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PRODUCING THE HIGH TEMPERATURE REUSABLE SURFACE INSULATION FOR THE THERMAL PROTECTION SYSTEM OF THE SPACE SHUTTLE

by

Kevin FORGSBERG

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Description of the Manufacturing Challenges in PRODUCING THE HIGH-TEMPERATURE REUSABLE SURFACE INSULATION FOR THE THERMAL PROTECTION SYSTEM OF THE SPACE SHUTTLE

By

Kevin Forsberg, Program Manager, Thermal Protection Systems
Lockheed Missiles & Space Company, Sunnyvale, California USA

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Description of the Manufacturing Challenges in

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ABSTRACT

The primary insulation system used to protect the Space Shuttle orbiter on reentry is an externally attached, rigidized, fibrous silica which has been machined into tiles approximately 15 to 20 centimeters (six to eight inches) square. The tiles constitute the HRSI (High-Temperature Reusable Surface Insulation) system and are used on over 70 percent of the vehicle exterior surface where peak temperatures range from 400°C to 1260°C (750°F to 2300°F). Carbon-carbon leading edges are used in areas where peak temperatures exceed 1650°C (3000°F) and a Nomex felt flexible insulation system is used in regions below 400°C (750°F). Approximately 32,000 tiles are used in the HRSI system and because of vehicle configuration, aerodynamic requirements, and weight considerations no two tiles are alike.

The Space Shuttle was designed to use existing technology wherever possible, but it also incorporates numerous engineering advances. Probably the most important advance - certainly the most visible - is the reusable surface insulation. This unique material is one of the breakthroughs that make the routine use of space possible. In fact without the HRSI system the Space Shuttle could not have become a reality.

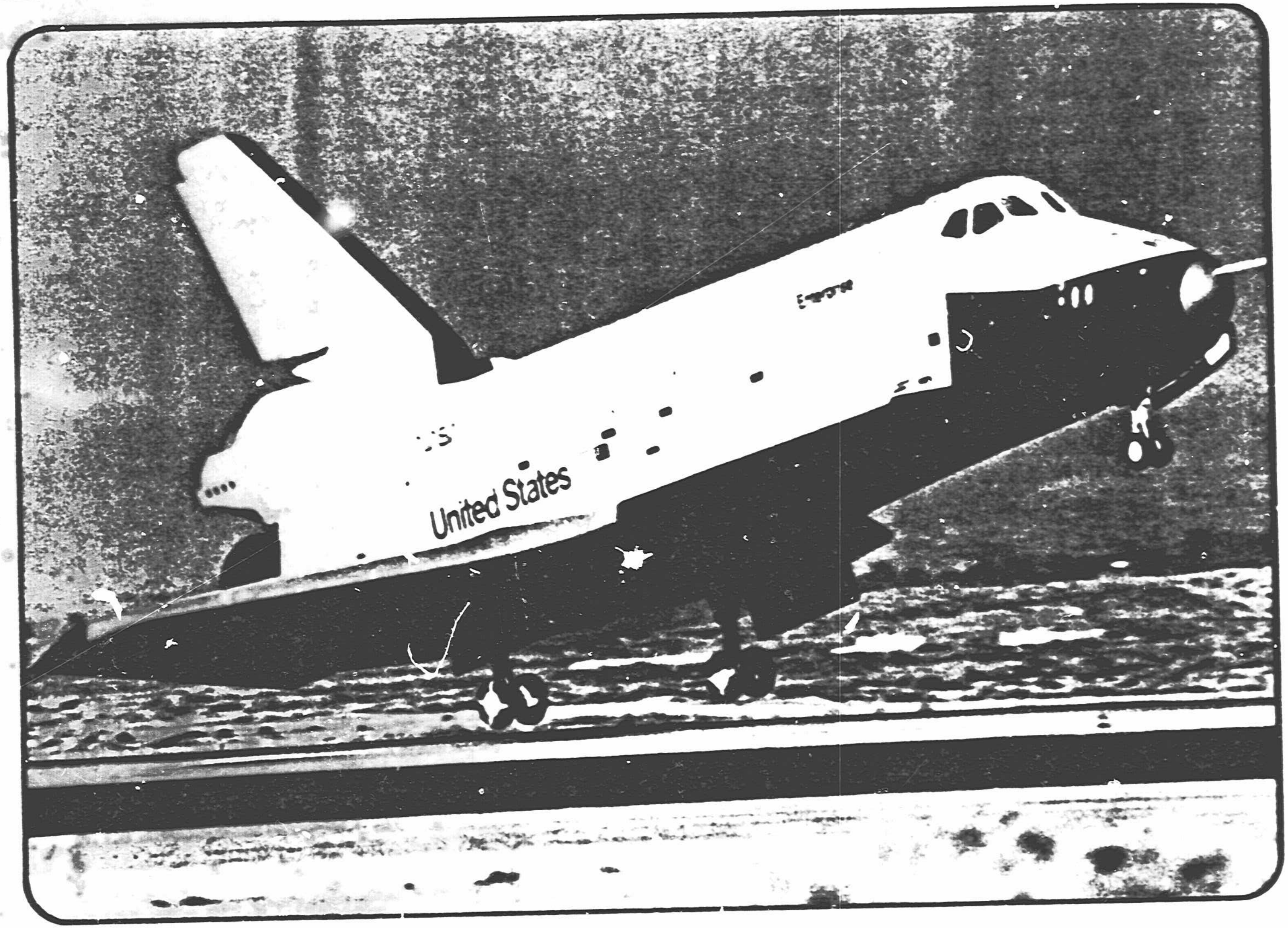
SPACE SHUTTLE ORBITER DURING FLIGHT TEST

The Space Shuttle Orbiter is a fully reusable spacecraft designed to carry up to 29,500 kilograms (65,000 pounds) of payload to low earth orbit and to remain in orbit for up to four weeks prior to reentry. The vehicle is designed to fly 100 launch and reentry cycles without significant refurbishment. The Space Shuttle was designed and is being built by Rockwell International for the National Aeronautics & Space Administration (NASA). The delta wing orbiter is approximately 37.2 meters (122 feet) long and weighs approximately 68,000 kilograms (150,000 pounds). The payload bay will contain a satellite up to 4.6 meters (15 feet) in diameter and up to 18.3 meters (60 feet) long.

In the launch configuration the Space Shuttle consists of the orbiter vehicle mounted on top of a large external tank which holds the fuel for the Space Shuttle orbiter main engines. Attached to the orbiter and external tank are two large solid rockets which provide additional thrust during launch. The solid rockets are ignited prior to liftoff, and when expended they are separated from the Shuttle and are recovered by parachute drop into the ocean. The solid rockets are designed to be reused for subsequent missions. The external fuel tank is the only truly expendable structure in the launch configuration, and it is ejected just prior to the time the Space Shuttle achieves orbit.

The photograph shows the first orbiter vehicle (Orbiter 101) during the approach and landing tests which were conducted in 1978. The orbital maneuvering system (OMS) rocket engines are used to initiate reentry. The remainder of the reentry trajectory is unpowered including the approach and landing.

SPACE SHUTTLE ORBITER DURING FLIGHT TEST



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SPACE SHUTTLE ORBITER DURING REENTRY

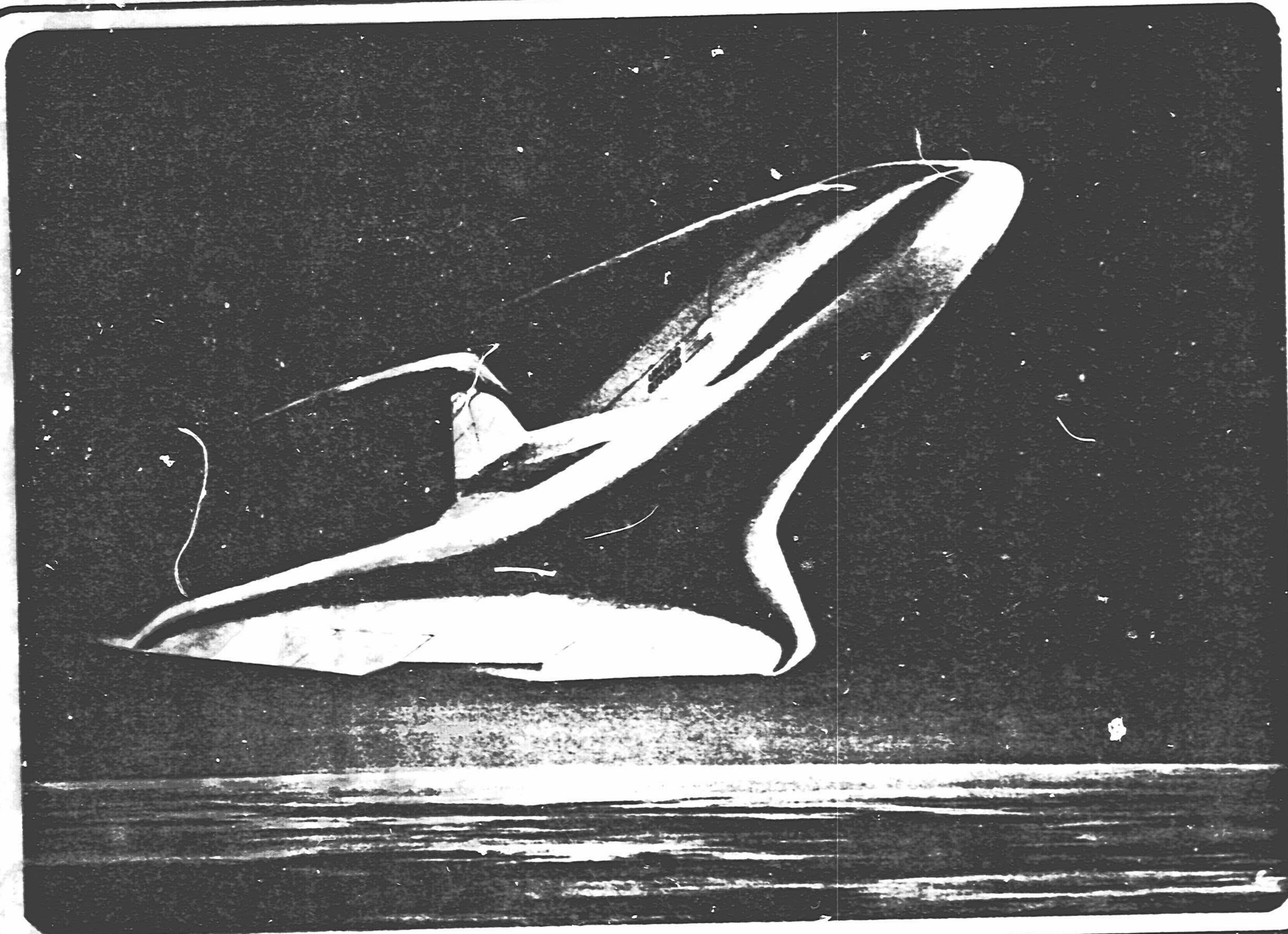
The artist's conception of the Space Shuttle orbiter during reentry highlights those areas on the vehicle which will experience maximum heating. The nose cap and outboard leading edges of the wing will experience temperatures in excess of 1650°C (3000°F). In these regions a silicon carbide coated carbon-carbon structure is used. The majority of the lower surface of the vehicle including inboard wing leading edge will experience temperatures up to 1260°C (2300°F) and in this region the High-temperature Reusable Surface Insulation (HRSI) system is used. Portions of the upper surface of the vehicle and all of the vertical stabilizer will also be covered with the HRSI tiles. Temperatures on the upper surface in these regions will vary from 400°C to 1200°C (750°F to 2200°F). About 25 percent of the vehicle surface, particularly on the payload bay doors and on the upper surface of the wings, will experience temperatures below 400°C and the structure is protected by a flexible Nomex felt insulation coated with a white silicone material.

The High-temperature Reusable Surface Insulation (HRSI) consists of an externally attached, rigidized, fibrous silica material called LI-900, produced by Lockheed Missiles & Space Company under subcontract to Rockwell International. The material is machined into tiles approximately 15 to 20 centimeters (six to eight inches) square and varying in thickness from 0.5 to 13 centimeters (0.2 inches to 5 inches) depending on location on the vehicle. Rockwell is responsible for the design and qualification of the insulation system, and for attaching the tiles to the vehicle. Lockheed is responsible for the material development and for tile production to the Rockwell design. A total of 23,400 tiles have been produced at Lockheed for installation on the orbiter. In addition, Rockwell will produce approximately 8,600 HRSI closeout tiles at Palmdale, California.

The basic airframe for the Space Shuttle orbiter is made from aluminum and the thermal protection system is designed to keep peak heating on the aluminum structure below 175°C (350°F). Peak heating on the external surface of the insulation is reached early in the reentry trajectory where the reference air pressure is about 0.03 atmospheres. Because of the thermal characteristics of the insulation system it takes a significant length of time for the heat to pass through the insulation system to the bondline; peak temperatures at the bondline in many areas are not achieved until after the vehicle is on the ground. The peak heating occurs for about ten minutes during the initial phases of reentry and the total cycle from start of reentry to landing is approximately 30 minutes.

During the design studies for the Space Shuttle orbiter conducted in 1969 through 1973, a number of thermal protection systems were evaluated. Metallic heat shields, ablators, and active cooling systems were considered, along with the rigidized fibrous silica materials. The ablative materials used on all previous reentry vehicles (including the Apollos) could protect the Shuttle during the reentry environment but they are not reusable. Active cooling systems proved to be too complex and too heavy. Metallic heat shields, marginal at temperatures anticipated in reentry (1260°C), require special coatings to survive even that environment and are significantly heavier than the rigidized fibrous silica tiles. The silica tiles have demonstrated the capability of withstanding the reentry heat pulse for 100 missions without degradation, and can survive the high acoustic level (165 db) experienced during launch. Thus it was established that the HRSI produced the lowest weight thermal protection system, and moreover it was (and is) the only system that meets the shuttle mission requirement of 100 launch and reentry cycles without significant refurbishment.

SPACE SHUTTLE ORBITER DURING REENTRY



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4-14-78

LI-900 FIFTEEN SECONDS AFTER REMOVAL FROM 1370°C (2500°F) FURNACE

LI-900 is a unique insulating material because of its very low thermal conductivity and low thermal mass. To illustrate this point a cube of material 5 centimeters (2 inches) on a side was put into a kiln at 1370°C (2500°F) and allowed to reach equilibrium. Fifteen seconds after removal from the kiln the block of material could be picked up as shown in the photograph. In fact the only light in the room when this photograph was taken came from the glowing LI-900 block. Not only does the man in the photograph still have all of his fingers, but he has been willing to repeat this demonstration on numerous occasions.

LI-900 15 SEC AFTER REMOVAL FROM 1370°C (2500°F) FURNACE

4-14-78

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BASIC MATERIAL CHARACTERISTICS

The thermal conductivity of LI-900 is lower than that for any other known rigid insulating material over the temperature range of interest for the Space Shuttle mission (-130°C to +1260°C or -200°F to +2300°F). While other materials have a similar low thermal conductivity in the range from room temperature to 260°C (500°F), LI-900 is unique in its low conductivity at temperatures above 260°C.

While fibrous insulating blankets have been used in many applications at comparable temperatures, they would require support structure of some nature if they were to be applied to the Space Shuttle. The rigid character of the LI-900 makes this material unique for application on the orbiter. The low density (144 kilograms per cubic meter or 9 pounds per cubic foot) is essential in minimizing the weight of the insulation system.

The LI-900 is made from a high purity, fibrous, amorphous silica. The thermal shock resistance of the material is impressive (the material can be taken from a 1370°C (2500°F) oven and immediately quenched in water with no structural damage). The amorphous silica is like a super-cooled liquid and has a very low coefficient of thermal expansion. Crystalline forms of silica (such as quartz or cristobalite) have a coefficient of thermal expansion over thirty times higher. It is the amorphous character of the silica that allows the LI-900 to withstand the very high thermal gradients developed in the insulation material during the Shuttle reentry without developing internal flaws due to thermal stresses. Cyclic entry thermal tests made with an alumina silicate (mullite) material of the same basic fiber characteristics show that the same low thermal conductivity can be achieved. However, the internal thermal stresses developed due to the much higher coefficient of thermal expansion in the mullite caused the mullite tiles to fracture during subsequent exposure to the simulated launch acoustic environment and render this material unacceptable for Space Shuttle use.

The LI-900 is designed for use at peak temperatures of 1260°C (2300°F). However, the failure mode for the material is a gradual increase in distortion as a function of time at temperature and tests have shown the material can withstand a 20 minute exposure at 1480°C (2700°F). Thus the LI-900 has the ability to withstand the 100 mission cycles at 1260°C for a ten minute exposure per cycle, while maintaining a substantial fail-safe over-temperature capability.

THE BASIC MATERIAL CHARACTERISTICS

BASIC CHARACTERISTICS OF LI 900

- LOW THERMAL CONDUCTIVITY (0.16 W/M-°K AT 815°C AT 1 ATM OR 1.13 BTU-IN./FT^2-HR-°F AT 1500°F AT 1 ATM)
- LOW DENSITY (144 KILOGRAMS PER CUBIC METER OR 9 POUNDS PER CUBIC FOOT)
- EXCELLENT THERMAL SHOCK RESISTANCE (LOW THERMAL EXPANSION – 7.2×10^{-7} M/M/°C OR 4×10^{-7} IN./IN./°F)
- RIGIDITY (1.03×10^5 N/M^2 OR 15 PSI SHEAR STRENGTH)
- LOW DIELECTRIC CONSTANT (1.15 UP TO 1150°C (2100°F))
- HIGH USE TEMPERATURE (NORMAL USE 1260°C (2300°F) PEAK: MAX USE 1480°C (2700°F))
- LONG LIFE (100 MISSION CYCLES AT 1260°C (2300°F) FOR 10 MIN PER MISSION)

RESULT

- LIGHTEST INSULATION SYSTEM FOR SPACE SHUTTLE ORBITER
- ONLY REUSABLE, NON-ABLATING THERMAL PROTECTION SYSTEM

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COATED LI-900 TILE CROSS SECTION

The photograph shows a cross-section of a coated LI-900 tile at a magnification of 160. Fiber diameters range from 0.5 to 8 microns with average of 1.5 microns. The fibers are dispersed in deionized water and are cast into felt-type blocks which are then rigidized by sintering at 1290°C (2350°F) for approximately three hours. The large blocks are then cut up into tile blanks which are machined to final configuration on numerically controlled mills. The coating is basically a borosilicate glass frit (powder) sprayed on with a carrier (either alcohol or water) applied as one would apply a coating of paint. Approximately 8 coats are used to achieve the 0.30 to 0.38 millimeter (12 to 15 mil) coating. The coating is glazed at 1200°C (2200°F) for approximately two hours. It forms a dense silica layer which provides emittance control, mechanical protection of the base material, and waterproofness for the exterior surfaces of the tile. Interior water repellancy is achieved by vacuum deposition of a silicone polymer which coats all fibers and renders them hydrophobic. Weight gain from this waterproofing is less than 0.5 percent. The silicone polymer burns off at temperatures above 560°C (1040°F) so the coating is designed to extend down the tile sides to a point where the peak temperatures are below that level (tile bond line reaches a maximum of 260°C (500°F)). Thermal cyclic tests followed by exposure to simulated rain for one hour prove that with this design the tiles remain waterproof for the shuttle mission environment.

COATED LI-900 TILE CROSS-SECTION

0.33 MM
(0.013 IN.)

160X MAGNIFICATION

DENSE SILICA COATING
(1600 KG/M^3 OR 100 LB/FT^3)

PURPOSE:
- EMITTANCE CONTROL
- MECHANICAL PROTECTION OF BASE MATERIAL
- WATERPROOFNESS

RIGIDIZED FIBEROUS SILICA
(144 KG/M^3 OR 9 LB/FT^3)

PURPOSE: INSULATION

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TILE APPLICATION DETAIL

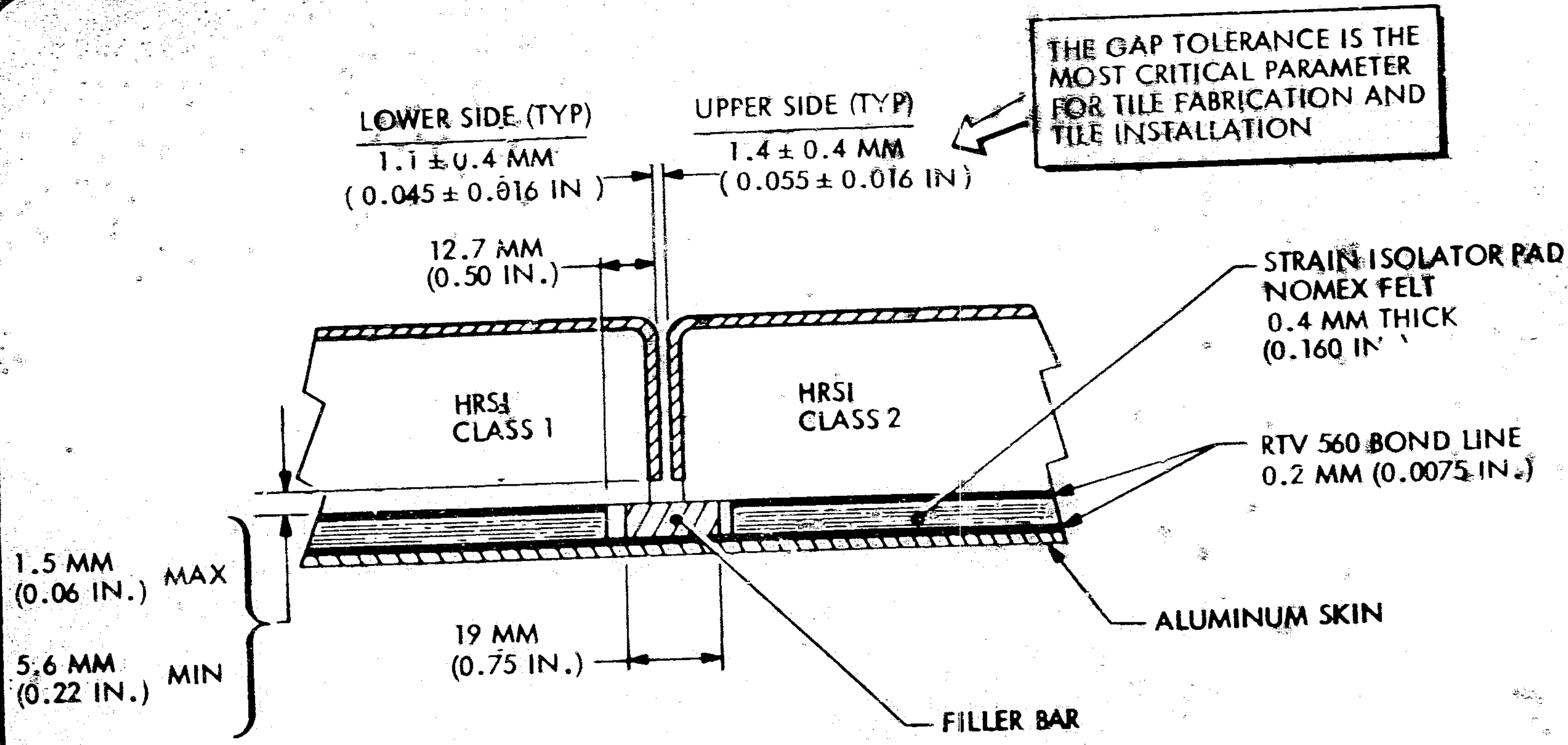
There are basically two types of HRSI tiles on the Shuttle orbiter: Class 1 tiles for use up to 650°C (1200°F) and Class 2 tiles for use in the range of 650°C to 1260°C (1200°F to 2300°F). The base material for both types of tiles is identical and the distinction between them is only in the coating. The coating materials are also essentially identical, consisting primarily of an amorphous borosilicate glass. The Class 1 tile coating is white and has a small percentage of alumina added to reduce solar absorptance. For Class 2 tiles an additive (boron silicide) is used to produce a black coating, which is designed to have an emittance in excess of 0.8 over the entire temperature range. This is critical because if the emittance were to drop to 0.5, for instance, the surface temperature in areas of peak heating could increase by as much as 220°C (400°F) for the same convective heating rate. The Class 1 coating system was designed to minimize on-orbit heating for thin tiles, and the white coating was selected because of its low solar absorptance. Although the emittance starts at above 0.8 at room temperature, it rapidly degrades above 650°C (1200°F) and for that reason the Class 1 tiles are used only in regions below 650°C.

In addition to the basic LI-900 material (which has a density of 144 kilograms per cubic meter or 9 pounds per cubic foot) approximately six percent of the tiles are made from a higher density material designated LI-2200. This mareria1 has a density of 350 kilograms per cubic meter (22 pounds per cubic foot). Tiles made from LI-2200 are machined and coated in exactly the same way that all other tiles are processed (with the single exception that coating glazing temperature is slightly higher). The LI-2200 is made from the same silica fibers and is processed in a very similar manner to the LI-900. The thermal conductivity is only slightly higher, and the mechanical properties are significantly enhanced (shear and tensile strengths increased by a factor of 3). Because of the weight increase use of LI-2200 is restricted to areas such as access door frames where a higher strength material is required.

The tiles are bonded to a strain isolator pad made of Nomex felt which in turn is bonded to the vehicle using a room temperature vulcanizing (RTV) adhesive designated RTV 560. The strain isolator pad is used to help isolate the tiles from the strain in the base structure to minimize bond line stresses.

Gap heating between tiles is a critical factor in the insulation system design. Since most of the gaps are not filled in order to allow for thermal expansion and contraction of the base structure during the orbiter mission, the dimensional control on the tiles to ±0.4 millimeters (±0.016 inches) is critical. The basic gaps on the lower side are 1.1 millimeters (45 mils) while on the upper side the gaps are 1.4 millimeters (55 mils). This is because the tiles on the lower side are basically 15 centimeters (6 inches) square while on the upper side larger tiles 20 centimeters (8 inches) on a side are used. A larger gap is required for the larger tiles because the deflection of the structure is a function of length for a given strain. The larger gaps can be tolerated because the heating rates (and hence gap heating) are lower in the Class 1 tile areas (typically the upper surface of the vehicle). A Nomex felt filler bar is used at the junction between two tiles to prevent hot gases flowing through the gaps from impinging directly on the aluminum structure. This filler bar is isolated from the tiles in order to ensure that the tiles move independently, thereby minimiz bondline stresses.

TILE APPLICATION DETAIL



HRSI – CLASS 2 – HIGH TEMPERATURE TILE (650°C TO 1260°C OR 1200°F TO 2300°F)
BLACK COATING (EMITTANCE IS OVER 0.8 AT 1260°C (2300°F))

HRSI – CLASS 1 – LOW TEMPERATURE TILE (400°C TO 650°C OR 750°F TO 1200°F)
WHITE COATING (EMITTANCE IS 0.65 AT 650°C (1200°F))
COATING DESIGNED FOR LOW SOLAR ABSORBTANCE ON ORBIT

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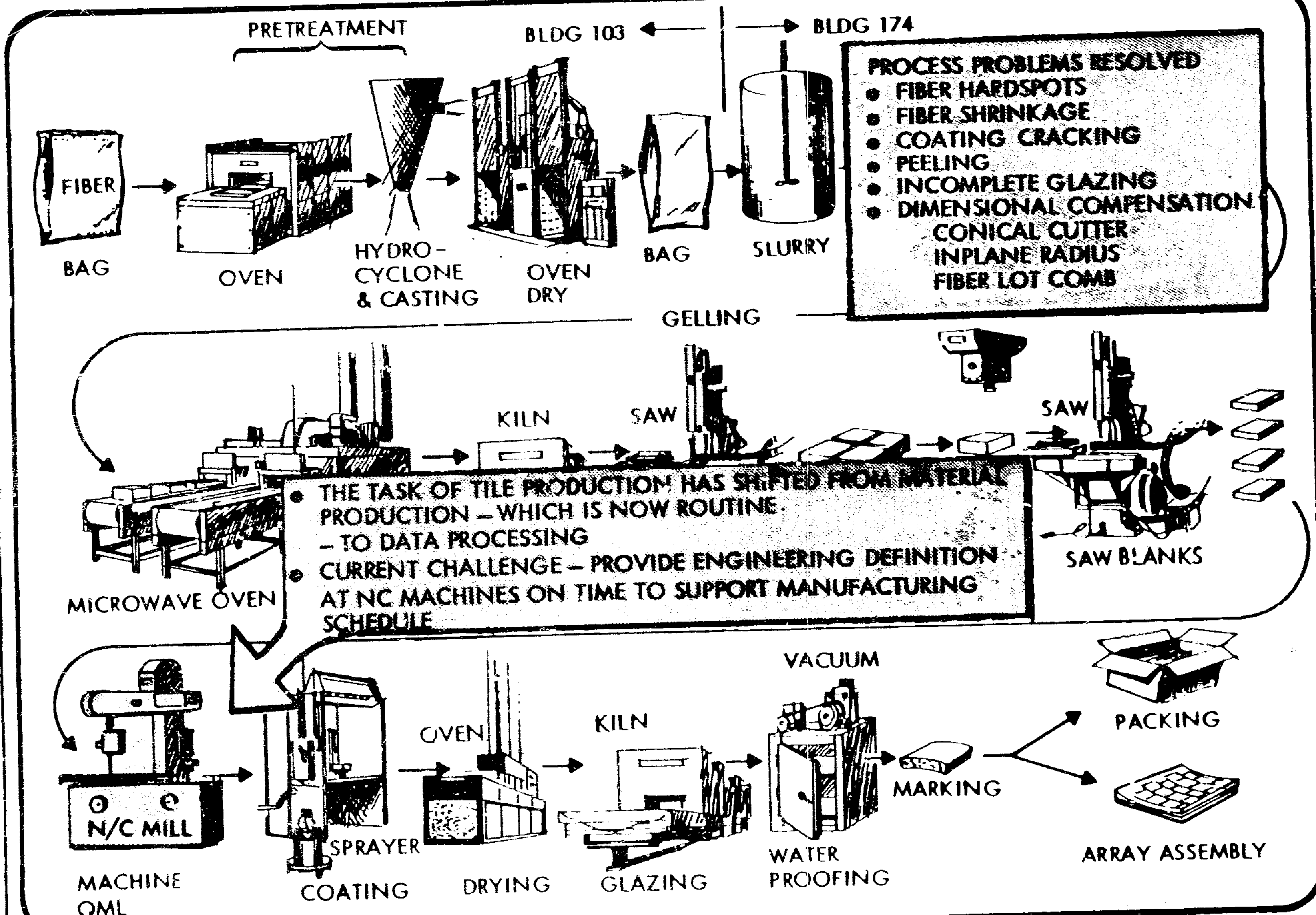
THE LAST MAJOR HURDLE

The basic LI-900 material has its roots in research conducted at Lockheed Missiles & Space Company as far back as 1962. Attempts to produce a rigidized fibrous all-silica insulator met with sporadic success until specific contaminants were identified as being detrimental to the process and were eliminated from the various raw materials. The transition from laboratory curiousity to production hardware spanned a six year interval and required the creative contributions of many research scientists and engineers. A multitude of technical problems were encountered which had to be resolved, such as contaminants which caused fiber hard spots and excessive fiber shrinkage. Coating materials had to be developed which matched the coefficient of thermal expansion of the base material to eliminate coating cracking during thermal cycling, and application techniques had to be developed to eliminate coating crazing and coating peeling. Firing techniques had to be developed to ensure complete glazing for tile configurations that were coated on portions of all six sides of the tiles. Dimensional distortion of the tiles had to be evaluated and compensated for.

While the technical challenges of solving the laboratory-to-production scaleup occupied considerable effort during the first years of the HRSI Program, that task was overshadowed by the effort required to convert the engineering data to computer tapes to drive the numerically controlled mills that were used to machine the individual tiles. At most facilities the part programming staff required to support production of numerically controlled machined parts is on the order of 15 to 20 people. During the peak production effort ... the HRSI Program, the part programming staff exceeded 90 people. The data processing job was so m... ...hat it required over 160 hours per week of Univac 1108 computer time for over 10 months.

THE LAST MAJOR HURDLE



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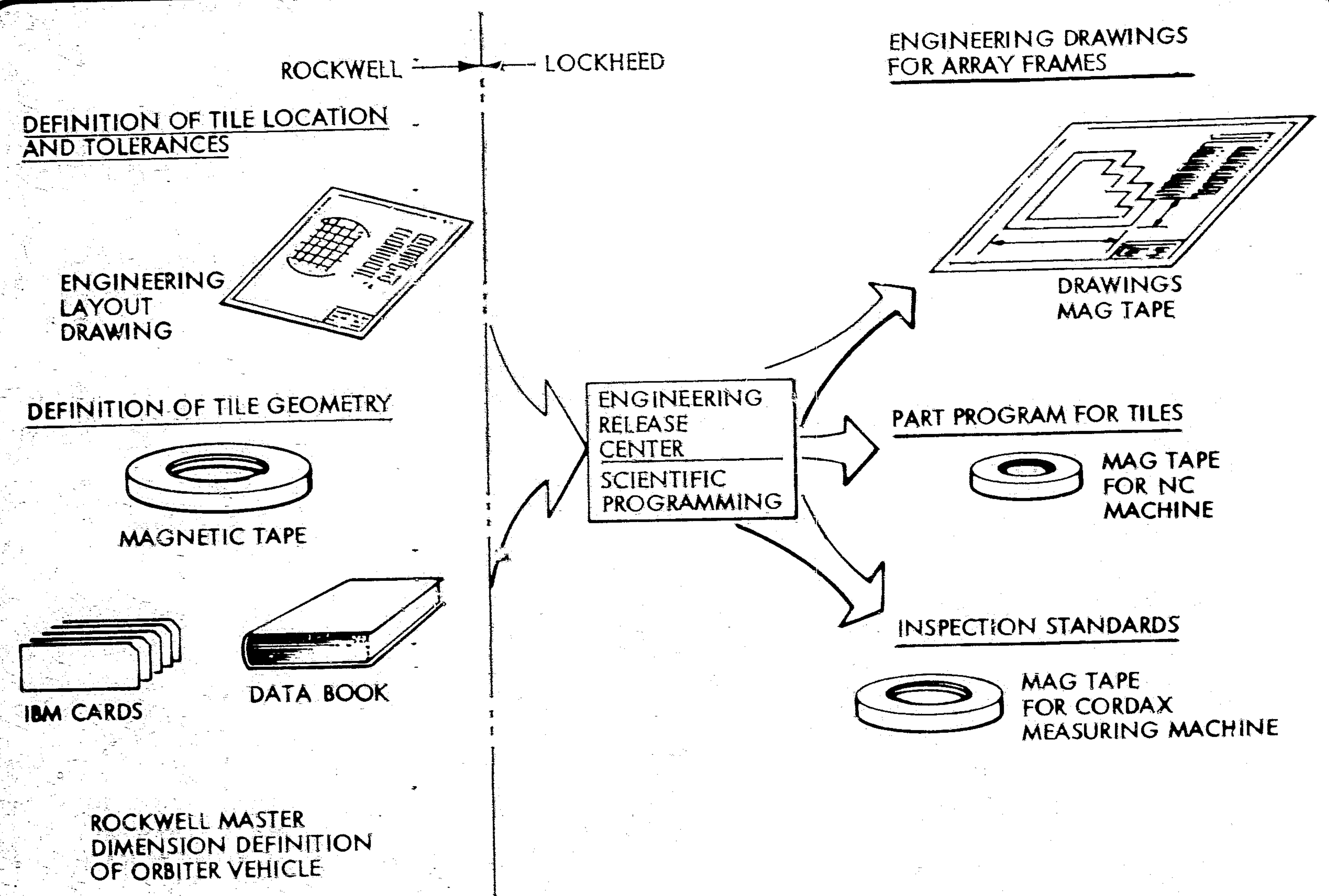
ENGINEERING DATA FLOW

The HRSI system was designed and qualified by Rockwell International. Initially Rockwell anticipated that there would be large groups of identical tiles which would minimize production and installation costs. As the design evolved, however, aerodynamic and thermodynamic requirements demanded that the contour be smoothly varying and that there be no significant steps from tile to tile. In addition the need to minimize thermal protection system weight required that the tiles be as thin as possible and that each tile should follow the local structural and aerodynamic variations. This led to a final design in which each tile was unique. The only similarity between tiles is that approximately 40 percent can be described by mirror image geometry.

Since the Shuttle orbiter is the size of a Boeing 727 jet, it was apparent that it would be a massive engineering task to describe all of the tiles via engineering drawings. For that reason it was decided to use drawings which present general planform arrangements but all tile definition would be contained in the mathematical master dimension equations of the structural surface (inner mold line) and aerodynamic surface (outer mold line). These data were described in a grid of X, Y, Z coordinates and local surface normals for portions of the vehicle, while in other areas equations were used to provide surface contour description.

The Rockwell layout drawings and master dimension data (contained on computer tapes, IBM cards, and master dimension reference books) were transmitted to Lockheed where these data were then further processed to transform the tile data from the vehicle coordinate system to a local tile reference system. After verification of data accuracy the information was transmitted to an engineering organization for description of array frame assemblies (used to hold groups of tiles for subsequent processing), to the part programmers for development of magnetic tapes to drive the numerically controlled machines, and to the inspection organization for development of computerized inspection standards to measure the tiles after machining and coating.

ENGINEERING DATA FLOW



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3-9-79

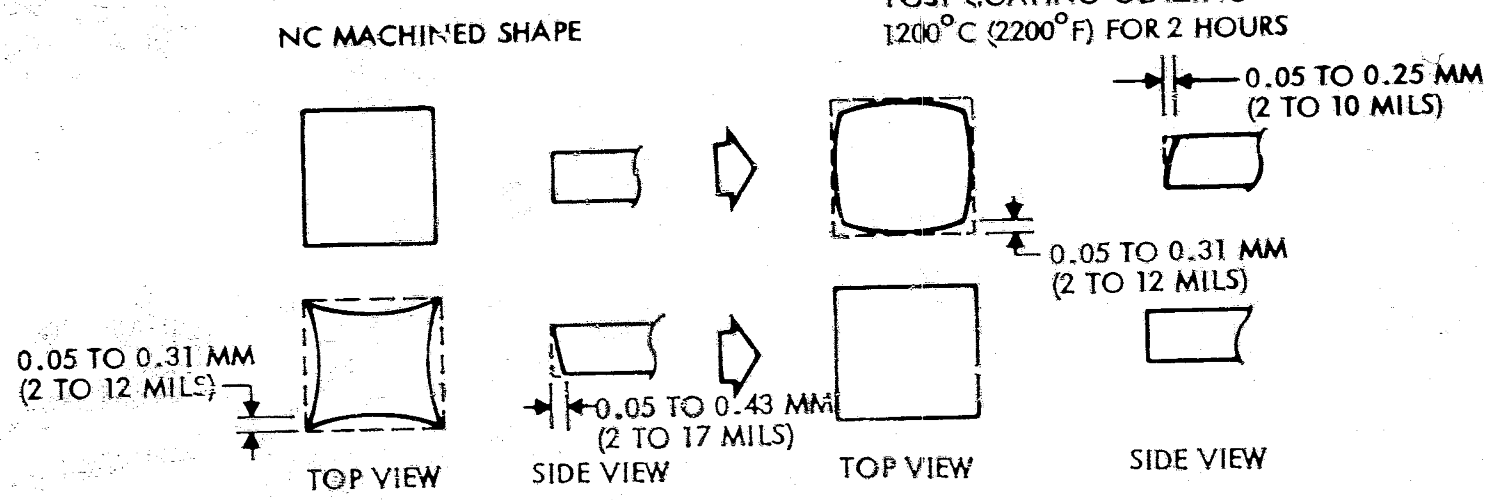
TILE FABRICATION REQUIREMENTS

The primary manufacturing challenge is to maintain dimensional control of the tiles. As noted earlier gap heating is a critical factor in the insulation system design and thus the dimensional tolerance of ±0.4 millimeters (±0.016 inches) is critical. Control of tile configuration during numerically controlled machining is well within industry practice. The challenge is that, after machining, a 0.30 to 0.38 millimeter (12 to 15 mil) coating is added which must then be glazed at 1200°C (2200°F) for approximately two hours. During this glazing operation the base material will shrink between 0.05 and 0.75 millimeters (2 to 30 mils) depending not only on tile planform but also on the fiber lot used for that specific tile blank. Thus each tile must have a different cutter compensation applied at the time of machining in order to compensate for subsequent distortion. Moreover, since all 23,400 tiles are unique, the response to the offsets and compensations will vary for each tile.

As illustrated in the figure, the glazing operation will cause a square tile with vertical sides to distort to a configuration having a curved planform and a sloped side. By contouring the uncoated tile and undercutting the sidewall the resultant tile configuration can be made to come out perfectly square with a perfectly vertical side after glazing of the coating. To simplify the programming, the planform contour is approximated by a circular arc for precoat configuration and a standard one-quarter degree conical cutter is used to undercut the sides of the tiles. These compromises prevent precise dimensional control but resulted in a 100 percent increase in tile dimensional yield. The distortion pattern is a function of tile geometry (both planform and thickness), but the magnitude of the distortion will very significantly from one fiber lot to another. Since approximately 50 tiles can be produced per fiber lot substantial variation in tile distortion has been experienced in production. This also means that in order to produce two identical tiles from two different fiber lots, the uncoated tile configuration must be different for the two. This is achieved in practice by identifying the fiber lot of the base material at the time it is initially processed and maintaining careful traceability throughout the processing to ensure that the proper fiber lot is known at the time of tile machining. When a tile is ready for machining a specific cutter offset is fed into the NC machine (automatically) to adjust the tile size as a function of fiber lot.

TILE FABRICATION REQUIREMENTS

- ALL ENGINEERING DEFINITION IS BASED ON COMPUTER (MASTER DIMENSION) DATA
- EACH TILE HAS UNIQUE PART PROGRAM FOR N/C MACHINING
- ALL MANUFACTURING AND INSPECTION OPERATIONS ARE CONTROLLED BY ONE IBM CARD PER TILE
- DIMENSIONAL REQUIREMENT IS ±0.40 MM (±0.016 IN.) ON LENGTH AND WIDTH FOR MOST TILES
- EACH TILE REQUIRES COMPENSATION FOR LI-900 SHRINKAGE DURING COATING GLAZING
- COMPENSATION VARIES WITH
  - FIBER LOT (WILL VARY FOR ANY REMAKE OF GIVEN TILE SHAPE)
  - THICKNESS
  - PLANFORM



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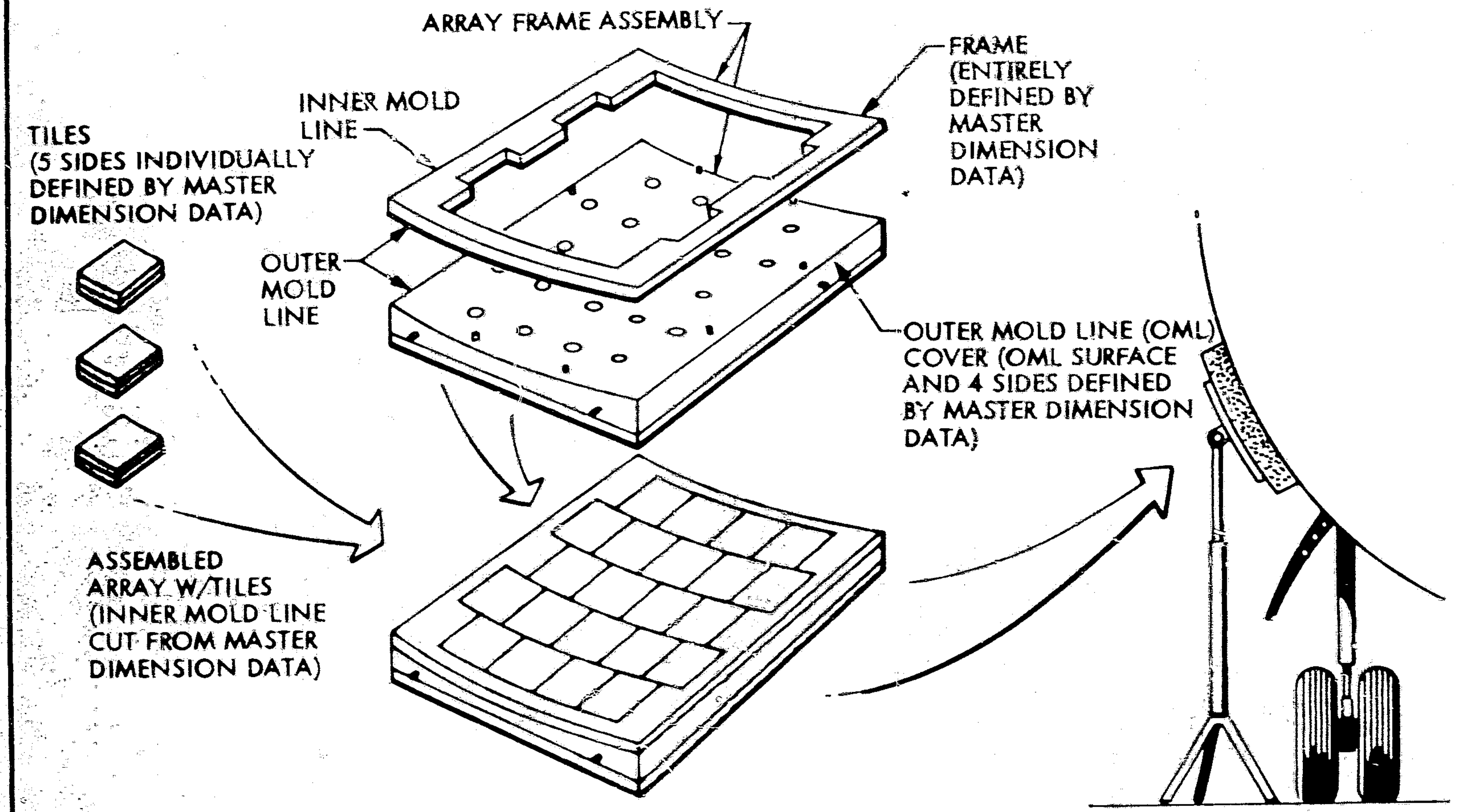
HIGH-TEMPERATURE REUSABLE SURFACE INSULATION SYSTEM

The tiles are machined on five sides, coated, and glazed individually. The tiles are then assembled into groups called arrays which average approximately 22 tiles, but with some groups having as few as two and some as many as fifty tiles. For groups of tiles having more than ten in an array, an array frame assembly was built. This frame assembly serves three primary functions: it holds the group of tiles while the inner mold line (the surface which will be bonded to the orbiter structure) is machined, it acts as a shipping container, and it serves as an installation tool during the bonding operations at Rockwell's Palmdale facility. The array frame assemblies are defined in contour by the same basic master dimension computer definition as used for the tiles. Although the overall tile processing yield has been on the order of 60 percent and is improving, the array assemblies often have one or two tiles which require six to eight remakes. Since each tile is unique and the yield for each tile is statistically the same, these remakes are of necessity sequential. The cause for remake is usually different for each iteration. This remake cycle causes substantial perturbation in production scheduling and provides a challenge to maintain a uniform and efficient shop flow. Computerized tracking methods combined with daily manual reporting have been necessary in order to maintain production control.

The array frame assemblies are machined out of polyurethane foam and are designed to be reused for subsequent orbiter vehicles. These array frames are designed and built by Lockheed to the Rockwell defined master dimension data.

HIGH-TEMPERATURE REUSABLE SURFACE INSULATION SYSTEM



INNER MOLD LINE IS THE VEHICLE STRUCTURAL SURFACE

OUTER MOLD LINE IS THE AERODYNAMIC SURFACE

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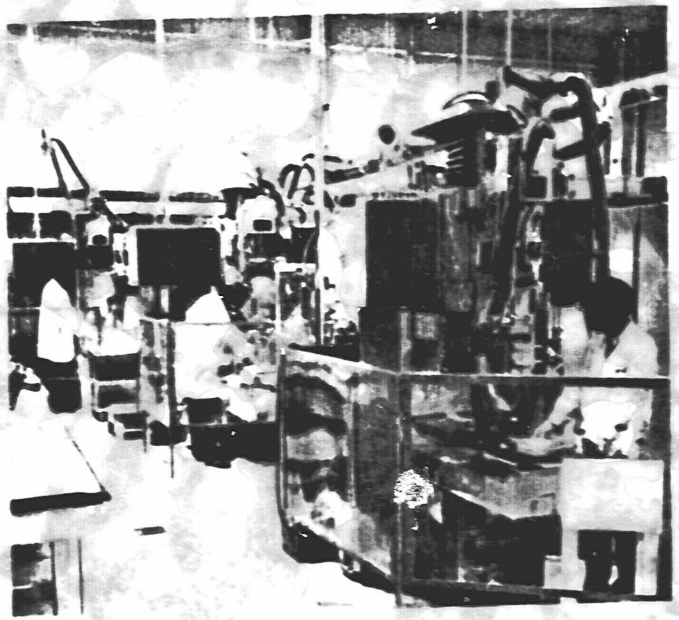
3-9-79

NUMERICALLY CONTROLLED MACHINING OF TILES

Three numerically controlled machines (one 3-axis and two 5-axis mills) are used to produce the HRSI tiles. Two larger 3-axis mills are used to machine the inner mold line on the array tile assemblies. The tiles are machined using diamond impregnated abrasive bits. A variety of cutters are used ranging from a 1.3 centimeter (0.5 inch) radius ball mill to 76 centimeter (30 inch) radius mushroom cutters for machining 5-axis surface contour. Typical parts require 12 to 15 minutes to machine, while some of the complex configurations (such as the one shown in the figure) require over one hour to complete.

A direct numerical control (DNC) computer is used to support the five computer numerical control (CNC) units which in turn drive each of five numerically controlled mills. All of the tile part programs are contained on the disk memory for the DNC, and are randomly accessed from each CNC by use of an IBM card which contains the tile part number. The five Danly NC mills are controlled by the Allen-Bradley designed CNC and DNC system.

NUMERICALLY CONTROLLED MACHINING OF TILES



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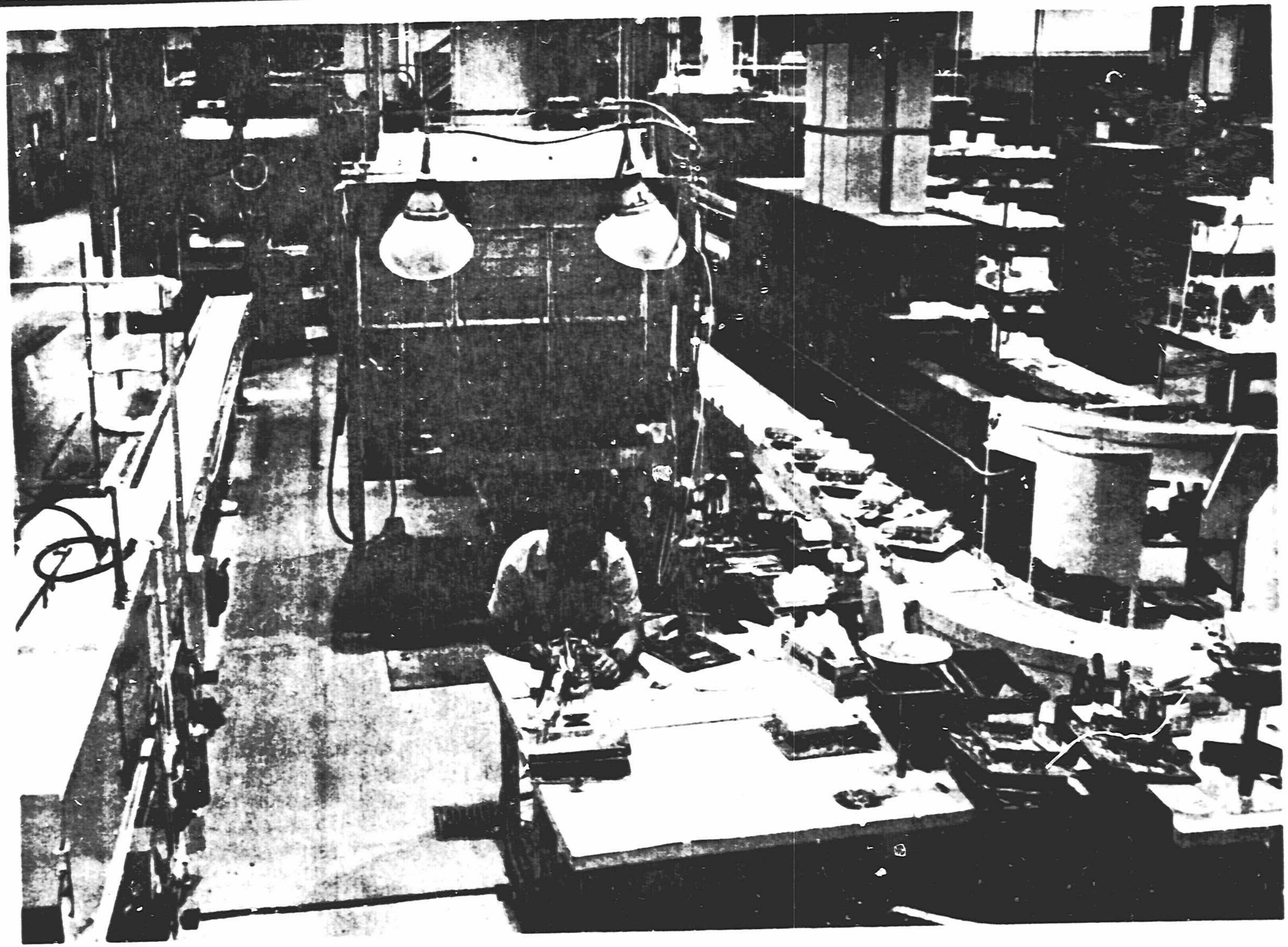
MANUFACTURING FACILITY - COATING AREA

The HRSI production facility is housed in approximately 5600 square meters (60,000 square feet). The coating area shown in the photograph occupies a portion of this facility. Various drying ovens and spray booths can be seen. One can also see a number of tiles which have been mounted in fixtures in preparation for coating application. There are a total of five spray booths used to process the HRSI tile during the coating operations.

MANUFACTURING FACILITY - COATING AREA



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SPRAYING OF TILE

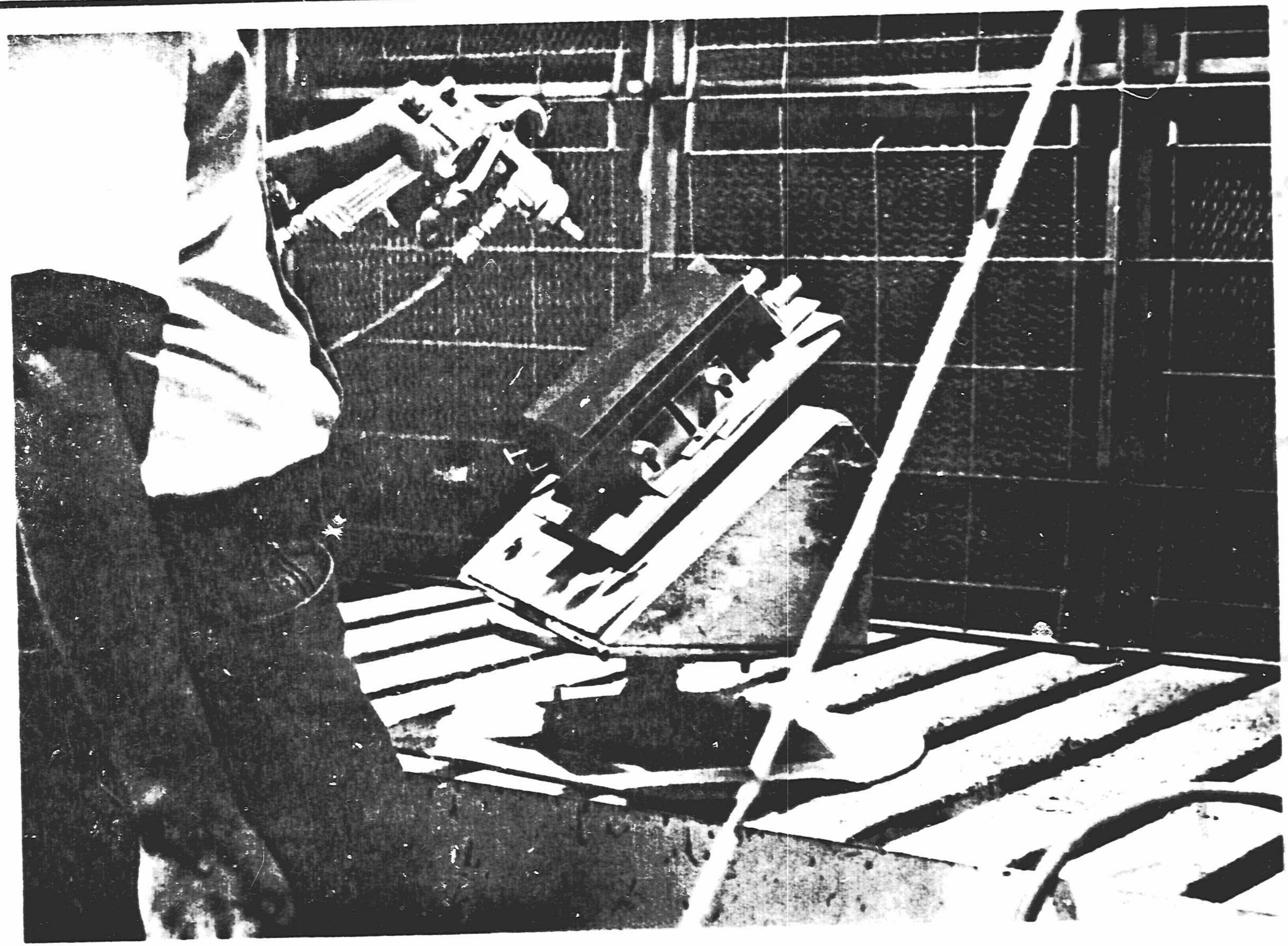
The coating is applied to the LI-900 base material in the same way that one would apply a coat of paint. The majority of the tiles were sprayed by hand as shown in the photograph. Robot sprayers developed by Binks were used for a portion of the production, but tile configuration varied sufficiently from one part to the next to negate the value of that approach. The objective in using the robot sprayer was to achieve more uniform application of the coats and thereby more consistent coating from one tile to the next. However, it was found that a person can develop sufficient skill within a month or so such that high repeatability on coating weight and coating thickness can be achieved even when dealing with a wide variety of tile shapes.

A design requirement for the tiles is that the coating terminate in the range from 1.5 to 5.6 millimeters (0.06 to 0.22 inches) from the tile inner mold line (IML). There are three reasons for this. First, it is necessary to have a breather space to allow air to vent on ascent. Second, if the coating were to go below the tile IML the coating would be cut during the final machining operations. This would produce chipping and cracking of the coating which is unacceptable. Third, the orbiter structure is not always in perfect conformance to the master dimension mold lines and some adjustment on the order of 0.5 millimeters (20 mils) is allowed by hand sanding at the time of installation of the tiles. If the coating were to go to the IML surface, it would not be possible to hand sand the LI-900 with the hard coating present and still maintain the necessary accuracy.

In the development phase masking tape was applied to the tile sides to provide a coating terminator. This proved to be unsatisfactory for production application because it is too easy to peel the edge of the coating when removing the masking tape. This was particularly true on complex configurations. As a result a shadow mask is used. After the tile has been machined on the outer mold line and on four sides, a final pass is made with a special tool which undercuts the tile by 0.3 millimeters (10 mils) to mark the coating termination. This machine cut is the easiest means available to establish the coating boundary since there are no drawings for reference. The undercut is used as a guide for adjusting the shadow mask blades shown in the photograph.

The coating material is a high purity, amorphous, borosilicate glass with a small percentage of additives necessary to control the emittance and solar absorptance. The glass is ground to a consistency like face powder with an average particle size of 6 microns. The glass is then suspended in alcohol for the Class 2 (black) coating while deionized water is used as the carrier for the Class 1 (white) coating. Choice of alcohol or water as the carrier is more historical accident in terms of laboratory development since either carrier can be used with equal ease and equal success. The desire to minimize change when scaling from laboratory to production resulted in the separate carriers being used for these two systems.

SPRAYING OF TILE



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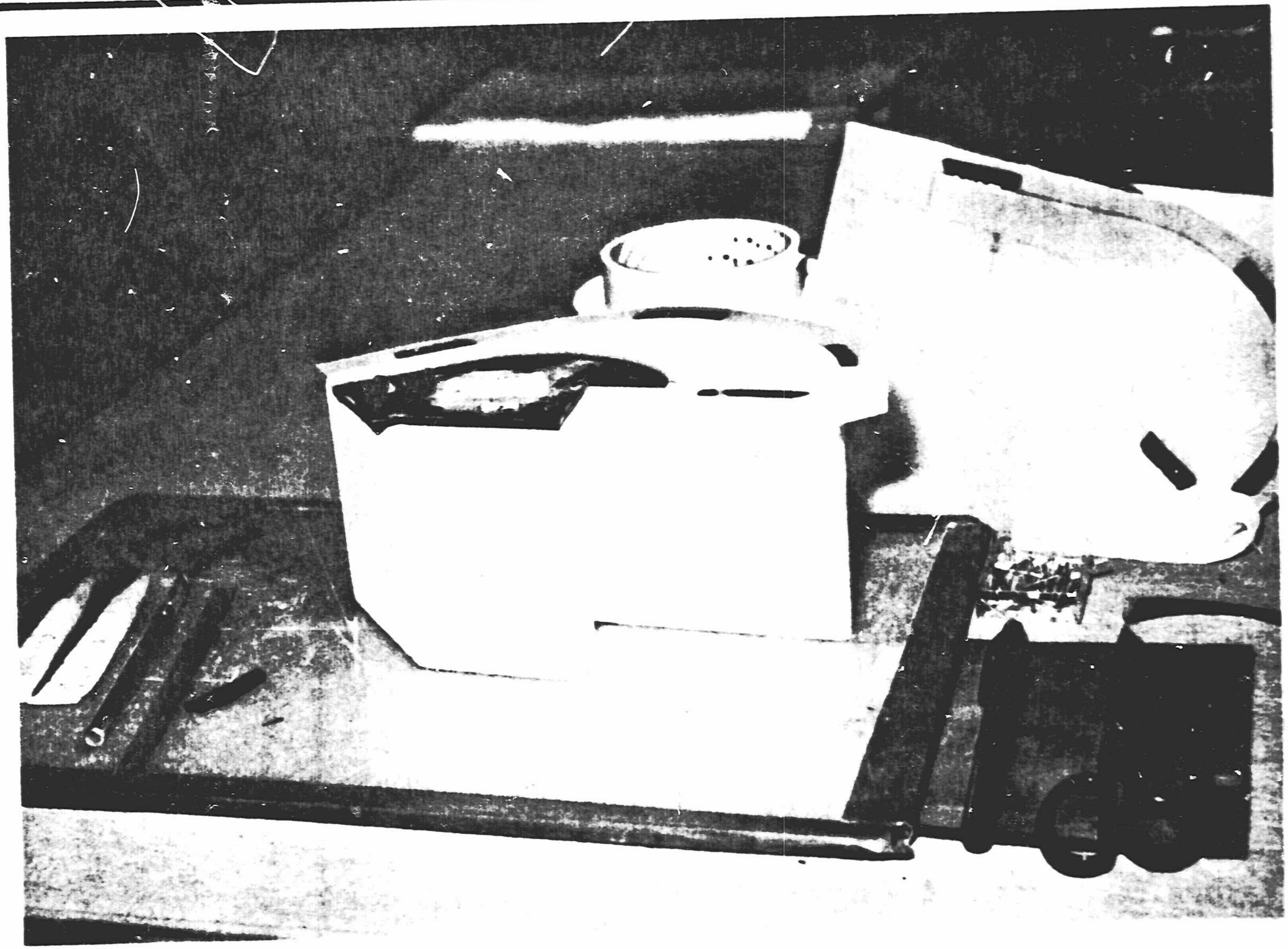
MASKING OF TILE

In most cases it was possible to machine a 0.3 millimeter (10 mil) undercut (witness line) on all sides of the tile to locate the coating termination line. This undercut was used to align the metal blades on the shadow mask as shown in the photograph on the preceding page. The coating boundary is defined as a line on the tile side at a constant offset from the tile inner mold line (IML). The IML surface is defined either by a grid of X, Y, Z coordinates and surface normal vectors, or by a set of equations. The tile sides are located by four corner points at the intersection of the tile side and the inner and outer mold line surfaces; planar or curved side surfaces are passed through these points. In almost every case the sides are at some odd angle to both the IML and the IML surface grid. Thus location of the intersection of the IML offset surface and the tile side requires a considerable amount of computation, and since it is more involved to drive a cutter along a line than it is to cut a surface, writing the commands to drive the witness line cutter is the most complex task involved in the tile part programming effort.

For about ten percent of the tiles, the configuration was such that it was not possible to provide an undercut at the time of machining the tile. In these instances it was necessary to generate a computer plot on mylar plastic showing the true projection of each tile side. In the photo a completed trace on mylar can be seen behind the tile as well as a mylar which has been cut to contour and placed on the tile side. A silicone rubber shadow mask cut to the proper contour and attached by pins to the tile side can also be seen. After establishing the proper position for the rubber shadow mask the mylar is removed from the tile. When all sides have been properly masked the tile will be put in the spray booth and coated. The metal shadow mask takes five to fifteen minutes to set up for most tile configurations in order to achieve the precision required. The mylar shadow masks require one to two hours or more to install depending on tile configuration.

MASKING OF TILE



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TYPICAL TILES

This group of tiles illustrates the range in size and configuration used on the Space Shuttle orbiter. The Rockwell part number for flight tiles is applied in a very specific location to ensure that the tile is located correctly when the inner mold line is machined and when the tile is installed on the vehicle. The part number is painted in yellow on the black tiles and in black on the white tiles.

Several of the tiles in the photograph have a large amount of LI-900 showing below the coating. These tiles have not yet had the inner mold line machined and the excess material is used simply as part of the manufacturing process. Several other tiles have the LI-900 machined to final configuration and only a small amount of material can be seen below the coating line.

TYPICAL TILES

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ELECTRONIC PROBE INSPECTION OF TILE DIMENSIONS

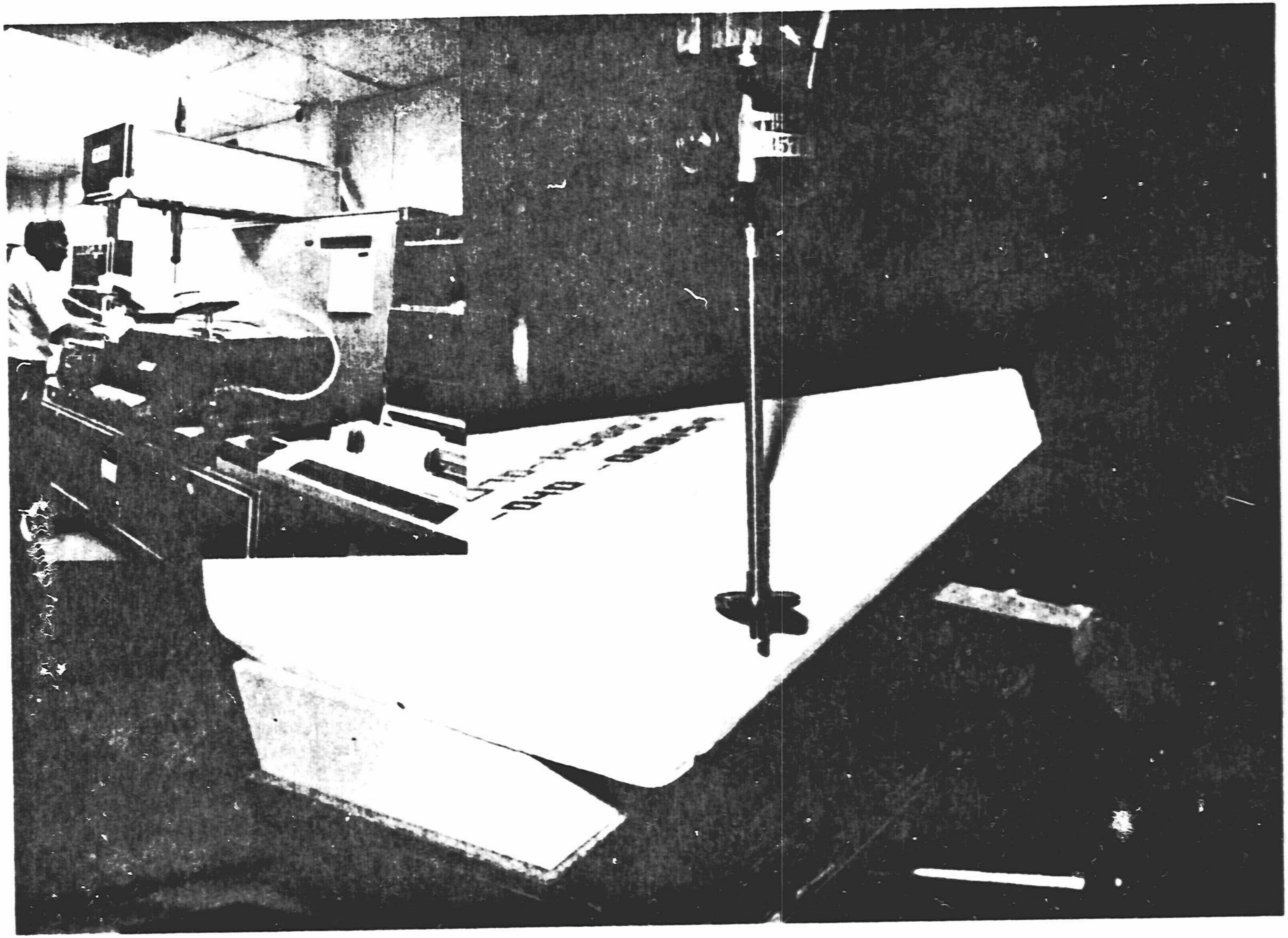
Since there are no drawings of the tiles, measurement of tiles is based on computerized standards used to drive a three-axis electronic probe. A common technique is to measure a part immediately after machining and while still mounted on the numerically controlled mill, using an electronic probe in place of the cutting tool. This method cannot be used here since the tile must be coated and glazed after machining but prior to final measurement. Thus a separate electronic measuring device must be used. Tile measurement was relatively straightforward for about two-thirds of the parts, but substantial complications were encountered on the remainder, particularly in establishing a reference system for comparing measurements to the standards; rigid-body rotations and translations are applied to the data to obtain a best-fit comparison with the standards, but minor setup errors, particularly for tiles with curved sides or acute angles between sides and top surface, made accurate measurements difficult. Since each tile is different, the generation of inspection data and procedures was a major task in the production of the tiles for the first Shuttle orbiter.

The photograph shows the 3-axis electronic probe in use measuring a tile machined on a 5-axis numerically controlled mill. Approximately 15 points per side and 5 points on the upper surface are measured for each tile. Tiles must be set up such that the tile sides are within five degrees of vertical. The computer performs the necessary rigid body rotation and translation to fit the measurement data to the standards. Because of setup errors and minor surface irregularities the tile measurement repeatability is only within 0.075 millimeters (3 mils).

Computer data were used to generate templates to measure by standard techniques some or all of the characteristics on about 2000 tiles. While this approach was used successfully, it too presented significant difficulties because there are no known reference surfaces on the tiles from which to index the templates. It was proposed that special index surfaces be machined on the tiles in an area which would later be cut off; however, the tile must go through the glazing cycle after machining and the resulting distortion negates the use of such special surfaces as a known measurement reference point. Since none of the boundaries are truly perpendicular, and since the outer mold line (aerodynamic surface) is curved on all tiles minor setup errors in the templates could (and did) create significant measurement errors. Moreover, since every tile is unique a standard setup could not be established.

For the first vehicle approximately 21,500 of the 23,400 tiles were measured. Late in the production cycle techniques were developed which would allow assessment of the tile dimensions by putting groups of tiles into the array frame and using the known dimensions of the array frame as verification of tile configuration. This technique proved to be effective and will be used extensively on subsequent tile production for the remaining orbiter vehicles. However, there will always remain a substantial group of complex tiles that require direct measurement for verification of tile planform.

ELECTRONIC PROBE INSPECTION OF TILE DIMENSIONS



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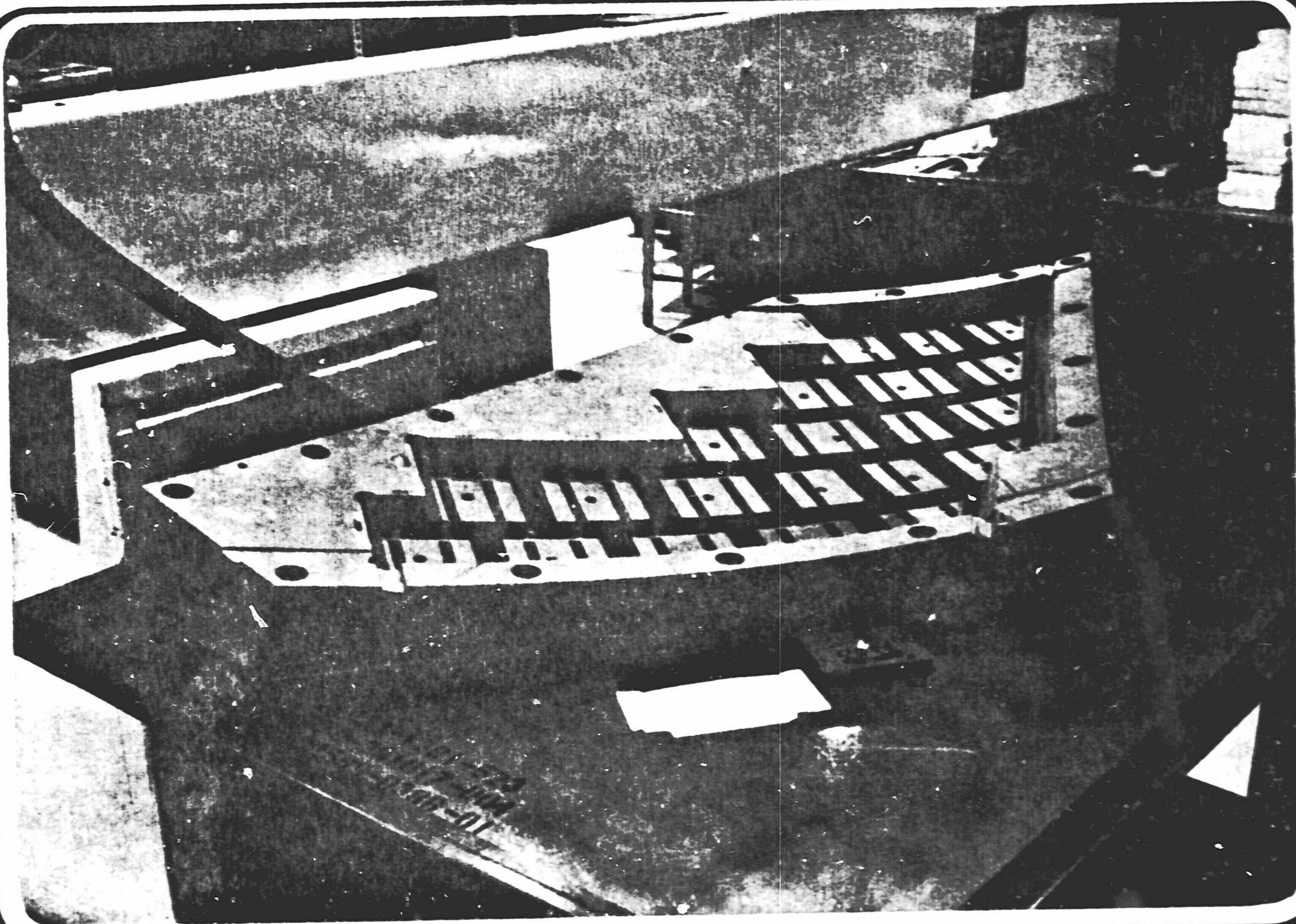
TYPICAL ARRAY FRAME

The array frames are designed to hold the tiles firmly during machining of the tile inner mold line (vehicle structural surface contour). For this reason the array frame assembly has vacuum ports to hold the coated side of the tile firmly in place during the machining operations. Cork and gasket material is also used to improve the vacuum hold down of the tile during the machining operations. A total of 821 array frames are used and, just as with the tile, no two array frames are alike, although approximately 45 percent are mirror images. Also just as the tiles are not really square, the array frames come in a variety of configurations. The arrays vary in size from a minimum of two tiles to a maximum of 55 tiles with an average of about 22 tiles per array assembly.

TYPICAL ARRAY FRAME



4-14-78

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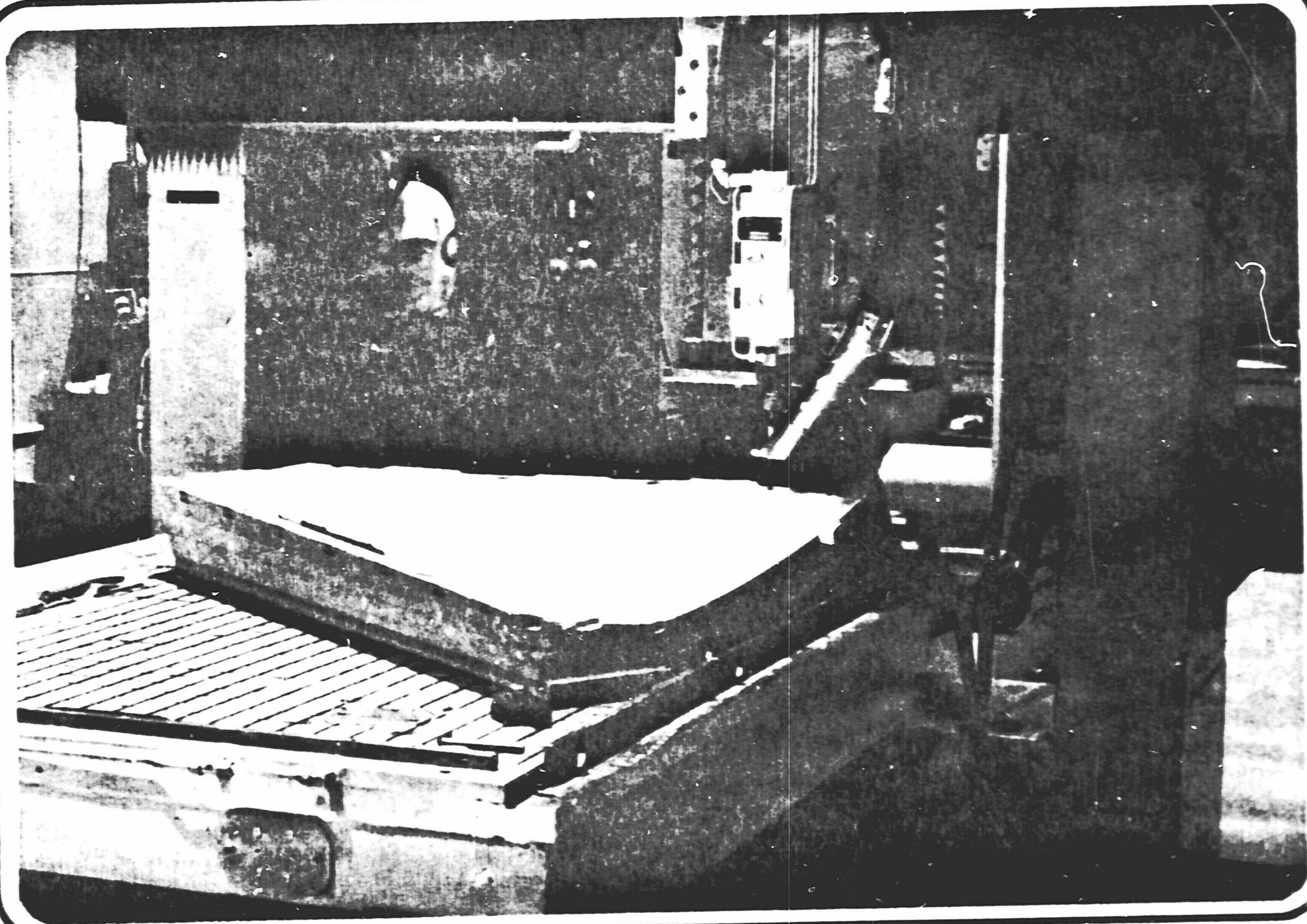
INNER MOLD LINE MACHINING OF TILE ASSEMBLY

The array frame loaded with tiles is placed on the bed of the large 3-axis numerically controlled mill for machining of the inner mold line. The array frame itself as well as the tiles are held to the machine bed by vacuum. The photograph shows use of a 76 centimeter (30 inch) radius mushroom cutter.

INNER MOLD LINE MACHINING OF TILE ASSEMBLY



4-14-78

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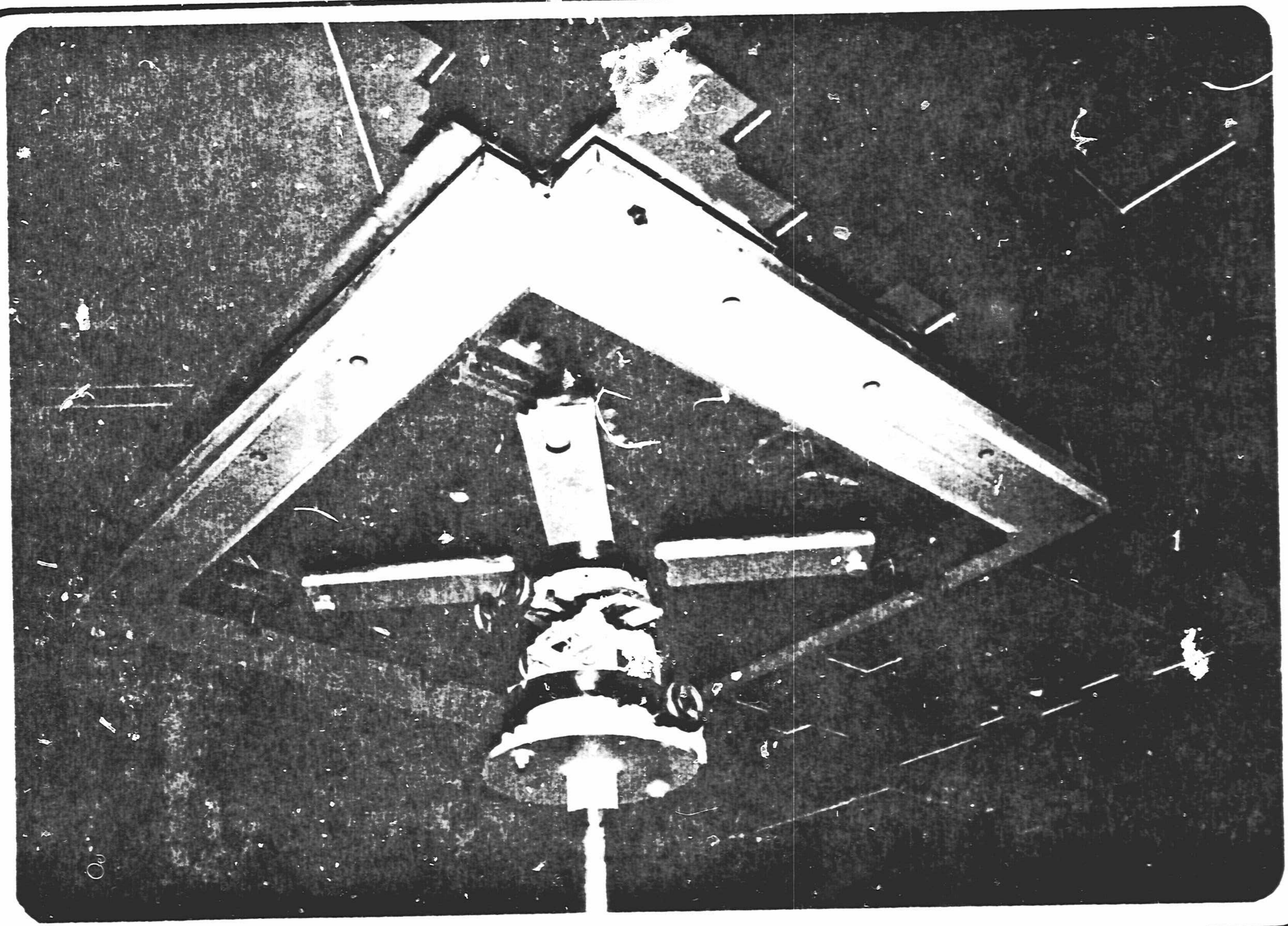
INSTALLATION OF ARRAY ON ORBITER

The array frame with tiles in place is vacuum bagged and shipped from the Lockheed Sunnyvale facility to the Rockwell Palmdale facility (approximately 650 kilometers or 400 miles away). The tiles are prepared for bonding to the vehicle by Rockwell personnel. A strain isolator pad is bonded to each individual tile and a thermal barrier is placed at the intersection of tiles. This assembly is then moved in place to be bonded to the orbiter structure as shown in the photo. One row of tiles along each of two sides of the array are put in place to help position adjacent tiles but are not bonded at the time of the array assembly installation in order to leave room for the use of an array frame to hold the tiles when bonding the adjacent arrays. Once several sets of arrays have been bonded to the vehicle, the omitted tiles are bonded in place individually.

INSTALLATION OF ARRAY ON ORBITER



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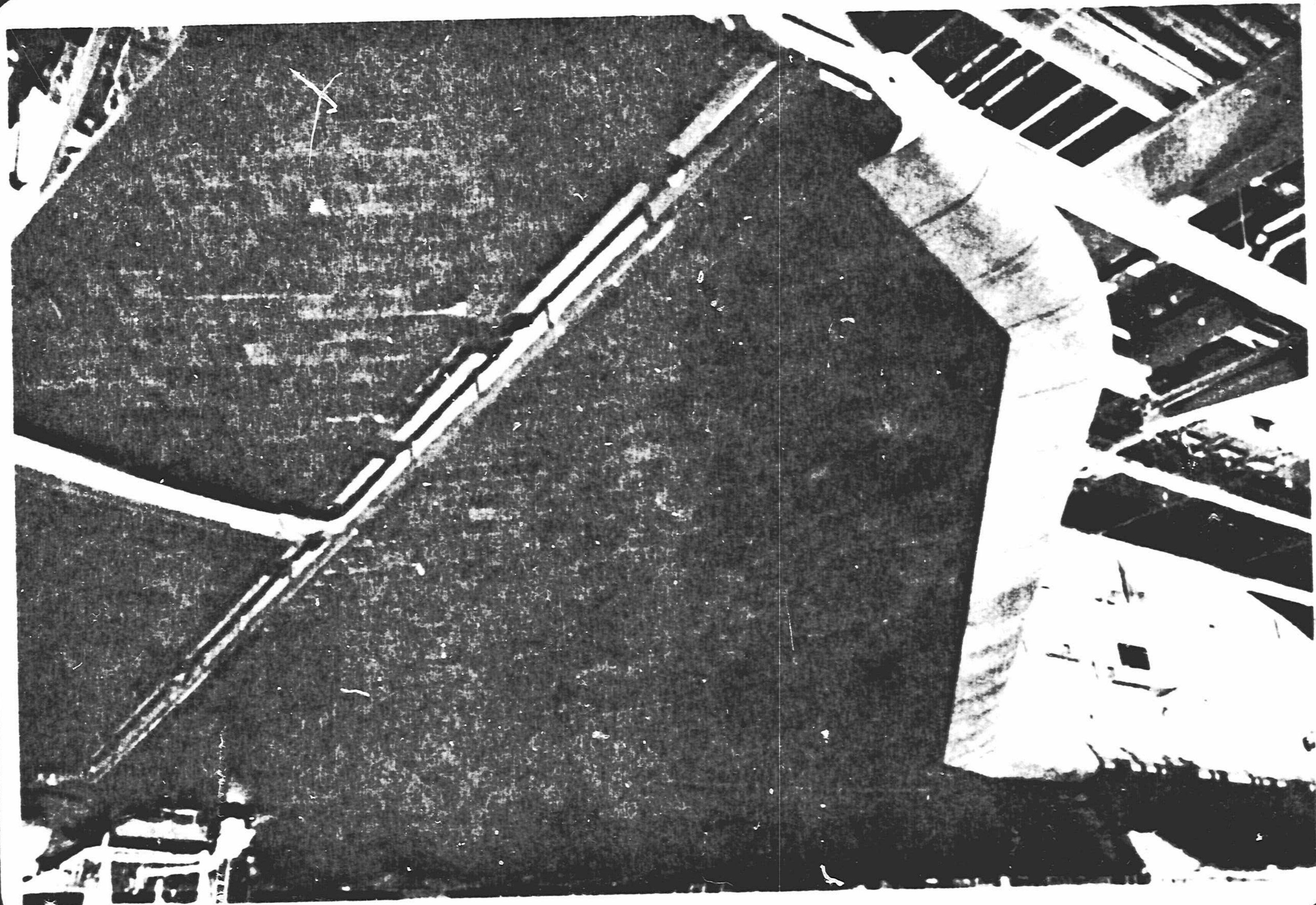
4-14-78

TILES ON ORBITER AT PALMDALE

The photo shows over 4,000 tiles bonded in place on the mid-body of the orbiter underside.

This photo emphasizes perhaps the most significant accomplishment of this program: It has been demonstrated that one company can create a detailed mathematical description of all of the surfaces of a vehicle the size of a Boeing 727 jet, the data can be transmitted to another company, and 23,400 unique parts can be produced to these data such that they fit precisely when installed on the vehicle.

TILES ON ORBITER AT PALMDALE



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4-14-78

ACKNOWLEDGEMENT

The High Temperature Reusable Surface Insulation system has evolved as a result of contributions and dedication of many people. Space does not permit naming all of the key players but two deserve special mention. The basic concept of using amorphous silica fibers, as opposed to crystalline silica fibers, to produce a rigidized insulation system was developed by Mr. Robert Beasley. Without his insight, technical judgement, and creative drive this material would never have seen the light of day. However, the material might well have remained a laboratory curiosity if it had not been for the engineering insight and programmatic drive on the part of Mr. John F. Milton. Mr. Milton was the program manager for the Space Shuttle design studies conducted in 1965 through 1973 at Lockheed Missiles & Space Company. He was the first to recognize the importance of this material as being key to the success of any Space Shuttle concept and he, more than anyone else, deserves credit for pursuing this concept through to its practical application.

Many personnel in both Rockwell International and the National Aeronautics & Space Administration have contributed to the development and growth of this program. The effort was funded under Contract No. M3J3XMA-483011D, "Production of High Temperature Reusable Surface Insulation Subsystem", a subcontract to Rockwell International who in turn is the prime contractor for the Space Shuttle orbiter with NASA.

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