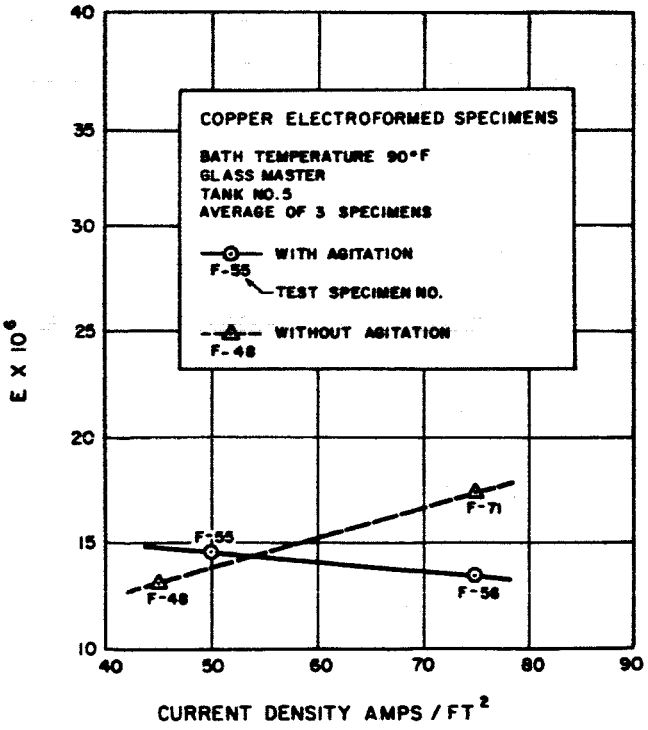


FIG. 34b

RELATION OF MODULUS OF ELASTICITY (E) TO CURRENT DENSITY

Group 17: Hardening Agent Concentration Change

The most promising additive for copper baths used with molasses has been found to be triisopropanolamine (triiso) added in minute quantities. The testing indicates that a concentration of 0.3 to 0.4 oz/gal of solution is probably the best approximation under the existing conditions. The data was derived at what is now known as a poor current density, so the strength figures are relatively low.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6	Triiso oz/gal
F-52	90	15	Yes	35.5	22.8	14.2	0.1
F-53	90	15	Yes	40.8	26.2	13.3	0.2
F-55	90	15	Yes	41.0	27.2	14.8	0.3
F-57	90	15	Yes	42.3	27.2	13.2	0.4

Group 18: Hardening Agent Change

The examples listed below are not intended for precise comparison of properties because the other parameters were varied. The last two samples, F-56 and F-71, represent the best combinations of 90° temperature high current density and the most promising additives. Of the two, F-71's Dayton Bright System additives appears to result in higher modulus, a key requirement in qualifying copper for electroforming ultra-thin shelled structures.

TEST RESULTS - AVERAGE OF 3 SPECIMENS

Sample No.	Temp. °F	Current Density Amps/ft^2	Agitation Yes - No	F_{tu} x 10^3	F_{ty} x 10^3	E x 10^6	Hardening Agent
F-44	90	45	No	48.0	39.0	13.0	Molasses
F-49	98	33-1/2	Yes	33.0	15.7	13.2	Triethanoline
F-56	90	75	Yes	60.0	41.8	13.5	Triisopropano-lamine
F-71	90	75	No	59.5	42.5	17.8	Dayton-Bright System

Microhardness measurements were taken on Specimens F-3-1, 2, and 3 (plated at 100°F, current density 10, no agitation). A Tukon hardness tester was used with a load of 500 grams on a Knoop diamond indenter. The results were as follows:

Sample	Hardness
F-3-1	KHN 247
F-3-2	KHN 257
F-3-3	FHN 257
	KHN 254 Average

3.2.3 Summary - Improvement in Physical Properties

Information obtained from the physical property testing of the various samples indicates that variations or improvements in physical properties can be achieved through careful control of the plating conditions. In the case of electroformed nickel, the bath temperature should be relatively high for increased strength, with an ultimate value near 140°F with agitation, or near 125°F without agitation. The current density should be low for maximum strength, probably in the 10 to 20 amp/ft^2 range. At the elevated temperatures (120°F and up), however, the decrease in values in the higher current density ranges cannot be considered severe. Agitation is of prominent importance for increased strength, especially at lower temperatures. The agitation has a less defined effect on modulus.

For copper electroforming, the temperature should be kept at the 90° to 98°F level. Current density should be high for good deposited grain structure - 60 to 75 amps/ft^2 or even slightly higher. Agitation seems to be of dubious value from the limited data on the copper testing (except to prevent polarization at high current density), and a further examination of this parameter by degrees of agitation may be indicated.

[redacted]

have been under development. If adequate controls can be maintained, concentrator design can be optimized to take advantage of these concepts, and necessary material properties can be adjusted to permit the reduction in weight of certain components, with an increased ability to withstand the conditions associated with launch environment and related shock and vibration loading.

4. ADVANCED COATING STUDIES

High reflectivity coatings that are compatible with electroformed structures and exhibit a high degree of resistance to degradation from environmental conditions encountered during processing, storage, launch and space conditions are of prime concern to this program.

4.1 Small-Scale Studies

A number of studies were conducted which provide a better understanding of the conditions or processes that are required to produce various durable, highly reflective surfaces on electroformed concentrators and mirrors.

4.1.1 Effects of Master and Substrate Materials

To determine the possible effect of the master or substrate materials on ultimate reflectivity, a number of sample reflective skins were plated using various structural materials. Although the quality of the master surface is reproduced very accurately in the electroformed replica, the materials employed in the master itself have no known ultimate effect on the reflectivity or durability of the resultant reflective surface. The reflectivity characteristics of the master surface, whether it is metal, plastic, or glass, will be reproduced faithfully in a replica mirror. In the case of nonconductive masters, such as plastic and glass, a sensitizing layer of silver, copper or other material is used prior to the electroforming process. The subsequent electroform reproduces the surface condition of this sensitizing or reflective layer.

There does not appear to be any measurable difference in obtainable reflectivities associated with the different materials that have been used to electroform the actual reflective face. Reflectivities measured from nickel, copper, brass, and other sample substrates which were overcoated with the same reflective materials that were electroformed over the same master showed identical characteristics. Replica-sensitizing materials or interlayers within the reflective

subject will be discussed in the following subsections.

4.1.2 Various Coatings for High Reflectivity

To evaluate, on a comparative basis, the various possible high reflectivity coatings, a method was devised whereby the initial surface and substrate materials could be duplicated in an accurate manner. Figure 35 shows the electroforming of the basic reflectivity samples. The rectangular, flat, plateglass master, approximately 12 by 15 inches, provides a basis for formation of reflective skins for all electroforming materials. Electrodeposition is achieved to a thickness of approximately 0.030 inch upon a chemically deposited silver sensitizing layer. Various vacuum deposited coatings also have been used as a comparison and in instances where the electroforming solutions are not compatible with chemical silver. The electroform is parted from the master and stopped off on both front and back using Kodak metal etch resist stop-off material. Circles are scribed through the stop-off material on the back or nonreflective side of the sample to expose the nickel. The part is put into an etching solution and electrochemically milled to produce individual flat samples approximately two inches in diameter. This process eliminates any possibility of bending or warping by physical machining or cutting techniques. It is necessary that the samples be flat to ensure reproducible measurements on the Perkin-Elmer spectrophotometer. The process provides a relatively large number of samples that are essentially identical in characteristics of surface condition and material. These are then coated simultaneously in a vacuum-deposition system to provide nearly identical samples for future tests of reflectivity and surface degradation.

The more common high reflectivity and protective coatings have been applied to these samples. Included are unprotected silver, which results from the sensitizing process required for the electroforming operation, unprotected aluminum, the same materials being protected with an overcoat of silicon monoxide, and chromium

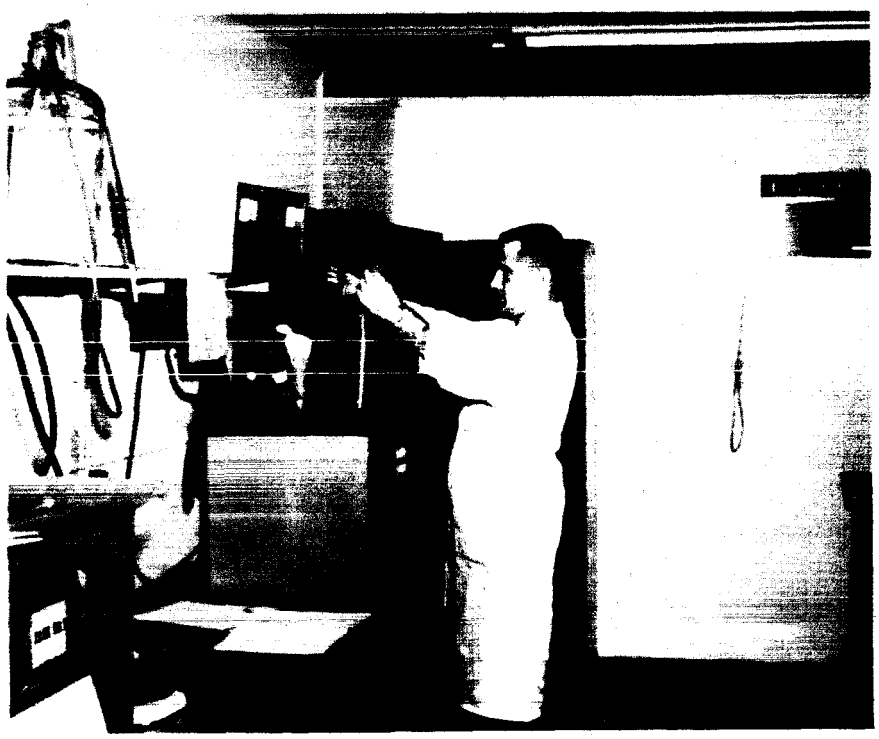


FIG. 35 PLATING OF REFLECTIVITY SAMPLES

adhesion and protection.

Four samples of each particular coating were prepared simultaneously. In some instances the as-formed silver surface was left intact and the various combinations of coatings applied over the silver. Other samples were made in which the silver was chemically removed, leaving a reflective nickel surface on which the various combinations of coatings subsequently were deposited. Specular reflectivity measurements were made on one of each of the four basic samples, to act as a control. The three remaining samples of each of the coatings were exposed to various environmental conditions.

It has been conclusively demonstrated by reflectivity and performance tests that the bright, fresh, silver surfaces provide, by a wide margin, the best reflectivity obtainable for solar concentration. Reflectivities of 94 to 96 percent in the wavelengths of interest for space power systems are not uncommon. Unfortunately, exposed silver surfaces degrade very rapidly under normal environmental conditions with a resultant drop in reflectivity. Among the more promising coatings are vacuum-deposited aluminum (which in itself is quite durable) and combinations of vacuum-deposited aluminum overcoated with silicon monoxide, which lends a far greater protection against scratching and abrasion. Reflectivities obtainable with these coatings range from 85 to 90 percent.

Table II lists the various reflectivity samples that were prepared. The structural or substrate materials are listed, together with the sequences of coatings that were used. Table III lists the resultant reflectivities achieved on the control samples. In certain instances there was difficulty in reproducing reflectivity values of similar samples. This was traced to warpage of the samples, which caused errors in readout of the spectrophotometer. Those samples that were questionable were remade and subsequent tests were conducted to substantiate or correct the prior information.

TABLE II REFLECTIVITY TESTS

Sample Number	Coating Description (Outermost Coating First)	Substrate (Mirror)
1	Ag	Ni
2	Silicone Oil/Ag	Ni
3	SiO/Ag	Ni
4	**Wax/Ag	Ni
5	Al/Ag	Ni
6	SiO/Al/Ag	Ni
7	SiO/Al/SiO/Ag	Ni
8	SiO/Al/SiO/Cr/Ag	Ni
9	Al	Ni
10	SiO/Al	Ni
11	SiO/Al/SiO	Ni
12	SiO/Al/SiO/Cr	Ni
13	*SiO/Al/SiO/Cr/Ag	Ni
15	Ag	Cu
16	Cr Plate	Ni
17	Rh Plate	Ni
18	SiO/Al/SiO/Cr/Ag	Cu
19	SiO/Al/SiO/Ag	Cu

* Vacuum Deposited

** Wax: Johnsons Metal Protector No. 6143 (Permacoat 60).

TABLE III REFLECTIVITY TEST RESULTS - CONTROL SAMPLES

Sample Number	Coating Description Outermost Coating First Substrate Last	Reflectance - Percent .26μ	.55μ*	1.20μ	2.00μ
1	Ag/Ni	20.9	93.5	89.9	90.1
2	Silicone Oil/Ag/Ni	22.7	93.3	90.7	89.9
3	SiO/Ag/Ni	5.1	93.7	97.0	91.6
4	**Wax/Ag/Ni	~1	46.0	71.4	84.4
5	Al/Ag/Ni	86.8	92.1	99.2	97.5
6	SiO/Al/Ag/Ni	27.9	83.8	95.1	97.0
7	SiO/Al/SiO/Ag/Ni	5.8	85.9	99.5	98.4
8	SiO/Al/SiO/Cr/Ag/Ni	28.1	75.4	87.0	86.9
9	Al/Ni	84.8	88.6	78.0	81.5
10	SiO/Al/Ni	34.2	87.3	80.9	87.8
11	***SiO/Al/SiO/Ni	36.5	77.2	95.6	94.8
12	SiO/Al/SiO/Cr/Ni	27.7	87.2	96.7	95.2
13	SiO/Al/SiO/Cr/V.D.Ag/Ni	36.8	89.5	95.4	95.7
15	Ag/Cu	16.2	97.1	98.0	94.2
16	Cr(Plate)Ni	51.6	67.3	60.9	76.9
17	Rh(Plate)Ni	59.4	82.0	88.1	94.0
18	SiO/Al/SiO/Cr/Ag/Cu	40.9	87.5	84.2	93.7
19	SiO/Al/SiO/Ag/Cu	45.0	88.1	89.6	91.8

* Emphasis is placed on the readings at 0.55μ because the preponderance of solar energy is found in that wavelength area.

** Wax: Johnsons Metal Protector No. 6143 (Permacoat 60).

*** Validity of data is questioned because of poor correlation with other SiO/Al/SiO results.

[illegible] overcoating for increasing total reflectivity that can be used with a variety of reflective surface materials is a multiple film of cerium dioxide and magnesium fluoride or cerium dioxide and silicon monoxide. Considerable work with these films has been accomplished by the U.S. Army Research and Development Laboratories at Fort Belvoir, Virginia. Details of this work are reported in a paper entitled "Optical Properties and Structure of Cerium Dioxide Films" by G. Haas, J.B. Ramsey, and R. Thun, Ref. Journal of the Optical Society of America, Vol. 48, No. 5, 324-327, May, 1958. These coatings show excellent abrasion and corrosion resistance, even when exposed to salt water spray, or when boiled in a 10 percent NaCl solution for several hours, according to the authors. The reflectance of the metal reflective layer can be increased over a broad spectral region by using pairs of these dielectric films with alternately low and high indexes of refraction. The films are effectively one-quarter wavelength thick and must be applied in the sequence of reflective metal, low-index film, high-index film. The visible reflectance of normal evaporated aluminum is approximately 90 percent in the visible range. The same surface, coated with the pairs of dielectric films, can achieve a maximum reflectance of 96 percent at 0.55μ and can be more reflective than uncoated aluminum at most wavelengths of the visible spectrum. Such results have been demonstrated by the work of G. Haas and associates at Fort Belvoir, Virginia. The results of a thermal test consisting of photospectrometer readings of samples undergoing fifteen 24-hour cycles from ambient temperature to 500°F with a 4-hour cooling period during each cycle are presented in Table IV.

It is apparent that the unprotected silver surfaces degraded very rapidly during temperature cycling and, in the case of silver on an electroformed copper substrate, the reflective surface completely degrades in a very short number of cycles. It was determined that the presence of silver as one of the underlying coatings

[illegible] RESULTS - THERMAL SAMPLES

(15 500°F CYCLES)

Sample Number	Coating Description Outermost Coating First Substrate Last	Reflectance - Percent .26μ	.55μ	1.20μ	2.00μ
1	Ag/Ni	1.4	3.2	10.8	13.2
2	Silicone Oil/Ag/Ni	<1	3.8	11.8	21.7
3	SiO/Ag/Ni	1.0	3.0	7.0	8.6
4	*Wax/Ag/Ni	<1	4.9	12.4	14.8
5	Al/Ag/Ni	25.5	40.4	62.8	74.1
6	SiO/Al/Ag/Ni	41.4	71.8	80.5	94.4
7	SiO/Al/SiO/Ag/Ni	13.6	85.4	89.1	96.8
8	SiO/Al/SiO/Cr/Ag/Ni	26.7	79.1	78.5	88.2
9	Al/Ni	59.3	85.3	82.7	82.2
10	SiO/Al/Ni	45.8	82.2	76.2	78.8

*Wax: Johnsons Metal Protector No. 6143 (Permacoat 60).

caused a more rapid degradation than occurred in samples from which the silver had been stripped prior to application of other reflective and protective coatings. After approximately one week of testing, definite degradation around the edges and at places where pin-holes existed was noticed in the surfaces on which the silver undercoat remained. No visible change occurred to the samples from which the silver undercoat had been stripped before coating. Adhesion remained good throughout the testing.

An additional sample of each of the coatings was exposed to outside environment on the roof of the building for an extended period of time (see Fig. 36). This is, of course, rather severe exposure compared to normal storage and handling conditions. After ten weeks exposure the samples were taken in for cleaning before test. None was cleanable without removing coating material. The test was judged too severe and unrealistic for evaluating the handling of concentrators.

One promising method of producing reflective and protective layers for electroformed concentrators is predepositing the coatings on the master before formation of the electroformed reflective-face skin itself. Experimental studies of this nature have been performed by G. Haas and associates at Fort Belvoir, Virginia, on small-scale samples, with relative success. During the course of the subject program at EOS, a variety of different predeposited combinations were applied to small samples prior to electroforming.

The glass master was coated by the vacuum-deposition process with a parting layer such as silver or copper. Next, and in succession, the desired protective and reflective coatings were applied by the vacuum-deposition process. Typical coatings that were tried experimentally included, in order, a SiO protective layer, an Al reflective layer, a second SiO layer to produce a protective sandwich for the aluminum reflective layer, and a conductive or sensitizing layer such

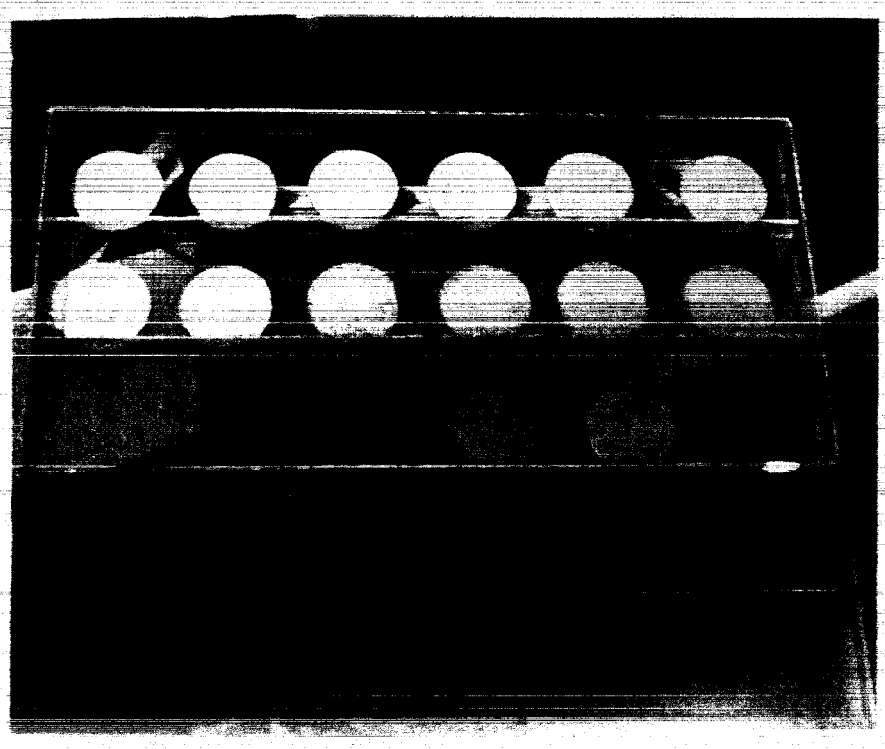


FIG. 36 REFLECTIVITY SAMPLES - ROOFTOP EXPOSURE

as silver, copper or nickel, as the basis for subsequent electroforming. A number of samples have been produced on which electroforms of both nickel and copper have been electrodeposited to the thickness required for reflective-face skins. After parting, the original silver or copper parting layer was removed from the front surface of silicon monoxide, leaving the completed mirror with coatings firmly adherent.

This process has great promise, since the reflective coatings are completely protected and the mirror is essentially complete upon removal from the master. No possibility of staining or lack of adhesion due to poor cleaning prior to normal reflective film deposition exists. There are certain problems associated with this technique, however, and for large size concentrators the facility requirements necessary to put down these selected films in a controlled manner on the master are severe.

4.1.3 Coating Adhesion and Durability Studies

The normal test for adhesion of vacuum-deposited coatings is the "Scotch Tape" test. In this test a freshly exposed surface of the adhesive side of cellophane tape is applied to the coated surface and pressed firmly into place. The tape is then jerked away rapidly, exerting maximum pull on the coating. This is a relatively severe test, and if the coatings remain intact and do not come off with the tape, the coating is considered to be firmly adherent. A number of alternative methods for testing the durability of films have been investigated but none appear to be practical for measuring the small variations in adhesion that may exist. All the tests appear to be "go no-go" devices. Since this "Scotch Tape" test appears to be a standard method for testing coatings within the optics industry, it was employed for testing the adherence of coatings produced on the current program. It is hoped that additional and improved adherence testing techniques may be developed in the future.

4.1.4 Plated Coatings

As previously mentioned, both chromium and rhodium protective overcoatings appeared to give maximum protection against

degradation caused by exposure, cleaning, handling, etc. Their reflectivity characteristics are, however, somewhat lower than for silver or aluminum surfaces. The basic reflectivities of rhodium and chromium surfaces, over a wide variety of wavelengths, are shown in Fig. 37. The reflectivity of both materials can be increased considerably by use of reflectivity increasing film combinations of pairs of dielectric films such as the aforementioned CeO_2 and MgF_2.

4.1.5 Methods of Protection and Cleaning

During exposure of the reflective surfaces to test conditions and storage for prolonged periods of time, it became evident that cleaning procedures which would not materially degrade the reflective qualities of the concentrator surfaces were necessary. The various dielectric films and overcoating with SiO offer substantial protection. Surfaces so treated can be washed or wiped as long as care is exercised to prevent definite abrasion. Unprotected surfaces of silver or aluminum can be wiped carefully with detergent and, in some cases, even polished with chalk or rouge to restore the reflectivity to its original value. It has been determined that silver surfaces can be cleaned a number of times to restore reflectivity and, although numerous visible sleaks appear after the cleaning operation, the reflectivity values and performance values are not affected appreciably by the multiple cleaning operations. There is no doubt that these sleaks and minute scratches would cause a degradation in the specular characteristics for the shorter wavelengths, but there appears to be no appreciable degradation of performance as related to solar concentration.

4.1.6 Detailed Procedure - Cleaning of the Reflective Surface of a Concentrator

1. Wash the surface with a suitable solvent such as acetone, alcohol or triclorethylene.
2. Wash with a mild detergent (e.g., Dreft or equivalent) 1/2 cup per gallon of lukewarm water. Use cotton, swabbing very carefully so as not to deform the thin mirror skin.

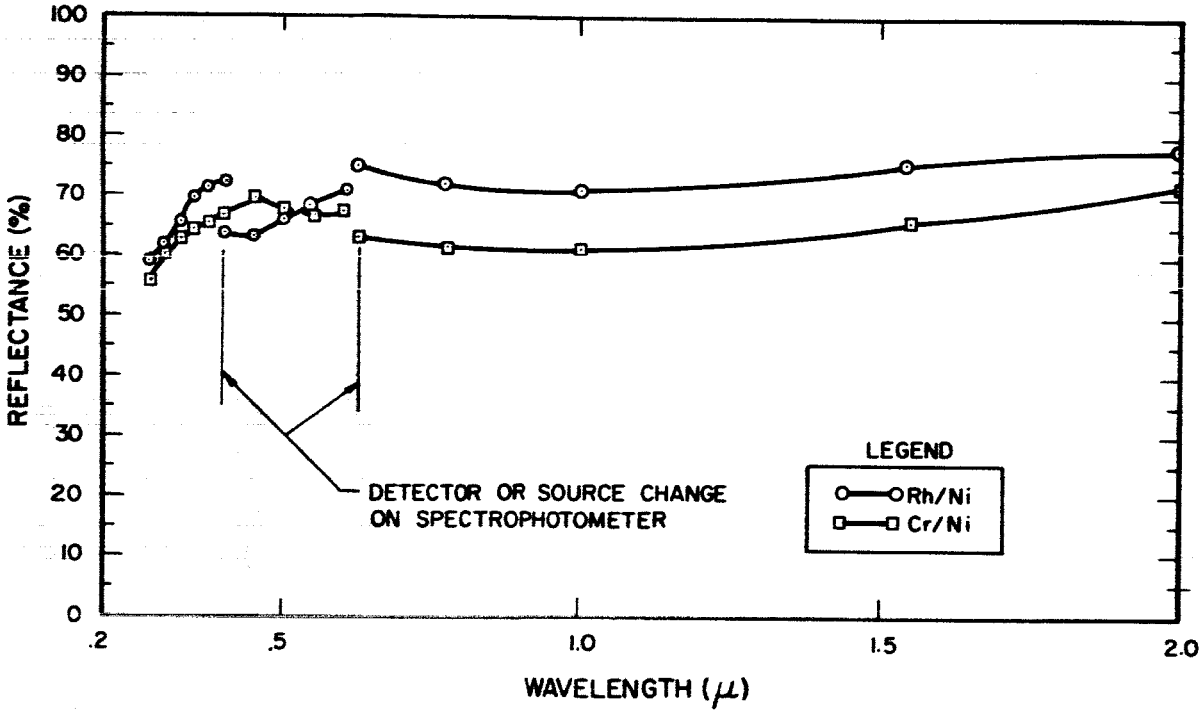


FIG. 37 REFLECTIVITY OF RHODIUM AND CHROMIUM SURFACES ON NICKEL

3. Rinse with distilled water.
4. Repeat the detergent wash if required.
5. If necessary for further cleaning, apply calcium carbonate chalk powder. Carefully swab with cotton.
6. Rinse with distilled water and dry with a warm air blower.

4.1.7 Sublimation Coatings

Consideration is being given to the possibility of coating the as-formed silver surfaces with a material that will evaporate or sublime under space conditions. This would allow protection of the silver reflective surfaces during handling and storage and through launch conditions until the normal earth environment (which appears to be the degrading factor relative to the reflective qualities of the silver surfaces) is left behind. The subsequent evaporation or sublimation of the protective layer would leave an exposed silver surface with maximum reflective properties.

4.2 Application of Protective Coatings

It has become evident from the experimental work performed to date that the techniques required for application of reflective and protective layers by the vacuum-deposition process are not the same for electroformed substrates as for glass. Much of the information available concerning cleaning, maximum adhesion, etc. is based on application of coatings to glass, quartz, or other similar materials. Certain modifications and deviations are required for the application of satisfactory coatings to electroformed metal mirrors.

4.2.1 Pretreatment, Cleaning, etc.

The possible future development of predeposited coatings (which will permit the formation and removal of electroformed mirrors from the master complete with reflective and protective coatings) may eliminate the need for involved pretreatment and cleaning techniques. In the meantime, however, it is necessary that techniques and processes be developed to ensure that the required subsequent coatings are firmly adherent to the reflective face.

Studies were conducted to determine the best method of cleaning the reflective face of the concentrator prior to vacuum deposition of the coatings. To date, the most effective treatment involves preliminary cleaning with solvent, detergents, etc., followed by a vapor degrease cycle in which any one of a number of solvents may be employed. After the chemical cleaning processes, it appears necessary that the glow discharge or ion bombardment technique be used for final cleaning in the vacuum chamber prior to actual deposition of the reflective coatings.

Preliminary tests also have indicated that deposition of an evaporated layer of chromium prior to deposition of the subsequent reflective and protective layers materially increases adhesion. On samples produced by this method, as well as on larger mirrors (if precleaning and glow discharge techniques were correct), complete adhesion was evident. In instances where the chromium layer was not applied, it was sometimes possible to remove the reflective layers using the "Scotch Tape" test.

4.2.2 Facility Requirement

4.2.2.1 Current EOS Vacuum Coating Equipment

EOS has installed a completely equipped vacuum coating facility that includes a 36-inch inside diameter chamber and related equipment. Experiments have shown that vacuum coating facilities operated in the same laboratories in which the plating is conducted can substantially improve the control required throughout the cleaning and coating processes. Maximum knowledge of techniques and quality control of the finished concentrators can be gained.

4.2.2.2 General Specification - Facility Requirements

The facility requirements for the application of high reflectance and protective films by vacuum evaporation on solar concentrators fabricated within the scope of this and prior programs are as follows:

1. Vacuum Chamber Size. The vessel ought to be of sufficient diameter to allow clearance for the work and support structures. The height should provide distances of four times the focal length of the mirror between the evaporative sources and the work, if possible. Shorter lengths may be usable, but require more elaborate source geometries. For 5-foot-diameter concentrators, a minimum diameter of 6 feet and length of 8 feet are recommended.
2. Pumping Requirements. The pumping station should permit exhaustion rates of the fully loaded chamber from atmospheric pressure to 5×10^{-5} torr (mm of Hg) in a period not over 1 3/4 hours.
3. Gaging. Gages should measure pressures continuously from 1 to 5×10^{-5} torr.
4. Power Supplies. The system should be equipped with continuously adjustable power in ranges of 0 to 20 v ac at 7 kw and 0 to 5,000 v ac or v dc at 1.5 kw.
5. Accessories. The system should have sufficient feedthrough at full low-voltage power, and at least one high-voltage electrode for high-voltage glow power (glow discharge ring).

A valve also should be provided for introduction of dry gases at controlled rates. Ideally, a supply of bottled O_2 and N_2 should be available. View ports should be provided for viewing the work during processing, preferably at grazing incidence to a light source within the chamber.

When possible, the following are also desirable:

1. Thermocouple and temperature monitoring device for work piece
2. Rotary seal and source shutter arrangement
3. Low current instrument feedthroughs
4. View port for observation of evaporative sources

4.3 Existing Facilities

There are at least eight commercial vacuum coating chambers in California of approximately six feet in diameter, which are periodically available for hire. Examples are chambers operated by the following companies.

1. Vacuum Metallizing Company, Van Nuys, California
2. Mirra-Cote Company, Inc., El Segundo, California
3. Optical Coating Laboratories, Santa Rosa, California
4. Plastic Dress-Up Company, El Monte, California
5. Plastic Coat, Inc., Culver City, California

Commercial equipment usually must be cleaned before concentrators can be coated. Certain accessories, such as a glow discharge ring, usually must be provided by the customer, who customarily does most of the work.

Vacuum coating equipment is possessed by the major astronomical observatories for coating their telescope lenses. The observatories have been reluctant to consider having the chambers used for a relatively routine coating procedure that could be accommodated by the commercial units. It is anticipated that for the coating of larger concentrators in the future these people may be approached. The following chambers are in existence:

1. 200-inch diameter capacity chamber at Mt. Palomar Observatory, California. (contact Dr. Bowen)
2. 100-inch diameter capacity chamber at Mt. Wilson, California (contact Dr. Bowen)
3. 120-inch diameter capacity chamber at Mt. Hamilton, California (contact Dr. Whitford)
4. 84-inch diameter capacity chamber at Kitts Peak, Tuscon,Arizona (contact Dr. Pierce)

Certain of the large aerospace companies have their own vacuum coating equipment. For example, Thompson-Ramo-Wooldridge, Inc., Inglewood, California, possess a chamber of approximately 10-foot diameter capacity. It is usually restricted to in-house use.

5. FABRICATION, COATING, AND TESTING OF 5-FOOT-DIAMETER CONCENTRATORS

One of the primary objectives of the program was to demonstrate the applicability of the various small-scale studies and the plating testing done during the first two-thirds of the program to the improvement of 5-foot-diameter concentrator design and fabrication techniques. Because of the ever-present question of validity in scaling in this type of design and fabrication, for which very little analytical work has been done, no realistic structural evaluations could be made on the small-scale specimens. The fabrication of 5-foot-diameter concentrators would allow actual environmental and structural testing and would incorporate reflective surfaces of enough area to assure the validity of calorimetric testing of concentrator efficiencies.

5.1 Program Schedule

5.1.1 Fabrication

The following 5-foot-diameter experimental structures were programmed to be fabricated during the final 4 months of the technical work:

1. A preliminary nickel test skin for the purpose of developing techniques for preparing the mandrel for the rolled edge. This plating was to be done with the master in the bottom of the tank in a stationary holding fixture, convex side up, without rotation. Agitation was to be provided by a gusher system. If the skin was usable, it was to be incorporated into item 2.
2. The first complete concentrator with a back-mounted torus, which was to be a proof mirror. It was to include the nickel skin (item 1) and an economical torus conventionally fabricated of aluminum. The main objective was to test techniques for mandrel development between skin and torus. This unit

also would be plated using the stationary holding fixture.

3. One or more nickel test skins, to be plated using the new rotational equipment for the purpose of proving techniques and anode arrangements peculiar to the rotating agitation approach. Material distribution was to be measured and, as required, additional platings conducted until the distribution was satisfactory.
4. The first all-nickel, all-electroformed concentrator. Emphasis was to be placed on proving fabrication techniques. The secondary objective was low specific weight. The rotating equipment was to be used on this and subsequent platings.
5. Other nickel test skins, as required, for checking adjustments in procedure encountered while producing item 4.
6. The second all-nickel, all-electroformed concentrator. Ultra-low specific weight was to be approached with this unit. Because its fabrication was scheduled for the ninth month of effort, it was to incorporate all improvements in plating parameters and techniques found in the earlier work.
7. One or more copper test skins, to be plated with the rotating equipment for the purpose of proving techniques and anode arrangements peculiar to the rotating agitation approach. As in the case of nickel, the material distribution was to be optimized.
8. An all-copper, all-electroformed concentrator. The primary aim was to duplicate the quality resulting from the work in nickel by using the same basic design, if possible. The secondary goal was the lowest specific weight consistent with strength requirements. Inasmuch as it was the last scheduled electroform, the fabrication was to incorporate the results from the experimental copper physical properties testing.

5.1.2 Coating and Testing

The three concentrators were to be given vacuum deposited coatings prior to testing. The thin films to be used were to be selected after the results of the advanced coating studies were available. Each concentrator was to be tested for efficiency using an EOS solar tracker. The axis and focal point were to be aligned with a calorimeter and energy readings taken while the mirror was oriented with the sun. The resultant data is presented in this report.

5.2 Preliminary Design Concept

Based on past information obtained from performance, shake and vibration testing, and small-scale studies conducted during the early portions of this program, a preliminary design concept for the 5-foot-diameter concentrators was developed. Prime factors considered involved simplicity, structural integrity, minimum weight, minimum complexity of tooling and electroforming techniques, and a multitude of other factors. Figure 38 shows the preliminary design concept for the torus-rigidized, 5-foot-diameter concentrator that resulted.

The all-electroformed torus was attached to the rim of the reflective skin in a rear-mounted position. The torus has three mounting, or support, points spaced 120°, or equidistant, apart. Necessary rigidizing for the torus at points of attachment for mounting was provided by electroformed-transition sections that were incorporated as an integral part of the torus. The attachment points and transition sections are shown in Fig. 39. A lightweight, stainless steel, threaded sleeve was encapsulated by a "grow-in" technique in the torus-transition section, which has a tapered wall thickness providing even distribution of loading from the points of attachment to the torus itself. An electroformed, continuous torus was grown over the transition sections while they were accurately positioned on an alignment and rotation fixture. This concept produced a torus section considerably lighter than those previously achieved for 60-inch-diameter concentrators.

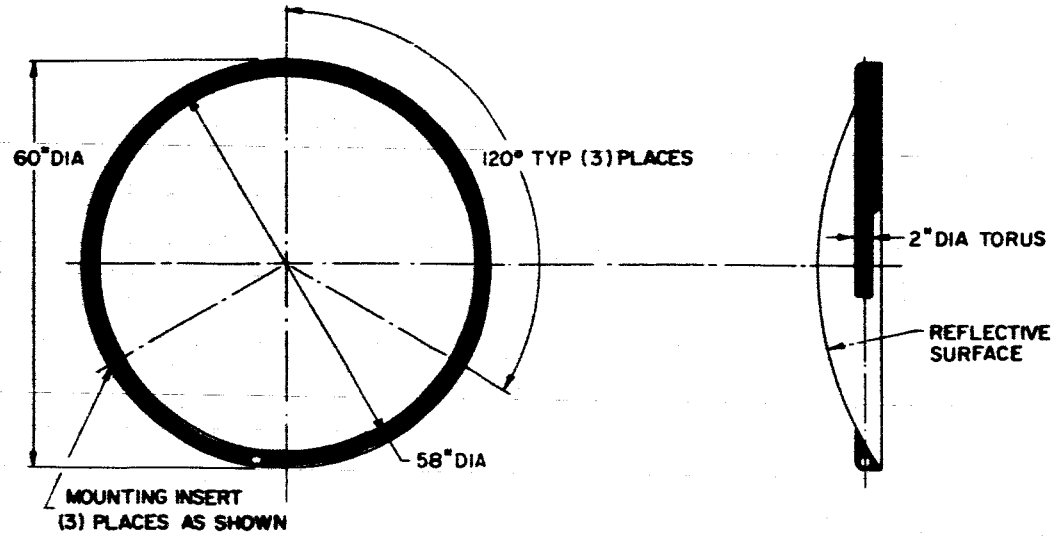


FIG. 38 TORUS RIGIDIZED 5-FOOT-DIAMETER CONCENTRATOR

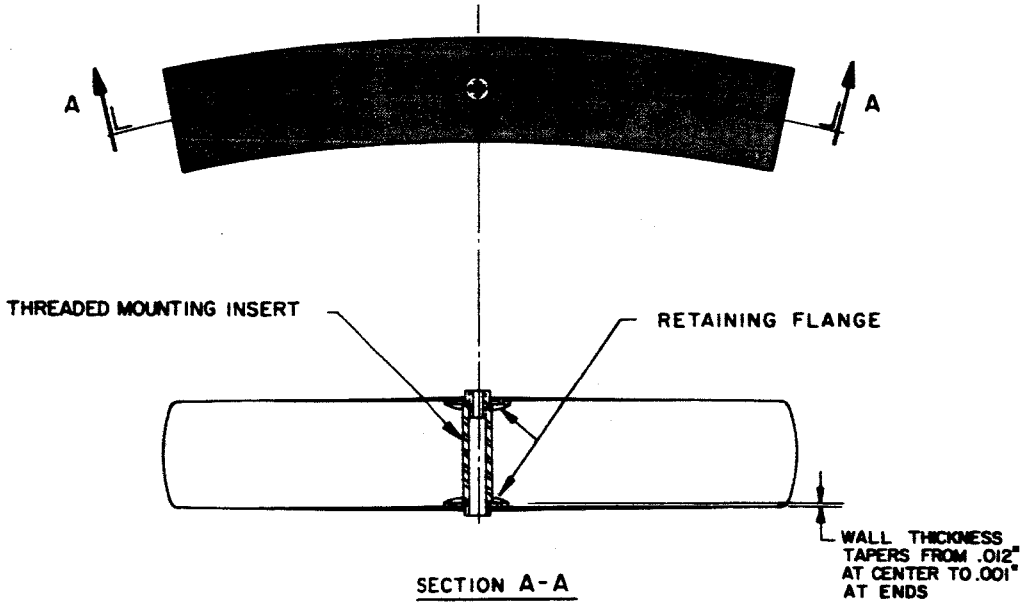


FIG. 39 ELECTROFORMED MOUNTING SEGMENT

5.3 Fabrication of Test Skins and Concentrators

5.3.1 Preliminary Nickel Test Skin

An experimental radius edge reflective skin was electroformed with the stationary holding fixture previously employed for fabrication of concentrators of this size. The objectives of the test fabrication were to work out details of tooling, mandrels, and other special equipment required to form the rolled edge on the 5-foot-diameter master and to evaluate the new problems that would be encountered in plating at this scale. Some of the mandrel tooling, the wax configuration at the rim, and the technique of sensitizing the wax with silver amalgam are shown in Fig. 40. Cathode power transmission was accomplished with a clamp ring attached to the outer rim of the mirror master. Power was fed to the clamp ring by a number of uniformly spaced cathode wires. The edge radius was produced by the use of a wax master extension, which was uniformly machined to contour by a swing arm positioned in the center of the mirror master. The shape of the edge radius is shown in Sect. A of Fig. 41. No attempt was made during this initial plating to maintain an exact balance or uniformity of skin thickness since this could be achieved more readily on the parts on which rotational techniques were used. The plating parameters are outlined in Table V.

Examination of the experimental 5-foot-diameter skin (EOS designation 60-POM3: R8) showed that leakage at the edge had been eliminated effectively, and that "edge roll," or distortion caused by the reverse rim and edge joining technique, was limited to a thin band approximately 1/8 to 3/16 inch wide at the periphery of the mirror. It was expected that this edge roll effect could be further minimized in subsequent plating and that undistorted effective mirror diameters of approximately 59 3/4 inches could be provided for concentrators having overall outside diameters of 60 inches.

5.3.2 Preliminary Concentrator with Aluminum Torus

Work commenced during the seventh month of the program on fabrication of the first complete assembly incorporating a back-mounted torus structure. Inasmuch as the rotating equipment was not

FIG. 40 MIRROR FLANGE MANDREL TECHNIQUE

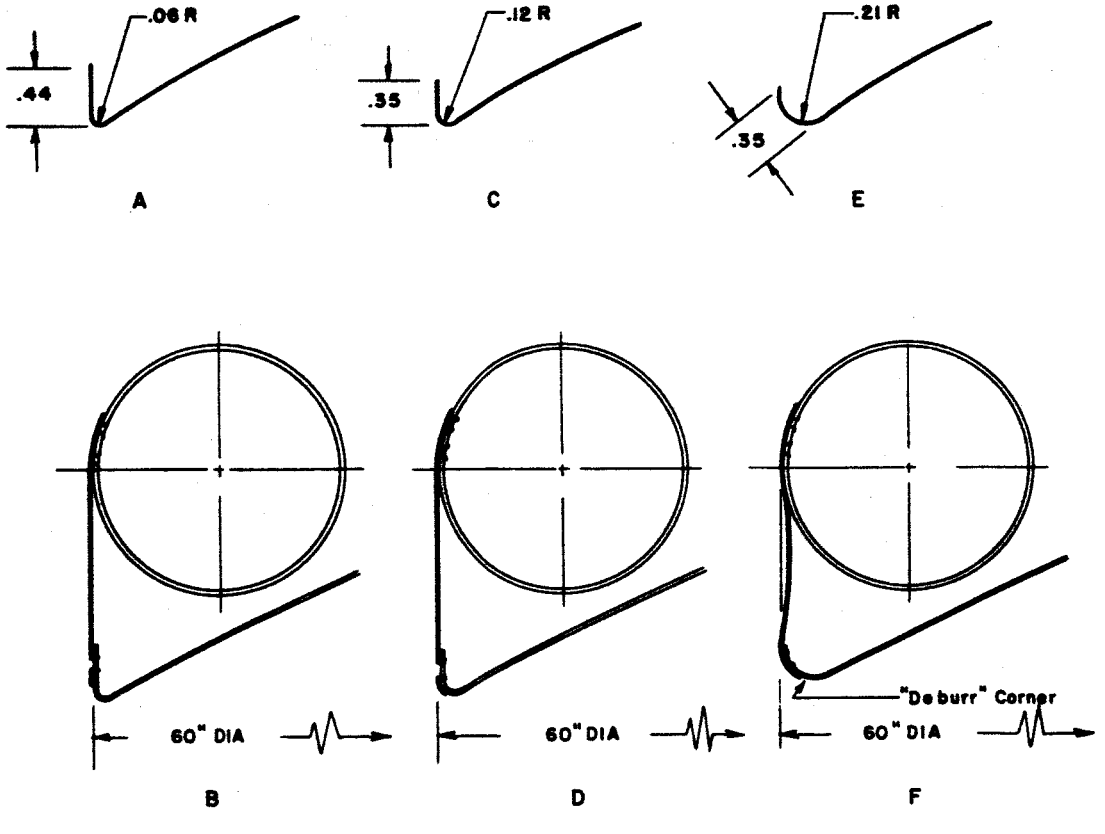


FIG. 41 TORUS FLANGE CONFIGURATIONS

TABLE V

PLATING PARAMETERS - 5-FOOT-DIAMETER TEST SKINS AND MIRRORS*

Replica No.	Description	Temp. (°F)	Current Density (Amp/Ft^2)	Agitation
60-POM3: R8	Proof mirror	100	8.0	Gusher
60-POM3: R9	1st test skin	113	16.0	Rotation 8 rpm Gusher
60-POM5: R3	2nd test skin	105	15.0	Rotation 8 rpm Gusher
60-POM5: R4	3rd test skin	105	15.0	Rotation 8 rpm Gusher
60-POM5: R5	4th test skin	104	15.0	Rotation 8 rpm Gusher
60-POM5: R6	1st attempt 1st mirror	104	15.0	Rotation 8 rpm Gusher
60-POM5: R7	2nd attempt 1st mirror	105	15.0	Rotation 8 rpm Gusher
60-POM5: R8	1st test skin 2nd mirror	107	17.5	Rotation 8 rpm Gusher
60-POM3: R10	1st attempt 2nd mirror	107	17.5	Rotation 8 rpm Gusher
60-POM3: R11	2nd attempt 2nd mirror	107	15.0	Rotation 8 rpm Gusher
60-POM3: R12	3rd attempt 2nd mirror	107	15.0	Rotation 8 rpm Gusher

*All plated in tank 1, containing a nickel sulfamate bath as described in Section 3.

complete and the experimental goal was limited to proving of the secondary plating of the torus flange, the decision was made to continue the procedure of using the stationary master and anode holding fixture as shown in Fig. 42, the same arrangement as was used in the plating of the preliminary test skin. The skin was used directly, without parting it from the master.

The mandrel configuration between skin and torus was poured and shaped. The torus flange of the assembly was then plated as shown in Sect. B of Fig. 41, and as illustrated in Fig. 43. A continuous bar anode around the entire part was used. Bath temperature of 100°F and current density of 8 amp/ft^2 were the same as in the plating of the skin. A robber strip on the masked torus was employed successfully in minimizing edge buildup on the plating.

After the mirror was parted from the master, the cleaning procedures were undertaken. Two methods of mandrel wax removal were tried. One method used radiant heat and a warm air blower, as shown in Fig. 44. The other involved mounting the concentrator on the newly completed swivel fixture (Fig. 18) and revolving the tilted rim in a warm solvent bath.

For two reasons it was determined that the volume of wax used in the mandrel would be reduced in following experiments. First, the rim parted slightly from the master along about one-fourth of its periphery during the torus flange plating, which permitted leakage between the concentrator's reflective skin and the master. This leakage must never be permitted, because it stains the skin in a way that is optically degrading. The excessive wax section in this experiment may have contributed to the premature parting and shrinkage.

The second reason for lowering the quantity of wax is to decrease the cleaning time. The leakage condition appears to have been aggravated by an extended time span between plating of the skin and final attachment of the torus, a result of the experimental nature of the work. Emphasis was placed on eliminating or reducing the time lag between plating stages on the subsequent mirrors.

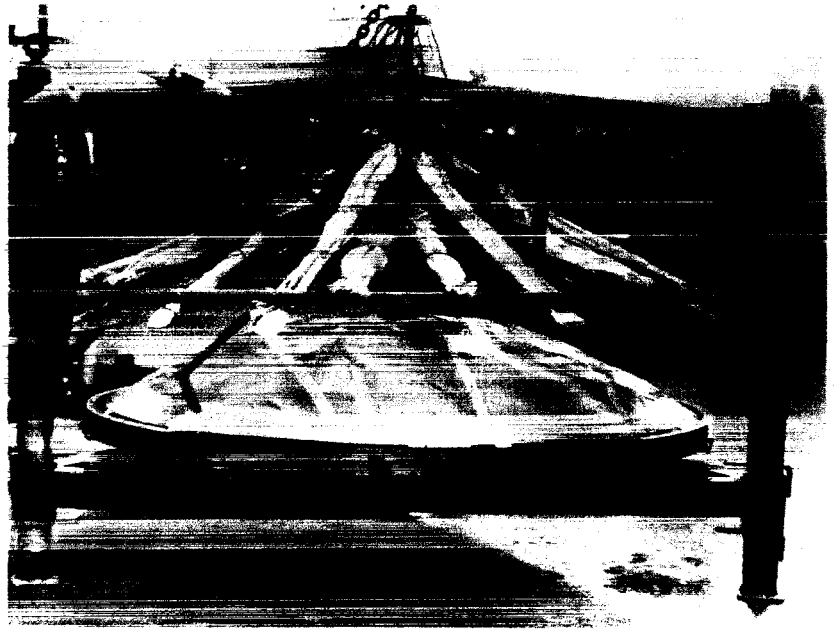


FIG. 42 STATIONARY HOLDING FIXTURE AND ANODE ARRAY

FIG. 43 TORUS FLANGE

FIG. 44 WAX REMOVAL AND CLEANING TECHNIQUE

5.3.3 Test Skins for Proofing Rotating Equipment

Work commenced in preparing the new rotating apparatus, which had been completed. The master (EOS 60-POM 3) was transferred from the stationary holding fixture to the new assembly with its rim bonded into the aluminum holding ring, as shown in Fig. 45. The completed assembly was checked for concentricity and reliability of the variable speed motor and drive line in various attitudes. A conforming anode array was assembled in a conical configuration as shown in Fig. 49. The plating bath was tested and modified to permit near-zero stress plating at a somewhat higher current density than formerly (a result of findings of the program's physical properties studies). The master was prepared for the test skin plating. The wax configuration was prepared for electroforming another skin, as shown in Sect. A of Fig. 41.

The part was plated at 113°F and at a current density of 16 amp/ft^2 to a nominal thickness of 0.009 inch. Rotation was set at 8 rpm, equivalent to a rim speed of 125 feet per minute. A filter outlet gusher, as shown in Fig. 49, also was used.

In parting the master suddenly cracked in an area about the center. However, the skin was usable for the scheduled experiment--sectioning for checking the material distribution. Fig. 46 illustrates a typical measurement location pattern for these skins. After being marked in the manner shown, the skin was cut up along the three planes shown and the skin's thickness was measured with a micrometer at each of the marked stations. With a ballpoint micrometer, even the rim groove area was examined. Because of the very even radial distribution that resulted from rotating the master over the anode array, only one plane's readings of each skin is given in Table VI.

The first skin (60-POM3: R3) was found to be heavy near the middle, so a mask was placed across the middle of the anode array. The cracked master was removed from the tooling and another master (60-POM 5) was put in place. It was decided that all subsequent test skins would be made at a reduced thickness, inasmuch as the distribution ratio would be the same.

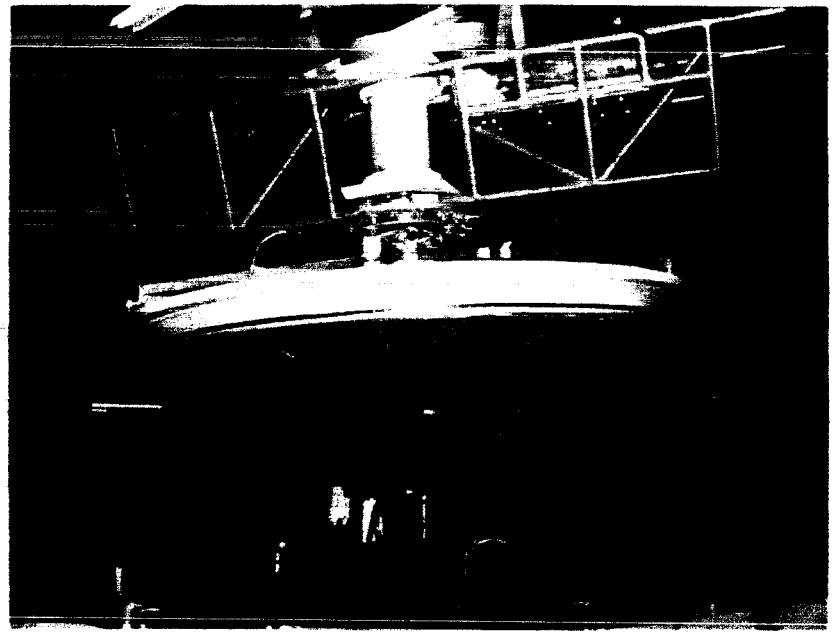


FIG. 45 COMPLETED MASTER ON HOLDING FIXTURE, ATTACHED TO ROTATING EQUIPMENT, PREPARATORY TO TORUS FLANGE PLATING

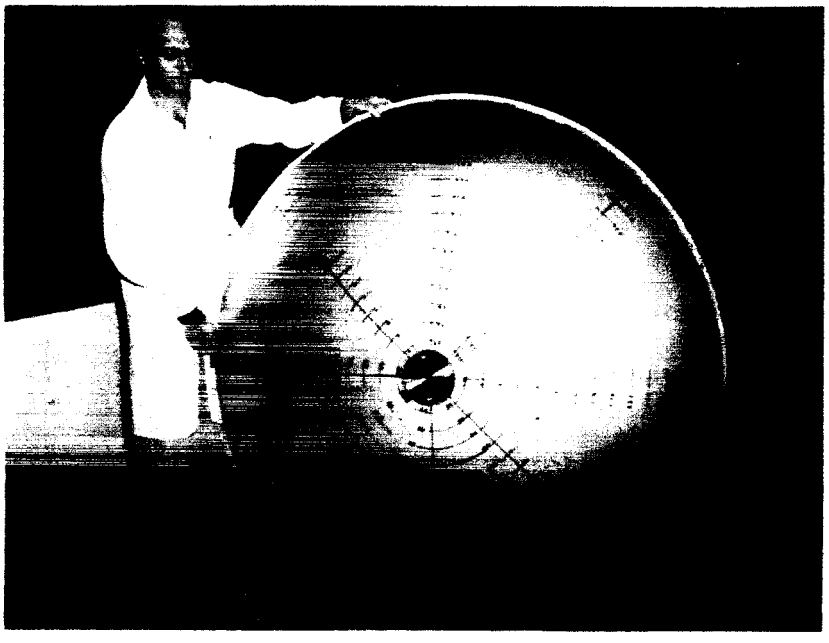


FIG. 46 TYPICAL MEASUREMENT LOCATION PATTERN

TABLE VI

MATERIAL DISTRIBUTION MEASUREMENTS - TEST SKINS

Radial Distance From Center (inches)	Thickness (inches)			
	60-POM3: R9*	60-POM5: R5*	60-POM5: R8*	60-POM3: R11*
4	0.0155	0.0056	0.0060	0.0047
6	0.0150	0.0051	0.0063	0.0051
8	0.0150	0.0052	0.0068	0.0058
10	0.0140	0.0052	0.0075	0.0065
12	0.0140	0.0053	0.0078	0.0070
14	0.0130	0.0055	0.0084	0.0074
16	0.0125	0.0057	0.0086	0.0078
18	0.0110	0.0055	0.0086	0.0080
20	0.0110	0.0057	0.0085	0.0081
22	0.0100	0.0056	0.0082	0.0082
24	0.0090	0.0053	0.0080	0.0082
26	0.0085	0.0052	0.0074	0.0083
28	0.0080	0.0051	0.0072	0.0088
30	0.0075	0.0050	0.0068	0.0089
31	-	0.0040	0.0064	0.0062
31.4**	0.0040	0.0025	0.0040	0.0048
31.7***	0.0090	0.0050	0.0075	0.0080

*EOS replica number

**Bottom of groove

***Flange wall of groove

The second plating was prepared and started, only to be quickly interrupted by some of the sensitizing silver falling away from the glass, resulting in a sharp drop in amperage delivered. The third test skin was successfully plated and indicated that most of the required correction in material distribution had been obtained. The anode mask was widened and a fourth skin was plated. This electroform (60-POM5: R5) was considered correct in distribution. This skin, like its predecessors, was given comparison tests, including visual inspection for similarity to high strength test specimens, for cracking and ductility.

5.3.4 The First All-Nickel Concentrator

While the aforementioned test skins were being plated, other work had been in progress on preparing and plating two lightweight tori for the complete concentrator assemblies. The "grown-in" plating technique was incorporated in their design in two stages. First, a stainless steel stud insert was encapsulated in the torus section as shown in Fig. 47.

The torus section was electroformed using an anode arrangement that would result in a tapered deposit, measuring just 0.002 to 0.003 inch in thickness at its ends to about 0.012 inch thickness adjacent to the encapsulated stainless steel stud insert. Total length of the section after trimming is 10 3/4 inches. The section was plated in a bath of the same composition as the bath used for plating the torus in which it was incorporated. Plating parameters also were similar. After electroforming, the mandrel was etched out of the section with acid and the section was cleaned.

For each torus, three of the sections were built into a mandrel as shown in Fig. 48 with polished aluminum tubing between the sections.

In the nickel torus mandrel, 1/8-inch-diameter holes were then drilled in a staggered pattern 1/2 inch apart around the outside of the mandrel, which would result in holes in the plated torus

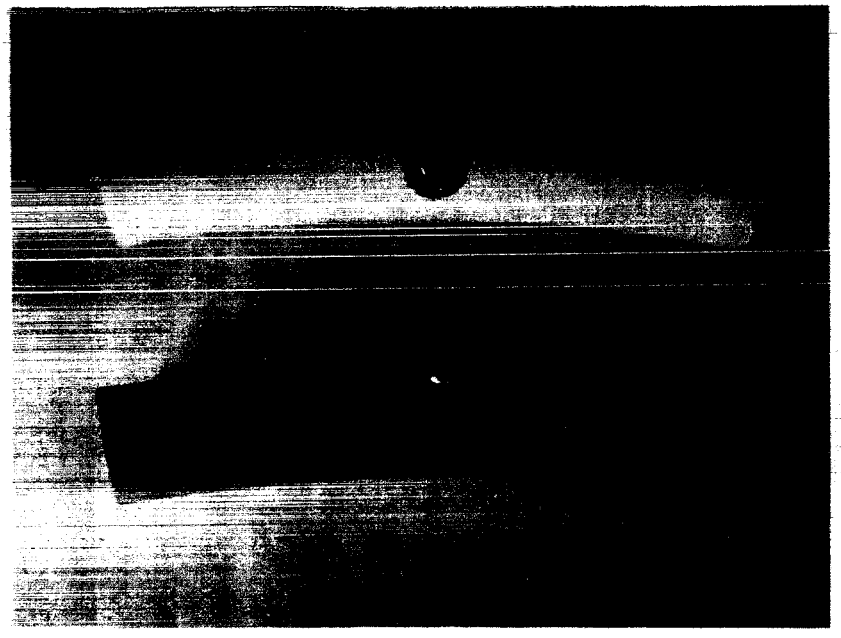


FIG. 47 ELECTROFORMED TORUS MOUNTING SECTIONS

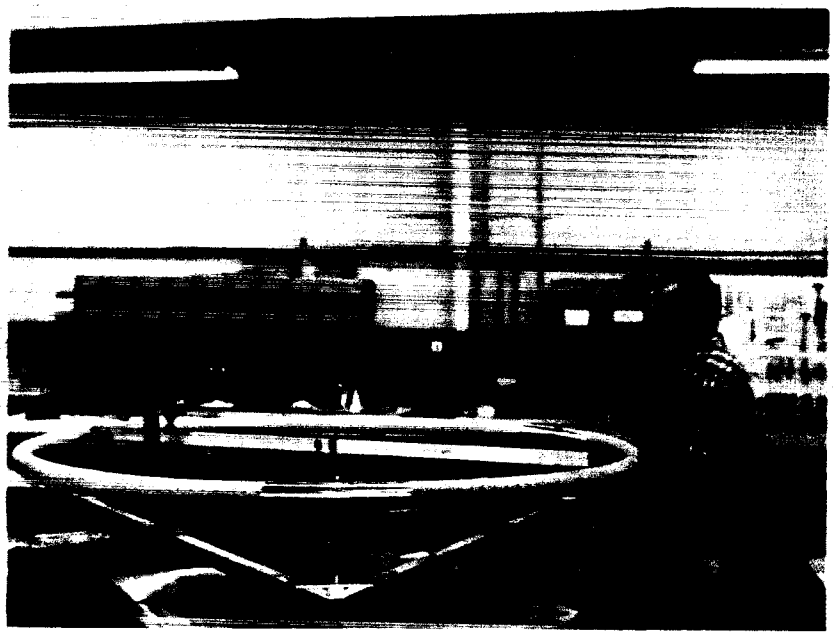


FIG. 48 COMPLETED TORUS MANDREL

(as shown in Fig. 48). This was not done in the case of the copper torus, because the plating characteristics of the copper sulphate result in excess buildup of deposited copper on the edges of the holes. Therefore, in this case the holes were drilled after plating.

The torus was then plated, using a sectional anode ar array. Plating parameters for all tori produced during the program are outlined in Table VII. After plating, the torus was lowered into an acid-etching bath and the aluminum inside the torus was completely etched out. After a thorough cleaning, the torus was ready for incorporation into a concentrator.

The master was prepared for plating a full thickness mirror skin and the electroforming was completed, only to result in a structure in which the rim groove area was even thinner than on some of the test skins, with voids indicating that additional effort was required in developing the sensitizing technique for the wax groove shape. The skin was discarded. During the parting, considerable difficulty was encountered in separating it at certain spots on the glass master which had rather pronounced chip holes. It was decided to resurface the master in these areas. This work was done using epoxy resin. Two changes were made to improve the rim thickness. On the next attempt at making a mirror skin, the entire assembly was tilted approximately 1 1/4 inches to eliminate possible gas entrapment in the groove, and an auxiliary anode (a 4-inch strip of titanium) was placed close into the groove.

The resulting skin (60-POM5: R7) was improved over its predecessor, although the groove area still appeared thin. It was decided to proceed with the preparations and electroforming of the torus flange. This was completed and the secondary plating for the torus flange was conducted. The configuration was the one shown in Sect. B of Fig. 41. However, when the assembly was removed from the tank, two problems were revealed. Slight leakage had occurred between the mirror's reflective skin and the glass, and cracks were observed at the joint of

TABLE VII TORI PLATING PARAMETERS AND WEIGHTS

Torus Number	Incorporated in Concentrator No.	Material	Temperature (^{o}F)	Current Density (amp/ft^2)	Agitation	Weight (lb)
171-4 *	60-POM5: R7	Nickel	100	10	Rotation 12 rpm	4.92
171-7 *	60-POM3: R12	Nickel	110	22	Rotation 13 rpm	4.12
171-8 **	To be plated	Copper	94	27	Rotation 12 rpm	5.25

*171-4 and 171-7 were plated in a nickel sulfamate bath with a composition as described in Section 3.

**171-8 was plated in a copper sulphate bath using the Dayton Bright additive system as described in Section 3.

the mirror's rim flange and the torus flange, which necessitated a third plating. This time a 5/8-inch-wide doubled strip around the entire mirror was electroformed over the cracked area. The parting resulted in some strain of the mirror skin, which caused visible optical deformation near the center. After its cleaning, the mirror was boxed preparatory to coating and testing. Completed weight was 17.02 pounds, some 2 1/4 pounds over the objective weight.

5.3.5 The Second Nickel Test Skin Experiment

A design change was made that modified the rim groove to the configuration shown in Sect. C of Fig.41. This was done, in view of the difficulties experienced during the several previous platings, to "throw" enough electrodeposited material down into the groove. The master was prepared with its wax edge in the new configuration and a plating (60-POM5: R8) was conducted. Upon its removal it was seen that the persistent problem of wax shrinkage had occurred, this time at the junction of the wax and the glass. Blisters of wax, in some cases protruding through the plated skin, indicated a concentration of current and resulted in burned spots. The skin was then cut up for material distribution measurements (Table VI), which resulted in outward adjustments of several of the large anodes in the main array to cause the change in thickness from center to rim to be almost linear. This was the last change in the nickel anode array required for the balance of the program (shown in Fig. 49).

5.3.6 The Second All-Nickel Concentrator

Preparations were made for plating a mirror skin for the second concentrator assembly. The master was to be resurfaced again, in that many of the epoxy resin patches had been pulled loose in the previous two platings and several new chips had appeared in the glass. However, the effort to etch the chip holes prior to repair resulted in still further degradation of the master's surface and its subsequent rejection from the program.

A master (60-POM 3) which had been cracked earlier in the program (see Subsection 5.3.3) was repaired on its concave face with glass doublers bonded with epoxy resin, as shown in Fig. 50. The master was leveled into rim plane on the rotation equipment (60-POM3: R 10) using an optical tooling level, and preparations were undertaken for a mirror skin. The plating was under way for 1 hour when burnout occurred along the rim between the silver amalgam on the wax above the groove surface and the chemical silver on the wax in the groove. Inspection upon removal revealed that shrinkage problems had not been completely solved by the changes in technique.

The continued problems in the groove area now resulted in a second change of the radius configuration (part e of Fig. 41), opening it up substantially to assure improved deposition. The preparations were made and plating of another skin (60-POM3: R11) was conducted. This experiment resulted in marked improvements over previous work, especially in regard to the groove area. A few small cracks in the skin prevented its use. These cracks developed in places where the wax apparently was not burnished into a very smooth surface. Increased attention to this area was to be given during subsequent platings.

At this point the auxiliary anode was enlarged, rigidized, and equipped with a rim jet gusher for improved agitation. The equipment is shown in Fig. 20. A final skin (60-POM3 R12) was then scheduled, and when plated was accepted. Work proceeded on the preparation and plating into the assembly of the second nickel torus, with the flange configuration per Sect. F of Fig. 41.

Figure 45 illustrates the master and torus flange mandrel just prior to plating. This plating was satisfactory, and the second concentrator was parted and cleaned. A small amount of mandrel wax had leaked under the skin and subsequently caused some problem in parting. Slight deformations due to parting are observable near the edge and in one streak across the face of this mirror. Final weight was 12.45 pounds, or 0.8 pounds under the target of 13.25 pounds. The detailed preparation instructions used in making this entire assembly are given in the next subsections. Plating parameters are listed in Table V.

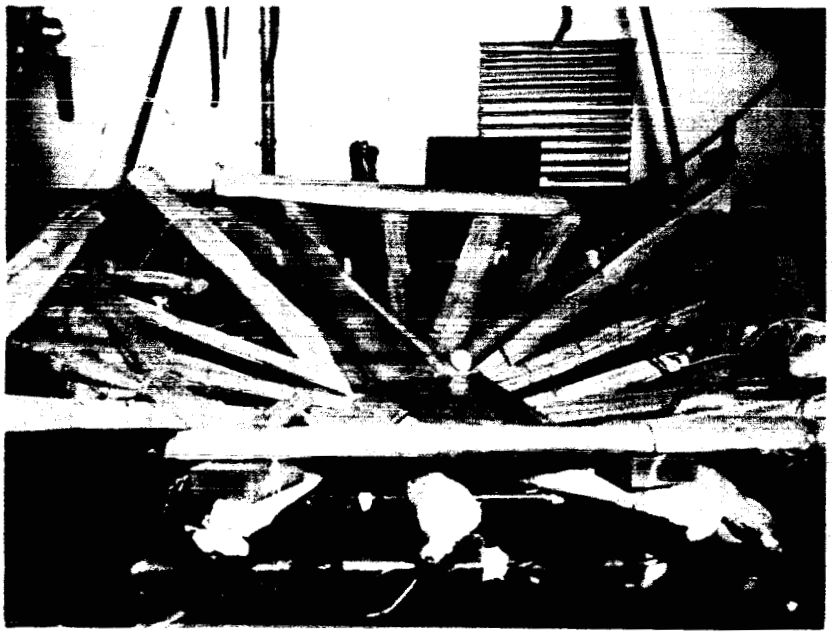


FIG. 49 FINAL CONFIGURATION OF MAIN NICKEL ANODE ARRAY

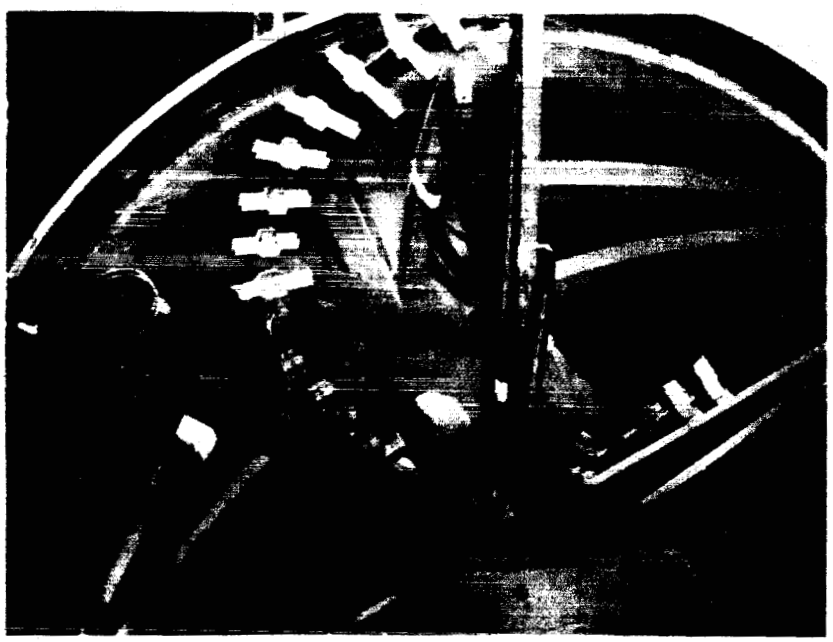


FIG. 50 MASTER NO. 60-POM 3 - VIEW FROM CONCAVE SIDE, SHOWING CRACKS AND REPAIRING METHOD

5.3.6.1 Detailed Procedure - Preparing the Master for a Skin Plating

1. After cleaning the master, attach its holding fixture to a bench with the convex side up.
2. Secure the outside dam around the master holding ring.
3. Pour wax to required depth.
4. Contour the wax to shape by cutting it at room temperature with the swing fixture indexed off a center shaft.
5. Mask off all wax outside groove area to be plated.
6. Inspect exposed wax and burnish it as required to eliminate all hairline cracks. Inspect for tight, smooth transition to glass.
7. Apply zinc chromate onto wax.
8. Apply silver amalgam (du Pont Co. - solvent - butyl acetate) on the zinc chromate surface and back onto the outside dam to bare metal for electrical contact. This work is illustrated in Fig. 40.
9. Inspect amalgam for flaws and retouch. Use extra care in applying a smooth transition coat at edge of glass.
10. Level master as required during an inspection with an optical tooling level. Measure at 12 or more points around the glass, equidistant from the center. Use the nuts retaining the master holding ring for the adjustment. The points must be in plane within 0.005 inch.
11. Mask off the amalgamed wax outside the area to be plated. Have the plating tape protrude over the edge of the groove 0.015 to 0.030 inch.
12. Check all electrical connections both on the rim and to the center plate. The master is now ready for silver sensitizing.

5.3.6.2 Detailed Procedure - Silver Sensitizing the Glass Master

Cleaning the glass master:

1. With the master mounted in a tilted position over the spray tank, apply acetone sparingly onto the glass with cotton. Avoid contact with the wax.
2. Rinse with tap water, 80° to $85^{\circ}F$.
3. Apply calcium carbonate chalk powder. Scrub it into a wet paste on the glass (8 to 10 minutes).
4. Rinse gradually with tap water, 80° to $85^{\circ}F$; continue to scrub.
5. Wash with detergent (Dreft, or equivalent, 1/2 cup per gallon) using lukewarm water and cotton.
6. Rinse with tap water, 80° to $85^{\circ}F$.
7. Wash with detergent (Dreft, or equivalent, 1/2 cup per gallon) using lukewarm water.
8. Sensitize the surface with stannous chloride - 5 gm/liter - dist. H_2O, reduced after solution with HCL to thin cloudy state followed by the addition of 2 cc/liter Duponol 80 organic wetting agent. Wipe over surface with cotton.
9. Rinse with tap water, 80° to $85^{\circ}F$. Keep all glass constantly wet; interject distilled water ($70^{\circ}F$) and wipe with cotton.

Silver sensitization:

1. Spray chemical silver over the wet glass, 9 to 12 minutes or until opaque.
2. Constituents: silver nitrate, sodium hydroxide, and 40% formaldehyde in water.
3. Rinse the glass with distilled water, 70° to $80^{\circ}F$.
4. Swab the wax groove with 1/2 to 1 lb/in^2 pressure, using a cotton swab, 2 revolutions.
5. Dry with a hand blower, emphasizing first the groove area.
6. Proceed with amalgam silver touchup.

Mandatory: The amalgam must be placed all around the glass-wax joint; all around the glass-center plate joint; all around the joints between center plates; full length of any cracks in the glass; and full length of any hairline cracks in the wax.

Note: If the silver must be removed for a repeated sensitizing, proceed as follows: Pour hydrogen peroxide and ammonium hydroxide over the tilted glass and then wipe across the surface with cotton. Rinse with tap water, 80° to 85°F. Dry thoroughly.

5.3.6.3 Detailed Procedure - Preparing for the Torus Flange Plating

1. After cleaning all plating solution off the entire master assembly, mount the master holding fixture on a bench with the convex side up.
2. Drill holes: first, to 0.050/0.070-inch diameter, then to 0.120/0.128-inch diameter in the mirror flange; 0.06/0.09-inch edge distance to top of flange, spaced at 1.0 ± 0.06 inch.
3. Remove any wax on the outside of the flange down to approximately 0.06 inch from the master's surface.
4. Grind the top of the flange as required to remove any plating beads. The outside surface of the flange must be flush.
5. Place the torus in position and tape a plastic film protective sheet over the mirror skin; then place tape between skin and torus.
6. Arrange a cylindrical dam about the flange and tape the holes in the flange on the outside. Pour wax to the required level.
7. Remove the cylindrical dam and contour the wax, cutting at room temperature.
8. Mask off the wax outside the flange, the flange and the torus, from the holes up.
9. Apply Z-spar enamel, white (Brolite Co.) in thin fog coats, intermittently sanding or burnishing it to a smooth surface. Continue until the surface is free of all imperfections.

(Total coatings may run 0.001 to 0.004 inch thick.) Allow to dry 12 hours minimum at room temperature.

10. Apply primer, dark grey (Ditzler Co., DZL 3475) in successive coats, drying 30 minutes minimum between coats. Wet-sand with 320 and then 400 grit cloth; polish the last coat with 600 grit.
11. Remove masking from the flange and torus, and sand nickel surface with 400 grit; polish with 600 grit. The mandrel surface is now ready for the plating.
12. Make final cut in wax outside flange, down to the master's surface, leaving a radius of wax as shown in Fig. 41, Sect. D, and carefully check seal between the plated skin and the master.
13. Check the electrical connections in the center. The unit is now ready for application of the silver sensitizing layer.
14. Clean and mask off nickel surface on mirror flange (over holes) and on torus (adjacent to and over holes).
15. Silver sensitize the area to be plated with several fog coats of sprayed silver amalgam (du Pont Co.). Carefully inspect each coat for cracks. Remove masking tape from bare metal. The assembly is now ready for plating, which should begin within 2 hours after sensitizing to avoid contamination and cracking of the exposed silver layer.

5.3.7 Copper Test Skin and Concentrator

The plating of the 5-foot-diameter unit has been delayed by the problems encountered, as outlined in the subsection on nickel mirror development (Subsection 5.3.4). Inasmuch as the copper work is incomplete, an addendum to this report will be issued in the future defining the copper plating experiments, with a final summary on the results of 5-foot-diameter mirror fabrication coating and testing on the program.

5.4 Coating the Concentrators

The first all-nickel concentrator was transported to a rented 5-foot-diameter vacuum coating facility and given vacuum depositions of chromium, silicon monoxide, and aluminum. The chromium is specified for

adherence between the sensitizing silver and the reflective layer. The silicon monoxide acts as a barrier to protect the reflective coating of aluminum. The aluminum has been confirmed by recent testing as the coating possessing outstanding reflectivity in a broad range of the solar energy spectrum, with reasonable durability if kept well covered when not in use. The coating apparatus, including EOS-supplied electrodes, glow discharge ring and material containers, performed as expected and the coating process was successful. Pressure-sensitive tape tests showed the coatings to be firmly adherent. The second nickel mirror and the copper unit will be coated at the same location and in the same manner. Any deviations from the process used on the first concentrator will be detailed in the addendum to this report.

5.5 Calorimetric Testing

5.5.1 The Technique

Concentrators produced on this program have been or are to be tested for efficiency with the calorimeter technique developed on earlier programs. This procedure was perfected on Contract NAS 7-10 and was reported in considerable detail in EOS Report 1587-Final. After first aligning the concentrator and calorimeter on axis and focal point with an integrated Hartmann screen (sun filter) in an EOS solar tracker, the readings are taken for orifice sizes ranging from 3/8 inch to 2 inches. A review of the data calculating procedure follows, using the hypothetical data shown in the following chart:

Data Source	Pyrhel. (mv)	Inlet (mv)	Inlet (^{o}F)	ΔT (mv)	Outlet (mv)	Outlet (^{o}F)	ΔT (^{o}F)	Pyrhel. (mv)	Flow (%)
Recorded	1.941	1.252		0.936				1.943	74.5
Reduced From Tables	1.941	1.252	88.52	0.936	2.188	128.42	39.9	1.943	74.5

Computation of K factor:

Pyrheliometer factor = 2.09 millivolts/cal cm^{-2} min^{-1} (Int.)

Btu equivalent = 1.77 millivolts/Btu ft^{-2} min^{-1}

$$\left[\frac{(\Delta T^{o}F)(\text{Flow - lbs } H_2O/\text{min})}{(\text{Pyr. mv})\left(\frac{1.77\text{ mv}}{\text{Btu/ft}^2/\text{min}}\right)(\text{mirror area})}\right]\cdot 100 = K\left(\frac{\Delta T^{o}F}{\text{Pyr.mv}}\right)\cdot\left(\frac{\text{Actual flow}}{\text{Specified flow}}\right)$$

Substituting,

Flow at 80 percent = 1.684 lbs H_2O/min

Mirror area = 19.77 ft^2

$$\left[\frac{(\Delta T^{o}F)(1.684\text{ lbs } H_2O/\text{min at } 80\%)}{(\text{Pyr. mv})(19.77\text{ ft}^2)\left(\frac{1.77\text{ mv}}{\text{Btu/min/ft}^2}\right)}\right]\cdot 100 = 4.81\cdot\left(\frac{\Delta T^{o}F}{\text{Pyr. mv}}\right)\left(\frac{\text{Actual flow}}{80\%\text{ flow}}\right)$$

Substituting

$\Delta T^{o}F$ = 39.9

Actual flow = 74.9%

$4.81\cdot\frac{39.9}{1.942}\cdot\frac{74.9}{80.0}$ = 92% efficiency

5.5.2 Calorimetric Test Results

Concentrator 60-POM5: R7 was considered somewhat degraded by the parting procedure before it was coated and tested. The data resulting from the test is shown in Fig. 51. Concentrator efficiency of 59 percent with the 1/2-inch orifice is considerably lower than the values obtained with earlier mirrors and is directly the result of the aforementioned damage to this unit. At larger orifice sizes the concentrator efficiency is relatively better inasmuch as the damaged areas were not severely deformed. For example, for the 1-inch orifice the efficiency is 78.5 percent and for the 2-inch orifice the efficiency is 85.8 percent.

The ultralightweight concentrator, 60-POM3: R12, was also degraded by the parting procedure but to a lesser degree than experienced with the first mirror. Calorimetric testing of this

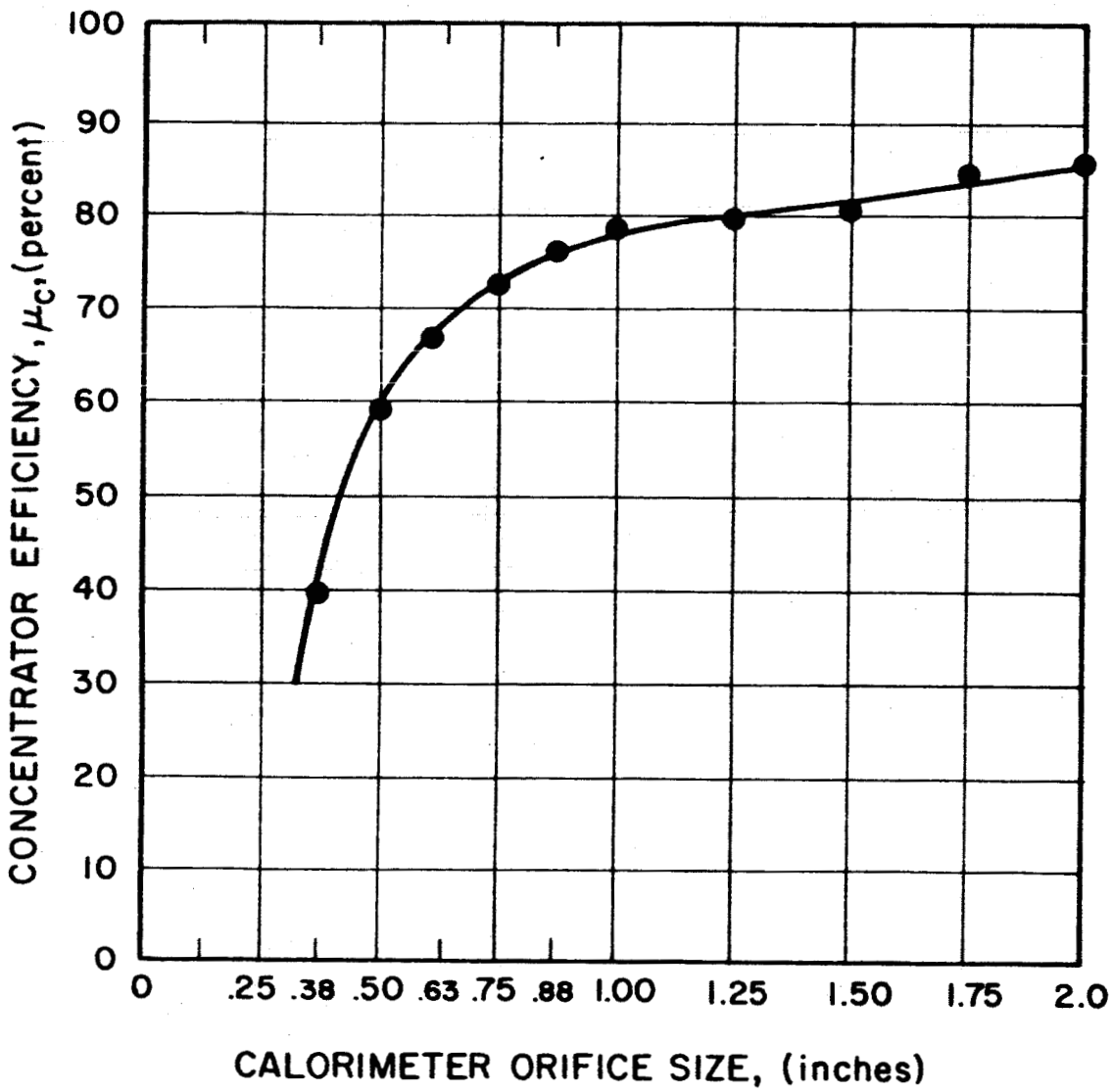


FIG. 51 TEST RESULTS - 60-POM5: R7

concentrator is in progress; it is expected that the data from this concentrator and also from the copper mirror will be discussed in the forthcoming supplement to this report.

6. SUMMARY OF PROGRAM

The developmental work performed during the course of this program confirms the feasibility of producing solar concentrators entirely by the electroforming process. Preliminary results of the work on concentrators possessing back-mounted torus structures tend to confirm the practicality of the approach of secondary plating for effectively locking together a highly efficient, thin-shelled structure. Although the final edge configuration does not give a completely reflective area, the design does represent a considerable improvement over the front-mounted torus employed earlier. Specifically, the front-mounted torus possessed an obscuration of 2 inches on the radius. The target for this program was 1/8 to 3/16 inch. The representative mirror (60-POM3: R12) uses 3/8 of an inch for the curved edge. Therefore, a major portion of the originally proposed improvement was achieved. The completion of the subject mirrors also confirmed the merits inherent in the rotation equipment application.

As was apparent during several previous programs, the electroforming processes require precise control and specific development for each variable in the work. On this program it was determined that scaling-up techniques must be analyzed carefully and perhaps limited in ratio. It was found that some design shapes and fabrication techniques that seemed satisfactory for 18-inch-diameter mirrors caused some difficulty until modified for the 5-foot-diameter mirrors.

The physical properties studies were especially beneficial in improving the state of the art, inasmuch as they firmly defined trends in the effect of the several key plating parameters on tensile strength, yield point, and modulus of elasticity. Bath controls and plating procedures have been improved and formalized into reasonably comprehensive, written procedures. Vacuum coating methods as applied to the finishing

of mirrors have been standardized, with some support for basic decisions from the results of the coating studies. These studies should be superseded in the future with more experiments, including more sophisticated approaches to specimen production and testing.

Specific problem areas include availability of reliable master tooling and copper plating solution control. The latter portion of the program was influenced by a critical shortage of 5-foot-diameter glass masters, a shortage that even threatened to halt the work in progress. This shortage of searchlight glass masters is now nationwide and underscores the need for replacement. The control and maintenance of an acceptable copper plating bath has continued to cause difficulty in that the hardening additives chemically degrade between platings. It is expected that development of a new approach in bath analysis procedures would lead to acceptable process reliability in the future production of high performance copper concentrators.

In summary, the present program brought to light new problems while solving others, answering questions, and improving existing design processes and techniques. The feasibility of the electroforming process for the production of an ultralightweight, high performance solar concentrator was again demonstrated. Future work should be concentrated primarily on tooling reliability and product improvement and, ultimately, on design and development of system hardware for flight test.