COR: James D. Hankins / EH44

LMSC-D880308

ORIGINAL PAGE IS
OF POOR QUALITY

(NASA-CR-170676) HIGH-SPEED MACHINING OF SPACE SHUTTLE EXTERNAL TANK (ET) PANELS Final Report (Lockheed Missiles and Space Co.) 81 p HC A05/MF A01 CSCL 13H

N83-13291

Unclas
G3/31 02037

TASK B
FINAL REPORT

HIGH-SPEED MACHINING OF SPACE SHUTTLE EXTERNAL TANK (ET) PANELS

15 SEPTEMBER 1982

Prepared for

National Aeronautical & Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Prepared by:

Joseph A. Miller
Missile Systems Division

Contract: NAS 8-34508
LMSC Number: D829426

LOCKHEED MISSILES & SPACE COMPANY, INC.

FOREWORD

Lockheed Missiles & Space Company, Inc. is pleased to submit this Task B final report to the National Aeronautics & Space Administration, Marshall Space Flight Center in accordance with Contract Number NAS8-34508. The program, summarized herein, covers Task B of the contract, plus changes specified by Change Orders No. 1 and No. 3. Change Order No. 1 essentially added the high-speed machining of an 8 foot long panel (Ref NASA letter of 18 December 1981 by James D. Hankins) and transferred the activity of Task A identified by the paragraph "Identify Potential High-Speed Milling Procedures" to Task B where it is entitled "High-Speed Milling Procedures and Times". Change Order No. 3 added video taping of the high-speed machining panel cutting process.

This submission is not intended to duplicate a Task A* report and documents only the results of the Task B activities.

---

* See Task A objectives under Introduction

CONTENTS

PRECEDING PAGE BLANK NOT FILMED

CONTENTS (Cont'd)

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

Section 1
INTRODUCTION

The External Fuel Tank (ET) of the Space Shuttle (see Figures 1-1 and 1-2) is not recovered after launch, therefore, a new one must be provided each time. Currently, the external "skin" panels of the tank are produced by machining from solid wrought 2219-T87 aluminum plate stock approximately 1-3/4 in. thick.

The reduction of costs in producing External Fuel Tank panels is obviously, then, of particular significance. This study which is divided into Tasks A and B was initiated to investigate the feasibility of increasing production rates and decreasing costs of the panels through the application of high-speed machining techniques.

1-1 TASK A OBJECTIVES

Task A, which has not yet been performed, is designed to address anticipated cost savings from converting to high-speed machining techniques from the current conventional machining process in manufacturing Shuttle External Tank panels. The cost savings are to be projected from conventional machining data and high-speed machining data generated and projected during Task B activities.

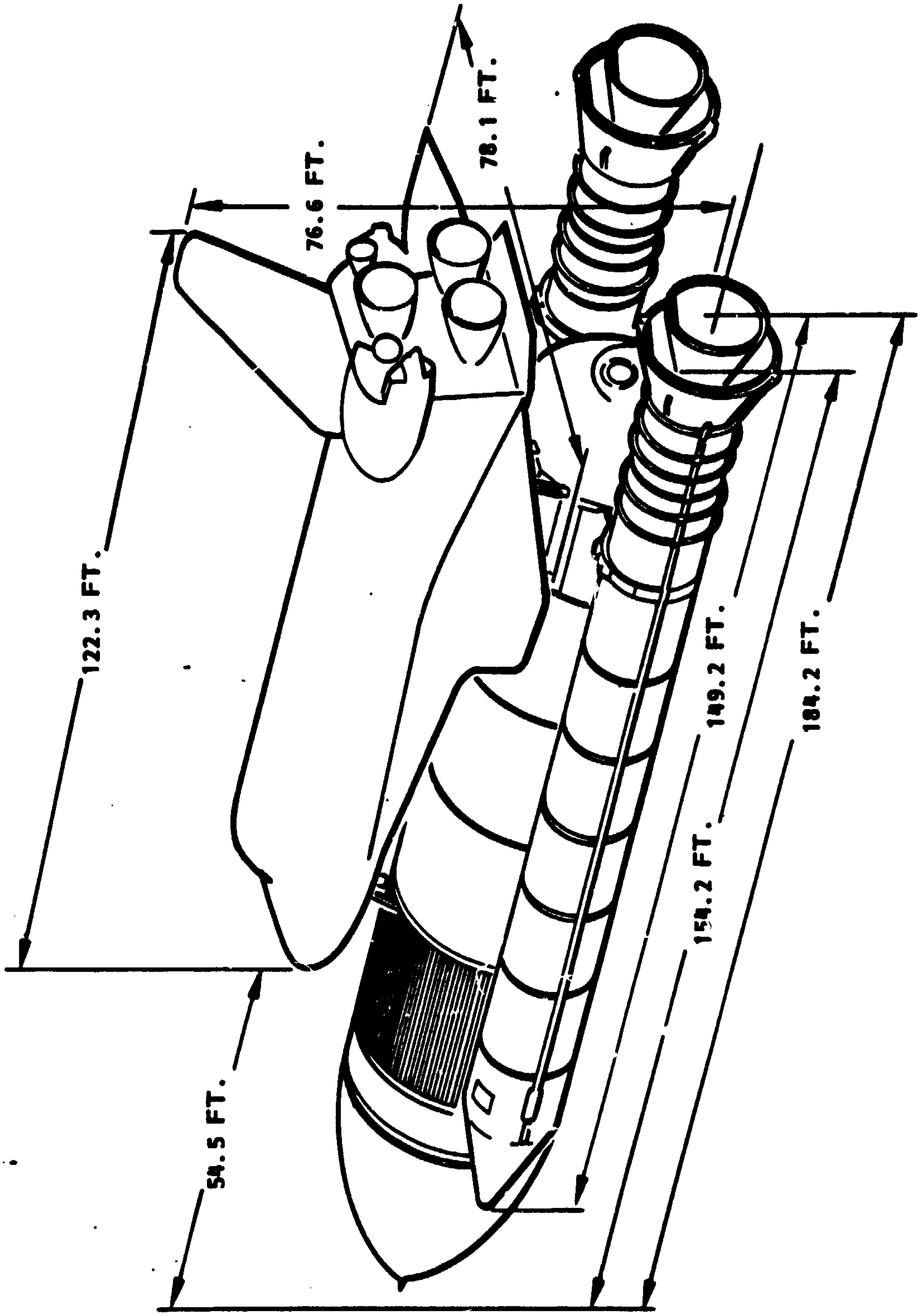


Figure 1-1 Space Shuttle Attached to External Fuel Tank

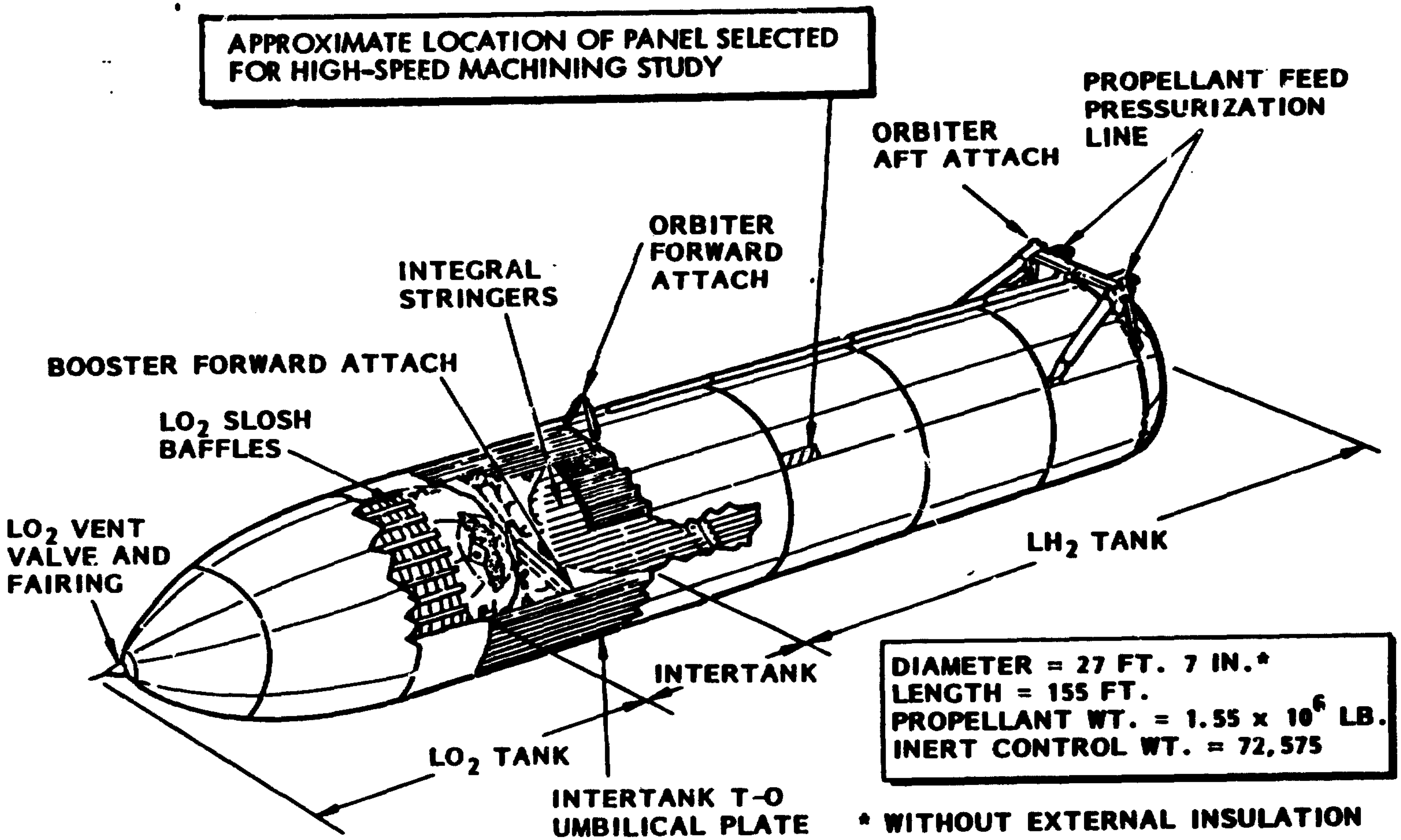


Figure 1-2 Detail of Space Shuttle External Fuel Tank

1-2 TASK B OBJECTIVES

The primary objective of Task B (the subject of this report) was to demonstrate the applicability and advantages of the high-speed machining process to the production of Shuttle External Tank panels by physically machining selected sample portions of an external tank panel. Figure 1-1 shows the relationship of the Shuttle to the External Tank to which it is attached for launching. The approximate location of the sample panel portion selected for this study is illustrated in Figure 1-2.

Section 2
TASK B TASKS

The elements of Task B as delineated in the original contract are as follows:

1) Select the panel sample configuration
2) Perform the milling demonstration
3) Produce a Task B final report

The scope of Task B was subsequently increased through Change Order No. 1 to include two additional tasks. The fourth task is the machining of an 8 foot long panel section, and the fifth, to incorporate the paragraph from Task A entitled "Identify Potential High-Speed Milling Procedures." This paragraph was relabelled "High-Speed Milling Procedures and Times".

A sixth task, the video taping of the high-speed machining process, was added by means of Change Order No. 3.

2-1 DELIVERABLE HARDWARE

The deliverable items under Task B of the contract are as follows:

1) 3 - 38 in. x 46-1/2 in. (approximately) tank panel sections
2) 1 - 38 in. x 94-1/2 in. (approximately) tank panel section
3) Several small T-rib cross-sections of sample panel
4) Video tape of high-speed machining panel cutting operation
   a) Original footage (with written narration)
   b) Rough edited version (with written narration)

Section 3

TASK B TECHNICAL APPROACH

A primary objective of the panel cutting of Task B was to demonstrate the advantage of high-speed machining for Shuttle tank panels within the limitations of equipment available at Lockheed and then to project to an ideal situation where equipment would be especially designed or adapted for this purpose.

3-1 EQUIPMENT LIMITATIONS

The only milling machines available at Lockheed, which were large enough to machine the panel samples selected, were the Sundstrand Omnimil NC machining centers. A model OM3 (Figure 3-1) was selected for the preliminary cutter and NC tape trials because of its availability and accessibility. However, a model OM4 (Figure 3-13) was required to accommodate the larger sizes during the final panel machining.

3-1.1 Table Feed

The maximum table feed capability of both the OM3 and OM4 Sunstrand models is 200 inches per minute (ipm) which is definitely a limiting factor when high-speed machining aluminum under these conditions. Higher cutting speeds (sfpm) could be attained by increasing the spindle speed; however, the volume of metal would not be significantly increased because the chip load would be simultaneously reduced unless the table feed could be increased accordingly.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

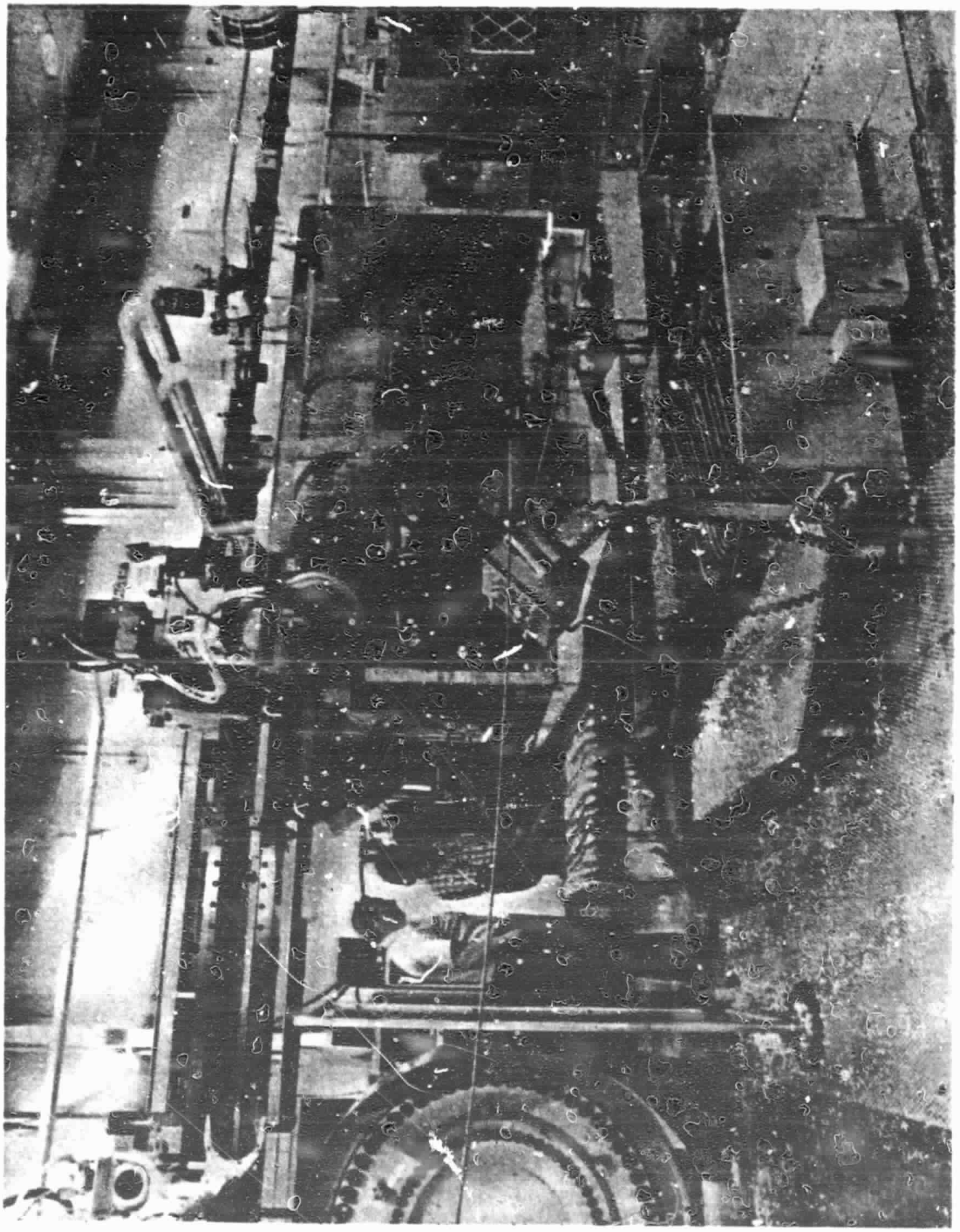


Figure 3-1 High Speed Machining Cutter Trials on Sundstrand OM3 NC Machining Center

3-1.2 Horsepower

Horsepower was also a limiting factor (16.6 hp maximum at 18,000 rpm and 5.5 hp at 8,000 rpm). If more horsepower had been available, more volume (cu in/min) of metal could have been removed by utilizing heavier depths of cut, larger diameter cutters, and higher feed rates.

3-1.3 Spindle Nose Configuration

The No. 30 Milling Machine Taper (MMT) of the Bryant 18,000 rpm spindle motor (Figure 3-2) was definitely a limiting factor in that the tool holder shank diameter of only 1-1/4 in. at the large end of the taper restricted the size of cutter which could be employed. This relatively small spindle nose also restricted the shank diameter of the cutting tool itself, thus automatically limiting the length of tool and depth of cut which could be utilized due to a lack of rigidity and/or stiffness.

3-1.4 Table Travel

The table travel of Lockheed's largest capacity machining center, the Sundstrand OM4, limited the size of panel which could be machined. When laying the panels down flat on the OM4 machine table (Figures 3-3 and 3-4), the maximum panel size attainable was 21 in. by 96 in. Consequently, the 38-in. finished panel width was achieved only by machining half of the panel width and then indexing to reach the second half.

3-1.5 Chip Removal Not Automated

The fact that the chip removal was not automated was not actually a substantial limiting factor for the sizes of panels involved in the project. However, for full-size Shuttle Tank panels, a conveyor system plus a system of

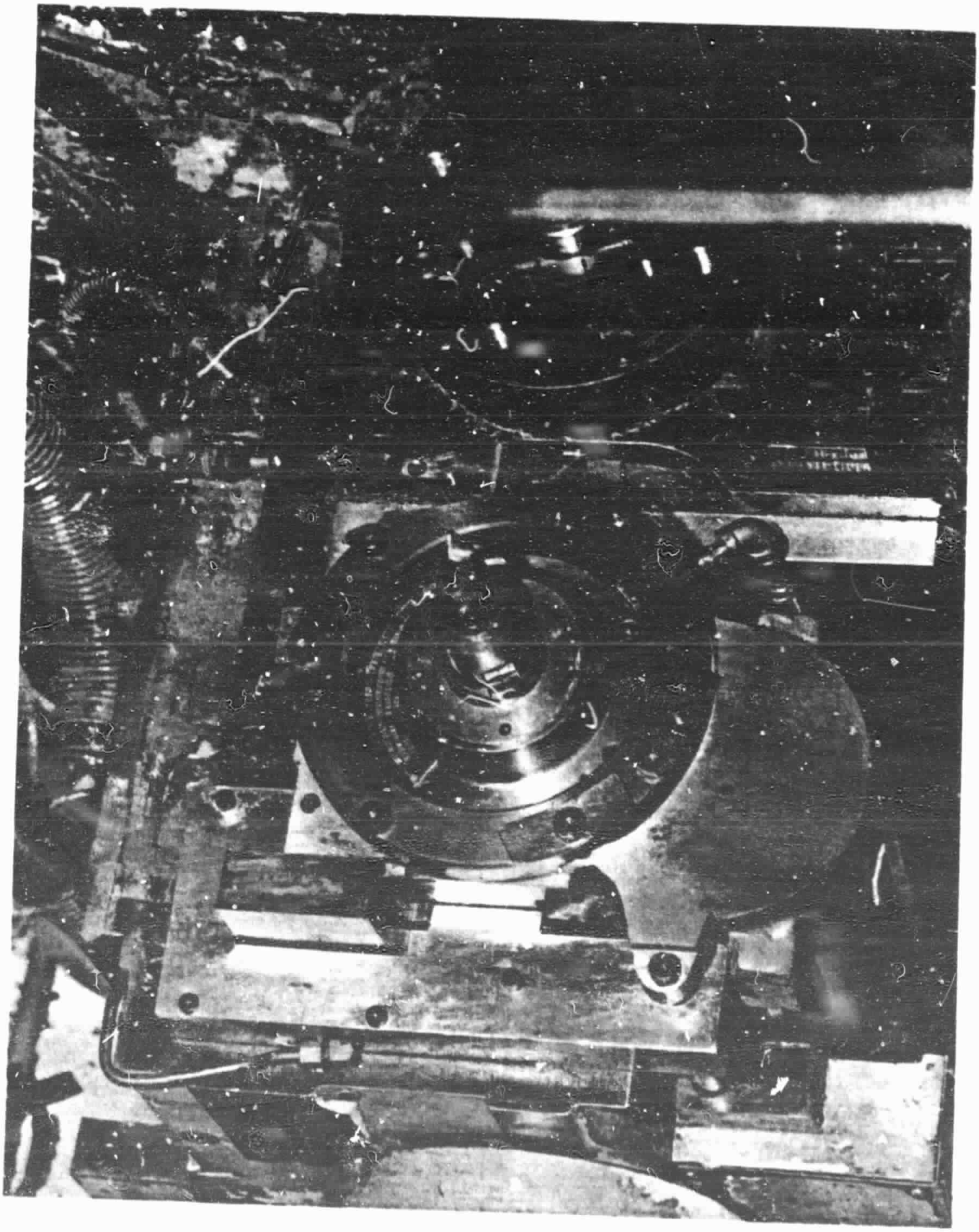


Figure 3-2 Close-up of 18,000 RPM Bryant Spindle Motor Installed in OM3

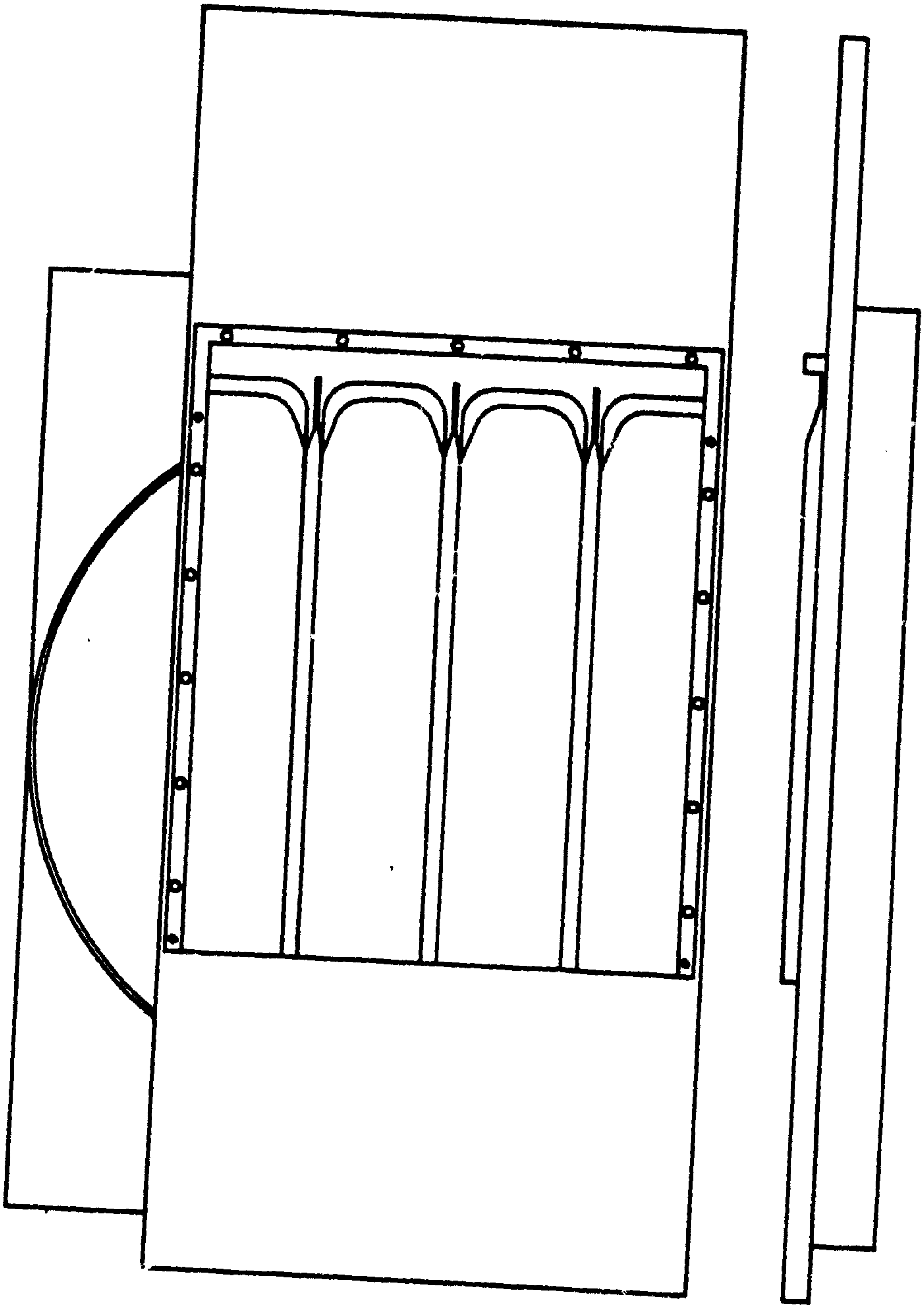


Figure 3-3 8 Ft Long Panel as Positioned on Base Plate and Machine Table

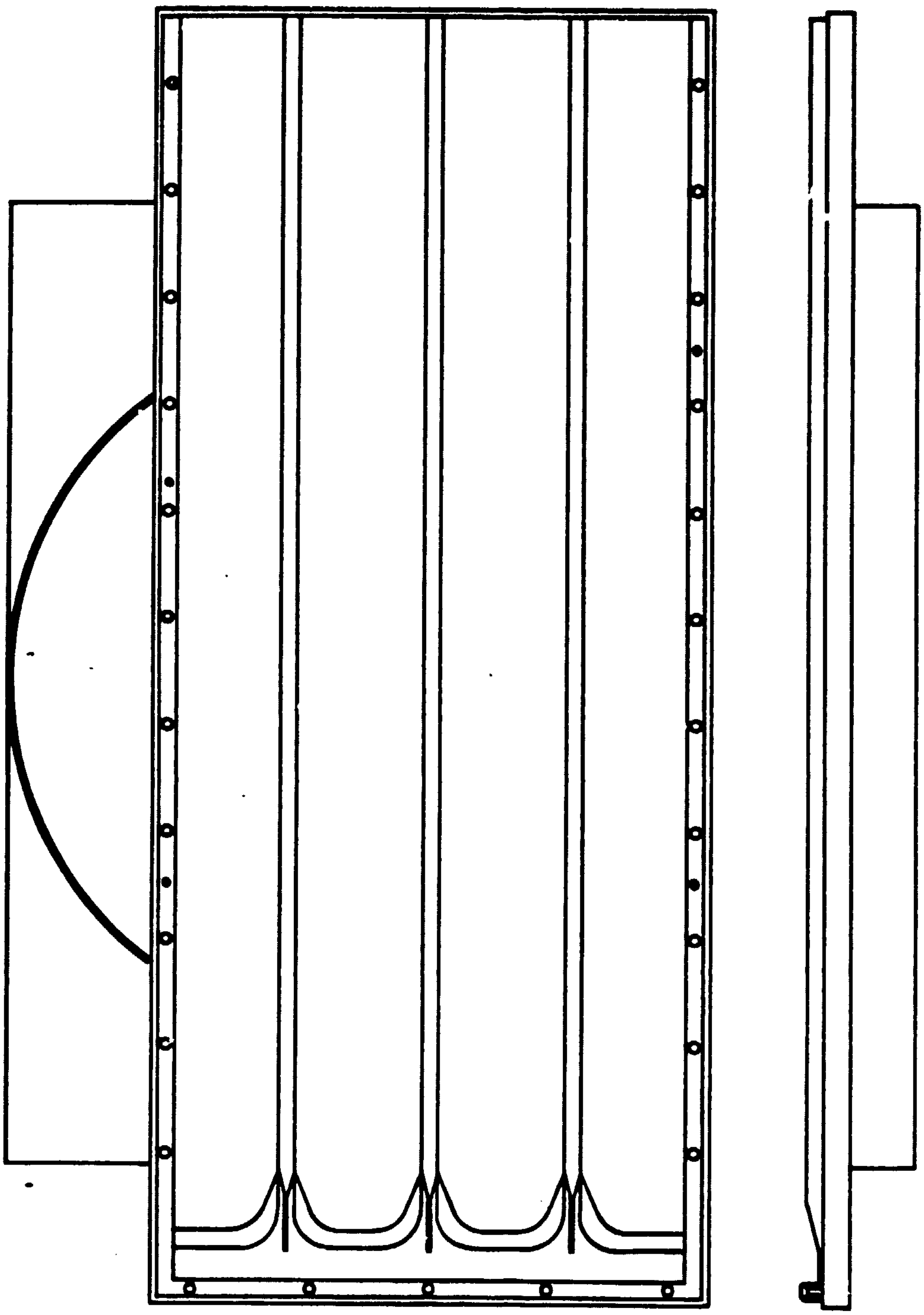


Figure 3-4 8 Ft Long Panel as Positioned on Base Plate and Machine Table flood coolant or air blast nozzles to move the chips to the conveyor would be recommended. Perhaps an even more functional approach for chip removal would be the use of a sufficiently powerful vacuum system to vacuum away the chips.

3-2 PANEL SELECTION

The selection of a specific Shuttle External tank panel which was felt to represent the majority of the panels (see Figures 1-1 and 1-2) was accomplished primarily by personnel from the Marshall Space Flight Center and their prime contractor for the Shuttle Tank, Martin Marietta. As the panels are generally 11 ft wide by 20 ft long, a full panel was not feasible for this study, especially in light of Lockheed's machine tool limitations. Therefore, approximately 4 ft by 4 ft and 4 ft by 8 ft sections of an appropriate panel were chosen. This panel is identified by Martin Marrietta drawing number 80914400984 with selected sections indicated on Sheet 2. The configurations of these panel sections are shown in Figures 3-3, 3-4, and 3-5 of this report and in subsequent photographs.

Following the panel selection, 2219-T87 aluminum material for the study was shipped from Martin Marietta to Lockheed. (See Paragraph 3-4.1.1 for details).

3-3 CUTTER SELECTION AND TRIALS

The diameters of the cutters to be used in high-speed machining the sample panels were limited by the horsepower and other parameters of the available equipment (See 3-1). The cutters selected had been successfully tested previously at Lockheed for the high-speed machining of aluminum, but of a different alloy. These chosen cutter designs had to be modified for proper corner radii to meet the panel configuration and for shank diameter to be utilized in the tool holder acceptable for the high-speed spindle motor selected for the project.

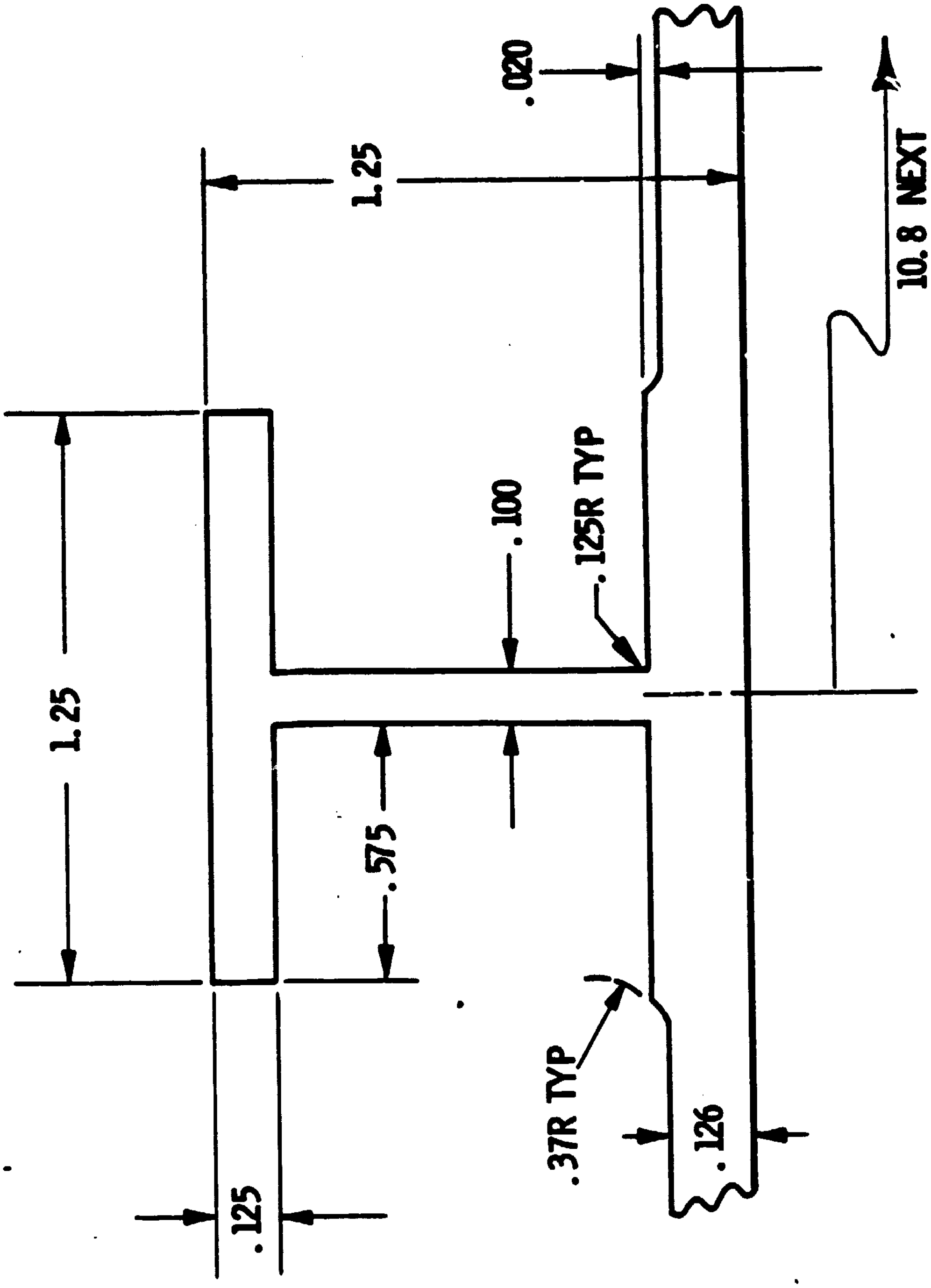


Figure 3-5 Section View of T-Rib Reinforcement of Fuel Tank Panel

Figures 3-6 and 3-7 show the 3-flute, 1-1/4 in. diameter end mill chosen as the roughing cutter to be used for removing the major portion of the pocket area between the T-ribs of the panel. The 3/8 in. corner radius end mill chosen for forming the 3/8 in. radii at the base of the T-ribs and for finishing the closed end of the panel is shown in Figures 3-8 and 3-9. This cutter has the same basic geometry as the roughing cutters except for the large radiused corners. Both 1-1/4 in. diameter cutters are made from ASP60 improved high speed steel.

The 4 in. diameter cutter chosen to cut the underside of the T-rib sections is shown in Figures 3-10 and 3-11. This cutter also had been previously used for high-speed machining aluminum. The corner radii of the teeth were increased to 0.125 in. to form the required fillets of the T-rib. The brazed inserts utilized in this cutter are made from Weldon Tantung, an alloy of tantalum and tungsten which is noted for its toughness.

Because of the required modifications of the cutters, the lack of experience in high-speed machining the 2219-T87 alloy, and the minimum time available on the Sundstrand OM4 NC machining center, cutter trials were conducted previous to the machining of the panels themselves. These trials were performed on a Sundstrand OM3 NC machining center (Figure 3-1) which was more readily available than the OM4. As the cutter trials were scheduled approximately one month in advance of the actual panel cutting demonstration, a safety period was thus provided during which further cutter modification could be accomplished if necessary. Furthermore, the cutter trials provided a means of testing the NC part program in advance.

Preparation for the cutter trials included the following activities. A somewhat reduced panel section which could be accommodated on the OM3 machining center was selected. The NC program was written. The cutters were modified and tool holders balanced. After the 18,000 rpm Bryant high-speed spindle motor was installed in the OM3, vibration tests were conducted to detect any resonant frequencies.

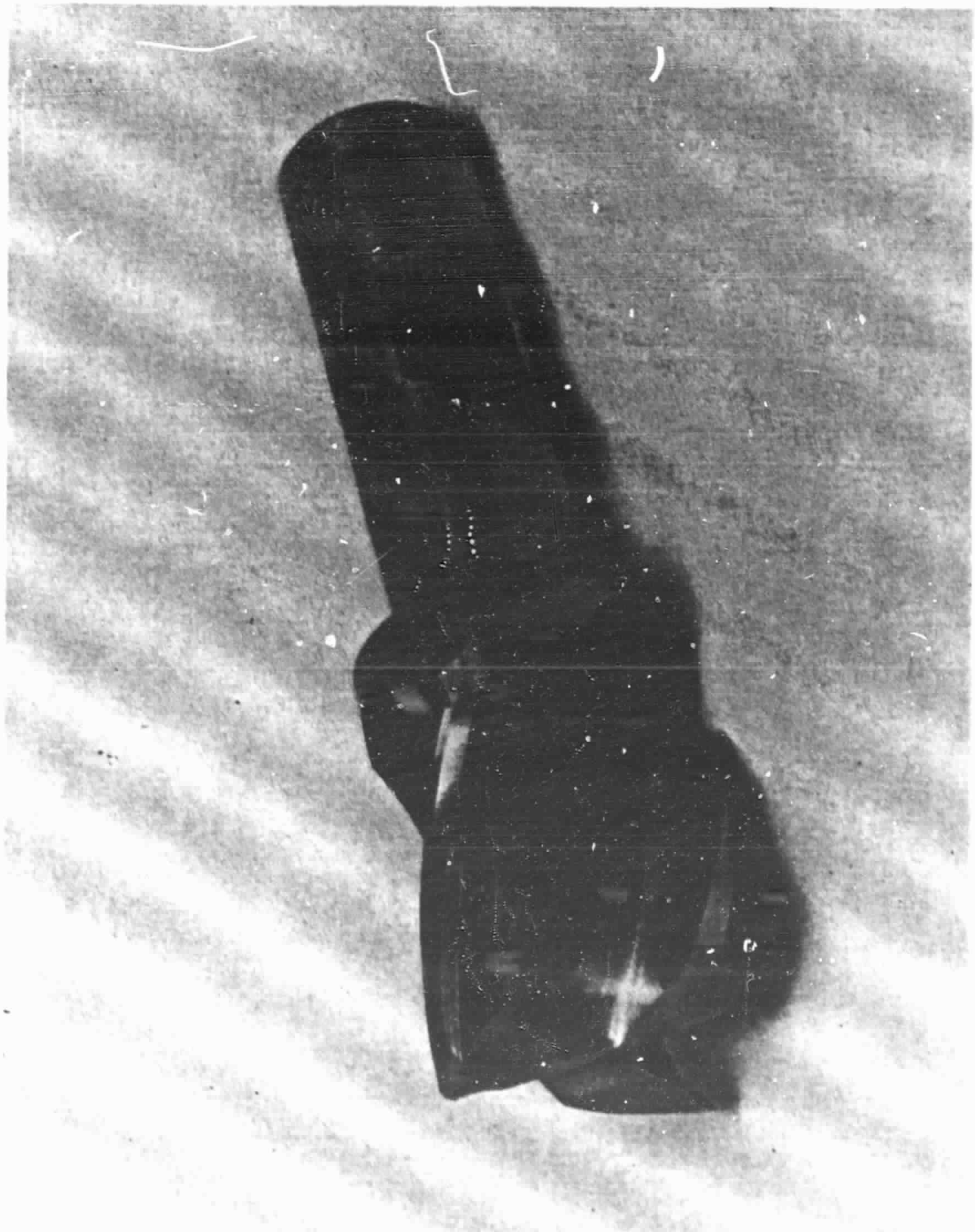
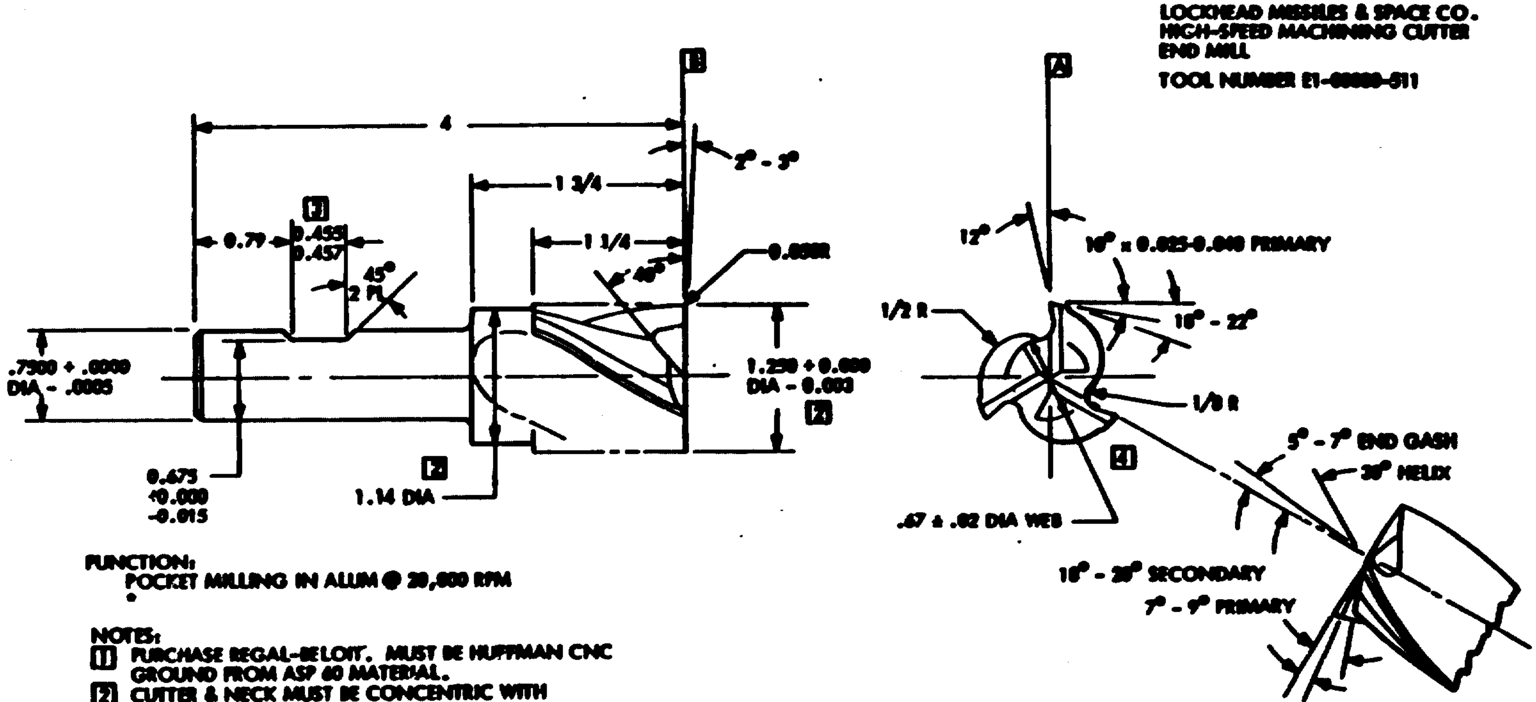


Figure 3-6 1-1/4 In. Diameter Three-Flute End Mill Selected as Roughing Cutter

ORIGINAL PAGE IS
OF POOR QUALITY



FUNCTION:
POCKET MILLING IN ALUM @ 20,000 RPM

NOTES:
1. PURCHASE REGAL-BELOIT. MUST BE HUFFMAN CNC GROUND FROM ASP 60 MATERIAL.
2. CUTTER & NECK MUST BE CONCENTRIC WITH SHANK WITHIN .0005 T. I. R.
3. FLAT MUST BE PERPENDICULAR TO -A- AT -B- WITHIN 10°.
4. AT LEAST ONE FLUTE MUST CUT TO CENTER.

Figure 3-7 Detailed Specifications for Roughing Cutter

Figure 3-8 1-1/4 In. Diameter 3/8 In. Corner Radiused End Mill Selected as Finishing Cutter

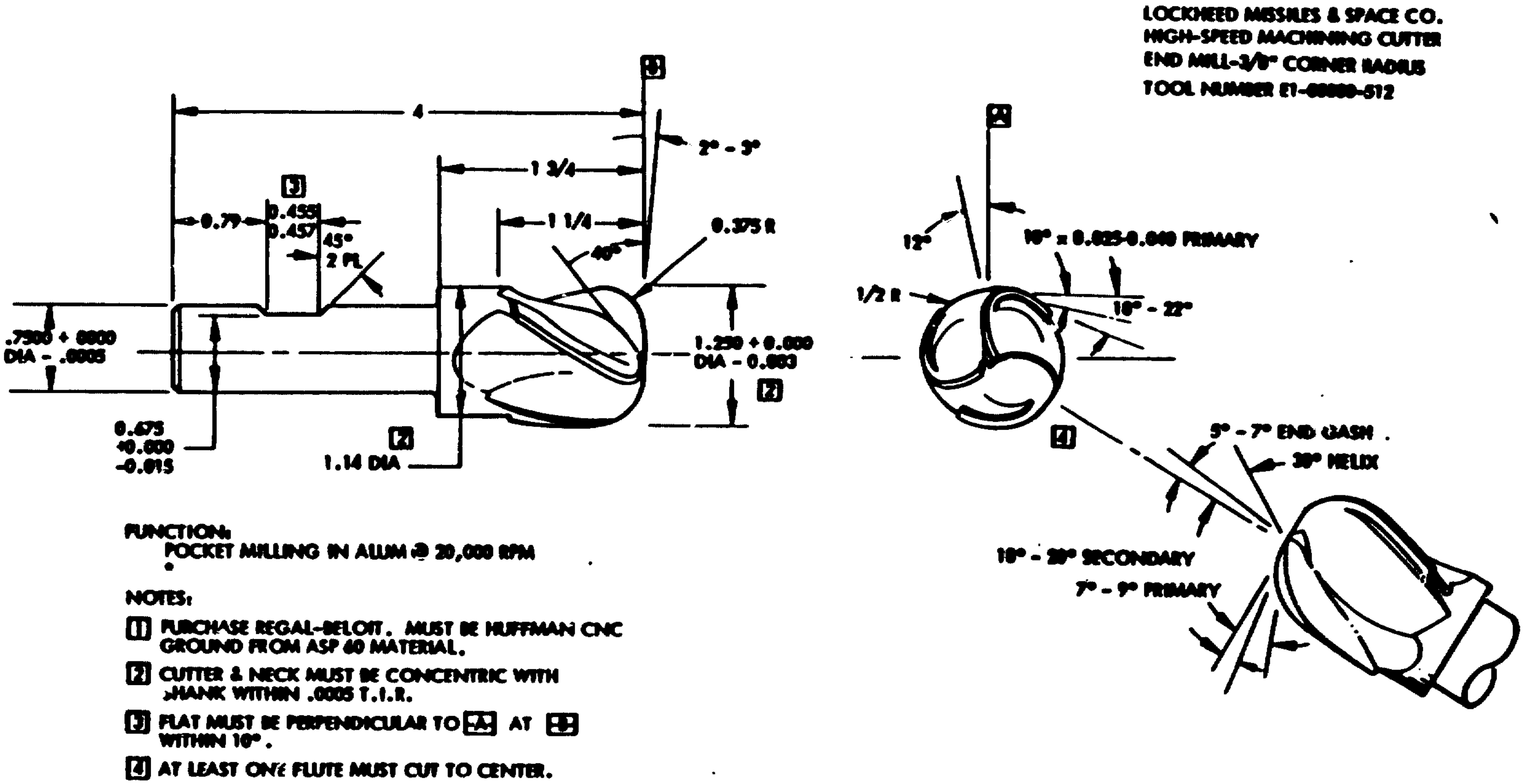


Figure 3-9 Detailed Specifications for Finishing Cutter

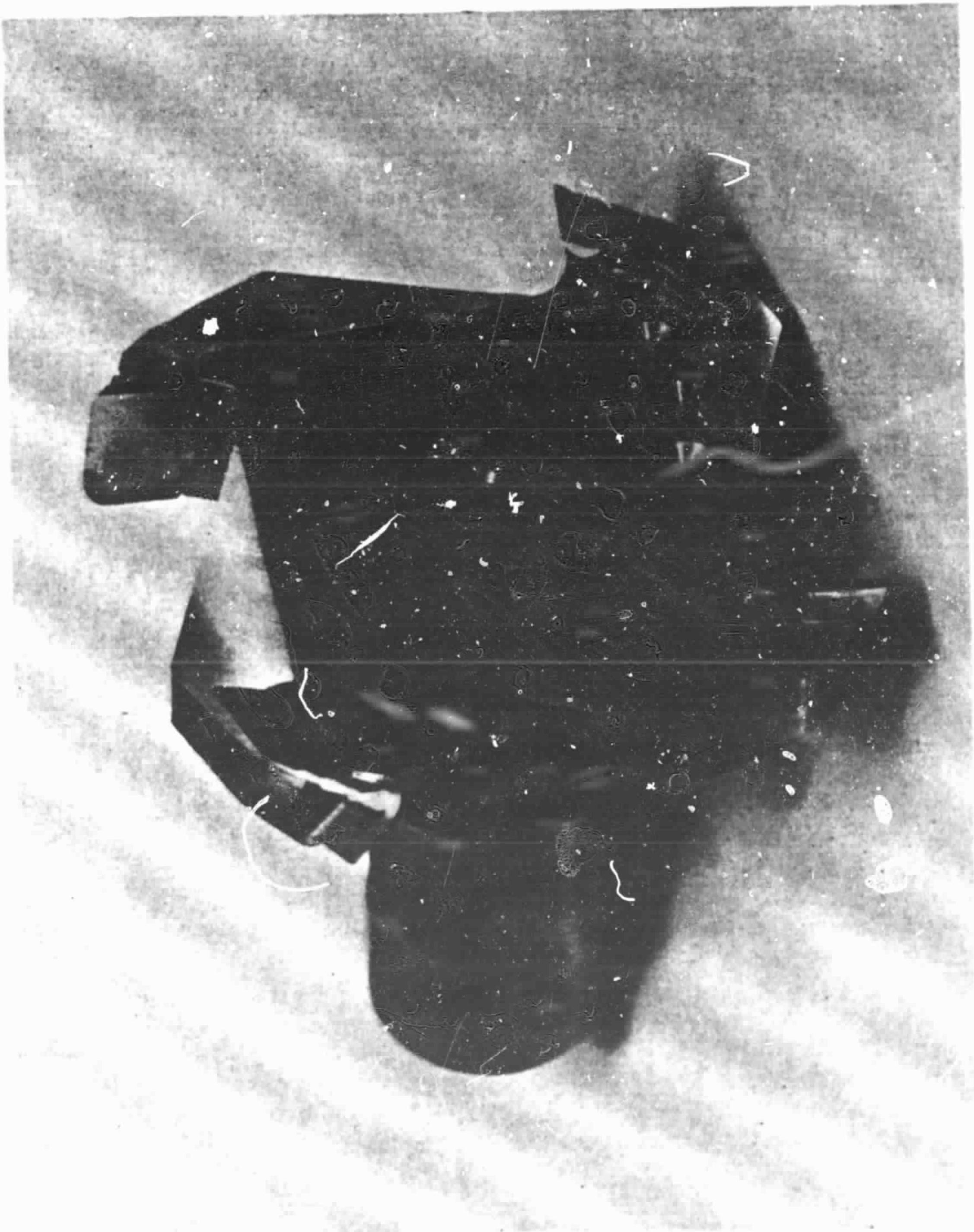


Figure 3-10 4 In. Diameter Cutter Selected for Machining T-Rib Sections

ORIGINAL PAGE IS
OF POOR QUALITY

LOCKHEED MISSILES & SPACE CO.
HIGH-SPEED CUTTER
TOOL NUMBER E1-0080-517

DET	DESCRIPTION	MATERIAL
101	CUTTER ASSY	
102	CUTTER BODY	AISI 4140
103	INSERT	VR/WESSON TUNTING - G

BALANCE CUTTER TO MAXIMUM UNBALANCE OF .01 OZ - IN.

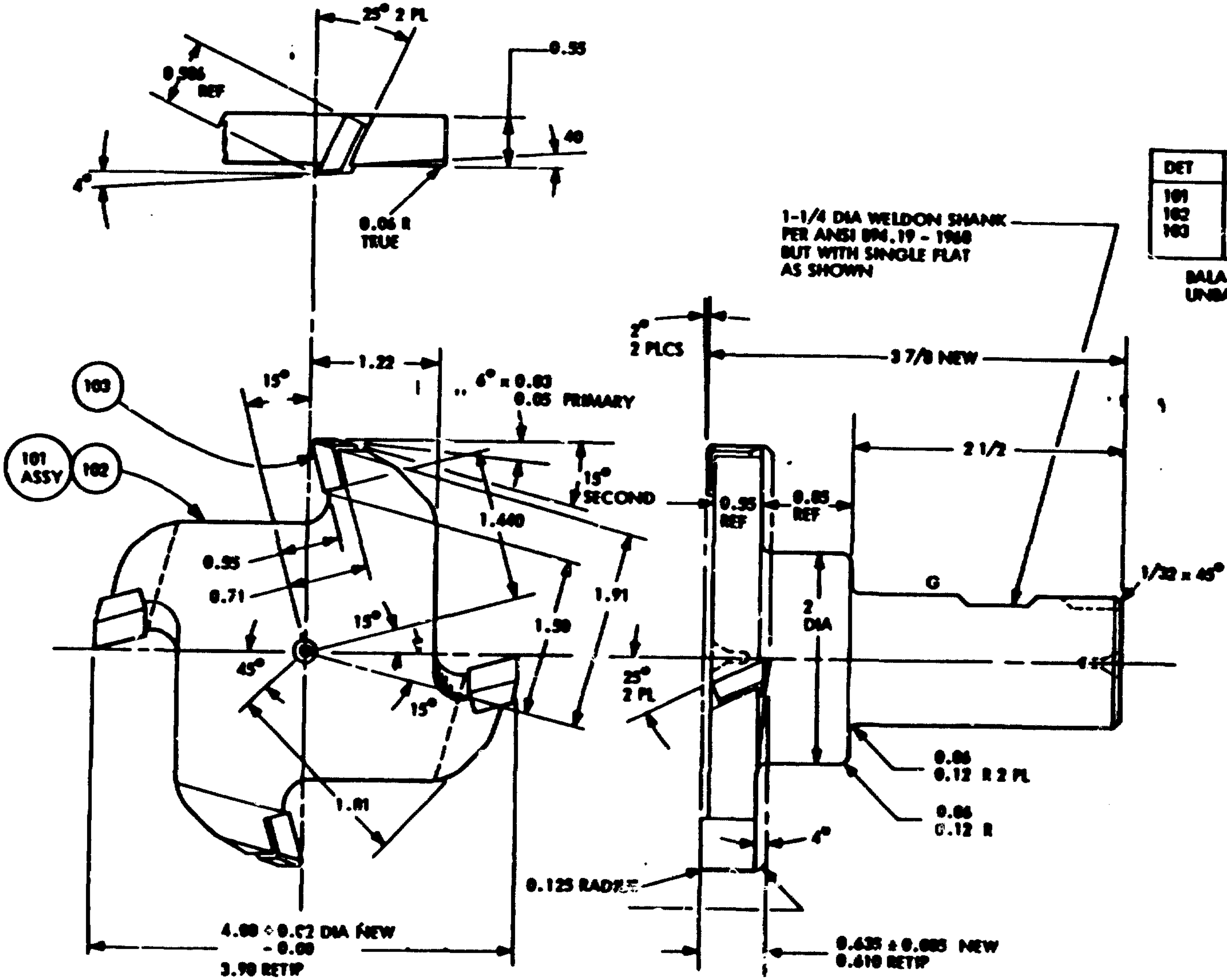


Figure 3-11 Detailed Specifications for T-Rib Cutter

Following the preparation steps, the cutter tests were run repeating the chosen pocketed section two times. As a result, each cutter received minor modification to provide additional chip clearances or room for the chips to clear the body of the cutter. A few minor adjustments were also made in the NC program, including the feeds and speeds, and the section was remachined the third time.

The resulting part was felt to be very satisfactory and, subsequently, planning was continued for the machining of the regular panel sections and the formal panel cutting demonstrations on the larger machine.

3-4 HIGH-SPEED MACHINING OF PANELS

3-4.1 Preparation

Preparing for the machining of the larger panel sections and converting the Sundstrand OM4 machining center for high-speed machining included several steps which are described below.

3-4.1.1 Panel Blanks - Identification and Premachining. The 2219-T87 wrought aluminum panel blanks as received from Martin Marietta were 2 in. thick and ink-stencilled with metal grain direction and both lot and individual panel identification numbers. To assure the maintenance and integrity of this information all the numbers were recorded and the individual panel numbers were steel stamped on three of the edges of each respective panel (See Appendix A for these numbers). The fourth edge was not stamped but ink-marked and then cut off to provide the 41 in. maximum width dimension that could be accommodated on the machining center. Care was taken to be certain that the grain flow was left in the longer direction of the panel thus guaranteeing that the grain direction in the finished panels would be parallel to the length of the T-ribs.

To ensure that the panel blanks would mount flat on the vacuum base plate, both sides were ground flat and parallel to each other. At the same time the blanks were reduced in thickness to the 1.75 in. specified by Martin Marietta drawings. Mounting bolt holes were provided around the perimeter on three sides of the panels.

3-4.1.2 Base Plate. To provide adequate backup and holding capabilities for the panels, a 2 in. thick aluminum vacuum chuck, or base plate, was decided upon. The base plate was designed, acquired, and prepared with vacuum grooves zoned in three separate areas to accommodate both the 4 ft. and 8 ft. long panels (See Figures 3-3, 3-4, and 3-12). Tapped mounting holes were also provided around the perimeter of the plate by which the panels were aligned and secured.

3-4.1.3 NC Program Preparation. The two numerical control machining centers used on the project were selected with similar controls to facilitate the expansion of the program utilized for the cutter trials to that of the fullsized panel sections. The use of the NC programming capabilities of Lockheed's CADAM system also helped in expanding both the width and length of the panels and in reprogramming the second half of each panel. The panels were programmed in halves to allow them to be indexed to produce 38-in. finished width panels on a machine wich has only a 21-in. width capacity when machining in the flat position. Feeds, speeds, and other machining parameters were used which were in keeping with Lockheed's previous high-speed machining experience and the findings of the cutter trials.

3-4.1.4 Machining Center Set-Up. After the installation in the Sundstrand OM4 Omnimil of the Bryant 18,000 rpm high-speed spindle motor with its peripheral support equipment, spectrum analysis vibration tests were run. this was done to guard aginst attempting to operate in any spindle speed range where natural resonance vibration frequencies might occur and thus cause possible problems with the machining process or damage to the equipment. (See spectrum analysis data in Appendix B.)

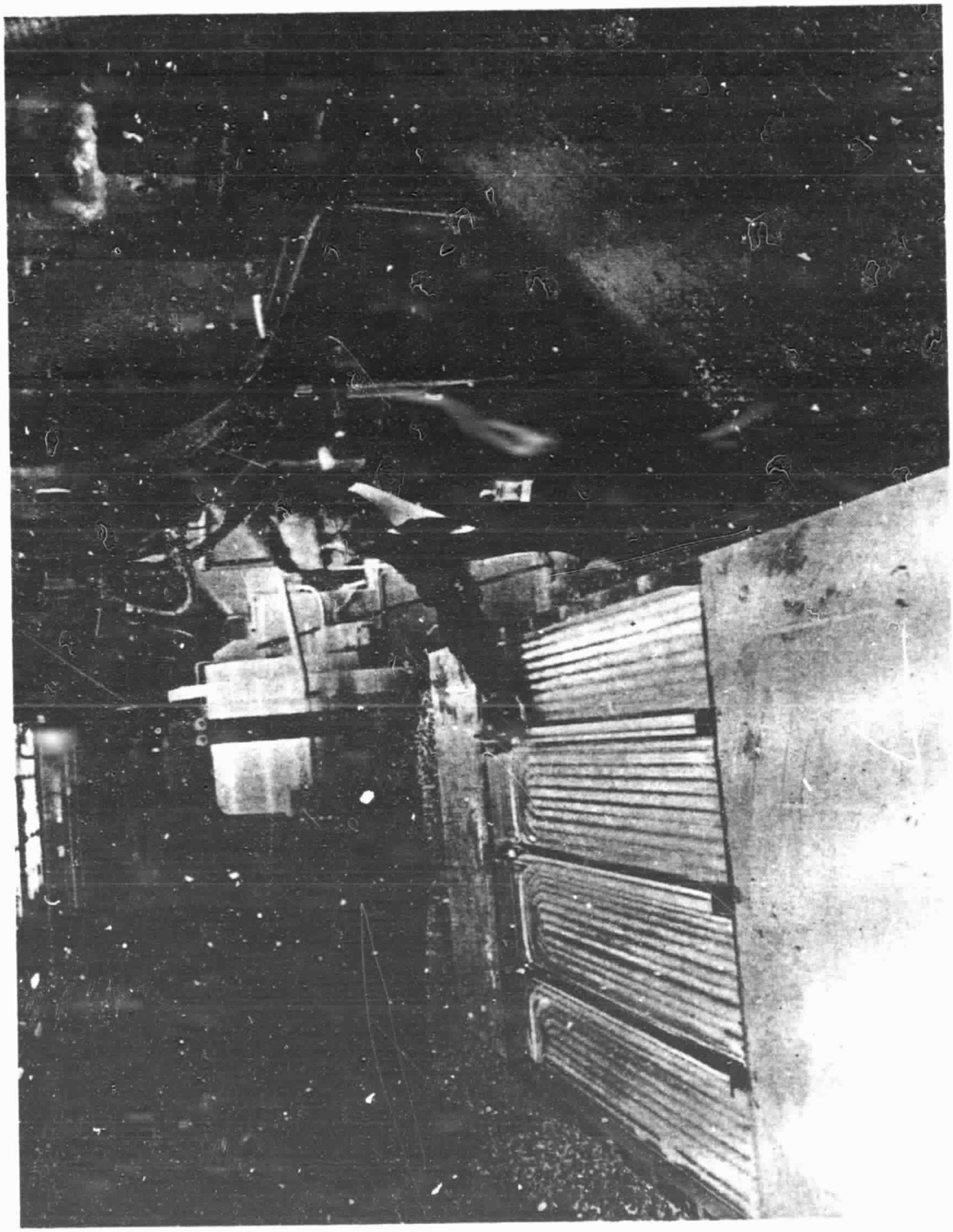


Figure 3-12 4 Ft Long Machined Panel on Vacuum Base Plate

Plastic Lexan shielding was mounted around the periphery of the machine table to provide safety protection for the machine operator and observers in the event of a tool breakage and also to provide containment for the flying chips and cutting fluid during machining. (See Figure 3-13.)

Two air nozzles were installed beside the spindle in addition to the two existing flood coolant nozzles to aid in keeping the chips out of the path of the cutter. In operation, the approach proved to be quite successful.

The base plate was next installed being properly aligned and secured to the machine table. This system including the vacuum feature also was later found to function very favorably.

3-4.2 Machining of First Panel

A 4 ft long panel was chosen for the first part to be high-speed machined on the OM4 machining center. The panel blank was first bolted in place and then sealed to the vacuum base plate with modelling clay. After the NC Program tapes were proofed by "dry running" on the machine, the panel was machined. (See Figure 3-12.) Following completion, the panel was shortened on the open end to provide small sections of T-ribs which were to be used as handouts during the scheduled panel cutting demonstration.

3-4.3 Panel Cutting Demonstration

The panel cutting demonstration was felt to be a major emphasis of this study. It was designed to demonstrate to NASA representatives and their invited guests the feasibility of utlizing high-speed machining as a means of producing the External Fuel Tank panels and thereby reducing manufacturing cost and time. These reductions were to be accomplished by increasing production rates and capacities and, in turn, reducing machine tool requirements.

The formal panel cutting demonstration was held on June 15, 1982 in Lockheed Building 181/182. Figure 3-13 is a photograph taken during the demonstration which shows the Sundstrand OM4 machining center on which the demonstration was performed and also some of the observers who were present. Formal attendees and the Lockheed crew are pictured in Figure 3-14. A list of attendees is provided in Appendix C.

The agenda (See Appendix D) included an introductory presentation which reviewed basic high-speed machining concepts as well as the objectives of the contract. Observation of the high-speed machining of a 4 Ft Long Shuttle Tank panel section followed.

A cutting speed of 5,890 surface feet per minute (sfpm) (over 60 miles per hour) was witnessed in the 1-1/4 in. diameter roughing and finishing cutters turning at 18,000 rpm. A table feed rate of up to 200 inches per minute (ipm) (the maximum capability of the machine) was observed as the roughing cutter removed up to 56 cu in./min of material while utilizing most of the maximum horsepower available (16.6) from the spindle motor.

The finishing cutter was fed at a rate of up to 180 ipm to remove up to 25 cu in./min of material. Rates up to 100 ipm table feed and 18 cu in./min were employed with the 4 in. diameter T-rib cutter which was operated at a cutting speed of 8,378 sfpm (8,000 rpm). Further detail is provided in Appendix E, "Setup and Operating Instructions for Machining 4 Ft Long Panels."

During the subsequent discussion period, NASA representatives emphasized their need for general specifications for a machine tool capable of high-speed machining the tank panels on a production basis. At least two attendees commented that because of the small size and tightly rolled shape of the chips produced by the high-speed machining process, they did not anticipate a problem with chip removal. Chip removal had been voiced previously as a serious concern.

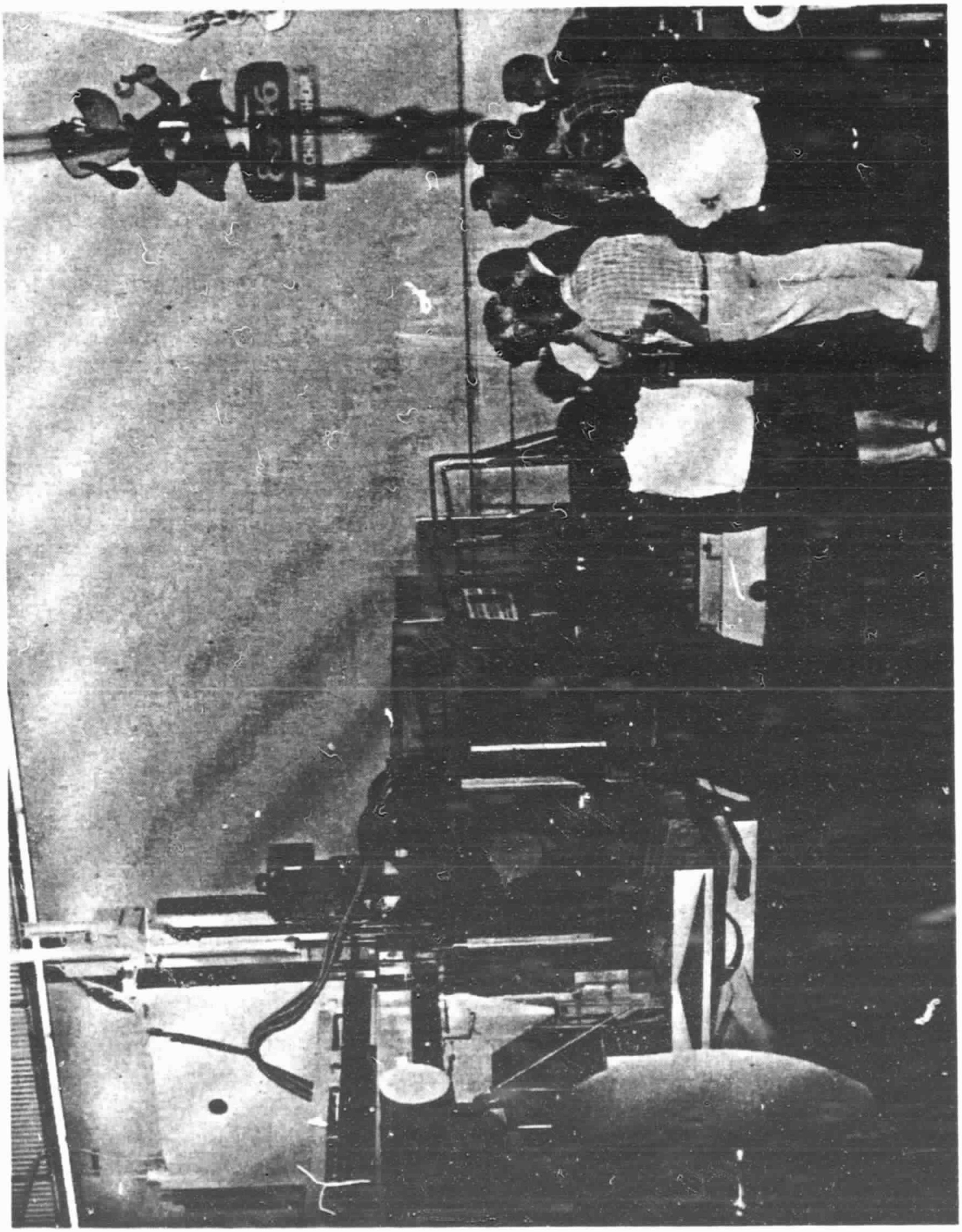


Figure 3-13 Observers at Panel Cutting Demonstration on Sundstrand OM4 NC Machining Center

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

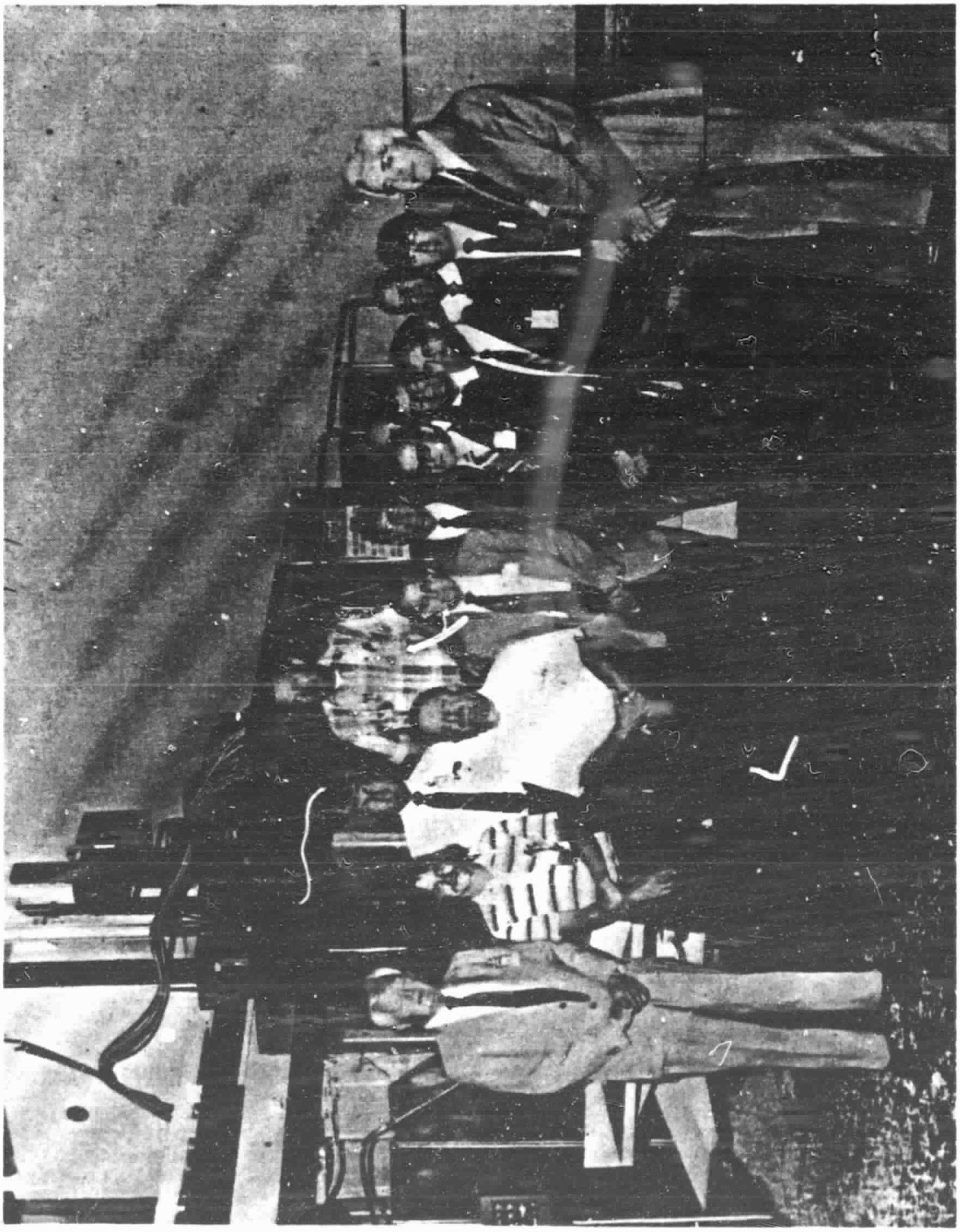


Figure 3-14 Attendees and Lockheed Crew at High-Speed Machining Panel Cutting Demonstration

3-4.4 Machining of Balance of Panels

Following the high-speed machining panel cutting demonstration, the balance of the deliverable panels (See Paragraph 2-1) was machined. A total of three 4 ft and one 8 ft long panels were completed. A video tape recording was made of the high-speed machining of the 8 ft long panel. Details of this effort are given in Section 4.

3-4.4.1 <u>Recording of Horsepower</u>. Ao. ' horsepower utilized in making the various cuts was recorded (See Appendix F.) for use in determining power requirements and in calculating cutting efficiency (See 6-1.).

3-4.5 Consideration of Cutter Wear

Particular attention was paid to cutter life (or wear) characteristics of the three cutter designs. Under proper conditions all three cutters showed excellent wear capabilities. Figure 3-15 is a photograph of the roughing cutter (See Figure 3-7 for detailed specifications.) which was used to perform the entire roughing of the 8-ft panel. The separate magnified views of the respective individual cutting edges shown in Figure 3-16 reveal only slight nicks (.002 in. max) at the tops of the utilized portions and at the height of the top of lesser depths of cut. The balance of the cutting edges show virtually no wear. The lighter area just back of the used portion of the cutting edges appears to be discoloration rather than noticeable wear. However, eventual crater wear would seem to be suggested.

The finishing cutter shown in Figure 3-17 was used for machining all four 4 ft long panels as well as the one 8 ft panel. No noticeable wear is seen in any of the views of this cutter. The detailed specifications for this cutter were given earlier in Figure 3-9.

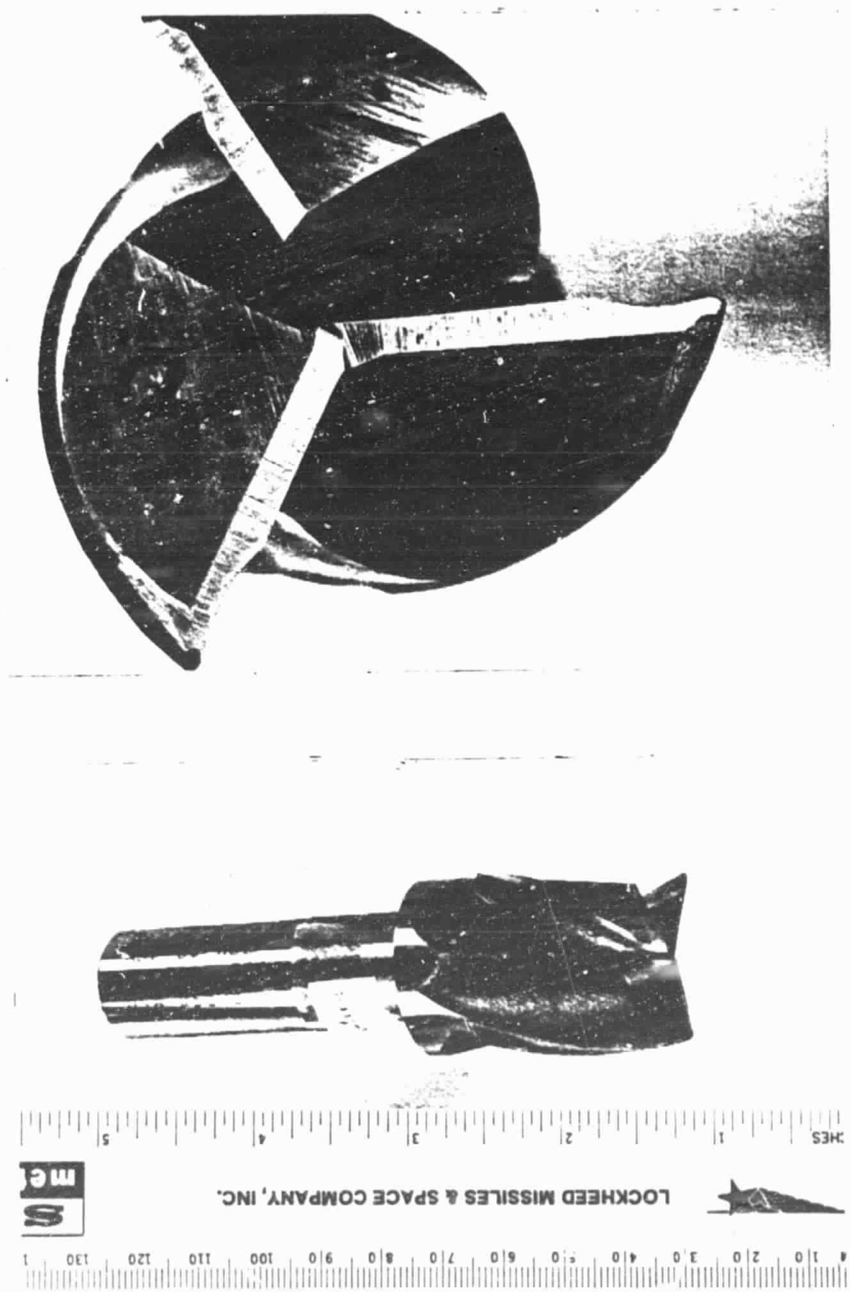
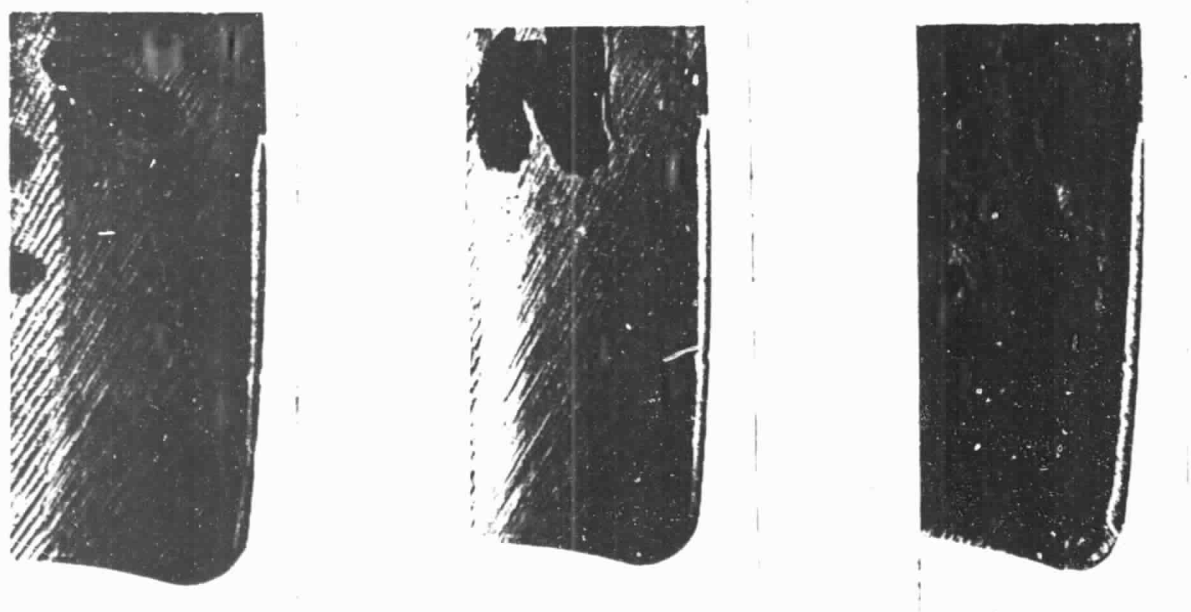
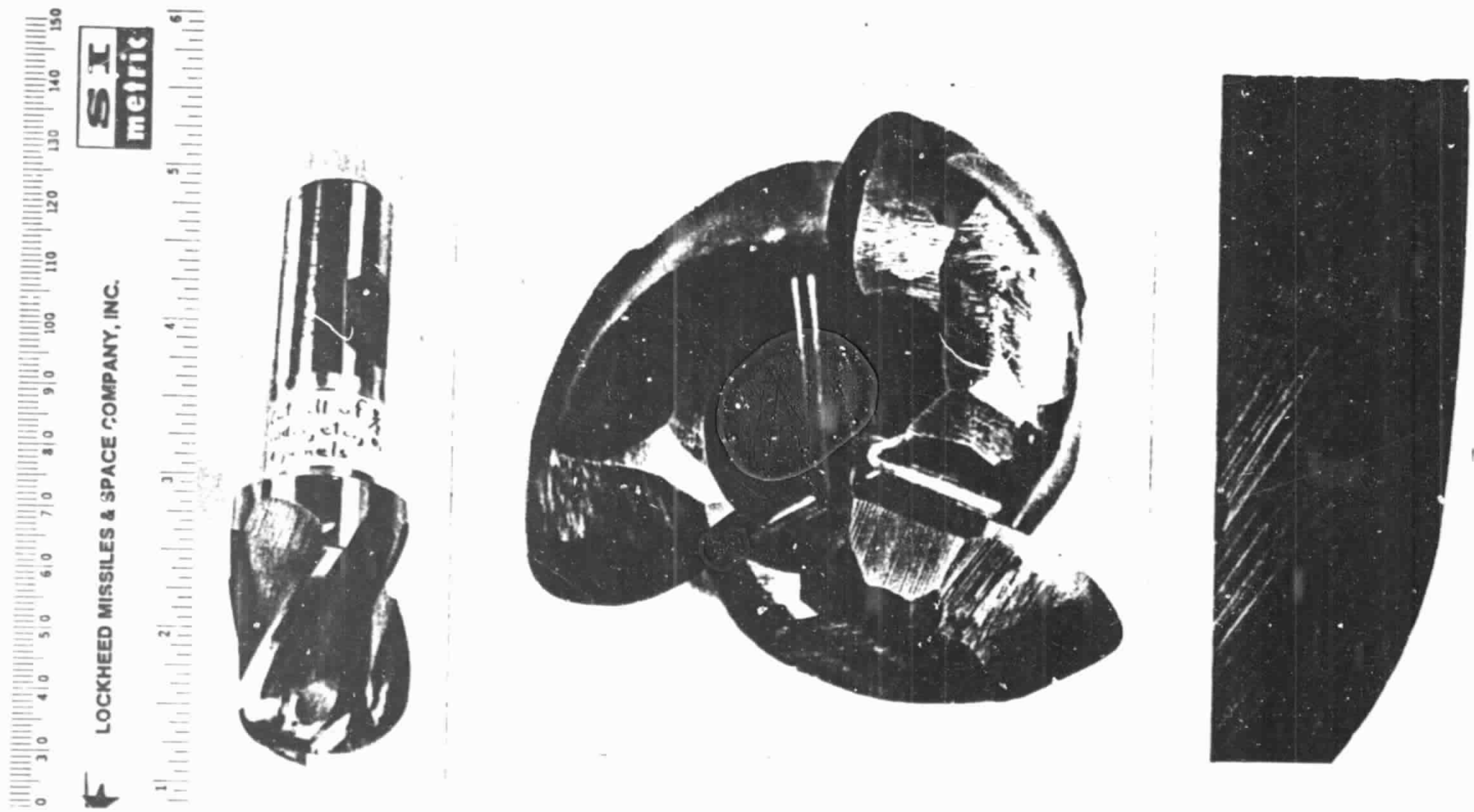


Figure 3-15 1-1/4 In. Diameter Roughing Cutter Used to Machine Entire 8 Ft Long Panel



CUTTING EDGE No.1　　CUTTING EDGE No.2　　CUTTING EDGE No.3

Figure 3-16 Cutting Edges of Roughing Cut r Used to Machine Entire 8 ft Long Panel (Showing Only Slight Wear at 7 x Magnification)



(REDUCED SIZE)

(APPROXIMATELY 3 x MAGNIFICATION)

TYPICAL CUTTING EDGE
(APPROXIMATELY 7 x MAGNIFICATION)

Figure 3-17 1-1/4 In. Diameter Finishing Cutter Used to Machine All Deliverable Panels (Showing No Noticeable Wear)

Figure 3-18 pictures the T-rib cutter used for machining all five of the panels. As with the roughing cutter only a slight discoloration is shown behind the cutting edges of the inserts (See magnified views in Figure 3-19). No measurable wear is present.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

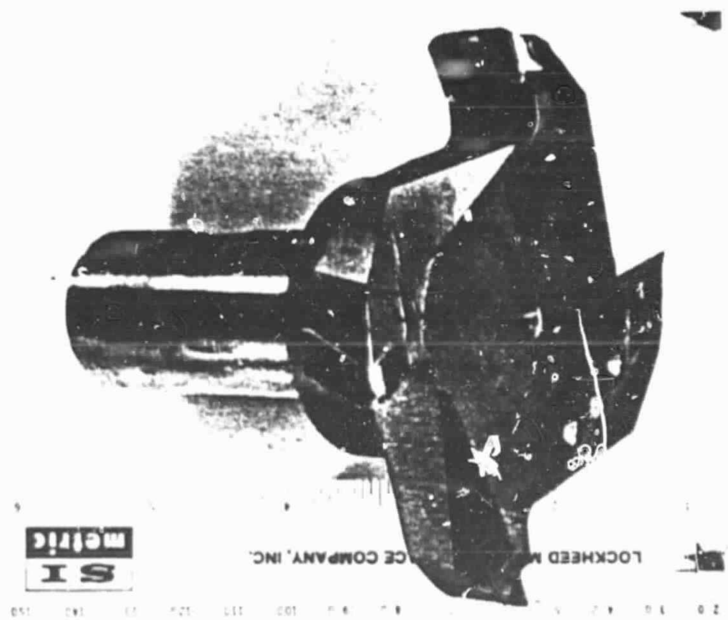
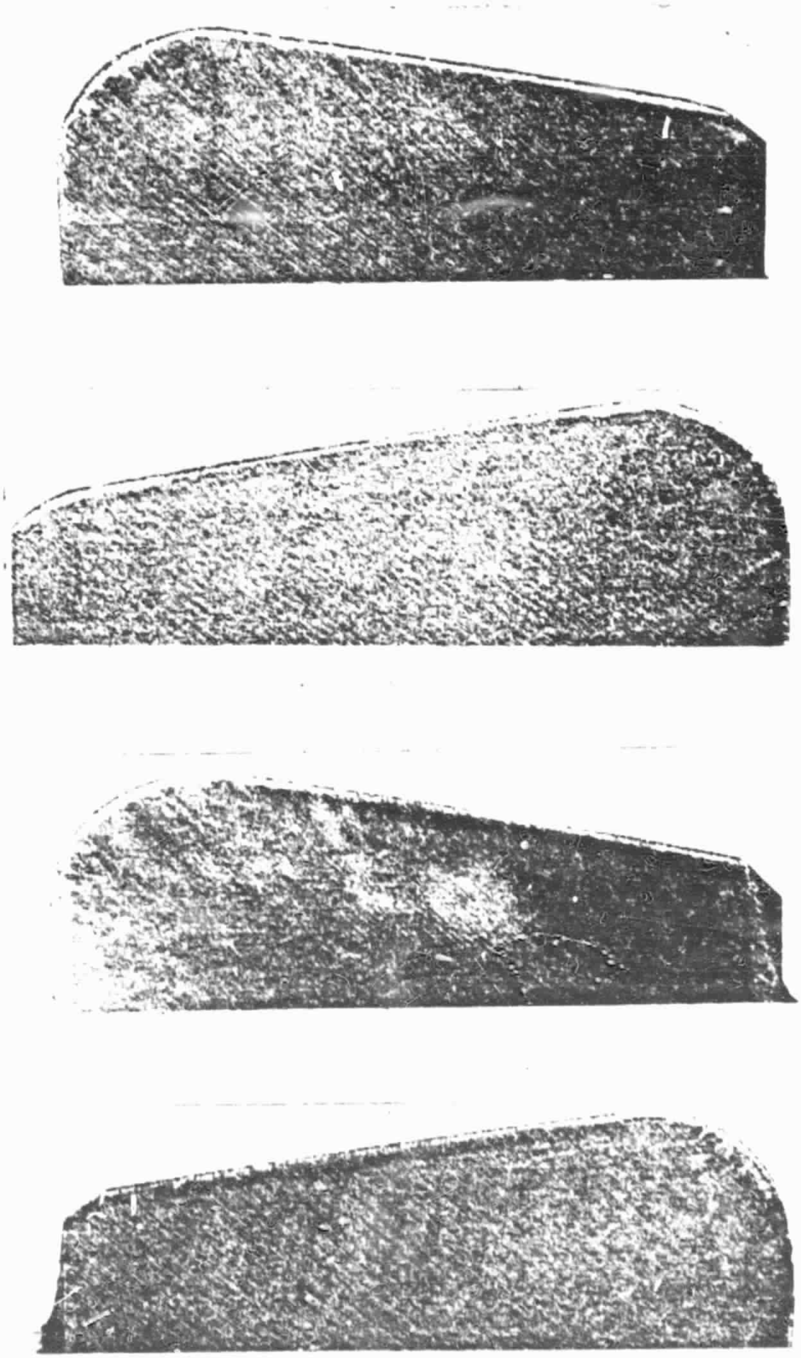


Figure 3-18 4 In. Diameter T-Rib Cutter Used to Machine All Deliverable Panels

ORIGINAL PAGE IS
OF POOR QUALITY



INSERT No.1 INSERT No.2 INSERT No.3 INSERT No.4

Figure 3-19 Insert Cutting Edges of T-Rib Cutter Used to Machine All Deliverable Panels (Showing Negligible Wear at 7 x Magnification)

Section 4

VIDEO TAPING OF HIGH-SPEED MACHINING PANEL CUTTING PROCESS

As an addition to the original contract authorized by Change Order No. 3, the machining of the 8 ft long panel was video taped in color. After careful planning, a total of approximately 50 minutes of original footage was taken using four 15 minute 3/4 in. Umatic tape format cassettes. The original footage was rough edited down to 23 minutes by omitting repetitious scenes and other extraneous portions. Both the original footage and the rough edited versions were narrated in writing and mailed to the Marshall Space Flight Center.

Section 5

FINAL PREPARATION AND SHIPMENT OF DELIVERABLE ITEMS*

The 1-1/2 in. margins used for mounting during machining were removed from the panels in preparation for shipment. The identification numbers which had been steel-stamped on the edges of the panel blanks were carefully transferred to the backs of the finished panels. The panels were then hand deburred and chemically cleaned to avoid corrosion. Figure 5-1 and 5-2 are photographs of the finished 4 ft and 8 ft panels, respectively.

The three 4 ft long (identification numbers LS1, LS3, and LS4 - See Appendix A) and one 8 ft long (LL2) finished panels were properly crated and shipped with the two remaining 4 ft long (LS2 and LS5) and one 8 ft long (LL1) panel blanks to the Marshall Space Flight Center.**

The video tapes were also properly prepared and shipped to the Marshall Space Flight Center (See 4.0 for details.).

---

* See Section 2.1 for list of deliverable items.

** Note: The sixth 4 ft by 4 ft (LS6) panel blank had been used for the cutter trials.

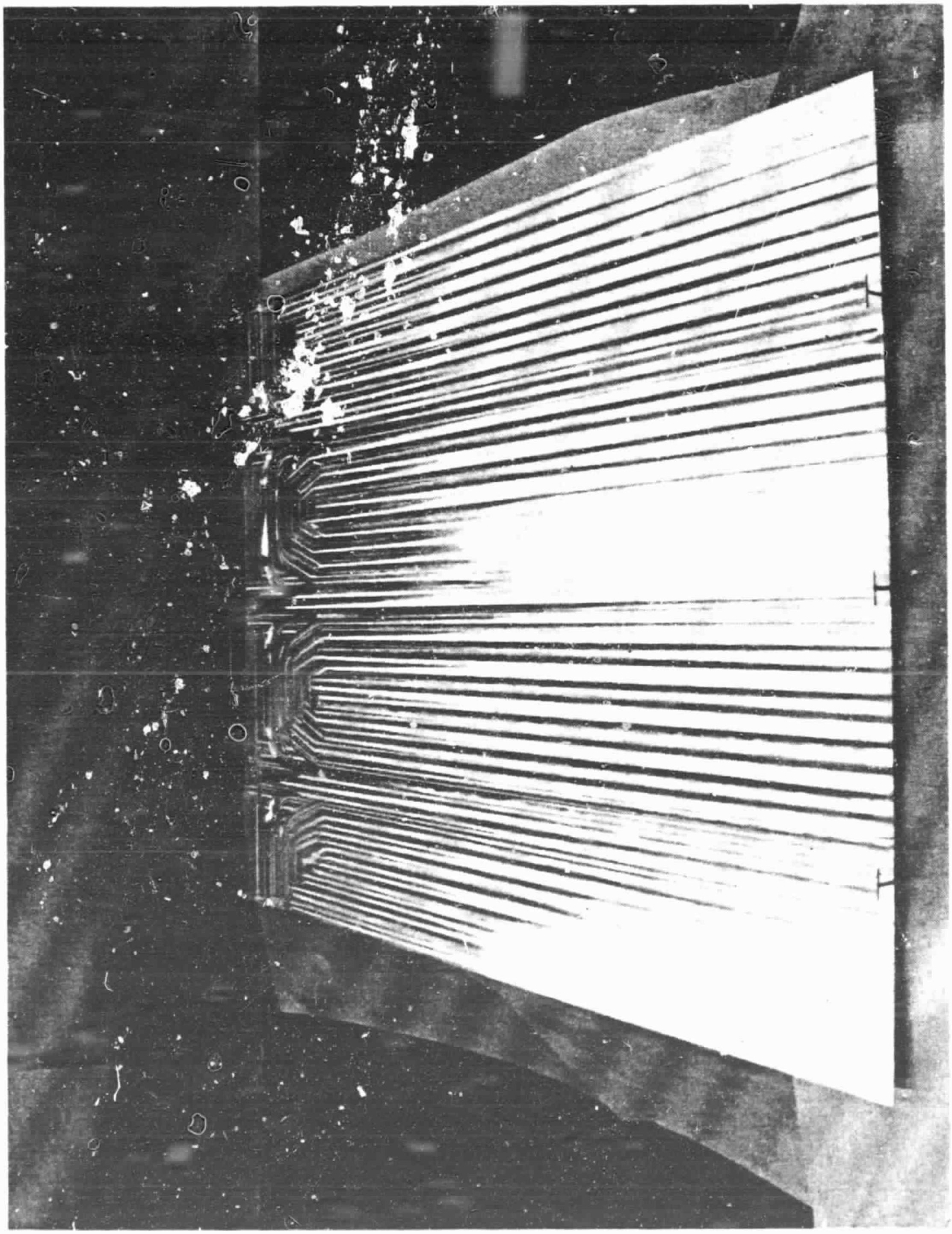


Figure 5-1 4 Ft Long Finished Panel

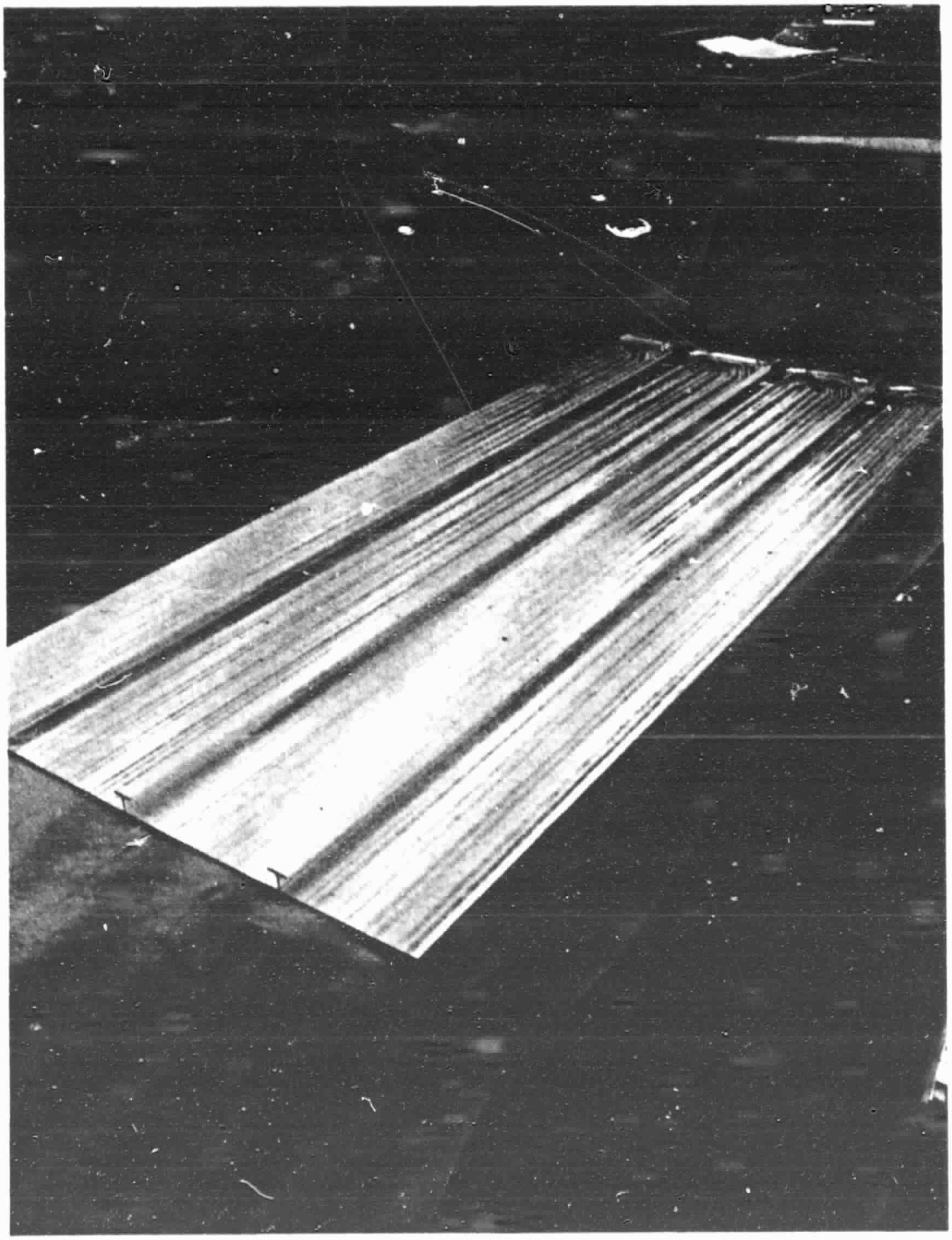


Figure 5-2 8 Ft Long Finished Panel

Section 6

HIGH-SPEED MILLING PROCEDURES AND TIMES *

The intent of this section is to identify the various high-speed machining process parameters, to describe the actual values of these parameters utilized in this project, and to identify optimum parameter values if different from those employed during the project. Times and operations involved in high-speed machining the Shuttle Tank panels will be stated and the time required to high-speed machine a complete panel will be projected.

6-1 DEFINITIONS AND ACTUAL VALUES OF HIGH-SPEED MACHINING PARAMETERS

The operations employed and the actual values of the various parameters used (See Table 6-1) are given below and in Appendix E, "Setup and Operating Instructions for High-Speed Machining of 4 ft Long Panels". The actual values are also given in Appendix F, "High-Speed Milling Data Sheet for 8 ft Long Panel #LL2." A compilation of these actual values is listed in Table 6-1.

6-1.1 Spindle Speed. Spindle speed is expressed in revolutions per minute (rpm) of the spindle or spindle motor. The spindle speeds used were 18,000 rpm for the 1-1/4 in. diameter roughing and finishing cutters (Figures 3-6 to 3-9) and 8,000 rpm for the 4 in diameter T-rib cutter (Figures 3-10 and 3-11).

6.1.2 Cutting Speed. Cutting speed when using a milling cutter is expressed as the peripheral speed of a cutter tooth tip stated as feet per minute (fpm) or surface feet per minute (sfpm). The cutting speed values employed in the high-speed machining of the tank panels were 5,890 sfpm for the 1-1/4 in. diameter cutters and 8,378 sfpm for the 4 in. diameter cutter.

* NOTE: This section was originally part of Task A but was transferred to Task B by direction of Change Order No. 1.

TABLE 6-1

ACTUAL AND PROJECTED PARAMETER VALUES FOR
HIGH-SPEED MACHINING TANK PANELS *

Parameter	Actual	Optimum: Proven Example: Cincinnati Milacron Gantry Mill	Optimum: Available or Expected to be available soon
Spindle Speed (rpm)	18,000	7,200 (9,000 available from Cincinnati Milacron)	60,000 with 20hp 40,000 with 40hp 12,000 with 100hp
Cutting Speed (sfpm)	5,890	3,600	4,000 - 10,000 currently felt to be most efficient. (20,000 now used on large dia face mills etc.)
Table Feed (ipm)	200	150 (300 available from Cincinnati Milacron)	400 (1500 with 20hp)
Chip Load (in.)	.0032	.010	.010?
Depth of Cut Axial (in.)	.300	1.0	Dependent on hp available and dia of cutter (Shuttle panel limited to 1.625 in. maximum)
Radial (in.)	1.250	2.0	Dependent on dia of cutter and hp
Metal Removal Rate (cu in./min)	56	300 with 75hp	400 expected with 100hp (Up to 450 now using large dia face mills)
Horsepower	13.4	75 at 7200 rpm	100 at 12,000 rpm

(Cont'd)

TABLE 6-1 (Cont'd)

ACTUAL AND PROJECTED PARAMETER VALUES
FOR HIGH-SPEED MACHINING TANK PANELS *

Parameter	Actual	Optimum: Proven Example: Cincinnati Milacron Gantry Mill	Optimum: Available or Expected To be available soon
Cutting Efficiency (cu in./min/hp)	4.0	4.0	?
(Unit hp-- hp/cu in./min)	0.25	0.25	?
Time to Machine 4 ft long Panel (hrs)	2.019		
Time to Machine 8 ft long Panel (hrs)	3.49		
Projected Time to Machine 11 ft x 20 ft Panel (hrs)	27.256 (Projected from 8 ft long Panel data)	6.0 (Base on Cincinnati Milacron data using hp) 5.1 (Based on maximum metal removal rates and adjusted using actual machining time)	4.48 (Based on inverse proportion of 100 hp vs time projected from 8 ft panel machine time)

* NOTE: These values are based on the maximum rates used for the roughing operation (Cutter No. 02). The blank panel is considered to be 1.75 in. thick and to have approximately 91% of the metal removed. Full-sized panels are considered to be 11 ft x 20 ft.

6-1.3 <u>Table Feed.</u> Table feed or feed rate when milling is the rate at which relative motion takes place between the machine table and the spindle, or head, of the machine. Table feed is expressed in inches per minute (ipm). Feed rates ranging from 150 to 200 ipm (the maximum capability of the machine) were used for the 1-1/4 in. diameter roughing and finishing cutters, and from 40 to 100 ipm for the 4 in. diameter T-rib cutter.

6-1.4 <u>Chip Load.</u> Chip load is the amount of metal that each flute or cutting edge removes as the cutter turns through one revolution as the workpiece is fed against it. Chip load is also called chip per tooth or feed per tooth and is expressed in inches (in). The chip loads utilized in high-speed machining the panels ranged from .0025 to .0032 in. for the roughing cutter, stayed constant at .0032 in. for the finishing cutter, and extended from .0016 to .0032 in. for the T-rib cutter. These relatively small chip loads helped to achieve the fine surface finish required by the part.

6-1.5 <u>Depth of Cut</u>. There are actually two types of depth of cut involved in milling. One is defined as axial depth of cut which is parallel to the centerline of the spindle. The other is called radial depth of cut and is perpendicular to the centerline of the spindle and cutter.

For the roughing cutter the axial depths of cut ran from .070 to .300 in. depending on how the levels, or layers, of cutter passes were divided. The radial depths, or widths, of cut ranged from 1.1 to 1.250 in., the full diameter of the cutter. The finishing cutter with the 3/8 in. corner radius was used primarily to provide the .370 fillet radius of the part. Therefore, both axial and radial depths of .370 in. were used. Axial depths from .075 to .635 in. and radial depths from .025 to.550 in. were utilized with the T-rib cutter.

6-1.6 <u>Metal Removal Rate</u>. This parameter is usually expressed in terms of cubic inches per minute (cu in./min) of metal removed. The values obtained were from 18 to 56 cu in./min (approximately 3X the comparable conventional machining rate at Lockheed) with the roughing cutter, to 25 cu in./min with the finishing cutter, to 18 cu in./min with the T-rib cutter. The two primary limiting factors in this case were horsepower and table feed.

6-1.7 Horsepower. Available power, or horsepower, to turn the cutter is the most limiting parameter where larger volumes of metal are to be removed, as with the tank panels. The Bryant 18,000 rpm spindle motor is rated at 16.6 hp at the full 18,000 rpm. Horsepower readings as recorded in Appendix F, "High-speed Milling Data Sheet for 8 ft Long Panel No. LL2", ran at approximately 13.4 hp for the roughing cutter for most of the cuts. Occasional peak loads ran momentarily higher. For Tool No.03, the finishing cutter, the loads ran at approximately 8.4 hp. The relatively light loads used with the T-rib cutter (Tool No. 04) drew a maximum of approximately 5.1 hp which was almost at the 5.5 hp maximum available at 8,000 rpm at which the spindle was operating.

6-1.8 Cutting Efficiency. Cutting efficiency is often expressed as cubic inches per minute per horsepower (cu in./min/hp). Using the values already cited in 6-1.6 and 6-1.7 to calculate cutting efficiency for the maximum metal removal rate, we find that 56 cu in./min divided by 13.4 hp yields a cutting efficiency of 4.18 cu in./min/hp. This value compares very favorably with the figure of 3.0 cu./min/hp which is felt to be a somewhat conservative number for high-speed milling of aluminum.

Cutting efficiency is the mathematical reciprocal of unit horsepower which is expressed as horsepower per cubic inch of metal removed per minute. The unit horsepower equivalent to the 3.0 cu in./min/hp given above is 0.33 hp/cu in./min.

6-1.9 Time to Machine 4 ft Long Panel Section. The actual machining, or chip cutting time for high-speed machining the 4 ft long panel sections is presented in Table 6-1. The 2.019 hrs listed is the time generated by the NC program and found to be reasonably accurate in actual operation. This time does not include such activities as part loading and unloading and tool changes.

6-1.10 Time to Machine 8 ft Long Panel Section. As with the 4 ft long panel, the 3.49 hrs listed in Table 6-1 as actual time for high-speed machining the 8 ft long panel was generated by the Lockheed NC program. This computer calculated time was also found to be reasonably accurate.

6-2 PROJECTED TIME TO MACHINE FULL-SIZED 11 FT X 20 FT TANK PANEL BASED ON ACTUAL PROJECT DATA

The NC program cutter paths and times for high-speed machining the 8 ft long panel section were meticulously expanded to project a cutting time required to machine the entire full-sized 11 ft x 20 ft panel from which the sample section was taken. The total estimated time (as given in Table 6-1) is 27.2567 hrs. As only 13.4 hp was employed in machining the 8 ft sample panel, it became very apparent that horsepower was the greatest limiting factor, especially in the roughing operation at which over 80 percent of the time was spent. Obviously, even though the demonstration panel sections were high-speed machined very successfully and convincingly, the rates attainable on the available Lockheed equipment were not optimal for machining full-sized tank panels.

6-3 PROJECTIONS OF OPTIMUM HIGH-SPEED MACHINING PARAMETERS AND TIMES

High-speed machining is presently in a dynamic state of development. Therefore, projections of what appear to be "optimum" parameter values today may not be optimum tomorrow. In an attempt to deal with this rapidly changing situation, two sets of optimum parameter values are presented in Table 6-1 in addition to the "actual" values utilized during this demonstration project.

6-3.1 Projections Based on Proven Data. The first set of optimum parameter values projected for high-speed machining Shuttle External Fuel Tank panels is based on proven data given as an example. This data was made available by Cincinnati Milacron * and is presented to emphasize that equipment capable of providing the high-speed machining parameter values listed in Table 6-1 is readily available today.

* T. Raj. Aggarwal. Research in Practical Aspects of High Speed Milling of Aluminum. Presented at the SME Annual International Tool and Manufacturing Engineering Conference, Philadelphia, PA, May 17, 1982.
(NOTE: T. Raj Aggarwal is an R&D Associate at Cincinnati Milacron).

As presented in Table 6-1, the impressive volume of 300 cu in./min of metal removed by Cincinnati Milacron was achieved using a 75 hp spindle turning a 2 in. diameter end mill at 7200 rpm. The surface finish resulting from the relatively heavy chip load of .010 in. and cutting speed of only 3,600 sfpm, no doubt, was acceptable for a roughing operation. However, to produce less tool side pressure and better surface finish which would likely be required for the T-rib sections of the tank panels, higher cutting speeds would probably be required. The higher cutting speeds could be achieved by either increasing the diameter of the cutter while keeping the rpm constant or by increasing the rpm with the same diameter cutter. In either event, a table feed faster than the 150 ipm cited in the example would be in order to be able to maintain a proper chip load.

Using the high-speed machining parameter values available as shown in this example, the projected time to machine a full-sized 11 ft x 20 ft panel was computed by two methods. Both projection methods yielded impressively less time than predicted from the 8 ft panel cutting data.

First, horsepower was used as a predictor as it had been found to be the dominant limiting factor in our Lockheed panel cutting operations. It was determined that cutting time could be expressed as being in a direct but inverse relationship to available horsepower. Based on a machining time of 27 hrs required by the 16.6 hp spindle motor used, it was determined that a 75 hp motor should be able to accomplish the same job in approximately 6.0 hrs.

The second method employed to predict cutting time for a full-sized panel was based on the computed volume of metal to be removed and the maximum metal removal rate for each of the spindles being compared. Using an estimated volume of 50,182 cu in. of metal to be removed, the 16.6 hp Lockheed spindle with a maximum metal removal rate of 56 cu in./min could be expected to machine the full panel in 14.9 hours. However, the actual projected NC program time to machine the panel using the 16.6 hp spindle was 27.3 hrs (See Table 6-1). Therefore, an adjustment factor of 1.83 was computed by dividing the 27.3 actual projected hours by the 14.9 calculated hours. By adjusting the 2.8 hrs calculated for the 75 hp spindle by this 1.83 factor, a more logical projected machining time of 5.1 hrs was determined. As noted above, either of these projected machining times would suggest considerable potential savings in machining time.

6-3.2 Projections Based on Capabilities Which are Available or are Expected to Be Available Soon. The second set of optimum parameter values projected for high-speed machining Shuttle External Fuel Tank panels is a compilation of information from various sources. Most of these capabilities are available singlely now. However, the exact combination of all "optimum" parameter values desirable for high-speed machining Shuttle Tank panels has probably not yet been assembled.

As horsepower was determined to be the most critical limiting parameter for the high-speed machining of parts requiring relatively large amounts of material to be removed, including Shuttle Tank panels, the "optimum machine" would most likely be fitted with as large a horsepower motor as possible. The 100 hp, 12,000 rpm spindle motor listed in Table 6-1 is the largest known to the author which has been conceived specifically for high-speed machining. Although this motor has not yet been built, the technology required is reportedly available and proven. If such a motor were capable of operating at a cutting efficiency of 4.0 as was demonstrated during the Lockheed panel cutting demonstration and claimed by Cincinnati Milacron in the example cited in Table 6-1, it would be able to remove 400 cu in./min. This would equate to a 2.5 in. dia cutter cutting at 1.624 in. deep (the maximum possible depth of cut required for machining a 0.126 in. panel skin from a 1.75 in. blank) at a table feed of 98.5 ipm. Since the cross-sectional area of 2.5 in. x 1.624 in. = 4.06 sq. in. essentially an entire pocket between T-ribs could be machined out in four passes at approximately 100 ipm. For finish machining the radii and for machining the T-rib sections, the cross-sectional area of metal to be removed per pass would be considerably less. Therefore, available table feeds should be higher in proportion to maintain as high a volume of metal removal as possible. As 300 ipm table feeds are available now for gantry-type machines such as would be expected to be used for machining tank panels, it is logical to expect that 400 ipm table feeds are either also available now or will be in the near future. Reportedly, one company has built a light duty gantry-type machine with a table travel capability of 1500 ipm.

Faster feed rates also require higher rpm to keep the chip/tooth loads light enough to minimize side loads on the T-rib sections and provide sufficient surface finish. The smaller the diameter of cutter used, the higher the rpm will need to be. Presently the bearings for relatively large horsepower motors are the limiting factors in increasing the rpm above approximately 9,000 to 12,000. For this primary reason, some manufacturers of high-speed spindles are developing magnetic bearings. To date, the author is not aware of any proven magnetic bearing spindles with the horsepower level recommended for machining tank panels.

A projected time to high-speed machine a full-sized tank panel was calculated based on the 100 hp, 12,000 rpm spindle. A value of 4.48 hrs was determined based on an inverse proportion using the 100 hp and the 27.3 hrs projected from the 8 ft long panel data. This represents an additional 25 percent reduction in time from the 6.0 hrs predicted for the 75 hp spindle. The assumptions of a continued cutting efficiency figure of 4.0 cu in./min/hp and the maximum metal removal rates used in the projections should be kept in mind.

SECTION 7
SUMMARY AND CONCLUSIONS

7-1 SUMMARY

Lockheed Missiles & Space Company, Inc. contracted with the NASA Marshall Space Flight Center in Huntsville, Alabama to provide certain technical services for the purpose of evaluating the flexibility of applying high-speed machining techniques to the milling of Space Shuttle External Fuel Tank panels. The contract was divided into two main categories or tasks. Task A was designed to document and evaluate the parameters currently involved in conventionally machining the Shuttle Tank panels and to compare them with equivalent high-speed machining parameters. An economic analysis was to be made projecting expected savings in machining costs from the comparison. This document reports Task B activities which are summarized below.

Task B was primarily designed to demonstrate the applicability and advantages of high-speed machining for producing Shuttle Tank panels by physically machining selected sample portions of an external tank panel. Lockheed was asked to show that the high-speed machining techniques and technical expertise employed in machining missile hardware could be transferred to the production of Shuttle Tank panels. Actual data from the high-speed machining of the sample panel sections were to be used to project the anticipated time for high-speed machining an entire Shuttle Tank panel using optimal equipment.

Specific Task B tasks were as follows:

1) Select a panel sample configuration
2) Perform a high-speed machining demonstration and machine additional panels
3) Prepare a Task B final report.

Through change orders the following tasks were added.

4) Machine an 8 ft long panel section
5) Incorporate the paragraph from Task A entitled "Identify Potential High-Speed Milling Procedures" including projections for using optimal equipment into Task B
6) Video tape the high-speed machining process.

The above tasks were successfully completed within budget, on schedule (as adjusted), and with all goals and specific technical objectives achieved.

The sample panel configuration was selected in accordance with Marshall Space Flight Center requirements and within the limitations of Lockheed's available equipment. Three cutter designs were selected based on the requirements of the part and on Lockheed's background in the high-speed machining of aluminum. After selection the cutters were tested on a sample part.

A Sundstrand OM4 Omnimil NC Machining Center was retrofitted with an 18,000 rpm Bryant spindle motor to machine the panels and perform the demonstration for NASA representatives and their invited guests. During the high-speed machining of the panels the various parameters involved were monitored and recorded. The spindle was operated at 8,000 and 18,000 rpm yielding cutting speeds of 5,890 and 8,378 surface feet per minute (sfpm).

Table feeds of up to 200 in./min (ipm) (the maximum capacity of the machine) producing metal removal rates up to 56 cu in./min (approximately 3x the comparable conventional machining rate at Lockheed) were employed.

From the data generated during the actual panel machining, projections were made to optimum rates which could be expected to be achieved if ideal equipment were available for machining full-sized Shuttle Tank panels. A video tape record was made of the machining of the 8 ft long panel.

CONCLUSIONS

In conclusion, the high-speed machining techniques utilized in Lockheed's missile production were successfully transferred to the manufacture of portions of Shuttle External Tank panels.

Furthermore, it was projected that with properly designed equipment, metal removal rates up to 300 cu in./min could be achieved and an entire Shuttle Tank panel could be high-speed machined from a 1.75 in. thick solid panel in as little as 6.0 hrs using equipment known to be available today. Even less time was projected using equipment for which technology to build is now available.

APPENDICES

APPENDIX A

IDENTIFICATION NUMBERS OF SHUTTLE TANK PANEL BLANKS

4 FT BY 4 FT PANELS

LS1
RS9-790460 MMS118M771
LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221 *
DATE 7/28/79 TRACEABLE

LS2
(Only partial stencilling)
RS9-7904
DATE 7/28/79 TRACEABLE

LS3
RS9-790460 MMS118M771 RTR-106
LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221
DATE 7/28/79 TRACEABLE

LS4
RS9-790460 MMS118M771 RTR-106
LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221
DATE 7/28/79 TRACEABLE

LS5
(No stencilled marks on edges)

LS6
(No stencilled marks on edges)

* The lot number 269-221 is the only lot number stencilled on the panel blanks that was excluded from the list of lot numbers provided by Martin Marietta in a letter dated January 22, 1982 from Gerry Scott to Dr. R.I. King of Lockheed. Also, the lot number 273-512, listed in Mr. Scott's letter, was not stencilled on any of the panel blanks.

PRECEDING PAGE BLANK NOT FILMED

APPENDIX A

4 FT BY 8 FT PANELS

LL1

RS9-790460 MMS1118M771 RTR-106

LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221

(No Date)

LL2

RS9-790460 MMS118M771 RTR-106

LOT CODE AWG LOT-269-211, 273-511,
255-331, 273-521-269-221

DATE 7/28/79 TRACEABLE

NOTE: LS and LL numbers were steel-stamped midway on 3 edges of each part. The stamp was omitted on the edge to be cut off to narrow the panels to 41 in.

LOCKHEED MISSILES & SPACE COMPANY. INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

REPORT 1961

8 July 1982

ENGINEERING TEST REPORT
SPECTRUM ANALYSIS OF OM3-3 AND OM4B
EQUIPPED WITH BRYANT 18,000 rpm SPINDLE

Prepared by: L. W. Martin
L. W. Martin

Checked by: TO for TO RAINFORTH
T.O. Rainforth

Approved by: R R Walton
R. R. Walton
Group Engineer, 85-74

FORM LMSC 5797-3

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

REPORT 1961

SUMMARY OF RESULTS/CONCLUSIONS:

A vibration spectrum analysis of the Bryant 18,000 rpm spindle mounted in the OM3-3 in Bldg. 170 and in the OM4B in Bldg. 182 was performed. The spindle was operated both with and without tools. The 1-1/4 inch diameter tool exhibited a minimum vibration level at 18,000 rpm while the 4.0 inch diameter tool minimum vibration level was at 8,000 rpm in the OM3-3. These speeds were successfully used to machine the NASA Space Shuttle Integral Stiffner Panels.

REFERENCES:

Test Authorization:	TM T26595 High Speed Machining of NASA Shuttle Tank Integral I Beam Panels
Test Procedure:	Op Order 15146
Test Start/Completion Dates:	5-12-82/6-9-82
Reference Documents:	Test Report 1736

I. Objective

The objective of this task was to determine the rotational vibrations and resonances of the Bryant 18,000 rpm spindle mounted in both the OM3-3 in Bldg. 170 and in the OM4B in Bldg. 182. The OM3-3 was used for cutter trials and the OM4B was used for cutting integral stiffner demonstration panels for the NASA Shuttle Tank High Speed Machining Test.

II. Test Spindle and Tools

The spindle tested was the Bryant 18,000 rpm direct drive spindle motor mounted in the Sundstrand OM3-3 in Building 170 and in the OM4B in Building 182. Tools tested consisted of a high speed steel, three flute 1-1/4 inch diameter cutter and a 4.0 inch diameter brazed insert cutter.

III. Test Procedure

An Endevco 2236 accelerometer was mounted radially on the face of the Bryant spindle. The accelerometer output was amplified by an Endevco Model 2735 charge amplifier and analyzed by a Schlumberger 1510 real time analyzer. The vibration data was recorded on an HP X-Y recorder.

The spindle was installed in the OM3-3 without a tool and operated at speeds from 6000 to 18,000 rpm. Data was taken at 2000 rpm intervals. This data is plotted in Figure 1. The data for the 1-1/4 inch and 4 inch diameter cutters is shown in Figures 2 and 3. The 1-1/4 inch diameter showed a minimum vibration level at 18,000 rpm and the 4.0 inch diameter cutter had less vibration at 8000 rpm. Tool tryout cuts were made at these speeds using this setup in the OM3-3.

The spindle was moved to the OM4-2 in Bldg. 182. The rpm spectral map for the empty spindle in this machine tool is shown in Figure 4. The data for the 1-1/4 inch and the 4.0 inch diameter cutters is shown in Figures 5 and 6.

The tool test data appears similar to that obtained in the OM3 except that the 1-1/4 inch cutter vibration level minimum was at 16,000 rpm. Successful demonstration cuts were made at 18,000 rpm using the 1-1/4 inch cutter and at 8000 rpm with the 4.0 inch diameter cutter. The table feed rate was 200 in/min.

cc: J. A. Miller 86-61/170

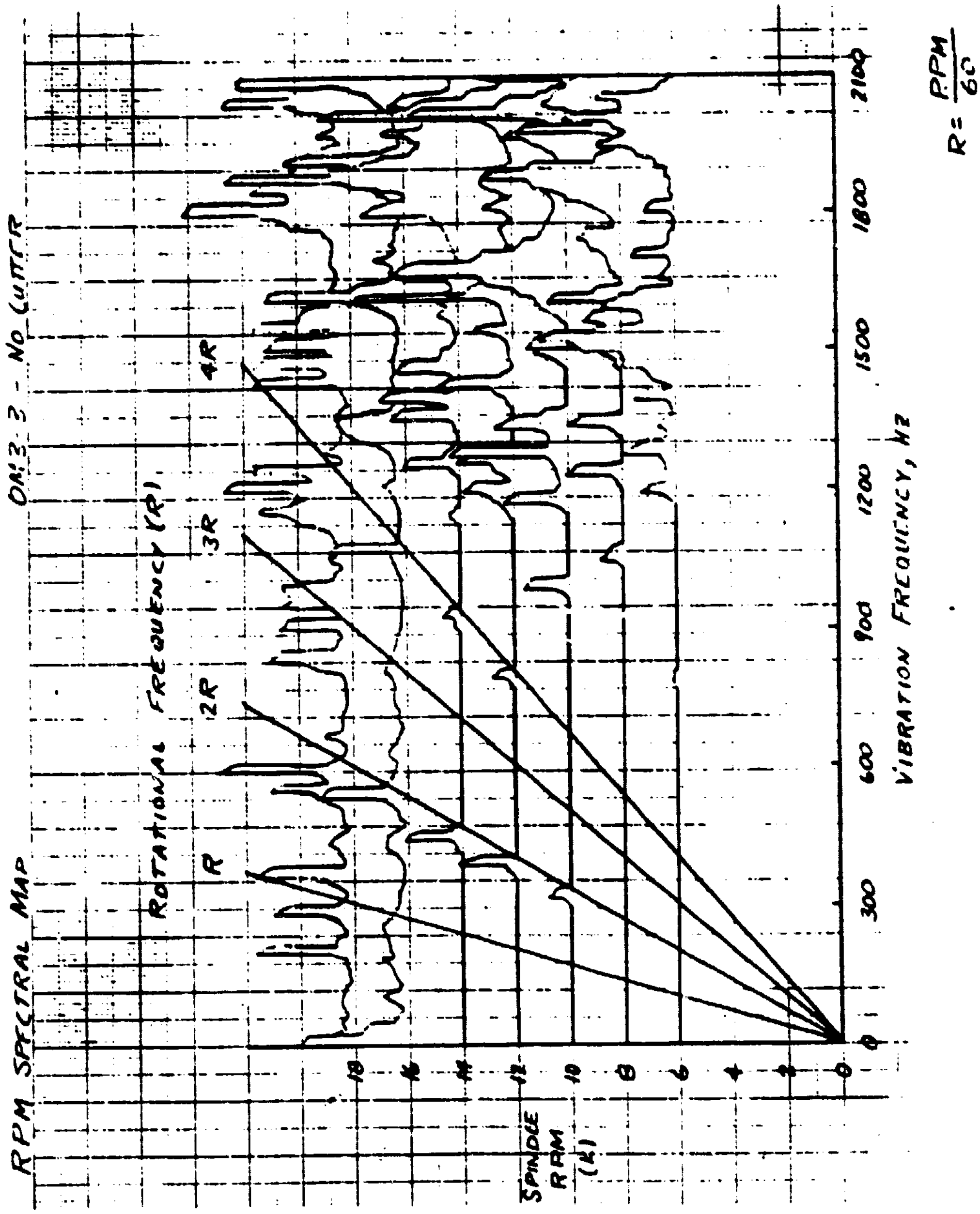

RPM SPECTRAL MAP
OM 3-3 - NO CUTTER
ROTATIONAL FREQUENCY (R)
R
2R
3R
4R
SPINDLE RPM (K)
18
16
14
12
10
8
6
4
2
0
0
300
600
900
1200
1500
1800
2100
VIBRATION FREQUENCY, HZ
R = RPM/60

Figure B-1

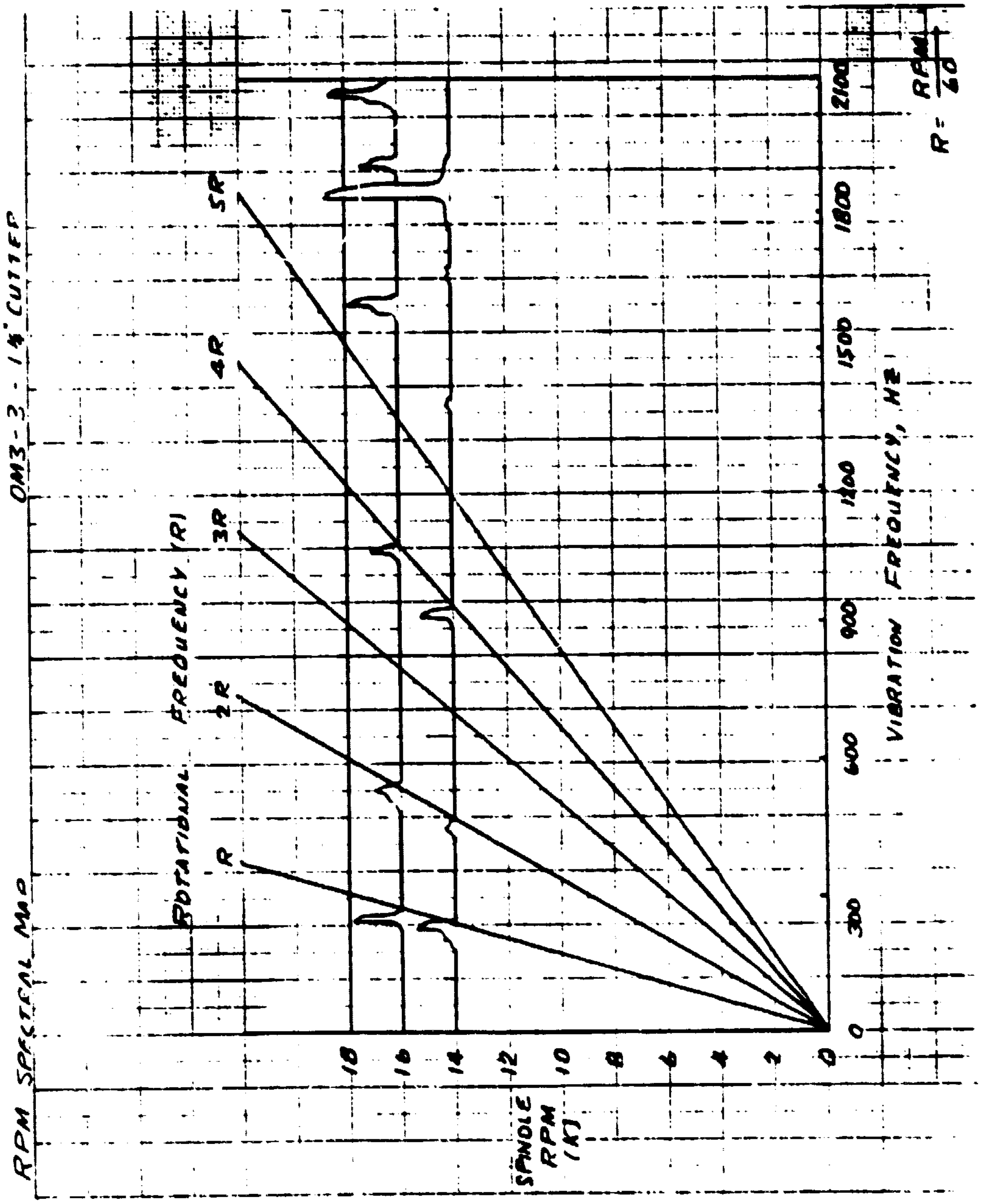

RPM SPECTRAL MAP
OM3-3 - 1¼" CUTTER
ROTATIONAL FREQUENCY (R)
R
2R
3R
4R
5R
VIBRATION FREQUENCY, HZ
0
300
600
900
1200
1500
1800
2100
SPINDLE RPM (K)
0
2
4
6
8
10
12
14
16
18
R = RPM/60

Figure B-2

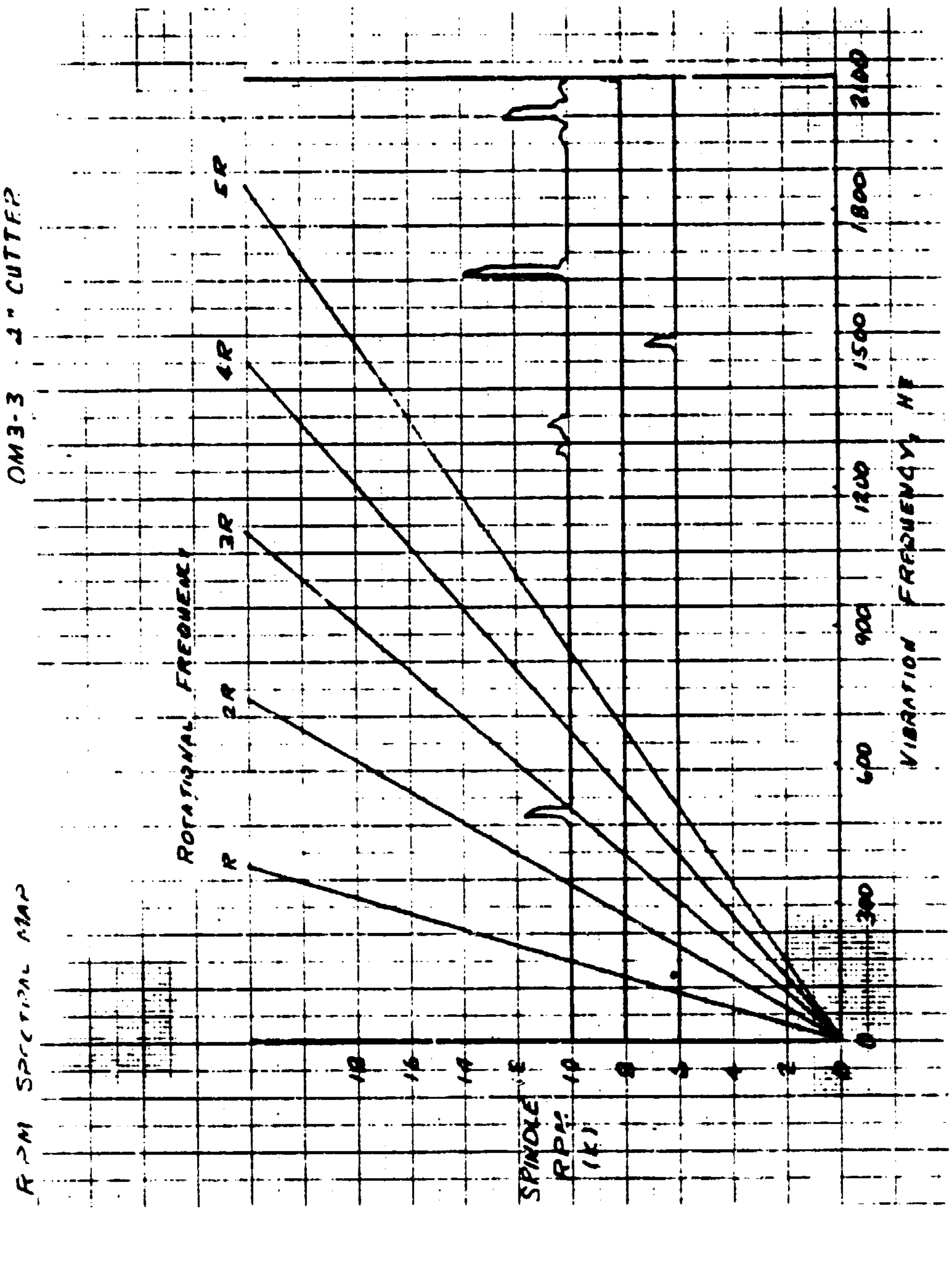

OM3-3
ROTATIONAL FREQUENCY
R
2R
3R
4R
5R
SPINDLE RPM (K)
VIBRATION FREQUENCY, HZ
0
300
600
900
1200
1500
1800
2100

Figure B-3

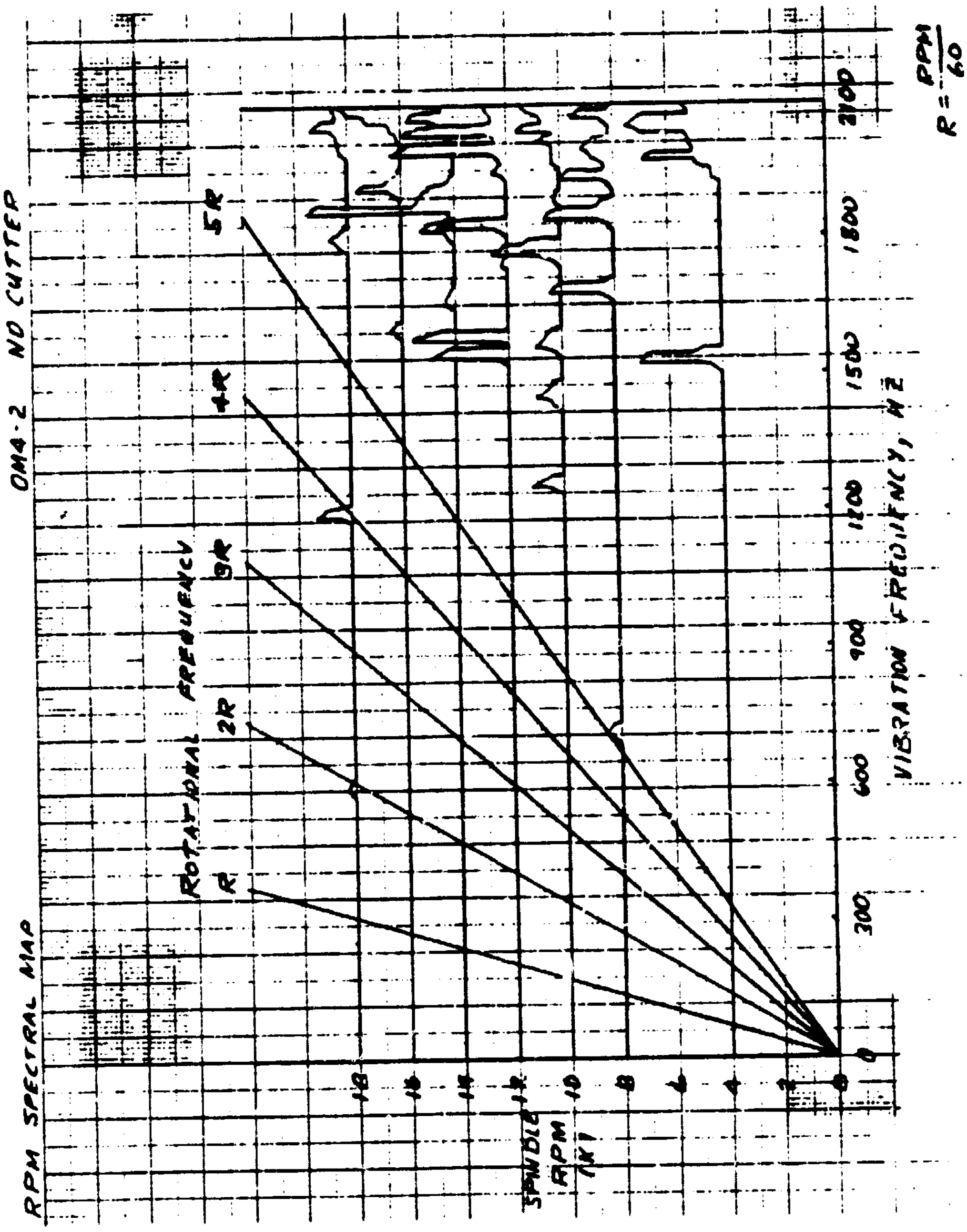

RPM SPECTRAL MAP
OMA-2 NO CUTTER
ROTATIONAL FREQUENCY
R
2R
3R
4R
5R
VIBRATION FREQUENCY, HZ
0
300
600
900
1200
1500
1800
2100
R = RPM/60
SPINDLE RPM (K)
0
2
4
6
8
10
12
14
16
18

Figure B-4

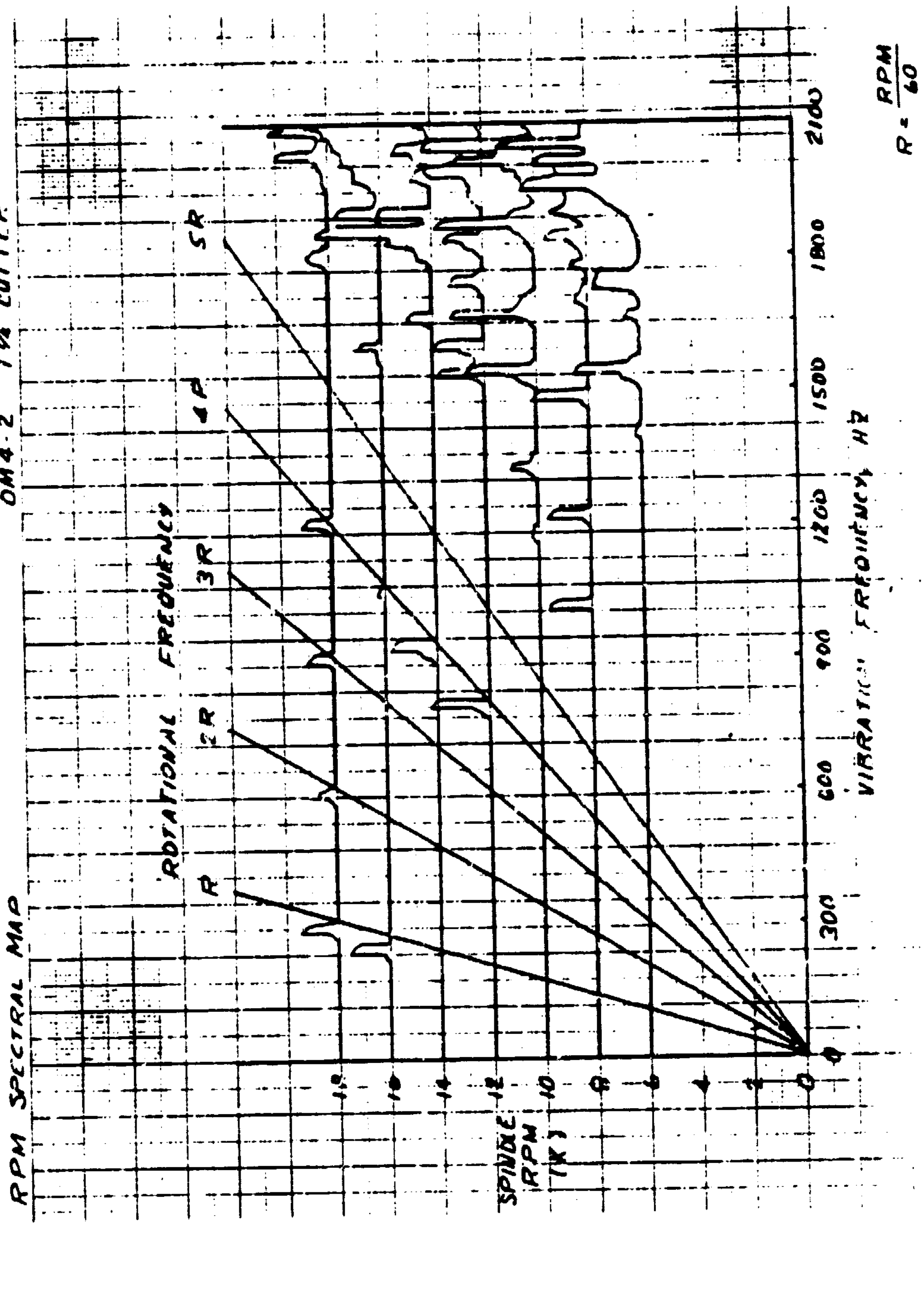

RPM SPECTRAL MAP
OM4-2
1½" CUTTER
ROTATIONAL FREQUENCY
R
2R
3R
4R
5R
SPINDLE RPM (K)
0
2
4
6
8
10
12
14
16
18
0
300
600
900
1200
1500
1800
2100
VIBRATION FREQUENCY HZ
R = RPM/60

Figure B-5

ORIGINAL PAGE IS
OF POOR QUALITY

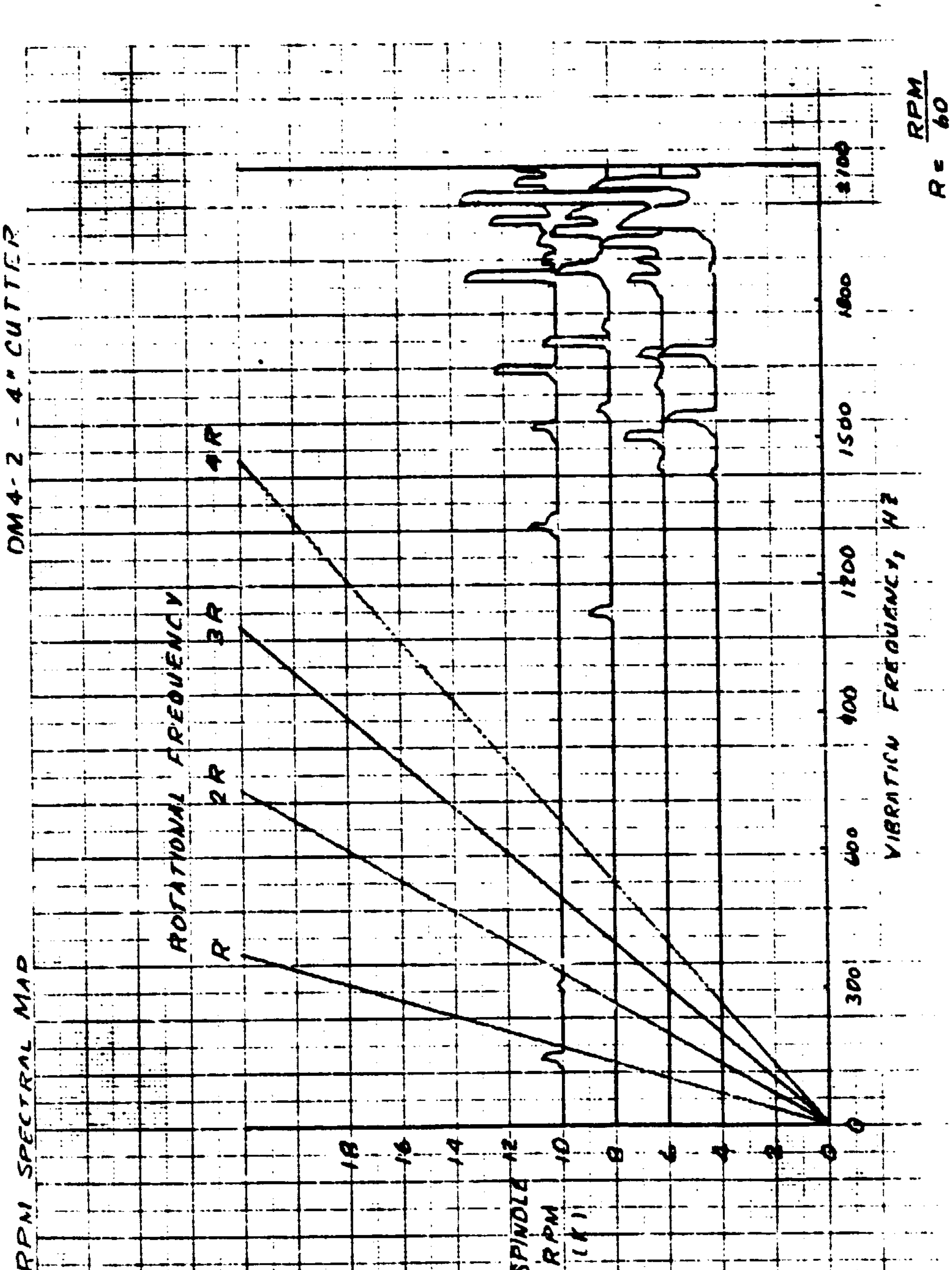


Figure B-6

APPENDIX C

Attendees at NASA Shuttle Tank High-Speed Machining Demonstration
June 15, 1982, B/181 and B/182

NASA Marshall Space Flight Center (MSFC)

Edward J. Bryan
Paul H. Schuerer

Martin Marietta

Gerry Scott
R. G. "Bob" Williams
Steven A. DeLony

Cleveland Pneumatic Company

John A. Wulf

Reynolds Metals Co.

R. J. "Bob" Kazmier

U. S. Navy - Sunnyvale

Mike Maionchi

LMSC

Robert I. King
A. J. Kish
J. A. Miller
E. A. "Gar" Eger
C. Gallman
R. N. Johnson
I. M Suarez
M. I. Jacobson

APPENDIX D

AGENDA

HIGH SPEED MACHINING OF SPACE SHUTTLE
EXTERNAL TANK PANELS
PANEL CUTTING DEMONSTRATION

June 15, 1982

8:15 a.m.	Arrive in Bldg. 181 Lobby
8:30 a.m.	Welcome (Navy Conference Rm. B) - Joe Miller, Program Manager
	MSD Background - Sam Dollar, Mgr., Manufacturing Program Support
8:50 a.m.	High-Speed Machining Concepts & Contract Briefing - Joe Miller
10:00 a.m.	Panel Cutting Demonstration (Sundstrand OM4B, B/182, Column E23)
11:30 a.m.	Lunch in Cafeteria (Bldg. 149)
12:45 p.m.	Panel Cutting Demonstration - continued
1:45 p.m.	Discussion Period - (Navy Conference Room B)
3:00 p.m.	Tour of LMSC Space Shuttle Tile Fabrication Facility (Bldg. 174)
4:00 p.m.	Return to Bldg. 181 Lobby

APPENDIX E

SETUP AND OPERATING INSTRUCTIONS

FOR

MACHINING 4 FT LONG PANELS

SETUP & OPERATING INSTRUCTIONS

1. Load NAS 8664 fixture onto OM-4 table and secure.
2. Load shuttle No. 1 tape into reader. Set block delete off and cycle tape.
3. Program stop. Indicate left locating pin. Retract "Z" axis and cycle tape.
4. Program stop. Indicate right locating pin. Home "Z" axis and cycle tape.
5. Program stop. Load part per sketch on page 3. Set block delete on and cycle tape.

SEQ. NO.	OPERATIONS	TOOL NO.
	Program stop. Touch off, on top of part using a 1.000 feeler. Cycle tape.	02
010	Mill .126 Dim.	02
020	Mill .126 Dim.	02
030	Mill .126 Dim.	02
040	Mill .320 Dim. and .141 Dim.	02
	Program stop. Touch off, on .126 Dim. using a 1.000 feeler. Cycle tape.	03
050	Mill .37 corner radius.	03
	Program stop. Touch off, on .126 Dim. using a 1.000 feeler. Cycle tape.	04
060	Mill under flange.	04

END OF PROGRAM.

TOOL NO.	TYPE	RPM	F/R
02	1.250 Dia. E.M. .060 R.	18,000	150-200
03	1.250 Dia. E.M. .370 R.	18,000	180
04	4.000 Dia. Wheel Cutter .125 R.	8,000	40-100

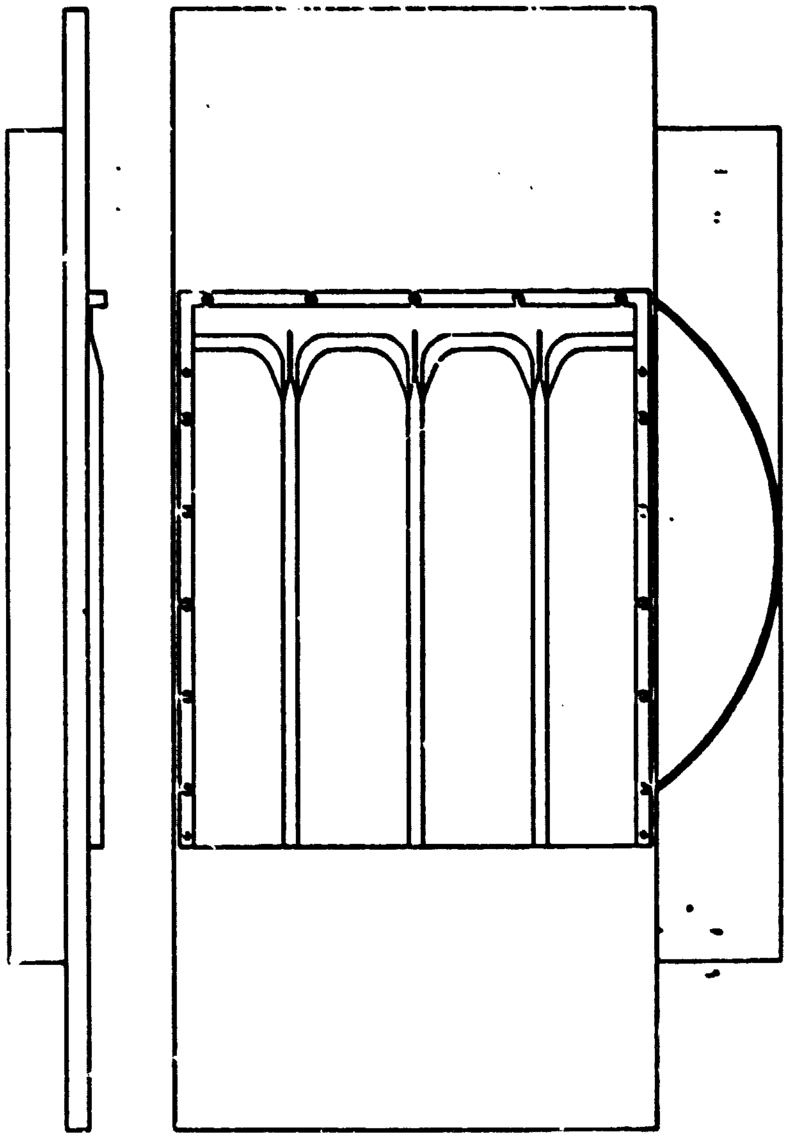
SHUTTLE-SHORT-1
REV Page 1 of 4

CUTTING DATA

TOOL NO.	DEPTH OF CUT	WIDTH OF CUT	CUBIC INCHES
02	.070-.300	1.1-1.250	18-56
03	.370	.370	25
04	.075-.635	.025-.550	18

TOOL NO.	SFM	CHIP LOAD
02	5,890	.0025-.0032
03	5,890	.003
04	8,378	.0016-.0032

APPENDIX E



ORIGINAL PAGE IS OF POOR QUALITY

SUNDSTRAND OMNIMILL 4X OM4 SHUTTLE 3 005 UNCLASSIFIED

CHART OF DIMENSIONS FROM HOME OR MACHINE ZERO. POSITION FOR SEQNO OR TMARK.

SEQNO.	X-DIMENSION	Y-DIMENSION	Z-DIMENSION	A-DIMENSION	C-DIMENSION	SPINDLE	TOOL NO.	HEAD
010	53.0000	-46.0000	-21.3750	25.0000	.0000		2	HIGH
020	26.0000	-47.0000	-21.3750	25.0000	.0000	S635 M17	2	HIGH
030	26.0000	-56.0680	-21.3750	25.0000	.0000	S635 M17	2	HIGH
040	64.4690	-63.5050	-21.8750	25.0000	.0000	S635 M17	2	HIGH
050	53.0000	-49.8590	-21.8750	25.0000	.0000	S635 M17	3	HIGH
060	53.0000	-50.2715	-20.0000	25.0000	.0000	S635 M17	4	HIGH

OM4 SHUTTLE 3 PAGE 4 OF 4 CHG

APPENDIX F

(FIRST HALF) LL2 No.1

HIGH SPEED MILLING DATA SHEET

FOR 8 FT LONG PANEL NO. LL2

TOOL # 02

.126 DIM.

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
1	-22.6750	.300	150	18000	13.4
2	-22.9750	.300	150	18000	13.5
3	-23.2750	.300	150	18000	13.3
4	-23.5750	.300	150	18000	13.4
5	-23.6290	.054	200	18000	7.2
6	-23.9290	.300	150	18000	12.0
7	-23.9990	.070	200	18000	7.4
1	-22.6750	.300	150	18000	13.4
2	-22.9750	.300	150	18000	13.8
3	-23.2750	.300	150	18000	13.1
4	-23.5750	.300	150	18000	13.2
5	-23.6290	.054	200	18000	7.1
6	-23.9290	.300	150	18000	13.3
7	-23.9990	.070	200	18000	7.8

.320 DIM.

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
1	-22.6750	.300	150	18000	13.4
2	-22.9750	.300	150	18000	12.6
3	-23.2750	.300	150	18000	12.8
4	-23.4350	.160	200	18000	12.0
5	-23.7350	.300	150	18000	13.4
6	-23.8050	.070	200	18000	6.8
1	-22.6750	.300	150	18000	13.3
2	-22.9750	.300	150	18000	13.0
3	-23.2750	.300	150	18000	10.9
4	-23.4350	.160	200	18000	10.3
5	-23.7350	.300	150	18000	13.4
6	-23.8050	.070	200	18000	6.8

APPENDIX F

(FIRST HALF) LL2 No. 1

HIGH SPEED MILLING DATA SHEET
FOR 8 FT LONG PANEL NO. LL2

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
		TOOL * 02			
		.141 DIM.			
1	-23.9840	.179	200	18000	6.2
1	-23.9840	.179	200	18000	6.2
		1.250 DIM.			
1	-22.6750	.300	150	18000	8.1
2	-22.8750	.200	200	18000	8.0
1	-22.6750	.300	150	18000	13.0
2	-22.8750	.200	200	18000	10.2
		TOOL * 03			
		.126 DIM.			
1	-23.9990	.370	180	18000	8.4
		.141 DIM.			
1	-23.9840	.370	180	18000	8.4
		.320 DIM.			
1	-23.8050	.370	180	18000	8.4
1	-23.8050	.370	180	18000	8.3
		.141 DIM.			
1	-23.9840	.370	180	18000	8.2
		TOOL * 04			
1	-21.8090	.635	40-50	8000	5.1
2	-21.6350	.150	100	8000	3.7
3	-21.9840	.150	100	8000	3.9

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX F

(SECOND HALF) LL2 No.2

HIGH SPEED MILLING DATA SHEET
FOR 8 FT LONG PANEL NO. LL2

TOOL # 02

.126 DIM.

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
1	-22.6750	.300	150	18000	12 8
2	-22.9750	.300	150	18000	12 4
3	-23.2750	.300	150	18000	12 5
4	-23.5750	.300	150	18000	12.6
5	-23.6290	.054	200	18000	6.8
6	-23.9290	.300	150	18000	12.8
7	-23.9990	.070	200	18000	6.2
1	-22.6750	.300	150	18000	12.7
2	-22.9750	.300	150	18000	12.4
3	-23.2750	.300	150	18000	12.4
4	-23.5750	.300	150	16000	12.4
5	-23.6290	.054	200	18000	6.7
6	-23.9290	.300	150	18000	12.4
7	-23.9990	.070	200	18000	6.3

.320 DIM.

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
1	-22.6750	.300	150	18000	12.9
2	-22.9750	.300	150	18000	10.9
3	-23.2750	.300	150	18000	12.6
4	-23.4350	.160	200	18000	10.0
5	-23.7350	.300	150	18000	12.4
6	-23.8050	.070	200	18000	7.1
1	-22.6750	300	150	18000	13.6
2	-22.9750	.300	150	18000	12.4
3	-23.2750	.300	150	18000	12.5
4	-23.4350	.160	200	18000	10.2
5	-23.7350	.300	150	18000	12.4
6	-23.8050	.070	200	18000	7.0

APPENDIX F

(SECOND HALF) LL2 No.2

HIGH SPEED MILLING DATA SHEET
FOR 8 FT LONG PANEL NO. LL2

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
		TOOL * 02			
		.141 DIM.			
1	-23.9840	.179	200	18000	10.2
1	-23.9840	.179	200	18000	10.2
		1.250 DIM.			
1	-22.6750	.300	150	18000	12.7
2	-22.8750	.200	200	18000	10.8
1	-22.6750	.300	150	18000	12.6
2	-22.8750	.200	200	18000	10.6
		TOOL * 03			
		.126 DIM.			
1	-23.9990	.370	180	18000	8.3
		.141 DIM.			
1	-23.9840	.370	180	18000	8.4
		.320 DIM.			
1	-23.8050	.370	180	18000	8.3
1	-23.8050	.370	180	18000	8.4
		.141 DIM.			
1	-23.9840	.370	180	18000	8.2
		TOOL * 04			
1	-21.8090	.635	40-50	8000	5.2
2	-21.6350	.150	100	8000	4.1
3	-21.9840	.150	100	8000	7.8