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FA-TR-75015

THE PROCESS AND TECHNIQUES OF MANUFACTURING REPLICA MIRRORS
(Cast Epoxy)

April 1975

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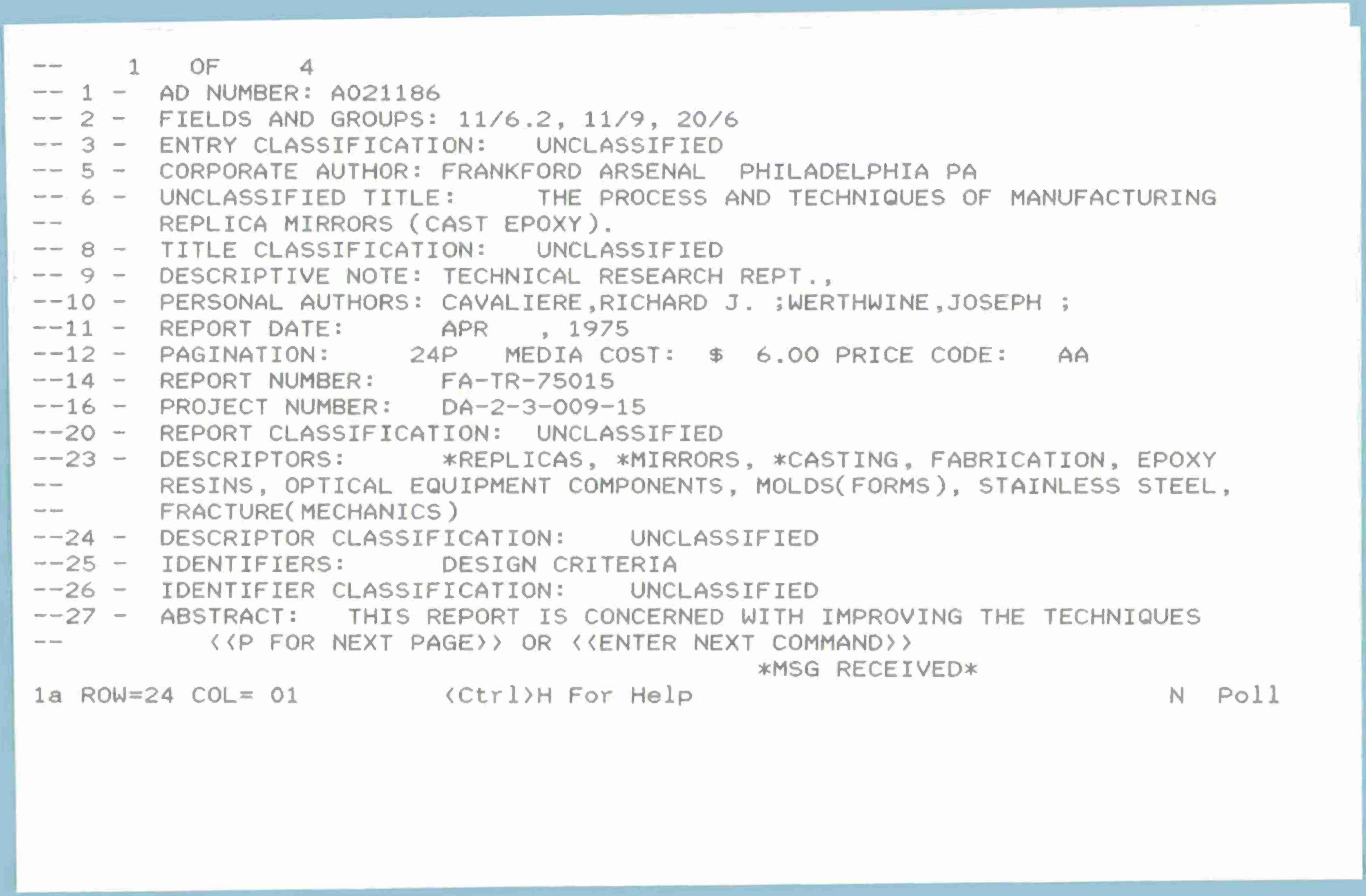
MANUFACTURING TECHNOLOGY DIRECTORATE

U.S. ARMY ARMAMENT COMMAND
FRANKFORD ARSENAL
PHILADELPHIA, PENNSYLVANIA 19137



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--     1   OF     4
-- 1 -  AD NUMBER: A021186
-- 2 -  FIELDS AND GROUPS: 11/6.2, 11/9, 20/6
-- 3 -  ENTRY CLASSIFICATION:   UNCLASSIFIED
-- 5 -  CORPORATE AUTHOR: FRANKFORD ARSENAL  PHILADELPHIA PA
-- 6 -  UNCLASSIFIED TITLE:     THE PROCESS AND TECHNIQUES OF MANUFACTURING
--      REPLICA MIRRORS (CAST EPOXY).
-- 8 -  TITLE CLASSIFICATION:   UNCLASSIFIED
-- 9 -  DESCRIPTIVE NOTE: TECHNICAL RESEARCH REPT.,
--10 -  PERSONAL AUTHORS: CAVALIERE,RICHARD J. ;WERTHWINE,JOSEPH ;
--11 -  REPORT DATE:       APR    , 1975
--12 -  PAGINATION:      24P   MEDIA COST:  $  6.00 PRICE CODE:    AA
--14 -  REPORT NUMBER:     FA-TR-75015
--16 -  PROJECT NUMBER:    DA-2-3-009-15
--20 -  REPORT CLASSIFICATION:  UNCLASSIFIED
--23 -  DESCRIPTORS:       *REPLICAS, *MIRRORS, *CASTING, FABRICATION, EPOXY
--      RESINS, OPTICAL EQUIPMENT COMPONENTS, MOLDS(FORMS), STAINLESS STEEL,
--      FRACTURE(MECHANICS)
--24 -  DESCRIPTOR CLASSIFICATION:    UNCLASSIFIED
--25 -  IDENTIFIERS:       DESIGN CRITERIA
--26 -  IDENTIFIER CLASSIFICATION:    UNCLASSIFIED
--27 -  ABSTRACT:   THIS REPORT IS CONCERNED WITH IMPROVING THE TECHNIQUES
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER FA-TR-75015	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) THE PROCESS AND TECHNIQUES OF MANUFACTURING REPLICA MIRRORS (Cast Epoxy)		5. TYPE OF REPORT & PERIOD COVERED Technical Research Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(*s*) RICHARD J. CAVALIERE JOSEPH WERTHWINE		8. CONTRACT OR GRANT NUMBER(*s*)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Frankford Arsenal ATTN: SARFA-MTT-O Philadelphia, PA 19137		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS Code: 3297.06.7261 DA Project: 673 7261
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Armament Command		12. REPORT DATE April 1975
		13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Replica
Master
Submaster
Preform
Layup
Parting

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report is concerned with improving the techniques of making replica mirrors as reported in "The Process and Techniques of Fabricating Replica," F.A. Report PP-T-2520-1 by Robert P. Hogan, Nov. 1967.

The process involves the reproduction of a polished mirror surface, in the form of a thin film epoxy casting complete in all details, on an aluminum preform.

20. ABSTRACT (Continued)

Double replication, used in this study, is a two stage process whereby an inverse replication of a master mirror surface is cast on a submaster, and is then conversely replicated on an aluminum preform. The epoxy, after proper vacuum coating, becomes the mirror, and the aluminum provides stability, rigidity and strength.

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GLOSSARY

REPLICA:	A thin film molded cast epoxy reproduction of an optical surface.
MASTER:	The form that contains the precise optical surface to be replicated.
SUBMASTER:	An intermediate vehicle for transferring the optical surface from the master to the preform.
PREFORM:	The permanent rigid backing for the replica mirror.
LAYUP:	The act of pouring the liquid epoxy and positioning the components to form the replica.
PARTING:	The act of separating the components that have formed the replica.

INTRODUCTION

Many attempts at making high quality optical elements have been tried and reported in the literature*.[1 to 4] Early techniques included the use of thick epoxy resin castings. However, because of the imperfect dimensional stability of even the best plastics, thick castings have failed to produce high accuracy elements.

Later programs*[5 to 7] have attacked the instability problem of plastics by reducing the thickness of the plastic layer, as much as possible, and obtaining rigidity by means of a stable preformed backing structure. The apparent problems encountered in these studies were: cracking of glass masters, plastic voids, cosmetic surface defects, and difficulties in separating elements after casting the epoxy.

This effort was directed towards; improvement of the mirror replicating process described in References 5 and 6; determination of process limitations; establishment of design criteria for fixtures, and components and a guide to economic feasibility. The Appendix of this report is a manufacturing process including the above.

SUMMARY

A review of the literature*[1 to 7] was made to gain familiarity with the process. A layup fixture (Figure 1 through 3 in the Appendix) was designed and manufactured to tight tool-room tolerances with respect to alignment and perpendicularity. Four paraboloid masters with a focal length of 4.2 inches and an aperture of 5 inches were designed and made out of pyrex. Two submasters with a 4.5 inch diameter and a spherical radius of 8.5 inches (best fit to paraboloid) were made out of 304 stainless steel. Aluminum preforms were made with a 4 inch aperture and with the same curvature as the submaster. An arbor press and an oven were set up level, and made suitable for the process.

The first attempt at producing a replica was made following precisely the procedures delineated in Reference 5, including; epoxy mixtures, release coatings, etc. The results were poor. The master cracked during the post cure cycle. The layup parted easily, but this was subsequently found to be true every time a master cracked. There were plastic voids in the replica surface; and, there were what appeared to be air bubbles in the cast epoxy. In addition, the plastic was not distributed concentrically even over the submaster.

The layup fixture had been made with bolts and lock nuts as position stops, which were difficult to set precisely, and depended on the force of gravity to hold the parts of the fixture together during

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*Refer to References on Page 23

the cure cycle. These details were remedied by providing hardened adjustable pins that could be locked in place with set screws, and locking screws that would hold the fixture together during the curing cycle.

Further attempts at replicating were made with much the same results except that difficulty in parting was encountered. A rough parting fixture was made utilizing spring pressure to affect a parting action on the layup. This worked on some occasions but was not completely reliable. In many cases, shock force in a splitting action had to be applied.

At this point the stock of glass masters was depleted, and a review was in order. The only thing behaving properly was the distribution of plastic so the layup fixture was not disturbed. Since the plastic was setting up with many defects a study of the effects of different proportions of epoxy resin and hardener was made. Since it was determined that master cracking was by thermal shock and internal stress, two masters were made of Cer-vit (a ceramic glass product of Owen-Illinois which has a thermal coefficient of 2×10^{-8}). As back-up to these, two masters were made of 17-4 PH stainless steel. For the sake of expediency, these four masters were made with a spherical radius of 8.516 inches. A new parting fixture (Figure 3 in the Appendix) was made with provision for "shock" parting.

It was found that a mixture of 100 parts epoxy to 15 parts hardener by weight produced a plastic with no visible defects, and this mixture was used throughout the remainder of the program.

Since the application of force would not be as catastrophic as it is on glass, the stainless steel masters were used for the next series of tests. Various materials were tried as release coatings, i.e. silver, aluminum and copper. Copper gave the best results, but its behavior differed with the thickness of the coating. It was found that the best results were obtained with a barely opaque coating of copper. This work was being conducted in an uncontrolled atmosphere, but when layups were made during periods of low relative humidity, the best results were obtained.

Since one of the primary purposes of this effort was to replicate parabolic surfaces onto spherical surfaces the condition of a thickness gradient was simulated by using sub-masters and preforms whose radii differed from that of the master by as much as .015 inches to determine the tolerable limits of plastic thickness. It was found that a thickness of less than .002 inches permitted the defects of the form to telescope through and a thickness of .012 or more caused measurable distortion. Plastic thickness limits were set at a minimum of .003 inches and a maximum of .010 inches.

One other point of consideration was the cure time established in References 5 and 6.* Sixteen hours is the normal downtime of a shop from one day to the next, and it could have been an arbitrary choice. With this in view some replicas were made using a 6 hour cure time, and the results were as good as those using 16 hours.

With the process revised to include all of the changes shown above a pilot production run was made using the one remaining Cer-vit master (one had cracked) and the two stainless steel masters. The other Cer-vit master cracked during this run. Data is documented in Table I.

There is very little discussion of vacuum coating in this report as the procedure was carried over, intact, from Reference 1 and is fully described in the appendix.

CONCLUSIONS

1. The quality of replica mirrors made from stainless steel masters are equal to those made from glass masters.

2. The process will not, at the present state-of-the-art, provide mirrors of the same high optical quality as precision glass mirrors. It will provide a relatively simple method for reproducing hard to machine surfaces with nominally good reflective surfaces; average 89% reflectivity using stainless steel masters, 91% reflectivity using Cer-vit.

3. The fact that the Cer-vit (very low expansion coefficient) cracked, indicates that ruptures were not caused by thermal shock. Rather it is believed that the diverse forces exerted by the differential expansion rates of materials in intimate contact with the glass coupled with internal stresses induced cracking.

RECOMMENDATIONS

1. The replication process can be used when the product specifications fall within the process capabilities.

2. The use of metal masters is recommended in lieu of glass. Other metals which can be used are:

   a. Any martensitic stainless steel.
   b. Tungsten carbide.

3. The replication process should only be used after making an economic analysis of alternate methods, using Appendix, Figure 7 as a guide.

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*Refer to References on Page 23

Table 1. Pilot Production Test Results

SAMPLE	MASTER MATERIAL	CURE TIME[1]	REFLECTANCE	RONCHI PATTERN	CURVATURE[2]	QUALITY	REMARKS
1	Cer-vit (Glass)	16 hrs.	92%	Good	4 rings L	Good	1st step parted easily, 2nd step required force.
2	Cer-vit (Glass)	16 hrs.	92%	Good	1 ring L	Good	1st step parted easily, 2nd step parted easily.
3	Cer-vit (Glass)	16 hrs.	90%	Poor	9 rings H	Poor	Master cracked. Mirror showed evidence of cracked master.
4	Cer-vit (Glass)	16 hrs.	89%	Poor	7 rings H	Poor	Master cracked. Mirror showed evidence of cracked master. Slight stain on surface.
5	Stainless Steel	16 hrs.	87%	Good	9 rings L	Good	Required force to part in both steps.
6	Stainless Steel	16 hrs.	89%	Good	6 rings L	Fair	Required force to part in both steps. Showed sputter marks on surface.
7	Stainless Steel	16 hrs.	88%	Good	4 rings L	Good	Parted easily both steps.
8	Stainless Steel	6 hrs.	90%	Good	9 rings L	Good	1st step parted easily, 2nd step required force.
9	Stainless Steel	6 hrs.	89%	Good	6 rings L	Fair	Required force to part in both steps. Slight stains on surface.
10	Stainless Steel	6 hrs.	91%	Good	9 rings L	Good	1st step required force to part. 2nd step parted easily.
11	Stainless	6 hrs.	89%	Good	6 rings L	Good	Both steps required force to part.
12	Stainless Steel	6 hrs.	87%	Good	3 rings L	Good	Required force to part in both steps. Some sputter marks. Slight stain on surface.
13	Stainless Steel	6 hrs.	90%	Good	2 rings L	Good	Required force to part in both steps.

1. Cure temperature was 130°F. Each sample was post cured for 1 hour at 200°F.

2. Curvatures were measured by the interference method using a 2.2 inch test glass. The Cer-vit masters measured 2 rings low, and the stainless steel masters measured 3 rings low.

THE PROCESS & TECHNIQUES OF MANUFACTURING REPLICA MIRRORS

(Cast Epoxy)

Contents

ILLUSTRATIONS

THE PROCESS & TECHNIQUES OF MANUFACTURING REPLICA MIRRORS

(Cast Epoxy)

1. PURPOSE. This manual provides a procedure for manufacturing spherical and aspherical mirrors by a double replication process using thin film cast cured epoxy resin as the replica.

2. SCOPE. The procedure described herein is typical for (but not restricted to) a concave mirror with a focal length of 4.25 inches and an aperture of 4 inches. The process will not provide mirrors of the same quality as precision made glass mirrors. It will provide a relatively simple method for reproducing hard to finish shapes and contours. Though dimensional precision can be accomplished, the maximum reflectance obtainable has been 90% and the surface finish exhibits some small cosmetic defects.

Glass masters are not recommended (because of the high incidence of cracking); however, the treatment of glass masters is included. A comparative curve of manufacturing hours required (Figure 7) for the replication process, individual manufacture of aspheric mirrors, and individual manufacture of spherical mirrors is included t serve as a guide to the production lots required to make the process economically feasible. Figures 5 and 6 show a flow diagram and chart for the replication process.

3. STATUS. This procedure is a suggested informational guide for other government installations or private facilities unless its use is made mandatory by official ruling.

4. FIXTURES, EQUIPMENT MATERIAL.

4.1 Fixtures

4.1.1 Layup Fixture (Figures 1 and 2).Should be designed with the same materials and precision of die sets and molds. Indexing pins and guide bushings must be used for precise alignment of parts and perpendicularity between parts. Stops must be adjustable and capable of being locked. Provision for locking two halves of the fixture together during the transfer from press to oven and the curing cycle must be made.

4.1.2 Parting Fixture (Figure 3). Need not be designed with the same precision as the layup fixture; however, the material used must be capable of withstanding shock.

4.1.3 Adapter (Figures 2 and 3b). Must be designed to receive the Preform and replace the master in the layup and parting fixtures.

4.2 Equipment

4.2.1 Standard

4.2.1.1 Equipment must include standard machine shop and optical shop equipment for making and inspecting masters and finished mirrors and for making fixtures and components.

4.2.1.2 Vacuum coating chamber with 3 electrodes, power supply, monitor and vacuum gages.

4.2.1.3 Forced draft, horizontal air-flow electric oven capable of maintaining a constant temperature of 130°F ± 1°F and large enough to hold the layup fixture in a level position during the curing cycle.

4.2.1.4 Forced draft, horizontal air flow electric oven with a temperature range of 100°F to 225°F and large enough to hold the parting fixture during the post-cure cycle.

4.2.1.5 A 3600 RPM centrifuge.

4.2.1.6 An analytical balance.

4.2.1.6 Miscellaneous
Mixing Cups
Cotton Swabs
Wood and/or Glass Stirrers
Lint-free Linen Cloth
Test Tubes
Beakers

4.2.2 Special

4.2.2.1 An arbor press (Figure 1) mounted level and modified to hold down the lower section of the layup fixture and raise and lower the upper section of the fixture in order to complete a layup.

4.3 Materials

4.3.1.Replica
Epon 828
Diethylaminopropylamine - DEAPA - hardner

4.3.2 Cleaning
Distilled water
Detergent (Joy)
Trichloroethylene
Acetone
Ethyl Alcohol
Isopropyl Alcohol
Ammonium Persulfate
Ammonium Hydroxide
Hydrochloric Acid
Nitric Acid
Stripping agent for cured epoxy resins Miller-Stephenson MS-111

4.3.3 Vacuum Coating
Copper
Chromium
Aluminum
Silicon Monoxide

5. FABRICATED COMPONENTS

5.1 Masters (Figure 2).

5.1.1 Glass (Any optical quality glass)

5.1.1.1 Specify tolerances and finish of mirror surface to be replicated somewhat better than desired mirror.

5.1.1.2 Design with diameter to thickness ratio of 6 to 1 and aperture at least 10% larger than diameter of submaster.

5.1.1.3 Dimension master for snug fit in layup fixture. (Fig. 2)

5.1.1.4 Machine external dimensions.

5.1.1.5 Generate surface to be replicated.

5.1.1.6 Grind and polish to specifications using standard optical shop practices.

5.1.2 Metal (Precipitation Hardening Stainless Steels 17-4-P.H.or15-5-P.H.)

5.1.2.1 Design as in sections 5.1.1.1 thru 5.1.1.3.

5.1.2.2 Machine external dimensions.

5.1.2.3 Generate surface to be replicated.

5.1.2.4 Heat treat to maximum hardness (See Metals Handbook for process).

5.1.2.5 Grind and polish to specifications using standard optical shop practices.

5.2 Submasters (304 or 316 stainless steel). (Figure 2)

5.2.1 Size and tolerance a spherical replica surface so that, with a minimum gap of .003" between the master and submaster, the maximum gap will be .010". Surface finish 16-32 microinches.

5.2.2 Design so that diameter of submaster is at least 10% smaller than the master aperture and at least 10% larger than the aperture of the preform. (Fig. 8)

5.2.3 Dimension submaster for snug fit in layup fixture. (Figures 2 and 3)

5.2.4 Machine submaster in accordance with standard machine shop practices.

5.3 Preform - Alluminum 2017-T4 or 2017 - T451 (Figure 3).

5.3.1 Size and tolerance a spherical replica surface so that, with a minimum gap of .003" between the plastic coated submaster and the preform, the maximum gap will be .010". Surface finish 16-32 microinches. (Fig. 8)

5.3.2 Design preform with diameter to thickness ratio of 6 to 1 and aperture at least 10% smaller than diameter of submaster.

5.3.3 Design for snug fit in adapter (Figure 3) which in turn fits in layup fixture.

5.3.4 Include overflow channel to receive excess plastic during layup. (Fig. 3)

5.3.5 Machine preform in accordance with standard machine shop practices.

5.4 Adapter steel 1040 (Figure 3).

5.4.1 Design adapter to receive preform and fit into layup fixture the same as the master fits in the fixture. Provide with set screws and threaded holes to secure the preform firmly.

5.4.2 Machine adapter in accordance with standard machine shop practices.

6. CLEANING PROCEDURES

Note: Throughout all processes, surfaces replicated or to be replicated should not be fingered.

6.1 Masters

6.1.1 Glass

6.1.1.1 Clean in trichloroethylene degreaser.

6.1.1.2 Wash with liquid detergent (Joy).

6.1.1.3 Warm water rinse.

6.1.1.4 Concentrated Nitric acid (Apply gently with cotton swab).

6.1.1.5 Warm water rinse.

6.1.1.6 Concentrated hydrochloric acid (apply gently with cotton swab).

6.1.1.7 Warm water rinse.

6.1.1.8 Precipitated calcium carbonate (apply gently with cotton swab).

6.1.1.9 Warm water rinse.

6.1.1.10 Distilled water rinse.

6.1.1.11 Dry in acetone degreaser.

6.1.2 Metal

6.1.2.1 Clean in trichloroethylene degreaser.

6.1.2.2 Wash with liquid detergent (Joy).

6.1.2.3 Warm water rinse.

6.1.2.4 Precipitated calcium carbonate (Apply gently with cotton swab).

6.1.2.5 Warm water rinse.

6.1.2.6 Distilled water rinse.

6.1.2.7 Dry in acetone degreaser.

6.2 Submasters and preforms (uncoated) same as subsection 6.1.2.

6.3 Submasters and preforms (plastic coated).

6.3.1 Strip copper (parting layer) with copper stripping solution.

- a. Ammonium Persulfate (75 gm/1).
- b. Ammonium Hydroxide (500 ml/1).
- c. Distilled Water
- d. Room Temperature

6.3.2 Warm water rinse.

6.3.3 Distilled water rinse.

6.3.4 Ethyl alcohol rinse.

6.3.5 Dry immediately with hot air heat gun.

6.4 Prepare masters, submaster for reuse.

6.4.1 Master

6.4.1.1 Master may have plastic flash on it from the excess use in replication. Use acetone or plastic stripper with cotton swab to remove flash.

6.4.1.2 Strip copper as in 6.3.1.

6.4.1.3 Warm water rinse.

6.4.1.4 Examine master (after a number of layups it may require a small amount of polishing).

6.4.1.5 Proceed as in 6.1.

6.4.2 Submaster

6.4.2.1 Remove plastic. This can be accomplished mechanically with a sharp cutting tool or chemically using a plastic stripping agent.

6.4.2.1 Proceed as in 6.1.2.

6.5 Glassware contaminated by plastic.

6.5.1 Soak in cured plastic stripper 24 hrs. (CAUTION: Use rubber gloves while handling).

6.5.2 Wipe off residue.

6.5.3 Soak in isopropyl alcohol for 1 hour minimum.

6.5.4 Remove and dry with hot air heat gun.

7. Vacuum Coating (Parting layer)

7.1 Master

7.1.1 Place master in a vacuum system in a suitable fixture at a source to substate distance of 15 inches or more.

7.1.2 Evacuate the system to 5×10^{-5} torr.

7.1.3 Without glow discharge, deposit a copper parting layer that is just opaque, as determined by the response of a photometer sensor or by visual observation.

7.2 Submaster.Same as 7.1.

8. Double Replication Process
<u>NOTE:</u> Humidity below 60% produces best results. Controlled atmosphere is desirable.

8.1 Prepare master (first replica)

8.1.1 Clean master as in 6.1. If previously used, start at 6.4.1.

8.1.2 Coat master (parting layer) as in 7.

8.1.3 Install master in layup fixture.

8.2 Prepare submaster.

8.2.1 Clean submaster as in 6.1.2. If previously used, start at 6.4.2.

8.2.2 Install submaster in layup fixture.

8.3 Set up layup fixture (first replica).

8.3.1 Place fixture in arbor press so that bottom section of fixture is anchored and upper section is fastened to the press ram with guide pins aligned.

8.3.2 Place soft thin tissue paper (.003" thick) on top of master and slowly lower upper section of the fixture so that the submaster rests on the paper.

8.3.3 Adjust fixture stops so that the gap (.003") is maintained between the master and submaster.

8.4 Mix epoxy resin and hardener.
CAUTION: Use rubber gloves while handling.

8.4.1 Weigh out 100 parts Epon 828 epoxy resin to 15 parts DEAPA hardner. (Use 4 times as much as is needed in the replica ,for large production runs the factor may be as low as 2 times).

NOTE: Hardener agent should be stored in a small container with a tight lid. It is particularly hydroscopic and has a full strength shelflife of much less than a year when exposed to air.

8.4.2 Mix resin and hardener thoroughly with wooden or glass stirrer for approximately 10 minutes.

8.4.3 De-gas the mixture for 5 minutes in a centrifuge.

8.5 Layup

8.5.1 Raise upper section of fixture.

8.5.2 Pour epoxy mixture on concave surface very slowly to avoid air entrapment.

8.5.3 Lower upper fixture very slowly until stops are engaged.

8.5.4 Secure the two parts of the fixture together so that there will be no relative motion between them during the curing cycle.

8.6 Cure Layup - Remove entire assembly from arbor press & place in pre-heated oven to cure. (6 hours at 130°± 2° F).

8.7 Post Cure

8.7.1 Remove assembly from oven.

8.7.2 Remove bonded master and submaster from the layup fixture.

8.7.3 Place master and submaster in parting fixture and tighten clamping nut until springs are fully compressed and the top of the fixture is clamped against the bottom.

8.7.4 Place fixture in oven (pre-heated to 200°F) and permit it to soak for 1 hour minimum.

8.8 Parting

8.8.1 Remove assembly from oven and permit it to cool at room temperature.

8.8.2 If the master and submaster have not parted at room temperature, place chisel in slots provided in fixture and strike sharply with hammer.

8.9 Prepare submaster.

8.9.1 Clean submaster as in section 6.3.

8.9.2 Coat submaster (parting layer) as in section 7.0.

8.9.3 Install submaster in layup fixture.

8.10 Prepare preform.

8.10.1 Clean preform as in section 6.1.2.

8.10.2 Install preform in adapter and put in layup fixture.

8.10.3 Second Replica - Proceed as in section 8.3 through section 8.8 replacing the master with the preform and adapter.

9. VACUUM COATING (MIRROR)

9.1 Strip copper and clean as in section 6.3.

9.2 Place in vacuum coating equipment at least 15 inches from the sources.

9.3 Reduce pressure in vacuum chamber to $5X\ 10^{-5}$ torr.

9.4 Deposit a 30-40 percent reflective film of chromium.

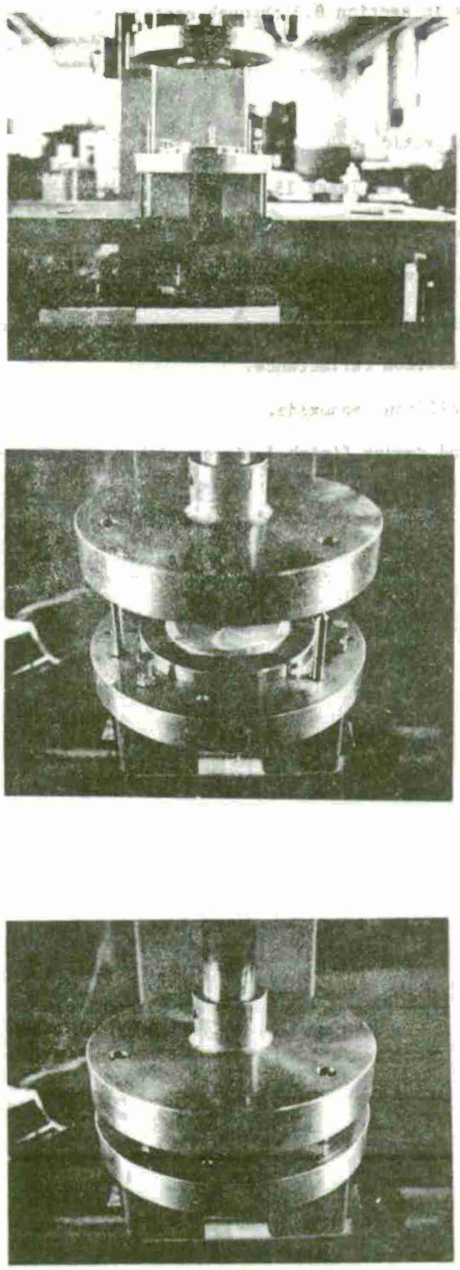
9.5 Follow immediately with a rapid deposition of $\frac{\lambda}{2}$ of silicon monoxide.

9.6 Rapidly deposit aluminum to maximum reflectance.

9.7 Slowly deposit a $\frac{\lambda}{2}$ of silicon monoxide.

9.8 Admit air to vacuum system and remove finished mirror. Bake at 175°F for minimum of 2 hours to improve coating adhesion.

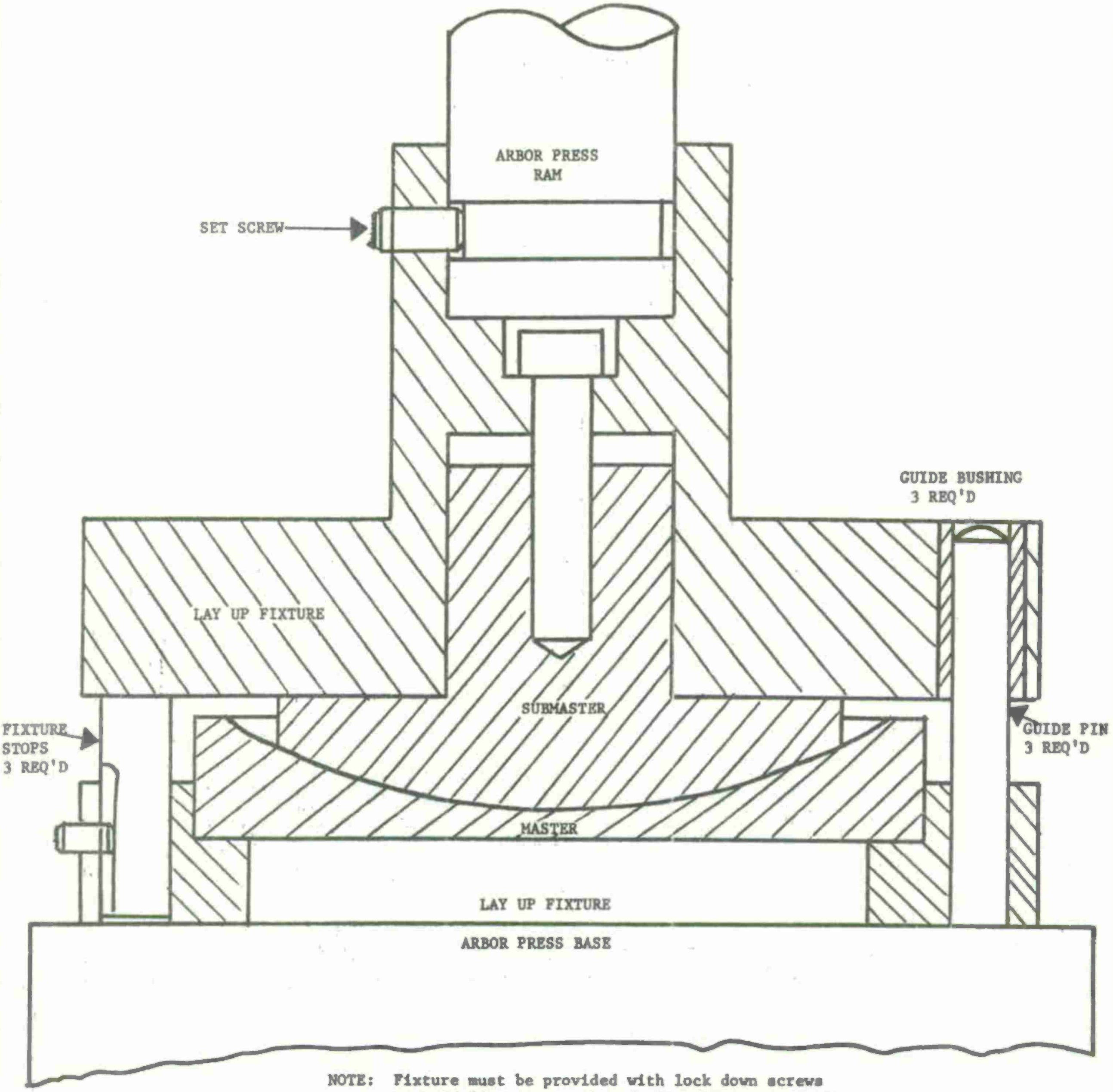
10. INSPECTION. Finished mirror shall be inspected in accordance with design specifications.



3 STAGES OF LAYUP FIXTURE

MOUNTED ON ARBOR PRESS

FIGURE 1

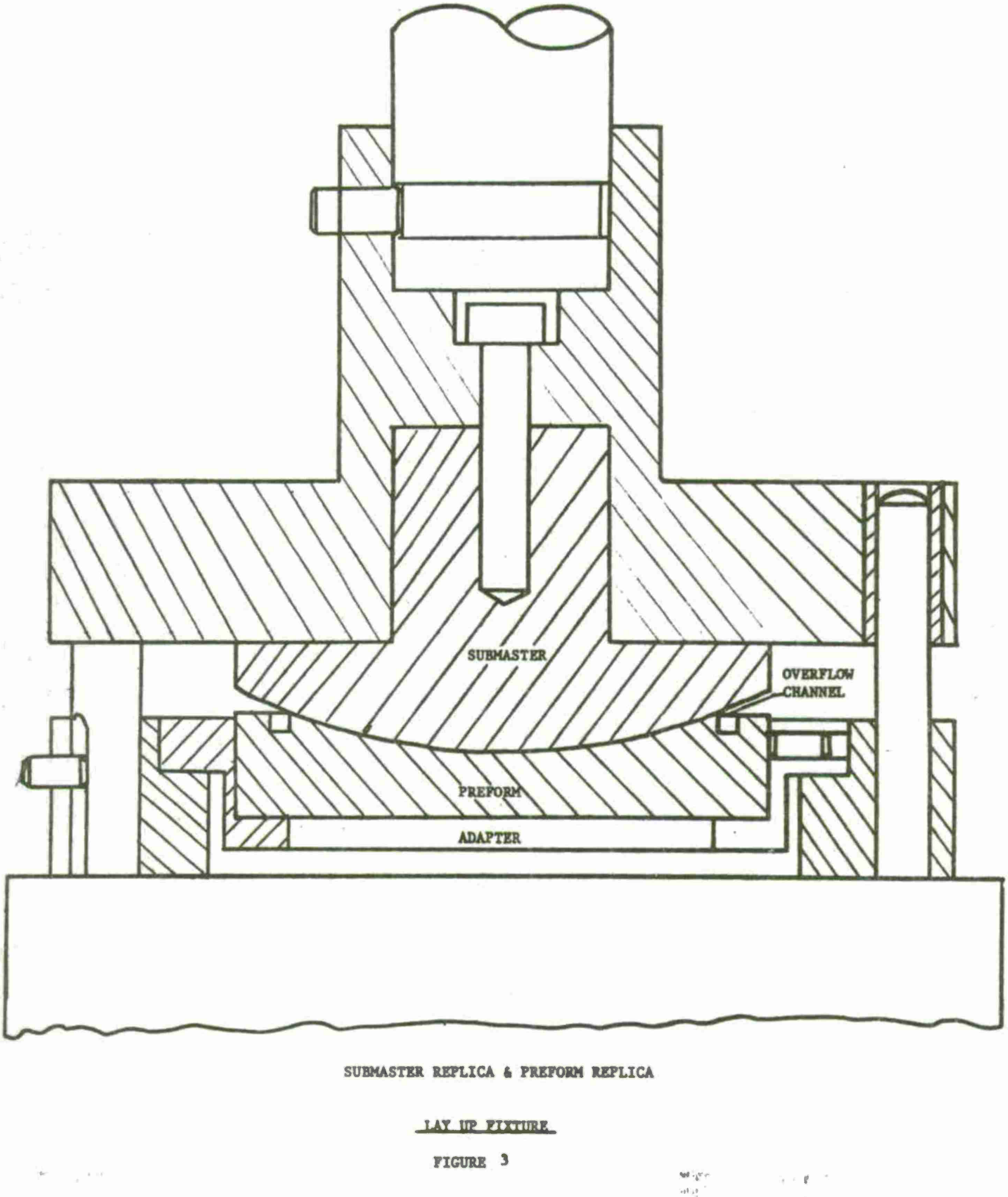


NOTE: Fixture must be provided with lock down screws to hold fixture together during the curing cycle.

MASTER & SUBMASTER REPLICA

LAY UP FIXTURE

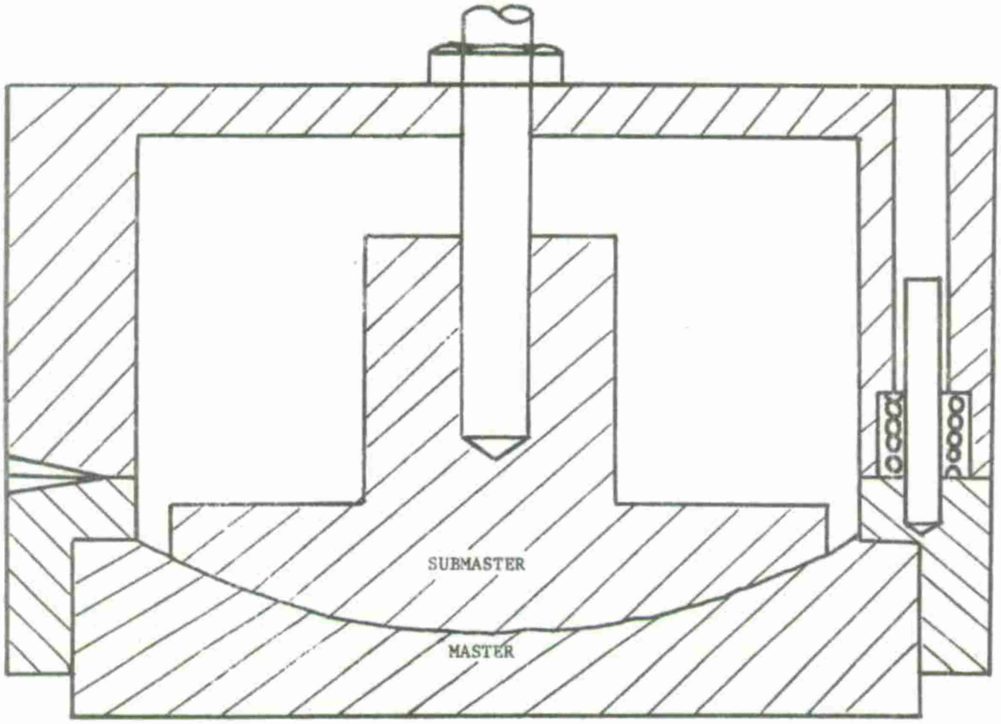
FIGURE 2



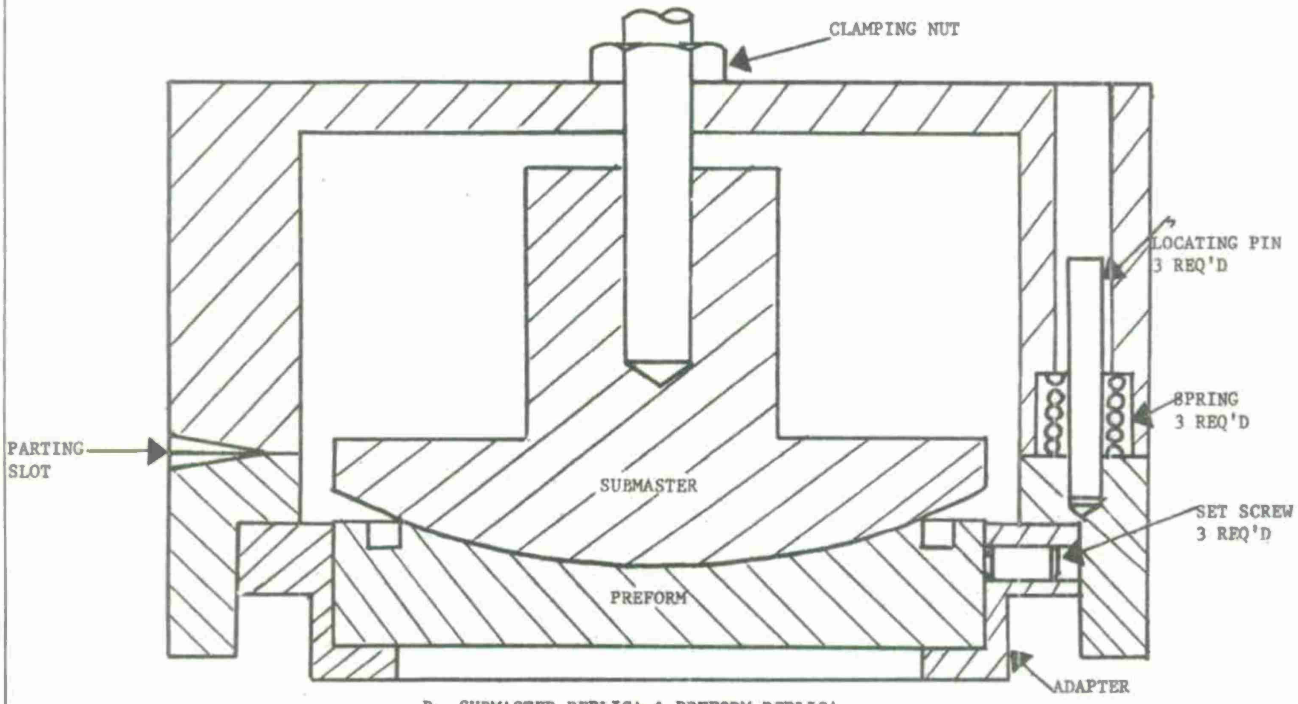
SUBMASTER REPLICA & PREFORM REPLICA

LAY UP FIXTURE

FIGURE 3



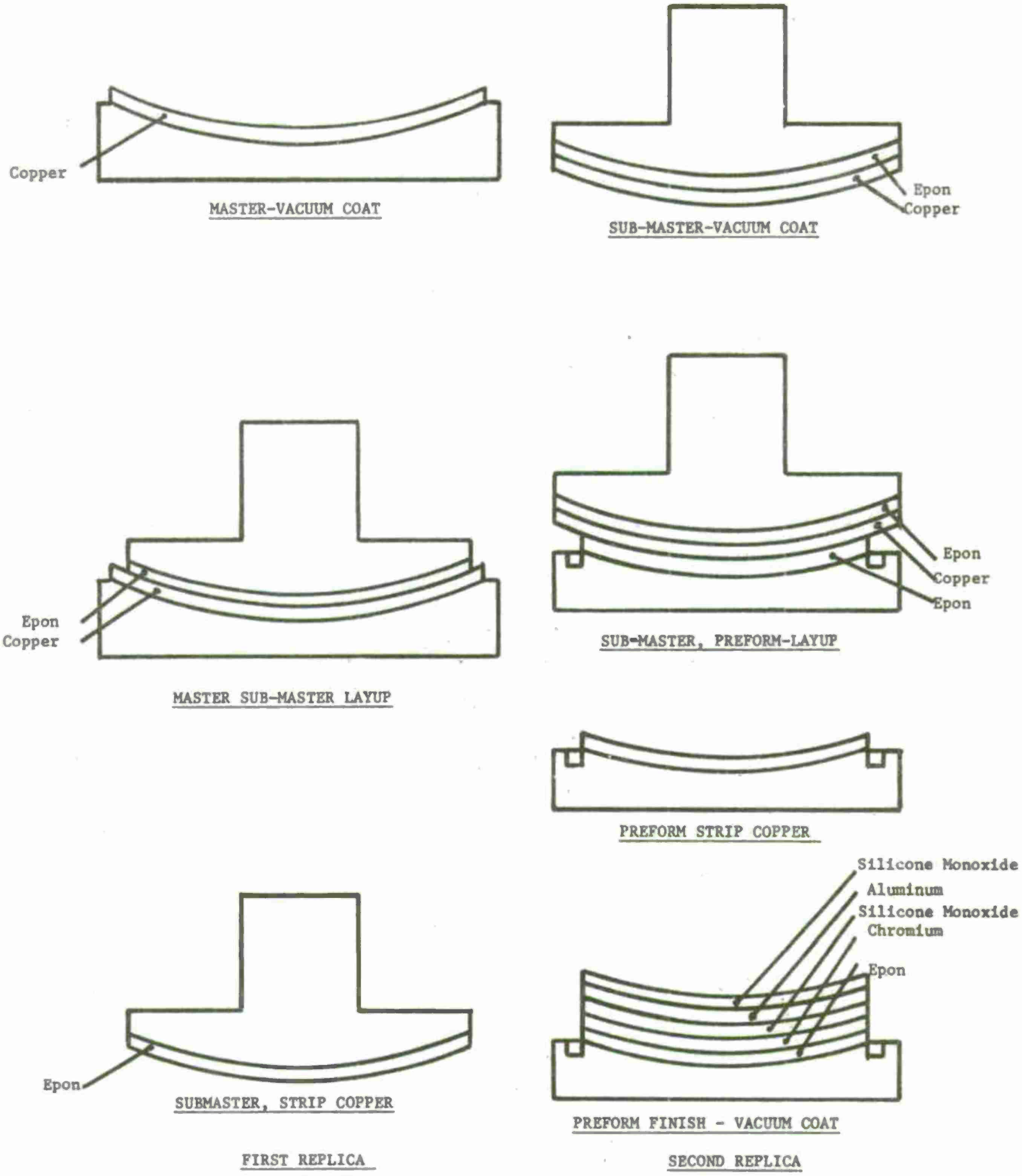
A. MASTER & SUBMASTER REPLICA



B. SUBMASTER REPLICA & PREFORM REPLICA

PARTING FIXTURE

FIGURE 4



MASTER-VACUUM COAT

SUB-MASTER-VACUUM COAT

MASTER SUB-MASTER LAYUP

SUB-MASTER, PREFORM-LAYUP

PREFORM STRIP COPPER

SUBMASTER, STRIP COPPER

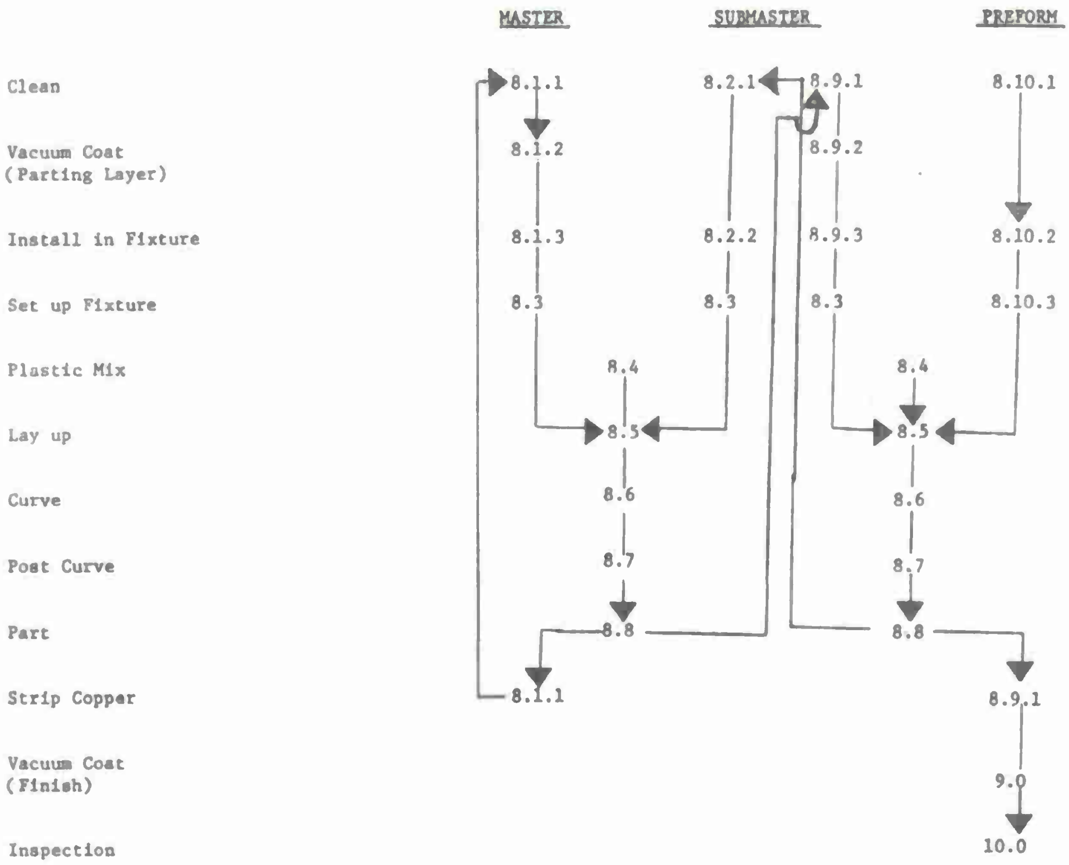
PREFORM FINISH - VACUUM COAT

FIRST REPLICA

SECOND REPLICA

DOUBLE REPLICATION PROCESS

FIGURE 5



FLOW CHART DOUBLE REPLICATION PROCESS

FIGURE 6

A study of Frankford Arsenal production runs on individually made glass spherical and aspheric mirrors revealed manufacturing times required for runs of up to 25 units. Included in the laboratory study of the replication process was a pilot production run of approximately 20 mirrors. Since the tools for the replication process are unique for each design the manufacturing time was averaged over the time to fabricate 25 replicas (much less than actual tool life) and was included in the total. Mirror materials are not included but will be a factor depending on production lot size. Cost of capital equipment was ignored.

Using the above data, experience curves were developed using the form:

$$Y = AX^{b}$$

where

Y = Manhours

and

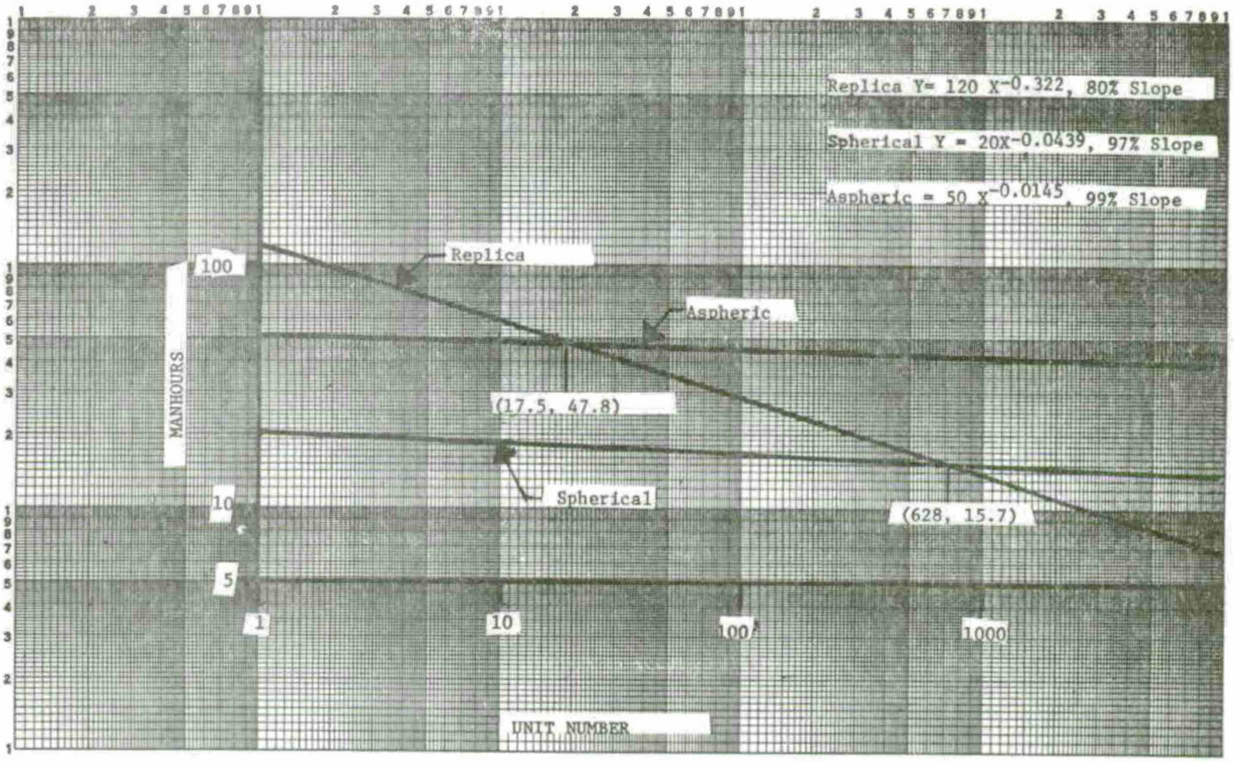
X = Unit Number

Whick in logarithmic form becomes

$$\text{Log } Y = \text{Log } A + b\text{Log } X$$

and can be plotted on log log paper as a straight line as shown below.

These curves are only suggested as a guide to production planning.



EXPERIENCE CURVES

Figure 7

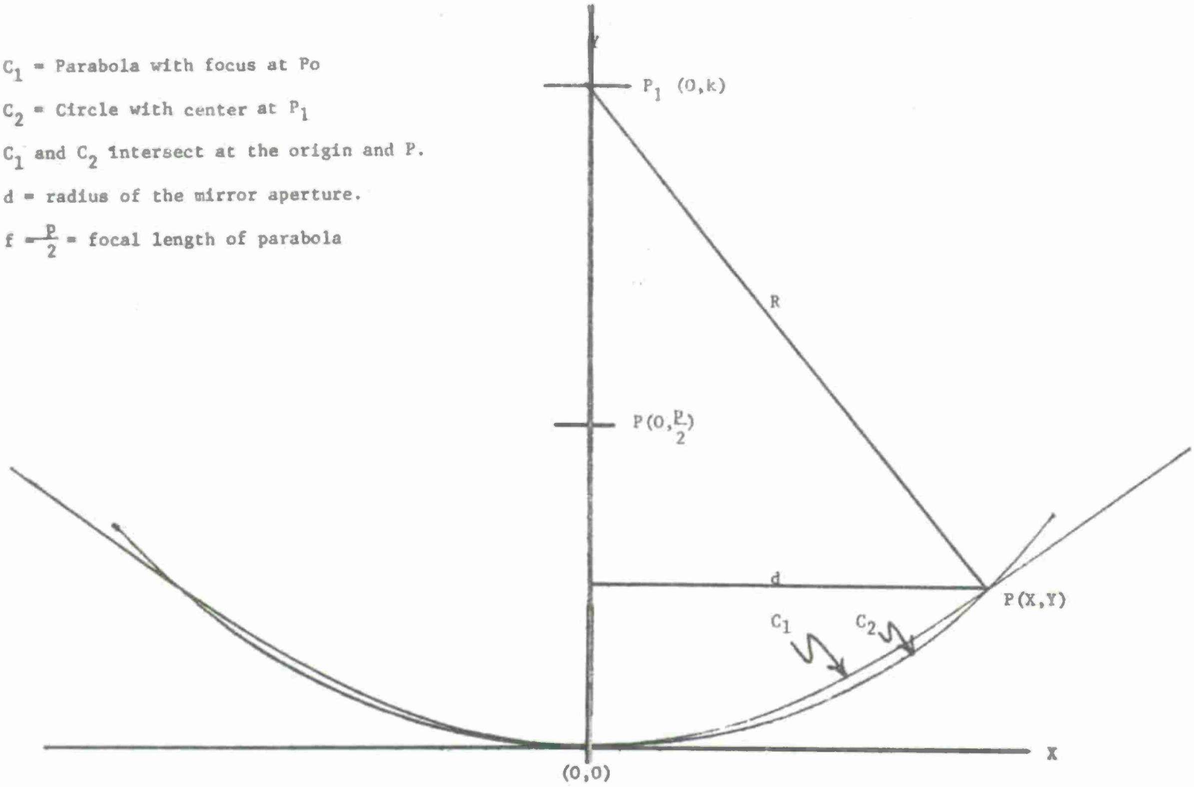
C_1 = Parabola with focus at Po

C_2 = Circle with center at P_1

C_1 and C_2 intersect at the origin and P.

d = radius of the mirror aperture.

$f = \frac{p}{2}$ = focal length of parabola



The general equation for C_1 is:

$$2\,py = x^2$$

since $f = \frac{p}{2}$

$$4f = 2p$$

and

$$y = \frac{x^2}{4f}$$

The general equation for C_2 is:

$$x^2 + (y-k)^2 = R^2$$

But k = R
and

$$x^2 + y^2 - 2Ry + R^2 = R^2$$

This reduces to

$$X^2 + y^2 - 2Ry = 0$$

and

$$R = \frac{x^2 + y^2}{2y}$$

Substituting $y = \frac{x^2}{4f}$ and x = d

$$R = 2f + \frac{d^2}{8f}$$

Where R is spherical radius of submasters and preforms

BEST FIT OF SPHERE TO PARABOLOID

FIGURE 8

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Date Printed: 9 January 1976

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