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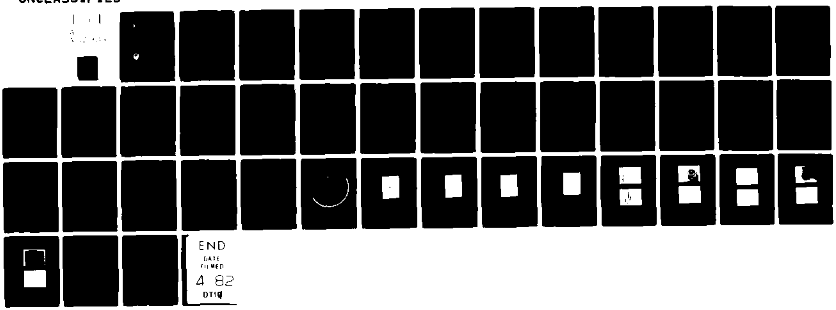

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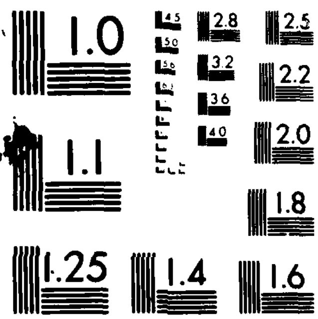

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TECHNICAL REPORT RH-CR-82-7

MM&T: PRECISION MACHINING OF OPTICAL COMPONENTS

INTERIM II

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December 1981

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

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

The second interim technical report describes the results of Option I of the contract whose purpose is to establish a commercial manufacturing base for cost-effective production of Army high energy laser and infrared optics and optical support items for Army systems applications.

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FOREWORD

This report is the IntOp Interim Manufacturing Methods Report called for under Contract DAAK 40-79-C-0255 at the conclusion of Option I. For consistent presentation this report format follows the sequence of the five tasks assigned under Option I.

This interim report covers the period of July 1980 to September 1981. A description of the personnel, machinery and results of the crew training program, a description of the output of the GFP flycutting flat generator, the check out of the facility environmental controls, illustrations of the proof parts assigned for construction on the GFP machine and a description of metrology implementation forms the body of this report.

The program is under the direction of the U.S. Army Missile Command. Mr. William Friday is the Project Engineer. The work at IntOp is under the general direction of Mr. Arthur E. Hess who is acting Program Manager. Technical support is assigned to the engineering department under the direction of Mr. Gordon J. Watt who is acting as Chief Investigator.

1.0 TASK V

1.1 FOREWORD

Paragraph 3.4.1.1 of the subject contract requires that a crew be selected and trained to operate the precision machine tools involved in this effort.

1.1.1 INITIAL CREW TRAINING

Two members of the IntOp crew were selected for initial crew training. These two people are a highly qualified tool maker and a superior mechanical technician. It was felt that a start with a basic cadre to work on areas of machine operation part tooling, fixturing and machine maintenance, would be less cumbersome than would a full unqualified crew receiving training simultaneously. Each crew member was instructed to maintain a log of work assignment and a detailed method sheet indicating initial and final conditions of things such as tool selection, feeds, speeds, coolant flow, etc. After the basic training of the initial group was completed more trainees were added for a total of five people.

1.1.2 PRECISION MACHINING CREW

The group of people that have been selected for training in the use of precision machinery consists of one mechanical designer, two machinist and two mechanical technicians. The designer underwent a modified training program since his objective is to gain first hand experience with diamond turning so that he will have a better understanding of the detailed requirements for part fixturing.

1.2 GFP TRAINING MACHINE

A single axis precision machine tool was made available for use in the crew training program as government furnished property.

The machine incorporates a horizontally mounted pivoting cutter head and spindle assembly and a generating head and spindle assembly with a vacuum chuck mounted on a work slide assembly. All are mounted on a common 3000 lb. granite bed. The granite bed is mounted on a stress free steel weldment which is in turn hydrostatically shock mounted for vibration isolation, and incorporates automatic self leveling.

All associated equipment and controls are attached to a floor-mounted guard wall surrounding the granite bed. The associated equipment includes spindle coolant reservoir controls, electrical and hydraulic controls, vacuum lines, and cutting fluid mist sprayer.

The machine was equipped with one three inch diameter tool mount and one diamond tool. A vacuum chuck is provided with the machine that will accommodate parts from one inch to six inches diameter.

Additional vacuum chucks were provided by IntOp so that work pieces up to eleven inches diameter could be mounted. In order to accommodate flat proof parts identified under Task VIII, a flycutter type cutting head was designed and constructed and mounted on the GFP machine. Appropriate sample fixtures were designed and built. Gem quality diamond tools for use with this flycutter head were purchased and installed.

1.3 PART FIXTURING

In order to broaden the training experience, IntOp machinery was used in this training program in addition to the government furnished machine. The trainees worked with IntOp fly-cutters of two difference sizes, with a spherical generator and with a single axis lathe. This allowed us to accommodate a larger variety of fixtures. In some cases the sample to be cut was directly mechanically fastened to the fixture. In other cases an epoxy resin was used to support the sample in the fixture and various clamping modes were used including such materials as low melting temperature bonding media, clay and putty. The reaction of the sample parts to the holding pressures and deflections was noted. The location of restraining points was changed to accommodate surface figure. In some cases damping media was added to the body of the fixture to prevent vibrations which were transmitted to the part and resulted in surface deformation.

1.4 CHIP REMOVAL - COOLANT FLOW

The variety of machinery in use also permitted us to gain experience with both vertical and horizontal spindle positions. The government furnished machine and the single axis lathe have horizontal work and tool spindles. The fly-cutters have a vertical tool spindle and a horizontal stroking work slide. The spherical generator has a vertical work holding spindle and a tilting tool spindle which may be set from the horizon to the zenith. The attitude of the work, whether is is horizontal or vertical, is a major determining factor in chip removal and coolant flow. Obviously the ideal method of chip removal is to extract the chip at its point of formation without allowing it to touch the finished work surface.

When cutting materials that benefit from the application of coolant it is desirable to direct the coolant flow at the face of the cutting tool.

The goverment furnished machine and both fly-cutters have rapidly rotating tools. This, of course, presents some difficulties in directing the coolant to the preferred location.

With the current design of machine a compromise application of coolant must be determined.

1.5 PART QUALITY DETERMINANTS

The parts to be produced under this program have both flat and spherical optical surfaces. The quality of these parts will be affected by the following factors:

1. Machine stability following set up
2. Stiffness between the tool and work
3. Ability to measure set up parameters
4. Machining forces between tool and work
5. Consistency of tool motion parallel to work
6. Selection of tool geometry
7. Feeds and speeds
8. Coolants and chip removal
9. Materials
10. Fixturing

The listing of the foregoing factors is not indicative of their importance. Their priority in fact, may very well depend upon the specification or the component that describes figure roughness, dig and scratch, diffraction, scatter, productivity rate and the like. Often it is difficult to sort out which of the above factors contribute to poor results and to what degree.

1.6 PART QUALITY

Examination of the quality of the surfaces produced under the training program to determine their compliance with the surface specifications set forth in paragraph 3.3.2 of the subject contract, emphasized the need for meticulous care required in the selection of tools, feeds, speeds, and coolant flow as applied to specific materials to be machined. A log was maintained by the operating personnel of the results obtained with various combinations of these parameters. It has been noted, for instance, that the direction of application of coolant flow will influence the surface finish produced. A selection of the coolant itself is another influencing factor.

It has been determined experimentally that tool selection - that is: rake angle, clearance angle, tool nose radius must be varied even when dealing with metals of the same general structure, such as, an aluminum 6061, 2024, 1100 series, etc. It has been found that these changes may in many cases be very subtle. A change of rake angle on the order of 'minutes of arc', for instance, can have an influence on the surface quality of the sample produced. For this reason several materials were cut experimentally. These included: various aluminums, copper, brass, electroless nickel plated parts, etc. It has also been determined that while broader tolerances of feeds and speeds are permissable, there are still however, limits within which one must work.

1.7 INTOP ASPHERICAL GENERATOR

In addition to the GFP Flycutting Flat generator, the two IntOp flycutters and the IntOp spherical generator, an aspherical generator was provided by IntOp for use in the training program. This machine has been designed and built by IntOp to answer the general requirement of Option II that the contractor obtain a multiaxis precision machine tool that can produce the tolerances required under paragraph 3.3.2 of the Basic Contract. It was agreed with Mr. Bill Friday, the project engineer for the U.S. Army Missile Command, that this machine be introduced in the training program for the dual purpose of training the crew and evaluating the equipment. The proprietary IntOp machine is in the general configuration of a chordal generator which will produce spheres and toroids with no dynamic control. In practice the best fit circular arc combined with dynamic correction of the appropriate axis produces the aspherical surface. Operating personnel have found that the aspherical generator requires the same care in the selections of tools, feeds, speeds and coolant flow as was required in the operation of the flycutters and G.F.P. machine. Particular attention was paid to machine operation in that machine stability, stiffness between tool and work, machining forces between tool and work, consistency of tool motion, etc., was monitored. For instance the strip chart recording shown in Figure 1. is typical of those produced throughout the machining operation. This trace shows the dynamic displacement of the tool spindle during the cutting of an aspherical surface. The trace was matched with the CNC input so that dynamic machine response could be monitored. In the sample trace it will be noted that, at the arrow, there is a protuberance in the trace line. Each small division on the chart is equal to two micrometers. The deviation in this trace is approximately one fifth of that dimension or 16 millionths of an inch. This translates to approximately 4 millionths of an inch displacement between part and tool. Perturbations of this type were constantly monitored by this and other means so that an analysis of their cause could be made and appropriate corrective action taken. As the nature of the influence each of these parameters has on the surface produced revealed itself, it became apparent that a machine operator, in order to do an adequate job, must be fairly well versed with the adjustments and selections available to him.

2.0 TASK VI - GFP FLY CUTTING FLAT GENERATOR

2.1 FOREWORD

Paragraph 3.4.1.2 of Option I of the subject contract states that the contractor shall be provided a single-axis precision machine tool as government furnished property. It will then be installed in the contractor's factory for use in crew training.

2.1.1 GFP FLY CUTTING FLAT GENERATOR

The machine provided is specifically designed for single point diamond cutting operations with the capability of producing a surface finish within one (1) microinch Arthmatic Average (AA) and flatness to within five (5) microinches per inch of surface on plane surfaces: and surface finish within two (2) microinches AA and surface figure to within twenty (20) microinches per inch of curve on spherical surfaces, except for the center .025 inch diameter on such spherical surfaces which has a degraded finish due to inherent geometric limitation of curve generation.

The machine has the capacity to generate spherical (concave, convex) radii infinitely variable from three (3) inches to infinity (plano) on a work piece two (2) to six (6) inches in diameter, and one quarter ($\frac{1}{4}$) inch to four (4) inches thick.

The machine can mill work pieces with face dimensions up to four (4) inches high by six (6) inches long, and from one half ($\frac{1}{2}$) inch to four (4) inches thick.

The cutter head assembly was provided with one three inch diameter tool mount and one diamond tool. One vacuum chuck to accommodate parts one inch to six inches in diameter was provided with the generator head assembly.

2.2 GFP MACHINE INSTALLATION

In addition to the space, air, power and vacuum requirements specified by the subject contract, additional diamond tools and fixtures were provided.

The addition tools and fixtures were required by the need to provide flat proof parts specified under paragraph 3.4.2.1 . The three inch diameter tool mount was supplemented with a one hundred and fifty millimeter flycutting head. An auxilliary vacuum chuck capable of holding parts up to eleven inches in diameter was provided. Additionally, adjustments were made to the alignment of the tool spindle axis with respect to the work axis so that flat parts whose surface figure conforming to the surface characteristics specification could be produced. This adjustment was made by means of appropriate shims. A maintenance log and machine use log was maintained in compliance with government property maintenance procedures.

2.2.1 OPERATION OF THE GFP GENERATOR

The GFP machine has two horizontal spindles; one for the work holder and one for the tool. The tool holder spindle axis may be rotated in a horizontal plane through an arc of plus 45° and minus 15° from coincidence of the tool and work holder axis. In addition, the work holder spindle may be translated in the 'X' direction normal to the zero axis location of the tool holder spindle. These adjustments give the machine the capacity to generate spherical concave and convex radii infinitely variable from three inches to infinity (or plano). In generating plano or flat surfaces two modes of operation of the generator are possible; in the first case, the 'X' axis offset of the work holder is used to translate the work holder spindle an appropriate distance so that the tool mounted in the fly-cutter head previously mentioned may be made to pass through the center of rotation of the work holder spindle. As in all cases of plano generation, the work spindle and tool spindle must be parallel. With this configuration the generator is caused to operate much like a single axis lathe. The resulting component surface will exhibit a rose pattern .

that has a central spot which has a degraded finish due to inherent geometric limitation of curve generation.

Flat surfaces were also produced by utilizing the 'X' motion of the work spindle. In this case, the work spindle was positioned to one side of the cutter head and with the cutter head rotating, the work was translated across the cutter face. When operating in this mode the work piece spindle must remain stationary. The pattern of the turned surface is identical to that produced in a normal flycutting machine. If however, the work is rotated as the work spindle is translated in front of the cutter, a confused pattern will usually be produced because this mode of operation superimposes additional minor misalignment and dynamic errors.

Fixturing in all cases consisted of vacuum type chucks.

3.0 TASK VII

3.1 FOREWORD

Paragraph 3.4.1.3 of Option I of the subject contract requires that the facility to house the precision machinery be checked to insure that its performance does meet the specifications written under paragraph 3.3.4.3 of the Basic Effort of Contract DAAK 40-79-C-0225.

3.2 GENERAL DESCRIPTION

A facility that meets the specifications generated under Task IV outlined in paragraph 3.3.4.3 of the basic portion of the subject contract has been constructed. The facility is generally described as a three stage environmental temperature controlled area. The first involves a basic structure that provides a very broad but controlled temperature. Second is a structure contained within this environment providing a more rigidly controlled temperature and humidity. It is within this structure that the GFP machine is housed. The third stage of this control is a local housing enclosing at least the workpiece-tool area of a single machine. Temperature within this housing is further processed.

3.2.1 PRIMARY ENCLOSING STRUCTURE

A section of the general plant that is adjacent to the general machine shop but separated from it by a full enclosing wall was selected. The concrete floor of the selected area is separated from the general shop floor by an epoxy expansion strip which acts to attenuate any floor-borne vibratory inputs. A rotary screw type compressor and a small vacuum pump, appropriately mounted, is the only floor mounted equipment located in the area. Year round temperature varies within the specified range of 55°F to 95°F and occurs at a seasonal rate.

3.2.2 ENVIRONMENTALLY CONTROLLED AREA

A free-standing, structurally independent, floor mounted housing has been constructed. This room has no common walls or ceiling and is entered through an air lock connected to the general shop. An auxiliary emergency exit door is not used except on rare occasion. The outer walls are constructed of wooden studding covered on the inside with smoothly taped wall board and insulated on the outside with glass wool which has been enclosed by a plastic thermal barrier. The ceiling is similarly constructed. There are no windows except those located in the anti-room doors. The general layout and dimensions of the structure is shown in Figure II. Inlet ducts, returns and sensors are shown.

It will be noted that all louvered inlets and outlets are ceiling mounted. The air enters the room through the two outside rows of ducts is projected down the walls to within about one to two feet of the floor and is returned via the central louvers. Direct drafts are thus avoided.

Air flow is approximately 2000 cfm with an inlet velocity of 500 ft/min at the register. Room air is changed 20 to 30 times per hour. Fibre glass ducting is used.

A refrigeration unit has been provided to initially chill the air to 55 to 60°F. This air leaves the diffusers at 60-65°F $\pm$ 1°F.

Trim heaters are located in the air duct exiting the air conditioning unit. These heaters are used in the final regulation of the air temperature. Dual sensors for both heat and cool are located centrally in the short walls at both ends of the room. They are located about five feet from the floor.

Figure III shows a typical temperature/humidity chart that is maintained within this facility. It will be noted that temperature is controlled to within one degree Fahrenheit.

Relative humidity control will be provided by the air conditioning unit. The relative humidity is controlled to 50 to 55 percent. The maximum heat load in the room is specified as:

2.0 watt/sq. ft.
6 people
12 horsepower

This load may vary considerably. For this reason appropriate valving for a hot gas by-pass has been provided. In addition the condensing unit has provision for independent operation for use during cold weather. The humidity control unit is mounted centrally on the long wall about five feet from the floor.

3.2.3 SUPPLEMENTARY CONTROL UNITS

When it is determined that the tolerances of a part to be produced can not be held when thermal excursions of a magnitude to be expected in the controlled room are imposed, a separate enclosure enveloping the vital machine areas must be provided. This enclosure will also be required when working with hygroscopic materials that require relative humidity of less than 55 per cent.

These units must be self contained and should work on the same principle as the basic room thermal controller. Inlet air will be taken from the basic room area at a temperature of 68° F $\pm$ 1° F. Provision must be made for chilling and then heating this inlet air so that a constant temperature of 68 °F $\pm$ 0.1° F may be maintained. Relative humidity must also be controlled to 40 to 45 percent. If required, filtration should be provided in these units. Care must be taken in the design of these enclosures to insure that they do no impart vibratory inputs of a mechanical or acoustical nature. Lighting within the enclosure should be provided by fibre optic transmission of similar means. A separate enclosure suitable for use with the aspherical generator is currently in the mock-up stage.

4.0 TASK VIII, PROOF PARTS

4.1 FOREWORD

Paragraph 3.4.2.1 of Option I calls for the manufacture of proof parts using the GFP precision machine tool after installation and machine check-out.

4.1.1 The following parts were described by Mr. Bill Friday Project Engineer, to satisfy this task of the contract.

TABLE OF PROOF PARTS

Quantity	Surface Figure	Material	Aperture
	Flat	Cu	10 x 10 cm square
	Flat	Cu	10 cm diameter circular
	Flat	Al	10 x 10 cm square
	Flat	Al	10 cm diameter circular
	1.000 m Rc $\pm$ 1mm CV	Cu	10 x 10 cm circular
	2.000 m Rc $\pm$ 1mm CC	Cu	10 cm diameter circular
	2.000 m Rc $\pm$ 1mm CV	Al	10 x 10 cm square
	1.000 m Rc $\pm$ 1mm CC	Al	10 cm diameter circular
	0.500 m Rc $\pm$ 1mm CC	Cu	10 cm diameter circular
	5.000 m Rc $\pm$ 1mm CC	Al	10 cm diameter circular

CV = Convex   Cu = Copper, OFHC
CC = Concave   Al = Aluminum, 6061-T6

4.2 PART DESCRIPTION

4.2.1 FLAT PARTS

A Fizeau type interferometer configuration has been constructed on a granite metrology bench, located in the environmentally controlled area adjacent to the micro machining area Figures IV through VII show the flat surfaces produced by the two methods mentioned above using the GFP machine Figure IV is a 10 cm square copper part. Figure V is a 10 cm square aluminum part. Both parts were produced by translating the work piece across the rotating tool in the milling mode. Figure VI is a 10 cm diameter copper part Figure VII is a 10 cm diameter aluminum part These parts were produced by rotating both spindles in the turning mode.

4 2 2 SPHERICAL PARTS

The Fizeau type interferometer constructed to meet this task was reconfigured to the Twyman-Greene mode so that interferometric measurement of the spherical surfaces produced could be measured and photographed.

Figure VIII shows the interferogram of two different samples and is shown to illustrate the consistency of figure from sample to sample. These components are aluminum material with a one meter convex mirror surface.

Figure IX shows the interferogram of two samples, again attempting to show consistency of figure. These components were made of copper and have a one meter convex surface.

Figure X shows the interferogram of two different components; again a consistency of figure quality can be noted. These components were of copper material with one half meter concave surface.

Figure XI shows the interferograms of two different samples with the same two meter concave surface. It will be noted that there is some deviation from constancy of optical figure. These materials are copper.

Figure XII shows two more spherical samples that have a five meter concave figure. In spite of the unusual appearance of the interferogram similarity of the two will be noted. The material was aluminum.

4.3 CHARACTERISTIC SURFACE FAULT

It will be noted that when the GFP machine is used in the generating mode with both spindles rotating and the cross slide stationary, a blemish is cut into the surface when the generator head assembly is retracted.

This is particularly noticeable in Figures X and XI.

The generator head moves axially to feed the work into the tool. At the end of the feed travel the head assembly is allowed to dwell for a few revolutions. A precision indicator was mounted to the head assembly and it was found that after the dwell period, operation of the return mechanism caused the head assembly to surge into the tool a distance of twelve millionths of an inch before retracting. The parts produced were checked and found to have about a ten millionths step.

No attempt was made to correct this condition.

5.0 TASK IX, METROLOGY IMPLEMENTATION

5.1 FOREWORD

Paragraph 3.4.2.2 of Option I requires that the metrology equipment necessary to check the proof parts produced under Task VIII meet the specification.

5.2 METROLOGY AREA

5.2.1 PRIMARY METROLOGY AREA

A metrology room has been constructed adjacent to the micro machining facility. The same environmental controls are used for both areas. In this way the conditions under which the parts are made is identical to that in which they are measured.

A four by eight foot granite table is located in this room and is used as the principal optical structure. On this base we have constructed an interferometer that can be used in the Fizeau and Twymann Green modes so that both flat and spherical work can be measured. The photographs shown in section 4.0 of this report were made using this equipment. Appropriate closed storage cabinets have been mounted in this area.

A plan view of this facility is shown in Figure XIII.

5.2.2 SECONDARY METROLOGY AREA

A secondary metrology area has been constructed adjacent to the general shop. This is an enclosed area that is temperature controlled to within plus or minus five degrees. This area is used for those inspections that do not have the same stringent requirements.

This area has a four by eight foot steel table that is used as the metrology base. An optical bench with a dark tunnel and a Twymann Green interferometer are located in this area. Both mechanical and optical measurements are performed here.

5.3 METROLOGY INSTRUMENTATION

A self contained Fizeau interferometer that has a five inch aperture is a standard IntOp product. This instrument is currently table mounted and is used to inspect flat surfaces for figure and finish. An equivalent instrument will be machine mounted for in-process inspection of flat surfaces.

A scanning interferometer with micro probe and positioner is currently in the checkout stage and is expected to be available in the near future for the measurement of aspherical surfaces.

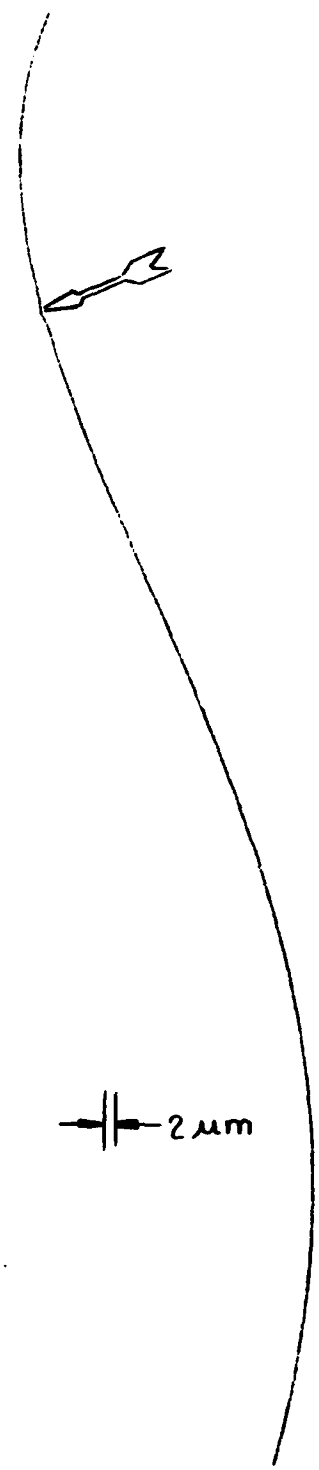

FIGURE I

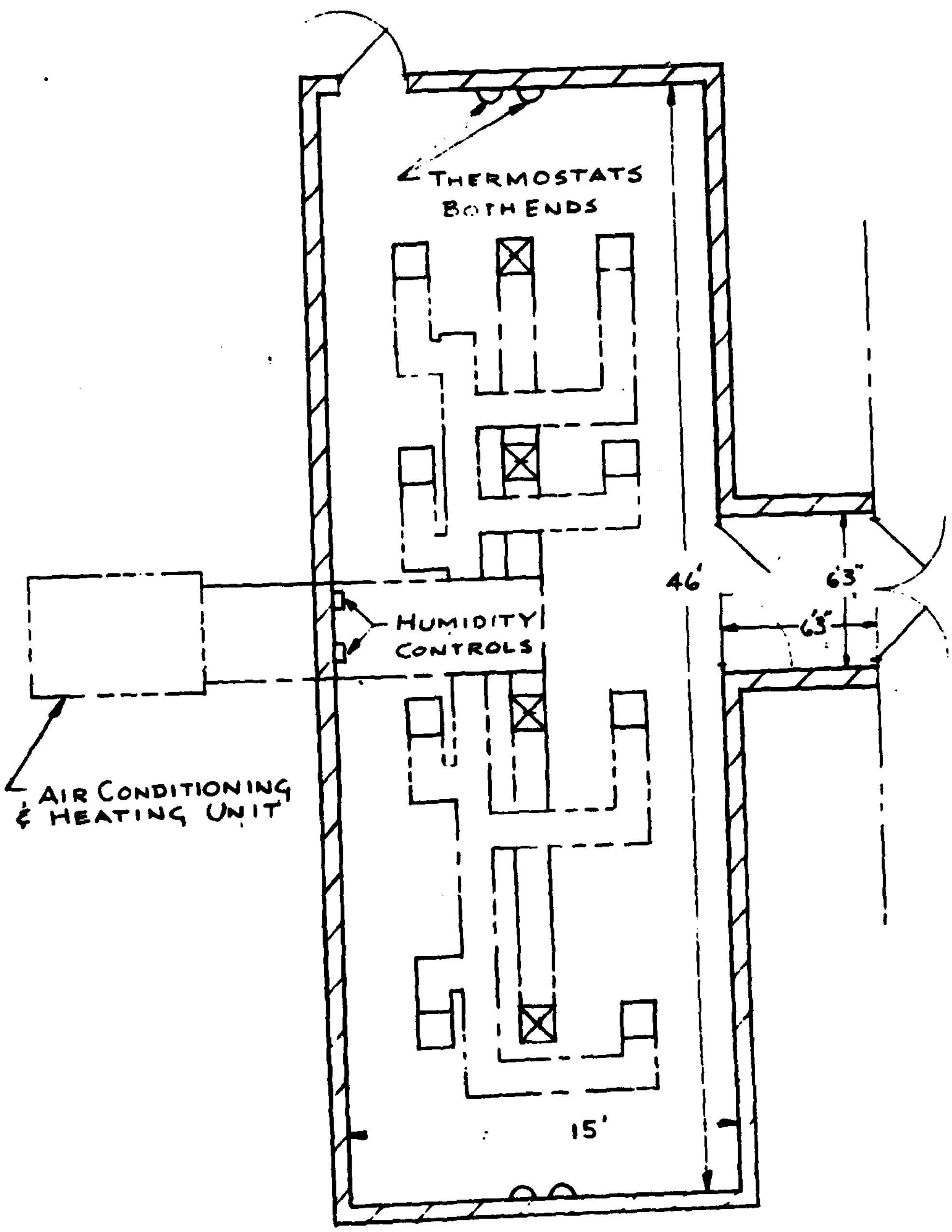
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FIGURE II

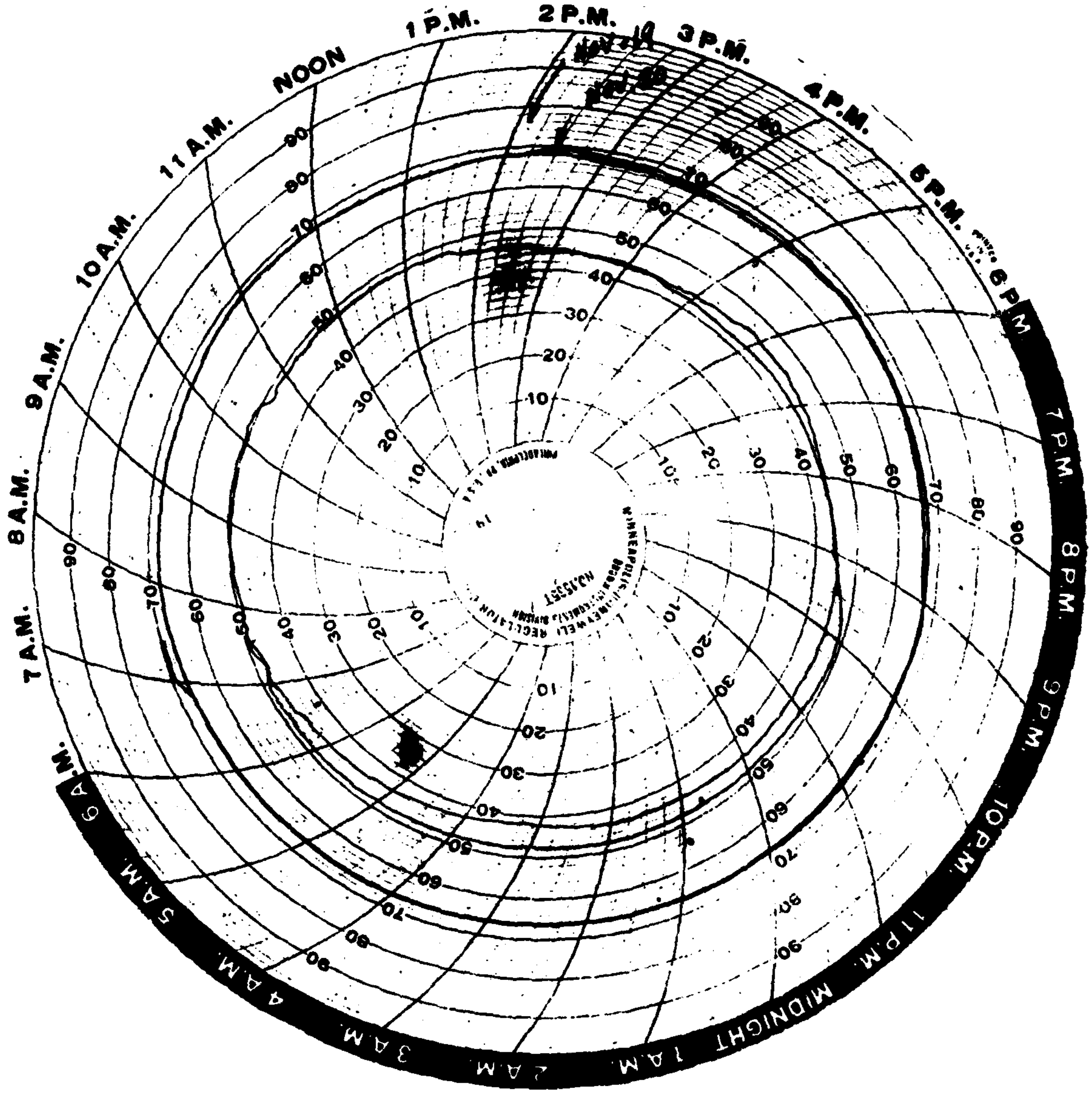
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FIGURE III

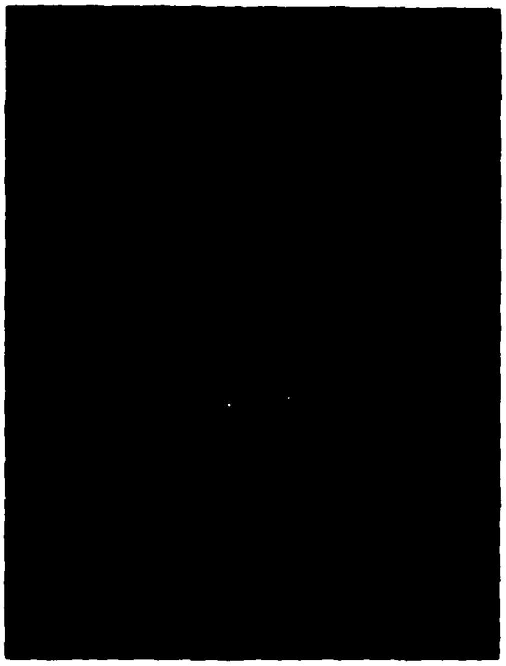


FIGURE IV

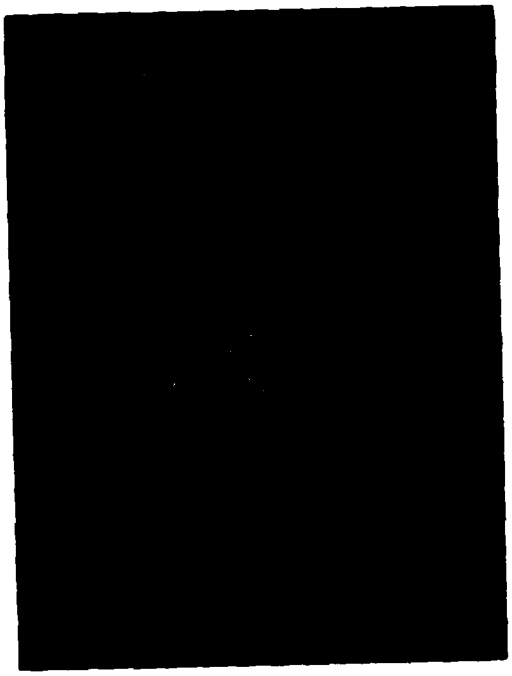
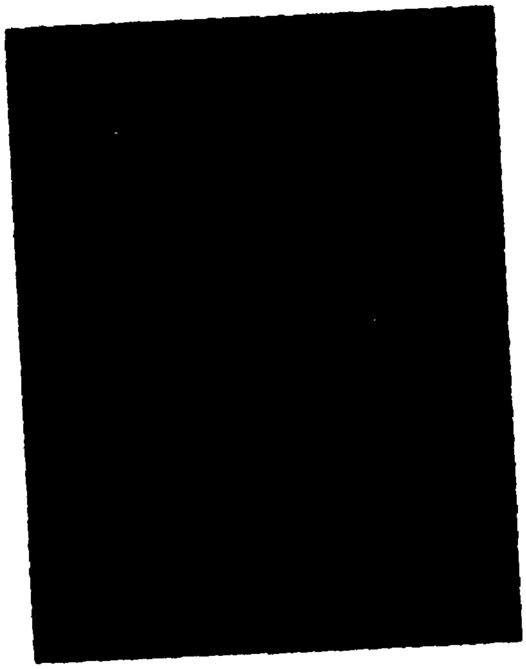


FIGURE V



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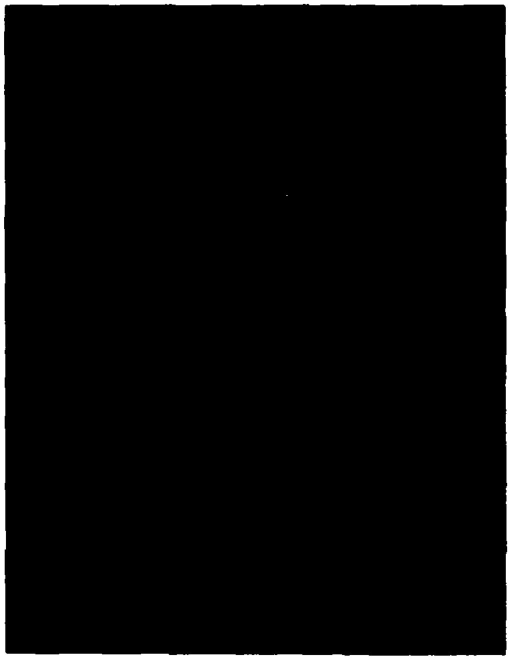

FIGURE VII

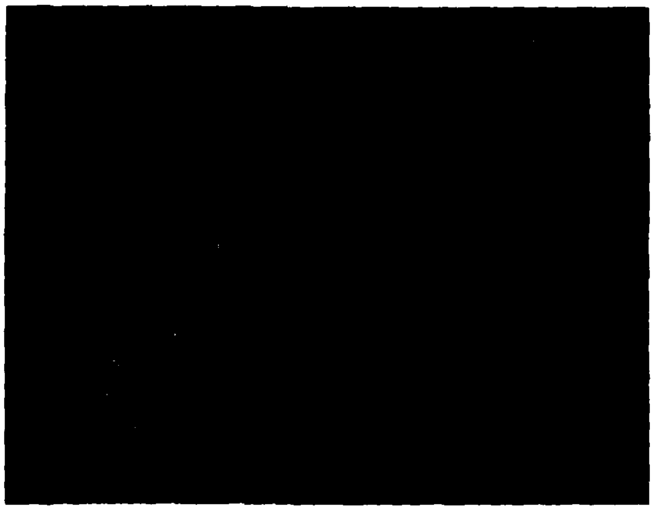

FIGURE VIII

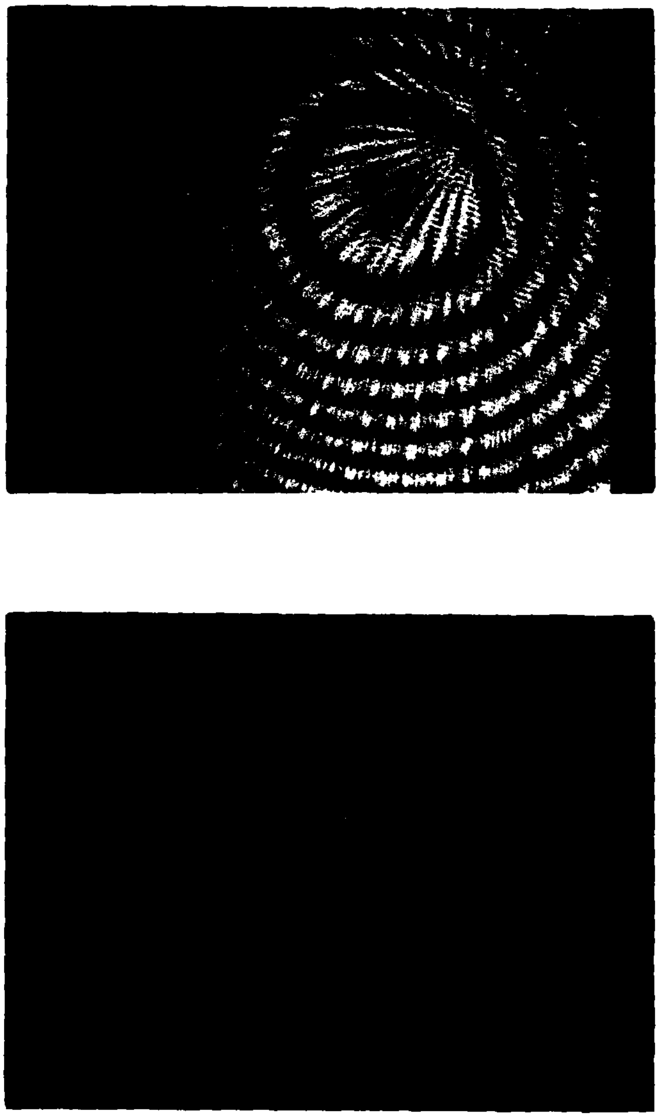

FIGURE IX

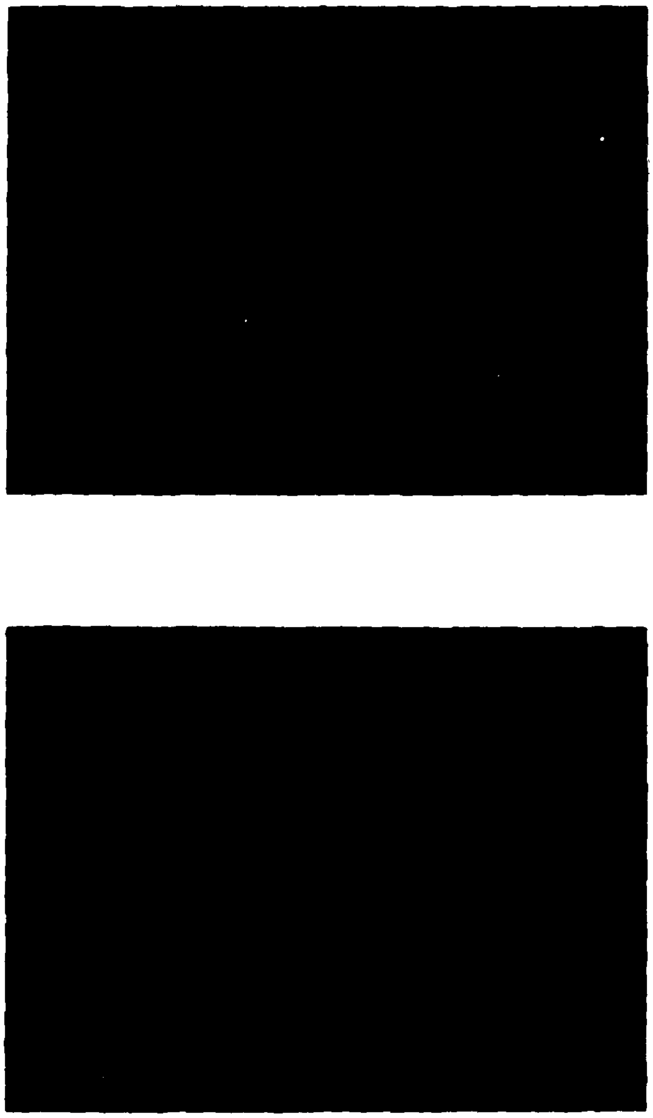

FIGURE X

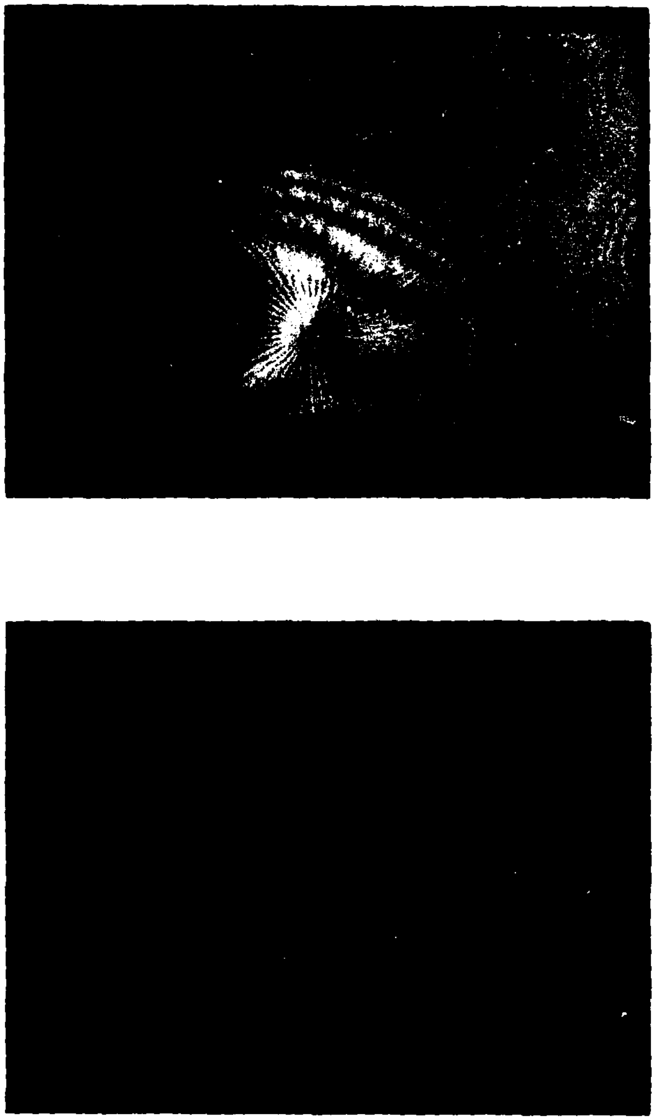

FIGURE XI

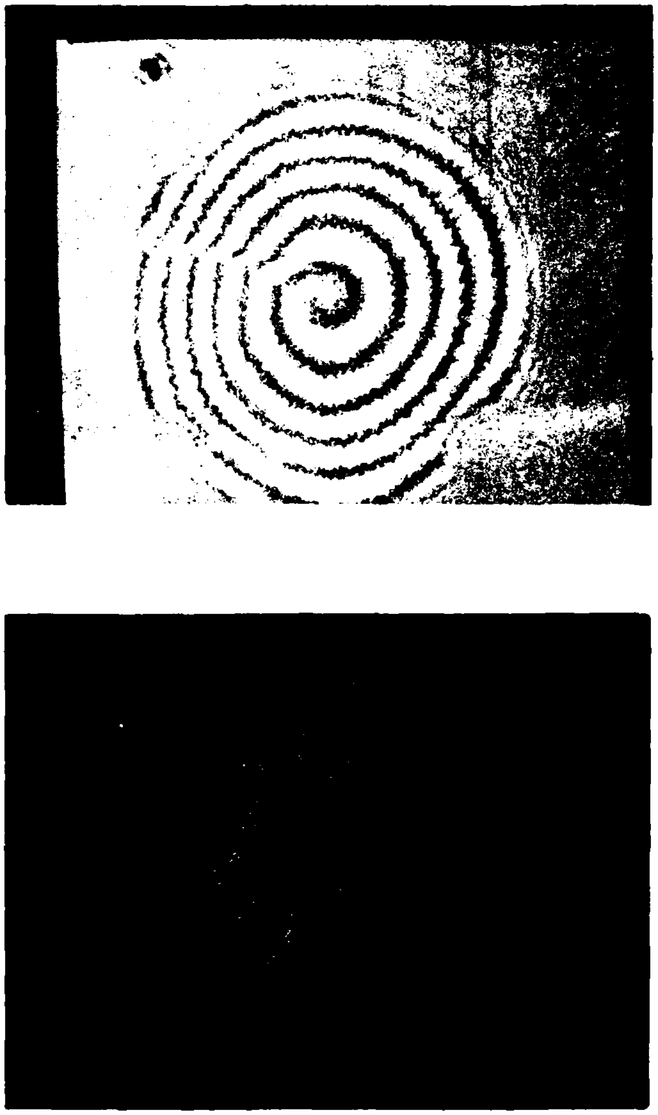

FIGURE XII

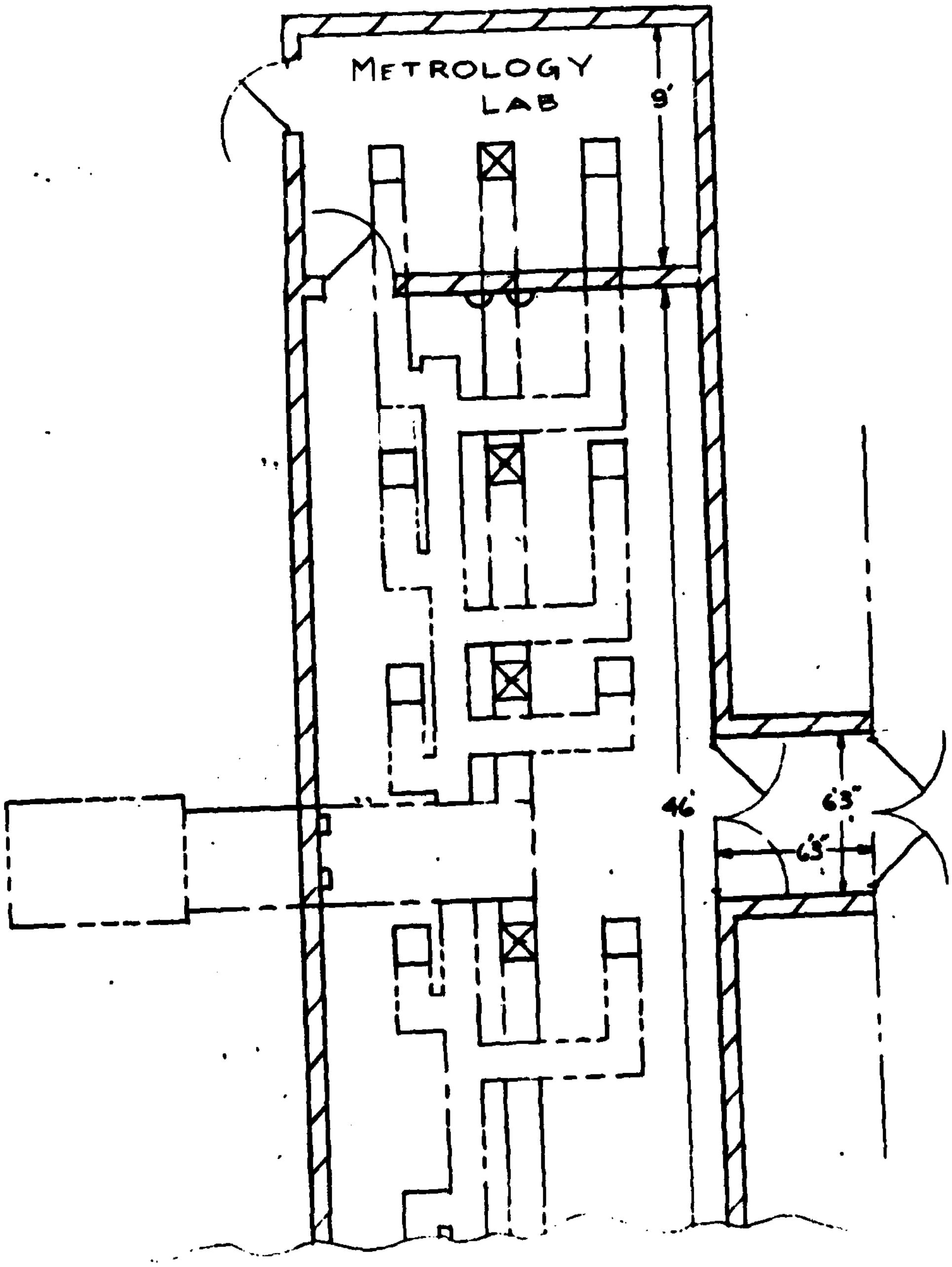

FIGURE XIII

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