NASA Technical Memorandum

NASA TM - 82557

HIGH SPEED MACHINING OF SPACE SHUTTLE EXTERNAL TANK LIQUID HYDROGEN BARREL PANEL

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November 1983

National Aeronautics and
Space Administration
George C. Marshall Space Flight Center

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM - 82557	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE

High Speed Machining of Space Shuttle External Tank Liquid Hydrogen Barrel Panel

5. REPORT DATE

November 1983

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

James D. Hankins

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS

National Aeronautics and Space Administration
Washington, D.C. 20546

13. TYPE OF REPORT & PERIOD COVERED

Technical Memorandum

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Materials and Processes Laboratory, Science and Engineering Directorate.

16. ABSTRACT

This report includes actual and projected optimum High Speed Machining (HSM) data for producing Shuttle External Tank (ET) Liquid Hydrogen Barrel Panels which are aluminum alloy 2219-T87. The data includes various machining parameters; e.g., spindle speeds, cutting speed, table feed, chip load, metal removal rate, horsepower, cutting efficiency, cutter wear (lack of) and chip removal methods. The results of a study by the Lockheed Missiles and Space Company for the George C. Marshall Space Flight Center under Contract NAS8-34508 are included.

17. KEY WORDS

High Speed Machining
Aluminum Alloy 2219-T87

18. DISTRIBUTION STATEMENT

Unclassified – Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	43	NTIS

MSFC - Form 3292 (May 1969)

ACKNOWLEDGMENTS

This report includes data and information provided by Lockheed Missiles and Space Company, Sunnyvale, California, under Contract Number NAS8-34508 to the George C. Marshall Space Flight Center. Dr. Joseph A. Miller was the Lockheed Project Manager for the High Speed Machining Study, with Dr. Robert I. King providing key inputs and guidance as an expert Consultant and Advisor.

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GLOSSARY

CADAM	Computer Aided Design and Manufacture
cipm	cubic inches per minute
cipm/hp	cubic inches per minute per horsepower
DIA.	Diameter
DIM.	Dimension
ET	Space Shuttle External Tank
fpm	feet per minute
F/R	Feed Rate (ipm)
FT. or ft.	feet or foot
HP or hp	Horsepower
hp/cipm	Unit horsepower
HSM	High Speed Machining
in.	inch(es)
ipm	inches per minute
LH_2	Liquid Hydrogen
LMSC	Lockheed Missiles and Space Company
LW	Light Weight (ET)
MMT	Milling Machine Taper
MSFC	George C. Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NC	Numerical Control
RPM or rpm	revolutions per minute
SFM or sfpm	surface feet per minute

TECHNICAL MEMORANDUM

HIGH SPEED MACHINING OF SPACE SHUTTLE EXTERNAL TANK LIQUID HYDROGEN BARREL PANEL

SECTION 1. INTRODUCTION

High Speed Machining (HSM) is a relatively new manufacturing technology with a high potential for improving machining efficiency in many applications. The Space Shuttle External Tank (ET) offers an excellent opportunity to benefit from HSM technology because the ET is expendable and the current mission profile calls for production rates of 24 tanks per year through 1993. Conservative estimates of machining time reduction for the aluminum alloy 2219-T87 ET panels are significant – 25 percent or $85,000.00 per tank.

HSM technology employs spindle speeds, feed rates, and cutter velocities much higher than conventional methods; e.g., typically greater than 6000 versus 2000 surface-feet per minute. Upper limits have not been defined, but work to date shows that increased machinability and decreased cost are definite benefits of HSM.

In November 1981, the George C. Marshall Space Flight Center (MSFC) issued Contract Number NAS8-34508 to Lockheed Missiles and Space Company (LMSC), Sunnyvale, California, to accomplish a "Feasibility Study for High Speed Machining of ET, Liquid Hydrogen (LH_2), Barrel Panels." LMSC was chosen for this work, based upon their considerable experience and nationally recognized expertise in HSM. Dr. Joseph A. Miller was the LMSC project manager for the study, with Dr. Robert I. King directly participating as HSM consultant and advisor.

The ET of the Space Shuttle (Figs. 1 and 2) is not recovered after launch, therefore, a new one must be provided for each flight. Currently the external "skin" panels of the tank are produced by machining from solid wrought 2219-T87 aluminum plate stock which is approximately 1.75-in. thick, 11-ft wide, and 20-ft long. The reduction of costs in producing ET panels is obviously of particular significance.

LMSC has successfully demonstrated the applicability and advantages of the HSM process to the production of ET panels by physically machining selected sample portions of a LH_2 barrel panel. Figure 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 selected for this study is illustrated in Figure 2.

SECTION 2. STUDY ELEMENTS AND HARDWARE

2-1. Study Elements

The elements of the study were as follows:

1) Select the panel sample configurations.

2) Determine HSM procedures and times.

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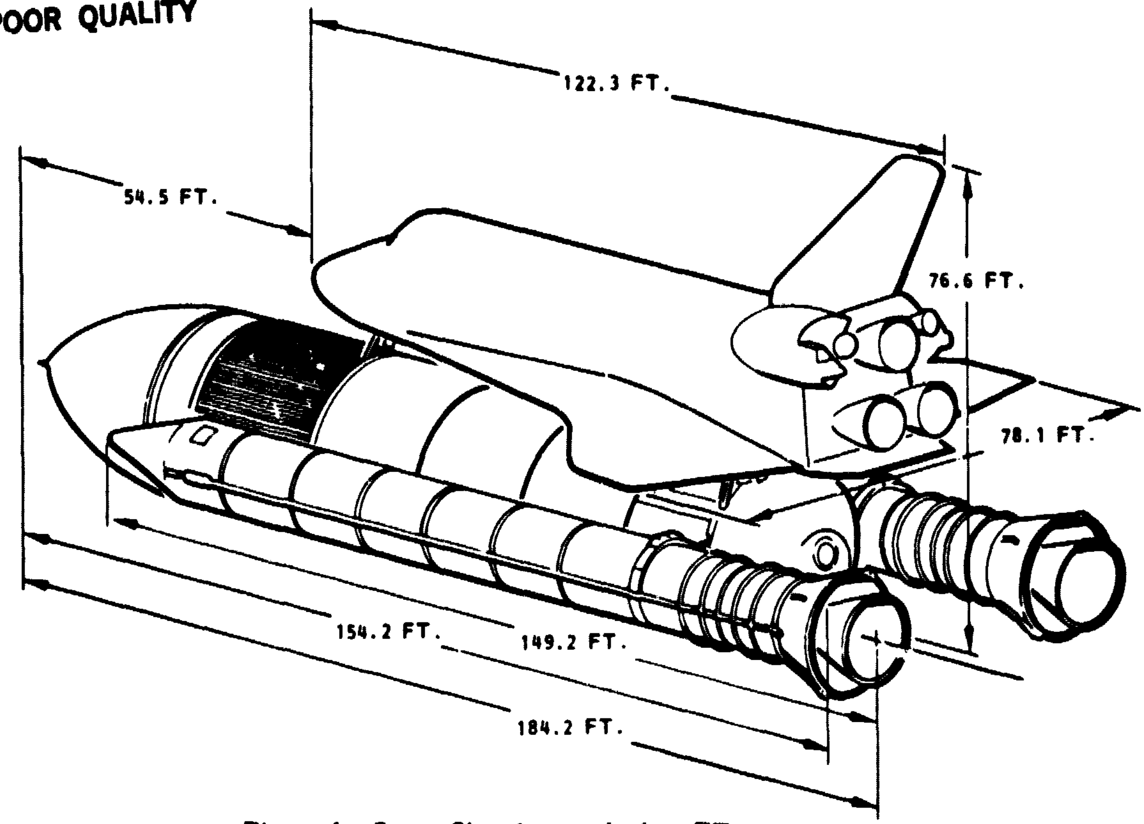

Figure 1. Space Shuttle attached to ET.

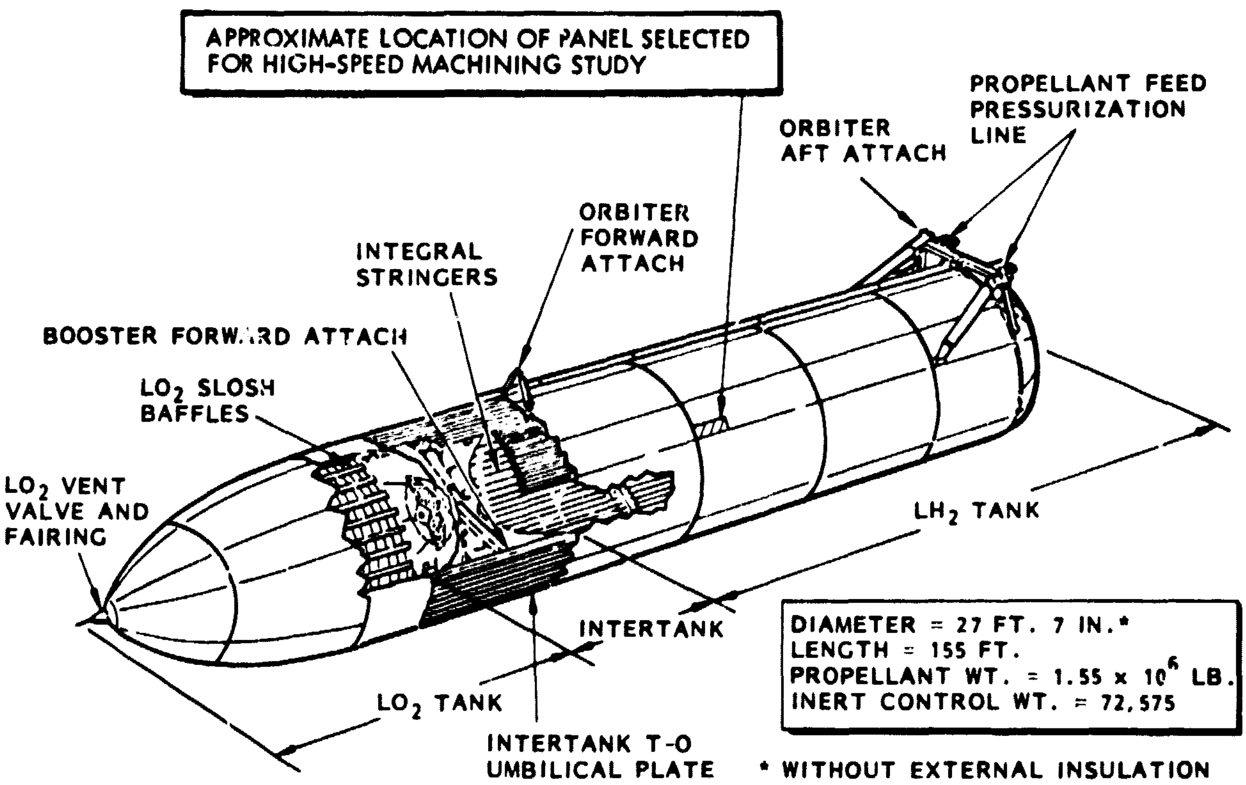

Figure 2. Detail of Space Shuttle ET.

3) Perform the milling demonstration.

4) Video tape selected portions of the HSM process.

5) Produce a final report.

2-2. Deliverable Hardware

The delivered items were as follows:

1) Three 38-in. by 46.5-in. (approximately) barrel panel sections.

2) One 38-in. by 94.5-in. (approximately) barrel panel section.

3) Several small T-rib cross-sections of sample panel.

4) Video tape of HSM panel cutting operation.

   a) Original footage (with written narration)

   b) Rough edited version (with written narration)

5) 1.25-in. cutters (new and used)

   a) Tool No. 2 (Figs. 10 and 11)

   b) Tool No. 3 (Figs. 12 and 13).

SECTION 3. TECHNICAL APPROACH

3-1. Objective

A primary objective of the panel machining was to demonstrate the advantage of HSM 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.

3-2. Equipment Limitations

The only milling machines available at Lockheed, which were large enough to machine the panel sample selected, were Sundstrand Omnimil NC machining centers. A model OM3 (Fig. 3) was selected for the preliminary cutter and NC tape trials because of its availability and accessibility. However, a model OM4 (Fig. 17) was required to accommodate the larger sizes during the final panel machining.

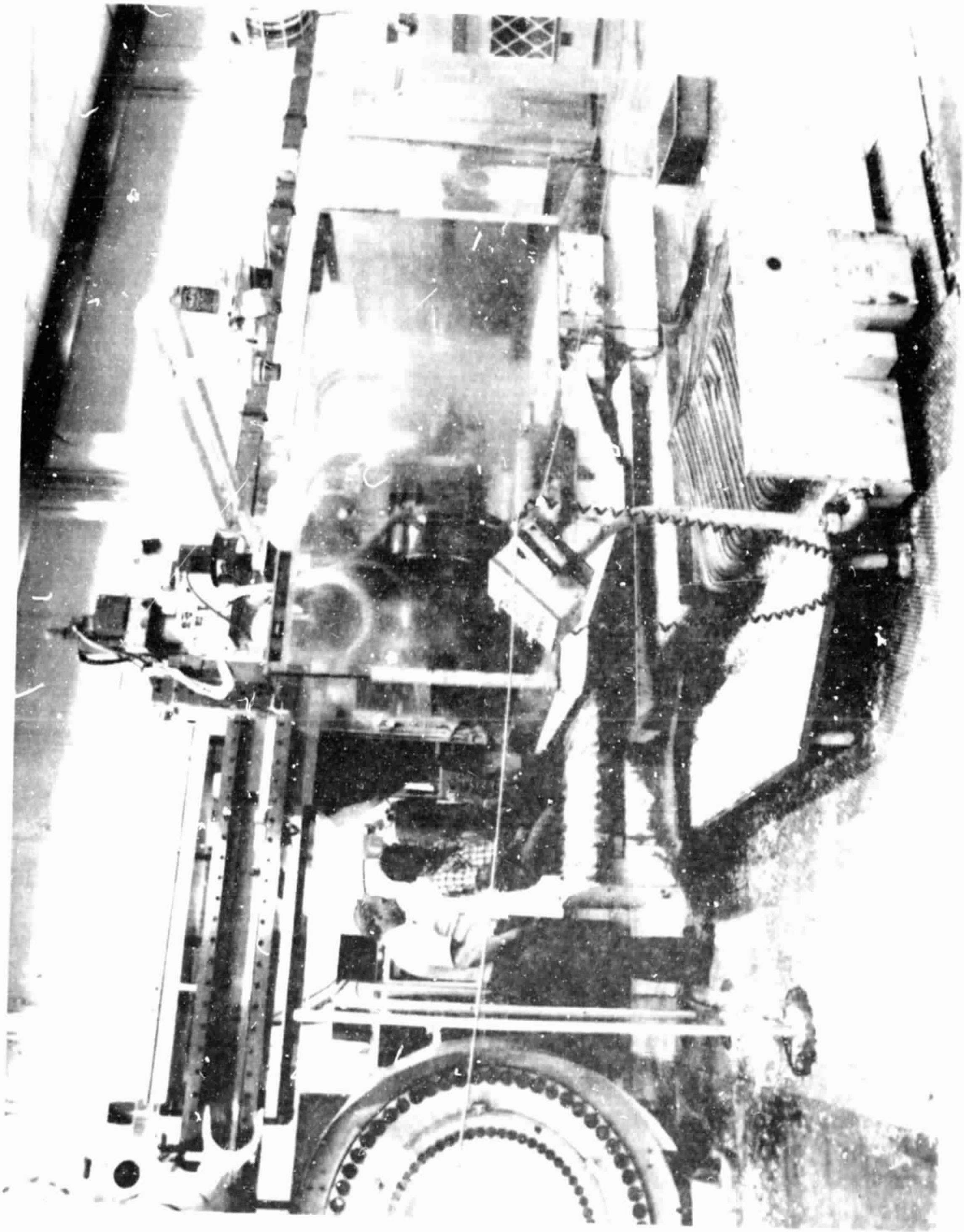

Figure 3. High speed machining cutter trials on Sundstand OM3 NC machining center.

3-2.1. Table Feed

The maximum table feed capability of both the OM3 and OM4 Sundstrand models is 200-inches per minute (ipm) which was 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.

3-2.2. Horsepower

Available 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.

3-2.3. Spindle Nose Configuration

The No. 30 Milling Machine Taper (MMT) of the Bryant 18,000 rpm spindle motor (Fig. 4) was a limiting factor in that the tool holder shank diameter of 1.25-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 stiffness.

3-2.4. 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 (Figs. 5 and 6), the maximum panel size attainable was 21 by 96 in. Consequently, the 38-in. finished panel width was achieved by machining half of the panel width and then indexing to reach the second half.

3-2.5. 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 ET barrel panels, a conveyor system plus a system of flood coolant or air blast nozzles to move the chips to the conveyor would be recommended. An even more functional approach for chip removal would be the use of a sufficiently powerful vacuum system.

3-3. Panel Selection

The selection of a specific ET barrel panel was accomplished primarily by personnel from the Marshall Space Flight Center and the prime contractor for the External Tank, Martin Marietta. As the panels are generally 11-ft wide by 20-ft long, a full panel was not feasible for this study. Therefore, approximately 4-ft by 4-ft and 4-ft by 8-ft sections of a typical panel, Martin Marietta Drawing Number 80914400984, were chosen. The configurations of these panel sections are shown in Figures 5, 6, 7, 8, and 9. Following the panel selection, 2219-T87 aluminum material for the study was shipped from Martin Marietta to Lockheed. (See paragraph 3-5.1.1 for details.)

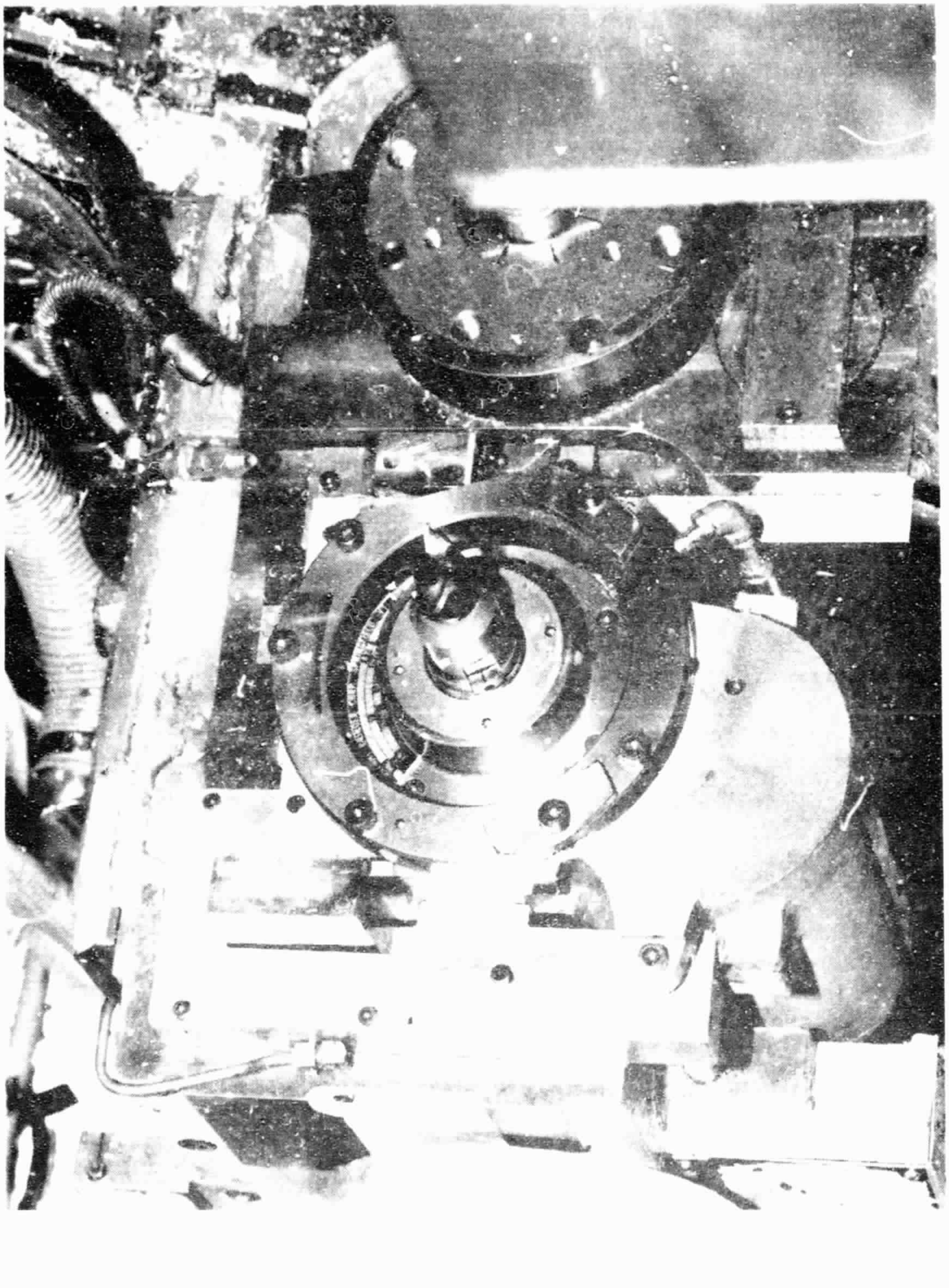

Figure 4. Close-up of 18,000 rpm Bryant spindle motor installed in OM3.

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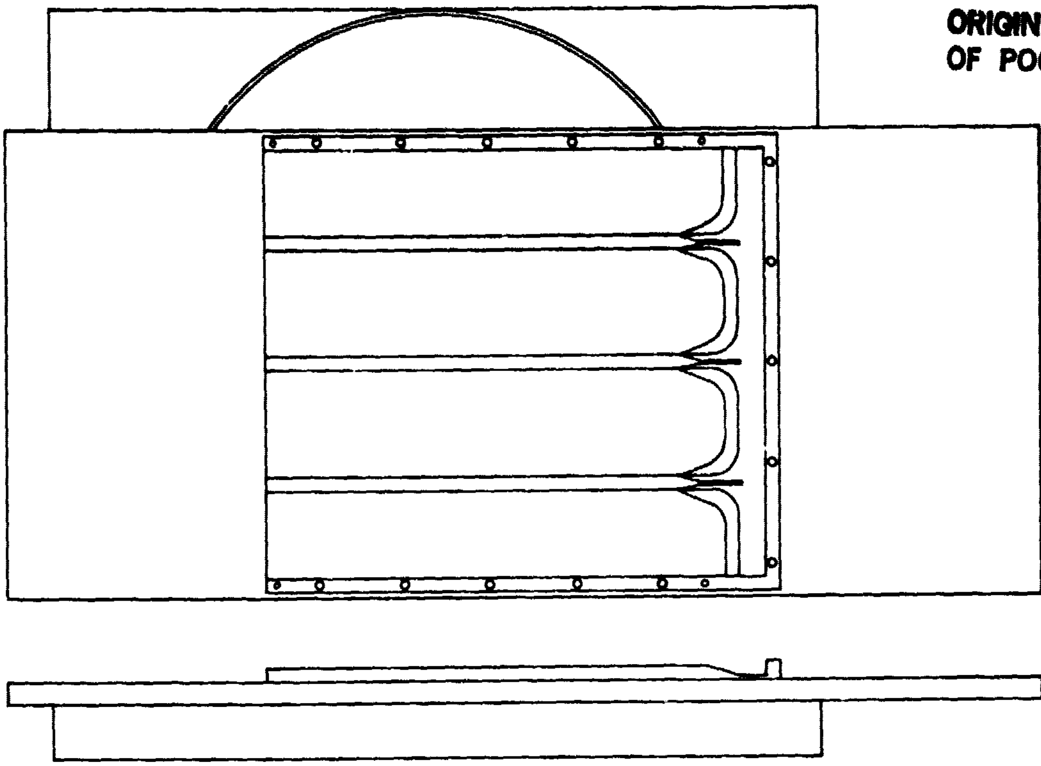

Figure 5. 4-ft long panel as positioned on base plate and machine table.

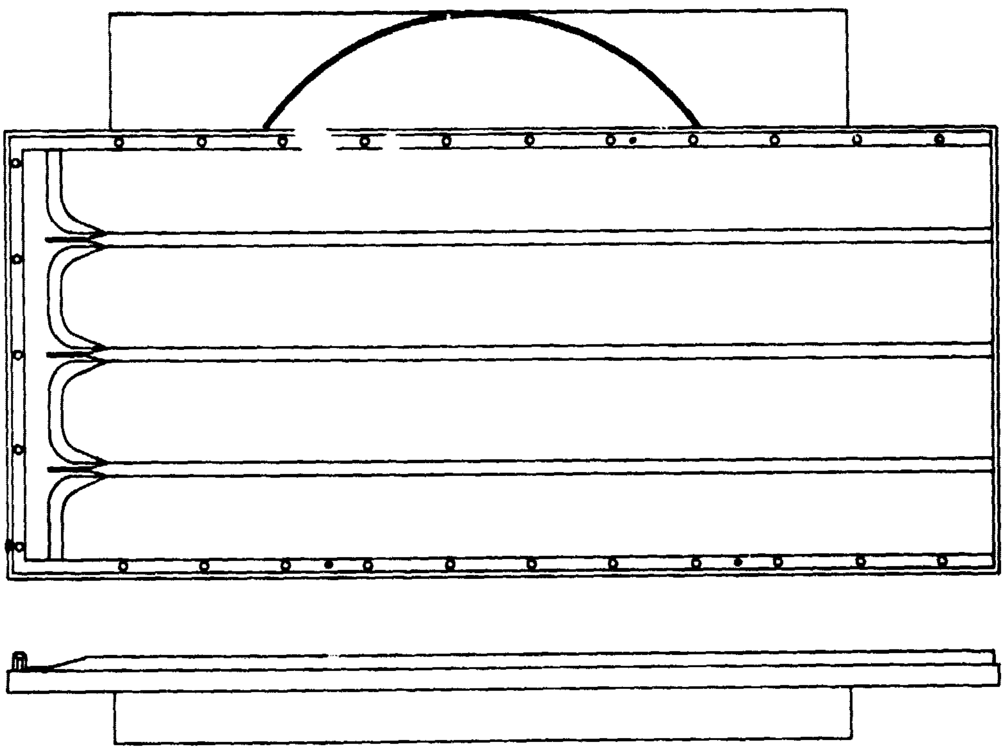

Figure 6. 8-ft long panel as positioned on base plate and machine table.

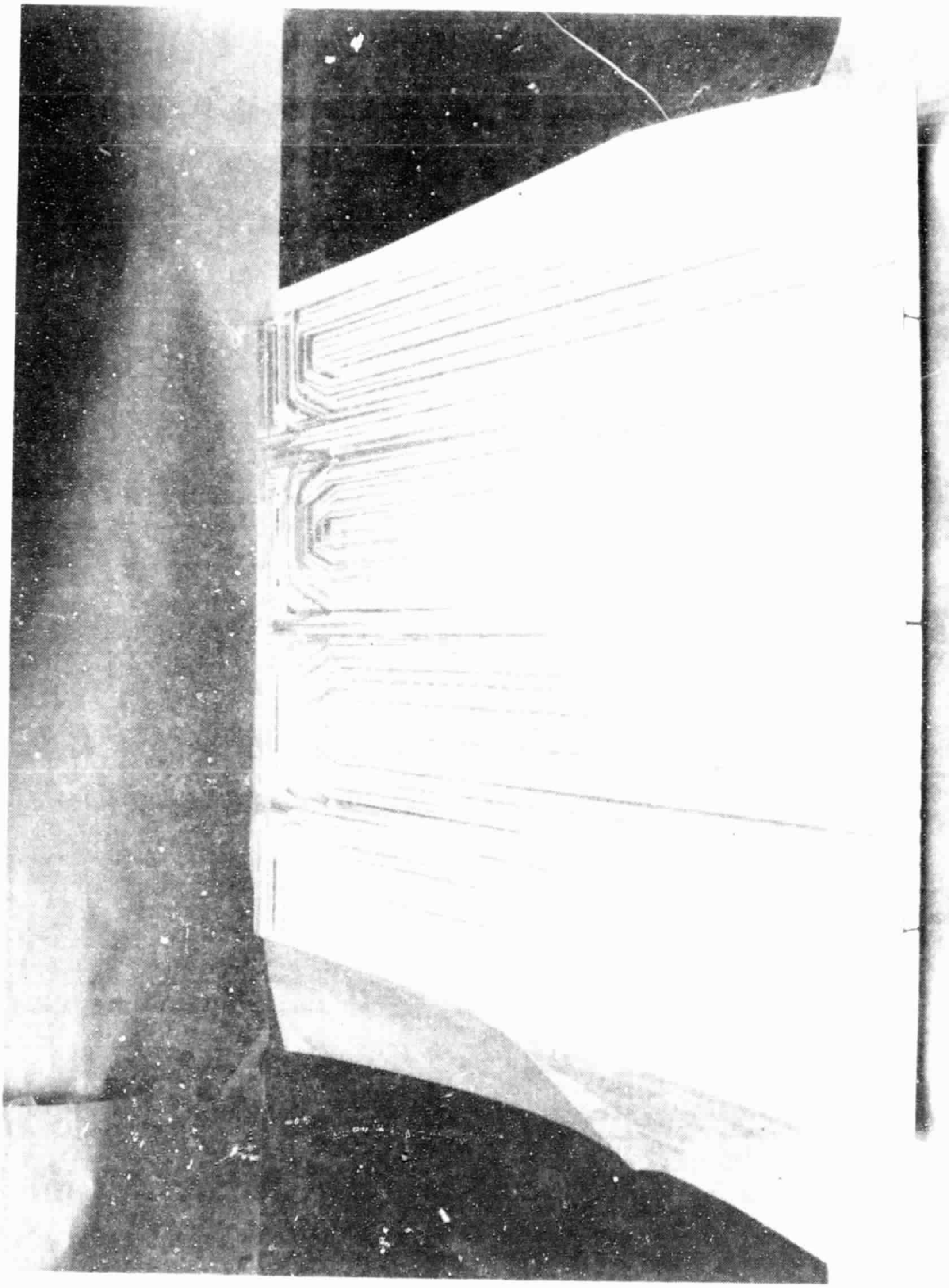

Figure 7. 4-ft long finished panel.

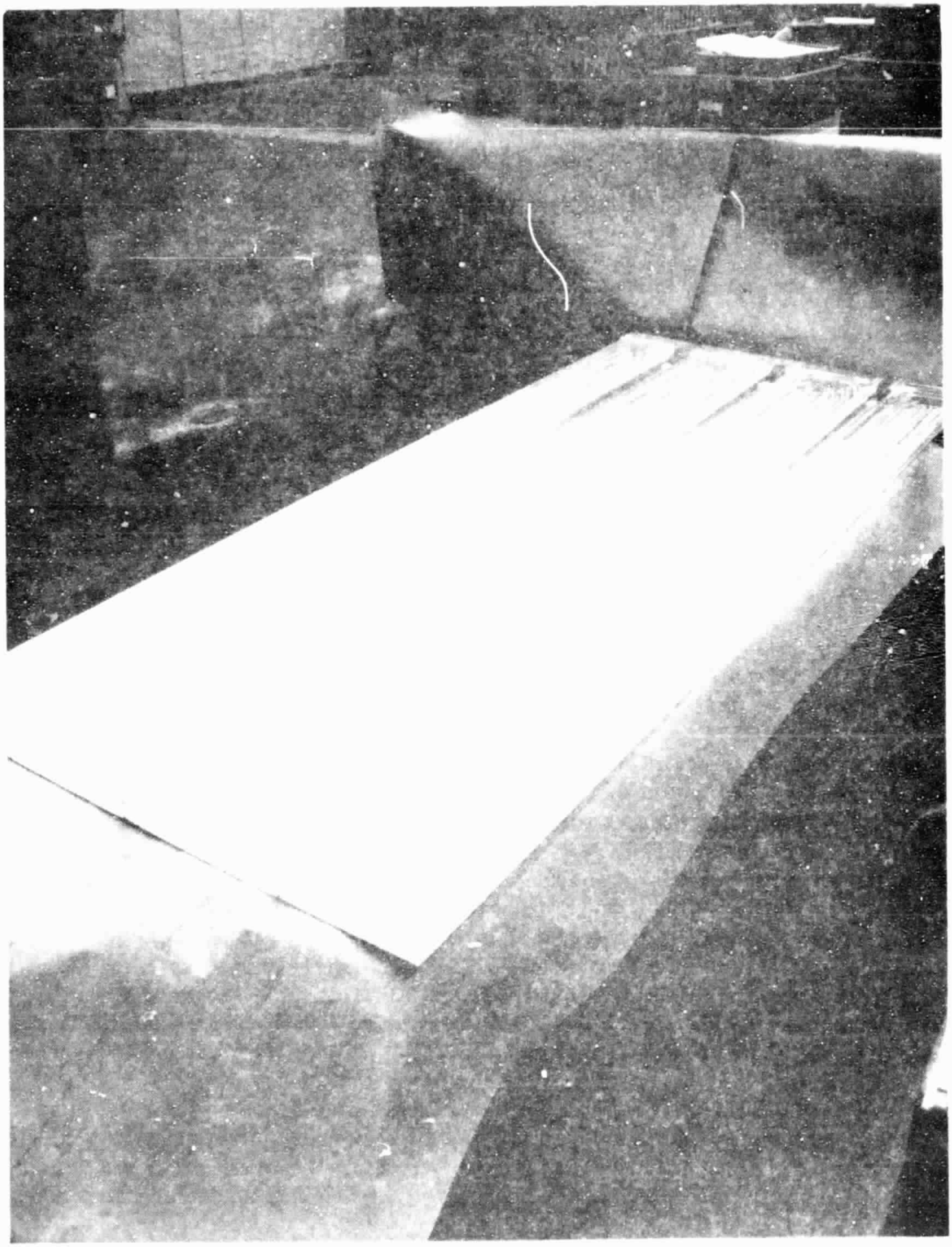

Figure 8. 8-ft long finished panel

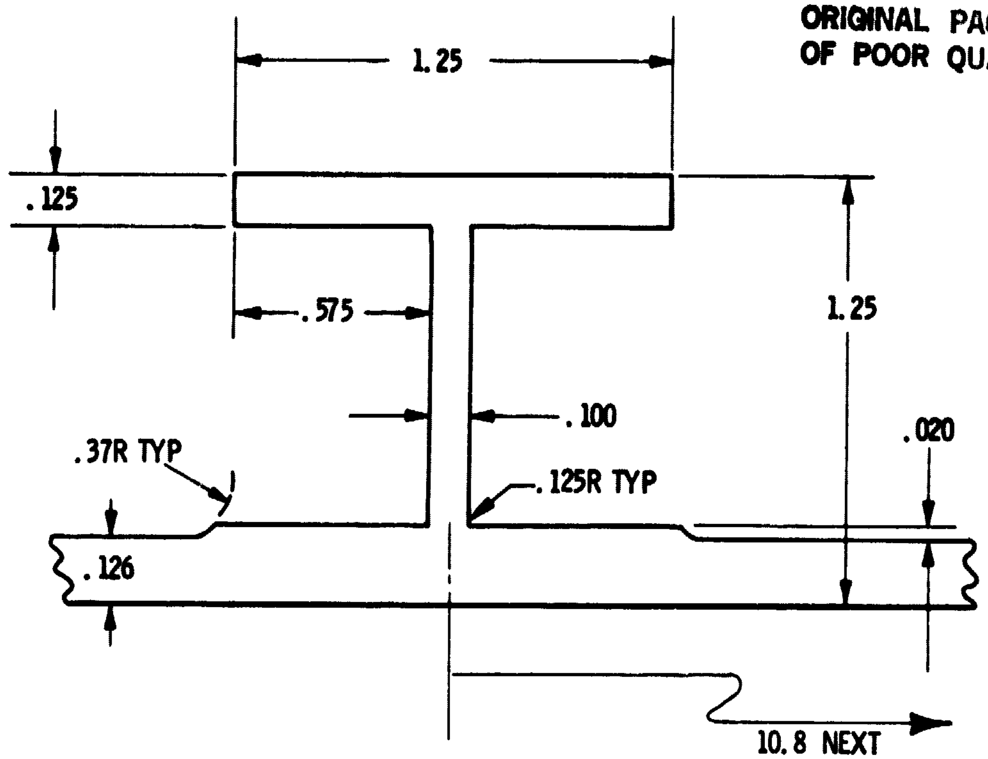

Figure 9. Section view of T-rib reinforcement of barrel panel.

3-4. Cutter Selection and Trials

The diameter 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 paragraph 3-2). The cutters selected had been successfully tested previously at Lockheed for the high-speed machining of aluminum, but of a different alloy. These chosen cutters were modified for proper corner radii (to meet the panel configuration) and for shank diameter to fit the tool holder acceptable for the high-speed spindle motor.

Figures 10 and 11 show the 3-flute, 1.25-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 0.375-in. corner radius end mill, chosen for forming the 0.375-in. radii at the base of the T-ribs and for finishing the closed end of the panel, is shown in Figures 12 and 13. This cutter has the same basic geometry as the roughing cutters except for the larger radiused corners. Both 1.25-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 14 and 15. 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 (1) required modifications of the cutters, (2) the lack of experience in high-speed machining the 2219-T87 alloy, and (3) the minimum time available on the Sundstrand OM4 NC mach-

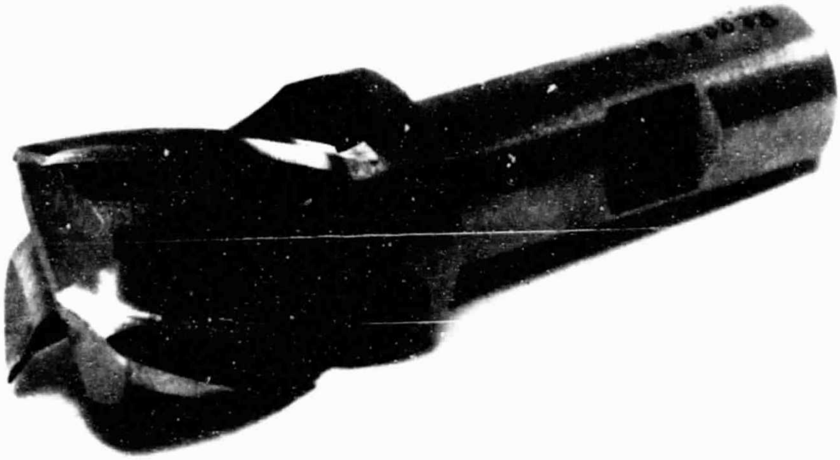

Figure 10. 1.25-in. diameter three-flute end mill selected as roughing cutter.

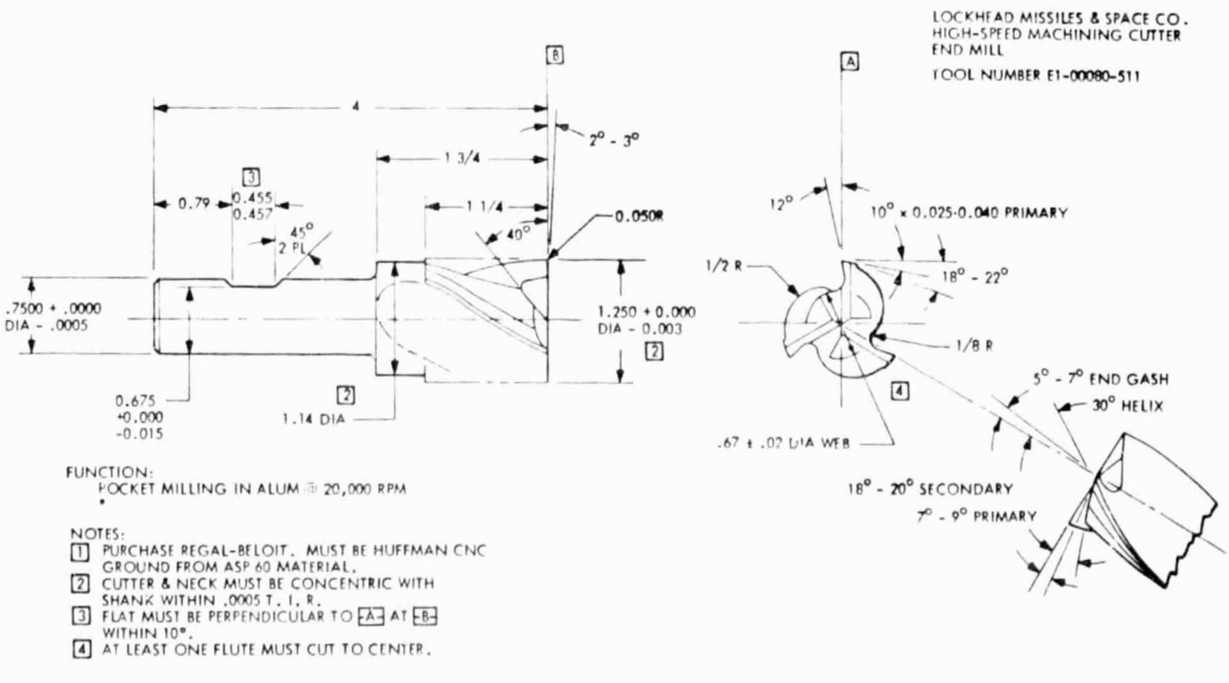

Figure 11. Detailed specifications for roughing cutter.

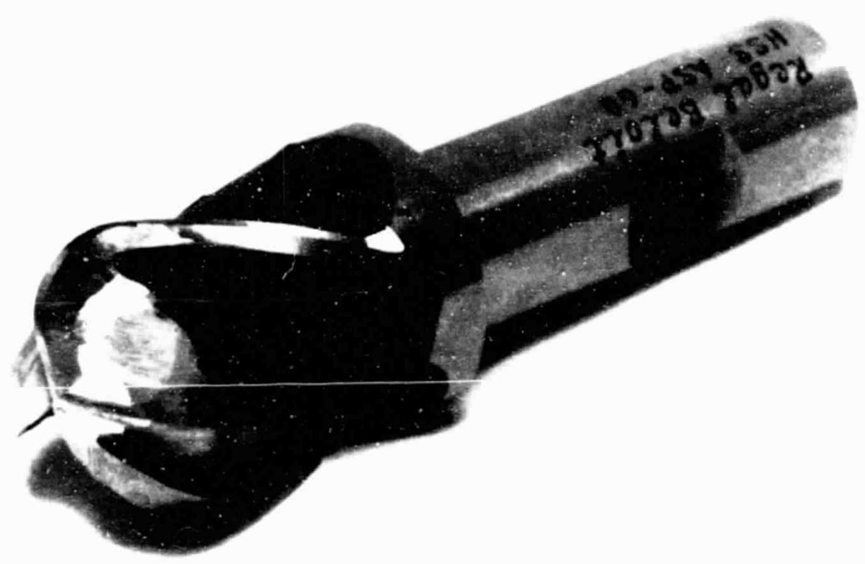

Figure 12. 1.25-in. diameter, 0.375-in. corner radiused end mill selected as finishing cutter.

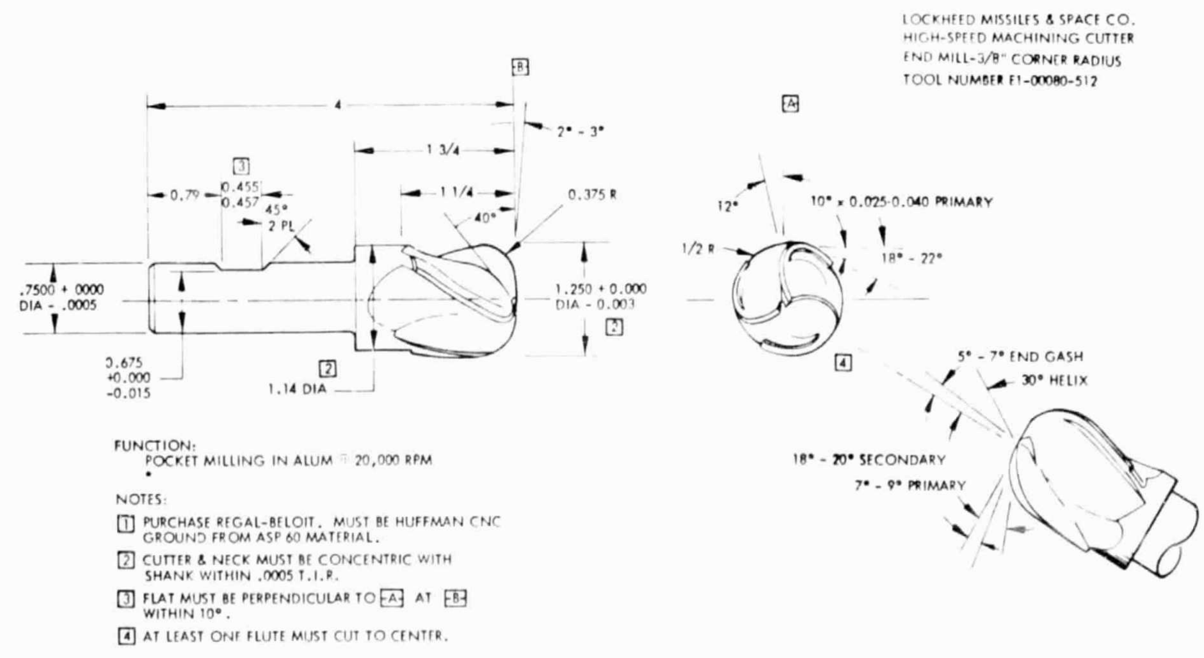

Figure 13. Detailed specifications for finishing cutter.

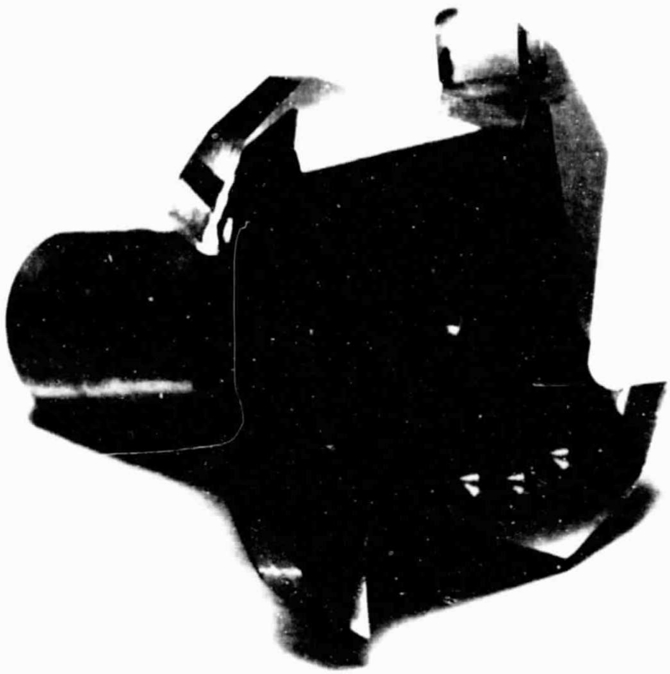

Figure 14. 4-in. diameter cutter selected for machining T-rib sections.

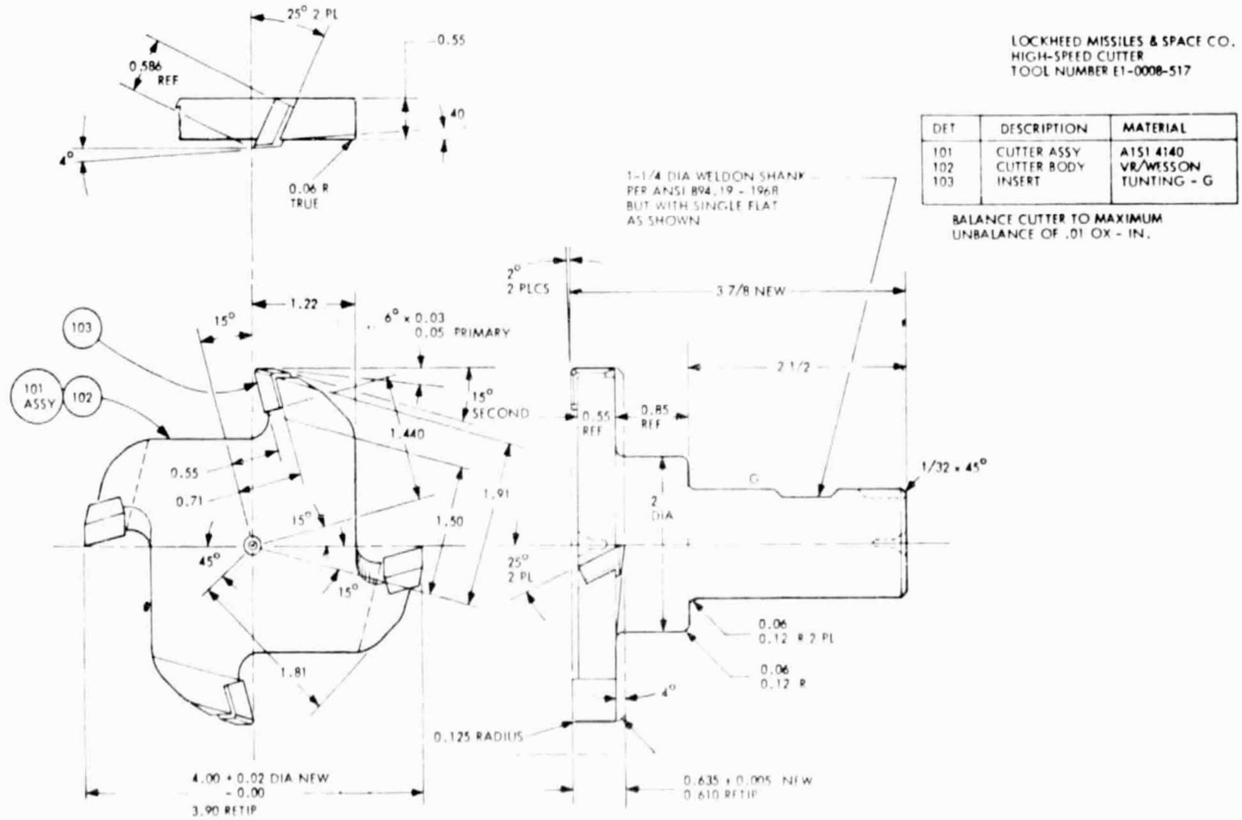

Figure 15. Detailed specifications for T-rib cutter.

ining center, cutter trials were conducted previous to the machining of the panels themselves. These trials were performed on a Sundstrand OM3 NC machining center (Fig. 3) which was more readily available than the OM4; also, the cutter trials provided a means of testing the NC part program in advance.

Preparation for the cutter trials included the following activities: a reduced panel section which could be accommodated on the OM3 machining center was selected, the NC program was written, the cutters were modified and the tool-holders were 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.

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 speed. The section was remachined a third time with the resulting part being very satisfactory. Subsequently, effort was continued for the machining of the selected panel sections and the formal HSM demonstration on the larger machine.

3-5. High Speed Machining of Panels

3-5.1. Preparation

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

3-5.1.1. Identification and Premachining of Panel Blanks

The 2219-T87 wrought aluminum panel blanks, as received from Martin Marietta, were 2-in. thick and ink stencilled with metal grain direction, lot numbers, 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 to assure proper identification and correlation during subsequent machining, testing and analysis. To ensure that the panel blanks would mount flat on the vacuum base plate, both sides were ground flat and parallel. At the same time, the thickness was reduced to the 1.75-in. specified by Martin Marietta drawings. Mounting bolt holes were provided around the perimeter on three sides of the panels.

3-5.1.2. Base Plate

To provide adequate backup and holding capabilities for the panels, a 2-in. thick aluminum vacuum chuck, or base plate, was used. The base plate was designed, acquired, and prepared with vacuum grooves zoned in three separate areas to accommodate both 4-ft and 8-ft long panels (see Figs. 5, 6, and 16). Tapped mounting holes were also provided around the perimeter of the plate by which the panels were aligned and secured.

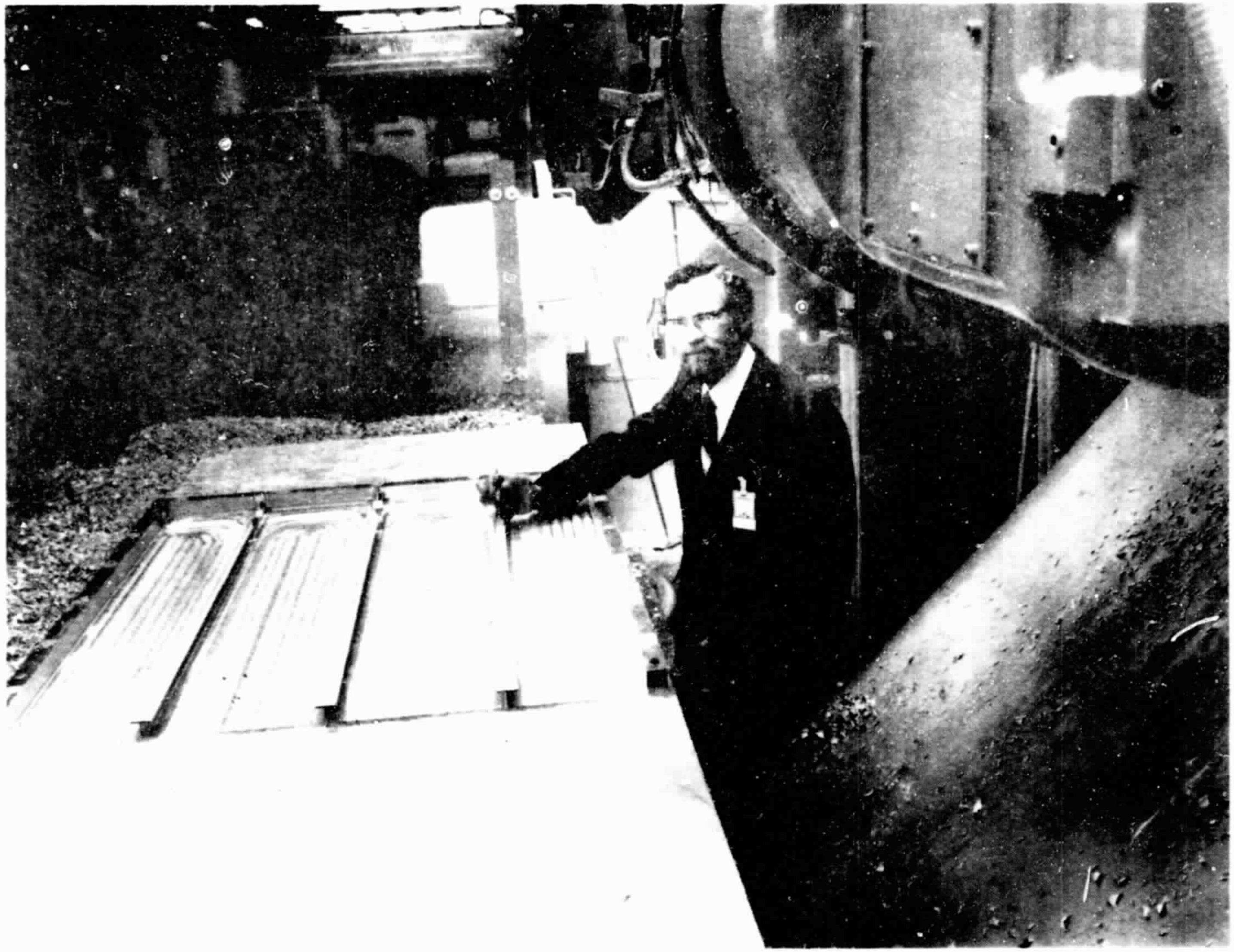

Figure 16. 4-ft long machined panel on vacuum base plate.

3-5-1.3. 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 selected 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 the 38-in. finished width panels on a machine which had only a 21-in. width capacity when machining in the flat position. Feeds, speeds, and other machining parameters were used which coincided with Lockheed's previous HSM experience and the findings of the cutter trials.

3-5.1.4. Machining Center Set-Up.

After the Bryant 18,000 rpm high-speed spindle motor with peripheral support equipment was installed in the Sundstrand OM4 Omnimil, spectrum analysis vibration tests were run to guard against operating in any spindle speed range where natural resonance vibration frequencies might occur and cause problems with the machining process or damage to the equipment. Plastic Lexan shielding was mounted around the periphery of the machine table to provide safety protection for personnel in the event of a tool breakage and also to provide containment of the flying chips and cutting fluid during machining (Fig. 17). In addition to the two existing flood coolant nozzles, two air nozzles were installed beside the spindle 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, properly aligned and secured to the machine table.

3-5.2. 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 (Fig. 16). Following completion, the panel was shortened on the open end to provide small sections of T-ribs for handouts during the scheduled panel cutting demonstration.

3-5.3 Panel Cutting Demonstration

The panel cutting demonstration was a major emphasis of this study. It was designed to demonstrate the feasibility of utilizing HSM as a means of producing the ET barrel panels and thereby reducing manufacturing cost and time. These reductions will increase production rates and capacities and, in turn, reduce machine tool requirements.

The formal panel cutting demonstration was held on June 15, 1982, in Lockheed Building 181/182. Figure 17 is a photograph taken during the demonstration which shows the Sundstrand OM4 machining center, on which the demonstration was performed, and some of the observers who were present.

A cutting speed of 5,890 surface feet per minute (sfpm) – over 60 miles per hour – was applied with the 1.25-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 obtained as the

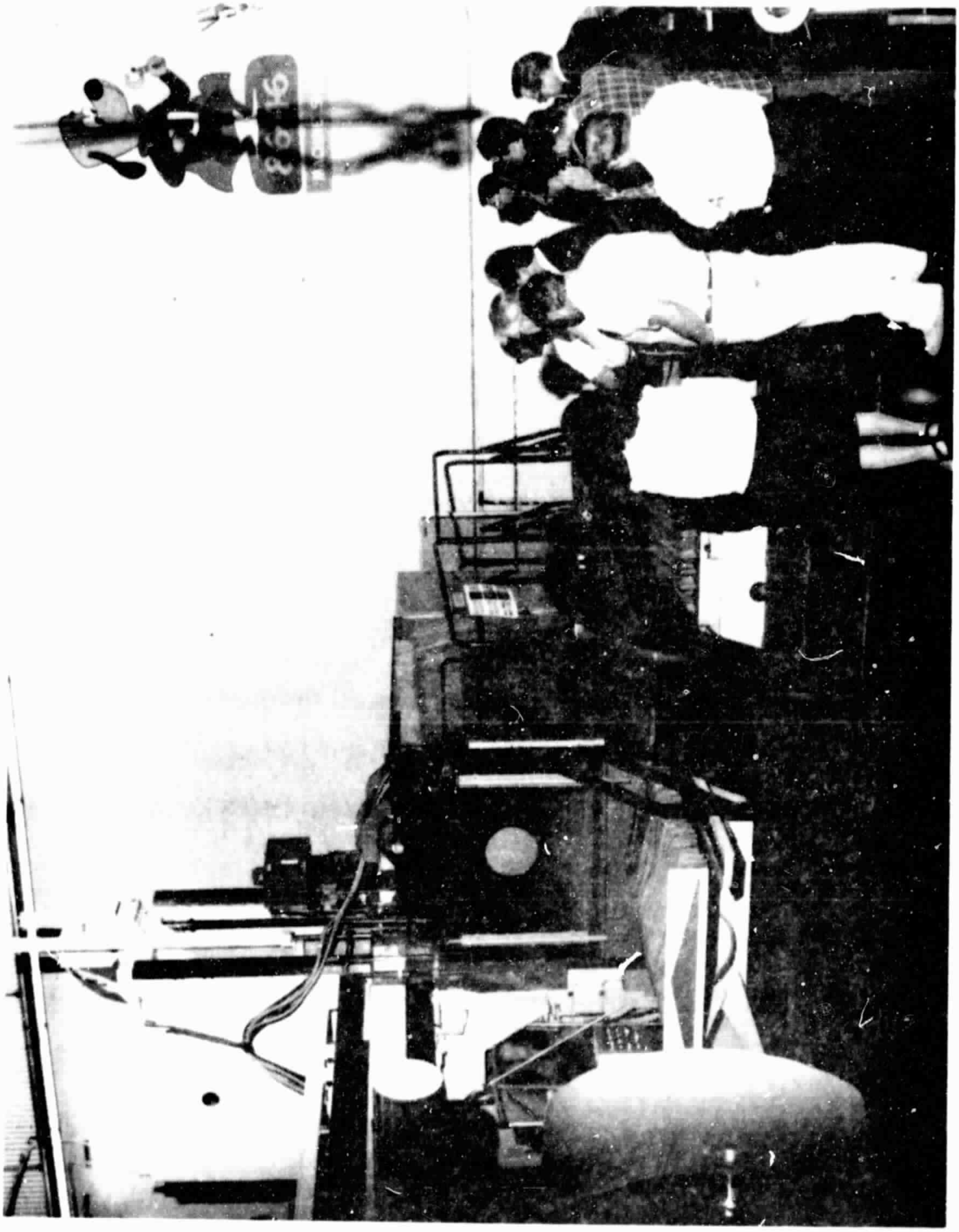

Figure 17. Panel cutting demonstration on Sundstrand OM4 NC machining center.

roughing cutter removed up to 56 cipm 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 cipm of material. Rates up to 100 ipm table feed and 18 cipm of metal removal 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 Table 1, "Setup and Operating Instructions for Machining 4-Foot Long Panels" and Table 2, "Cutter Feeds, Speeds and Cutting Data."

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.

3-5.3.1. Recording of Horsepower

Actual horsepower utilized in making the various cuts was recorded (Tables 3, 4, 5, and 6) for use in determining power requirements and in calculating cutting efficiency (paragraph 4-1).

3-5.4. 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 18 is a photograph of the roughing cutter (Fig. 11 gives 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 are shown in Figure 19. The finishing cutter shown in Figure 20 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 the finishing cutter were given earlier in Figure 13.

Figure 21 shows the 4-in. diameter 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 (Fig. 22 gives magnified views). No measurable wear is present.

SECTION 4. HSM MILLING PROCEDURES AND TIMES

This section identifies the various HSM process parameters, describes the actual values of these parameters utilized in the study, and identifies optimum parameter values if different from those employed during the project. Times and operations involved in high-speed machining the panels are stated and the time required to high-speed machine a complete panel are projected.

4-1. Definitions and Actual Values of HSM Parameters

The operations employed and the actual values of the various parameters used (Table 7) are discussed below and shown in Tables 1 and 2. The actual values are also given in Tables 3, 4, 5, and 6. A compilation of these actual values is listed in Table 7.

TABLE 1. SETUP AND OPERATING INSTRUCTIONS FOR MACHINING 4-FOOT 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 FIGURE 3–3. 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

NOTE: DIMENSIONS IN INCHES

TABLE 2. CUTTER FEEDS, SPEEDS AND CUTTING DATA

SPEEDS AND FEEDS

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

CUTTING DATA

TOOL NO.	DEPTH OF CUT*	WIDTH OF CUT *	METAL REMOVAL**
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

RPM – REVOLUTIONS PER MINUTE
F/R – FEED RATE (INCHES PER MINUTE)
SFM – CUTTER TIP SPEED (SURFACE FEET PER MINUTE)

*DIMENSIONS IN INCHES
**CUBIC INCHES PER MINUTE

TABLE 3. HSM DATA SHEET FOR 8-FOOT LONG PANEL NO. LL2 (FIRST HALF)

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
TOOL # 02			.126 DIM.		
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	12.8
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.		
1	−22.6750	.300	150	18000	13.4
2	−22.9750	.300	150	18000	13.4
3	−23.2750	.300	150	18000	10.8
4	−23.4350	.160	200	18000	10.0
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

NOTE: DIMENSIONS IN INCHES

TABLE 4. HSM DATA SHEET FOR 8-FOOT LONG PANEL NO. LL2 (FIRST HALF)

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
TOOL # 02		.141 DIM.			
1	−23.9840	.179	200	18000	6.2
2	−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	13.4
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
2	−23.8050	.370	180	18000	8.3
		.141 DIM.			
1	−23.9840	.370	180	18000	8.2
		UNDER T			
TOOL # 04					
1	−21.8090	.635	40−50	8000	5.1
2	−21.6350	.150	100	8000	3.9
3	−21.9840	.150	100	8000	3.9

NOTE: DIMENSIONS IN INCHES

TABLE 5. HSM DATA SHEET FOR 8-FOOT LONG PANEL
NO. LL2 (SECOND HALF)

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
TOOL # 02			.126 DIM.		
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	18000	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		
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	12.8
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

NOTE: DIMENSIONS IN INCHES

TABLE 6. HSM DATA SHEET FOR 8-FOOT LONG PANEL NO. LL2 (SECOND HALF)

PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
TOOL # 02			.141 DIM.		
1	−23.9840	.179	200	18000	10.2
2	−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	10.4
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
2	−23.8050	.370	180	18000	8.4
			.141 DIM.		
1	−23.9840	.370	180	18000	8.2
TOOL # 04			UNDER T		
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

NOTE: DIMENSIONS IN INCHES

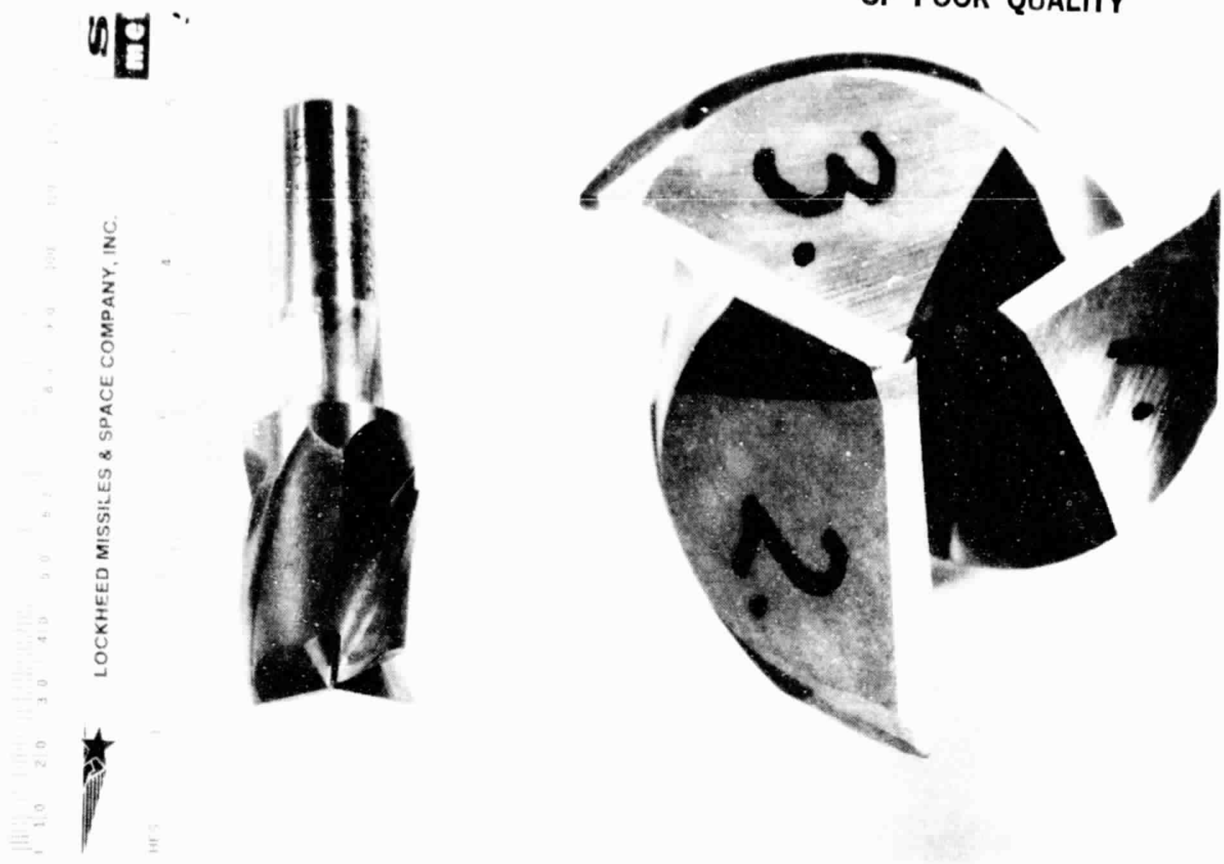

Figure 18. 1.25-in. diameter roughing cutter used to machine entire 8-ft long panel.

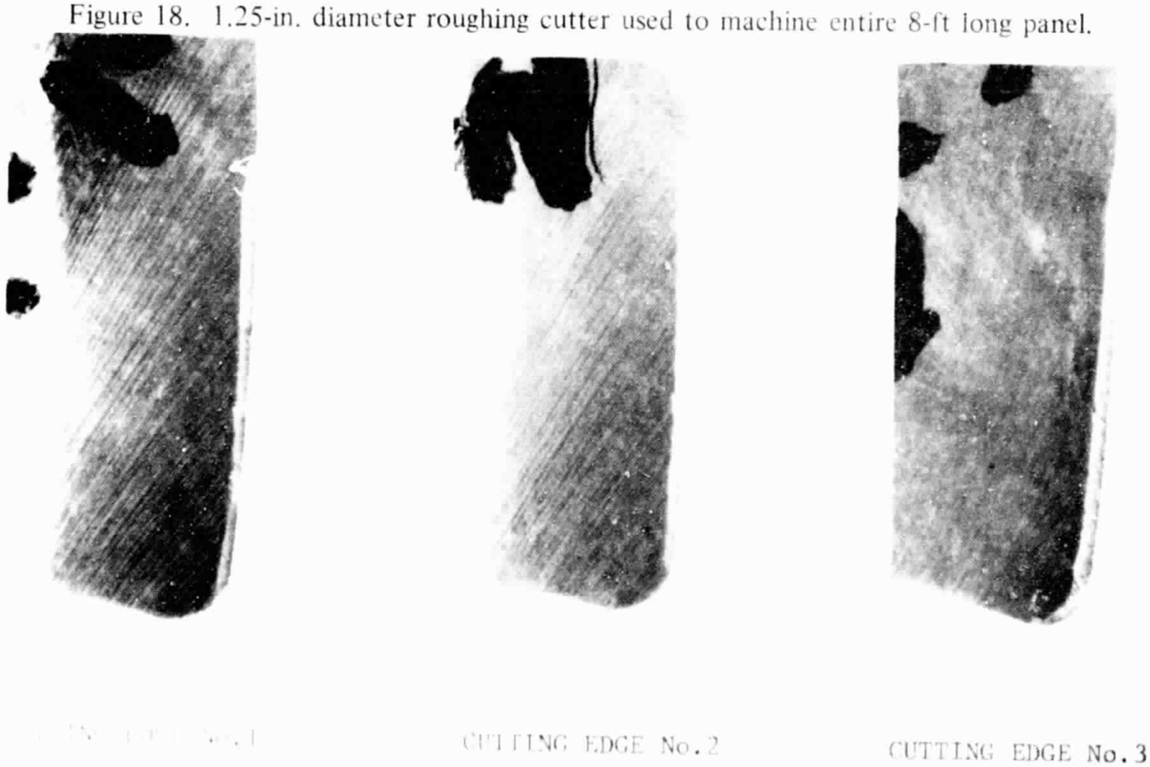

Figure 19. Cutting edges of roughing cutter used to machine entire 8-ft long panel.

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(REDUCED SIZE)

(APPROXIMATELY 3 x MAGNIFICATION)

TYPICAL CUTTING EDGE
(APPROXIMATELY 7 x MAGNIFICATION

Figure 20. 1.25-in. diameter finishing cutter used to machine all delivered panels.

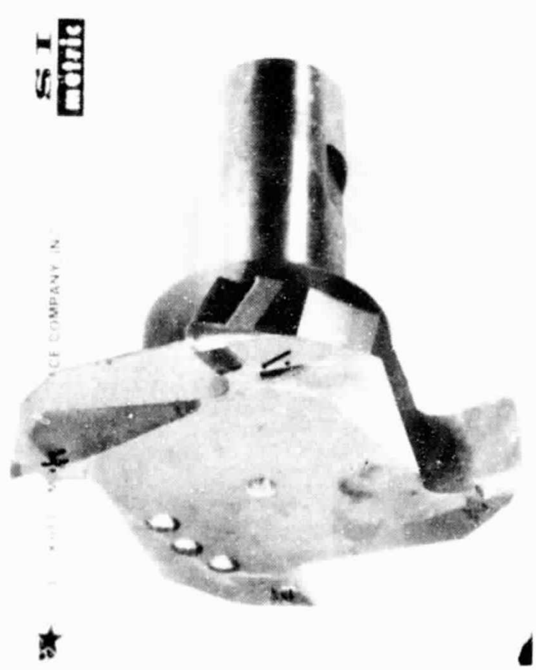

Figure 21. 4-in. diameter T-rib cutter used to machine all delivered panels.

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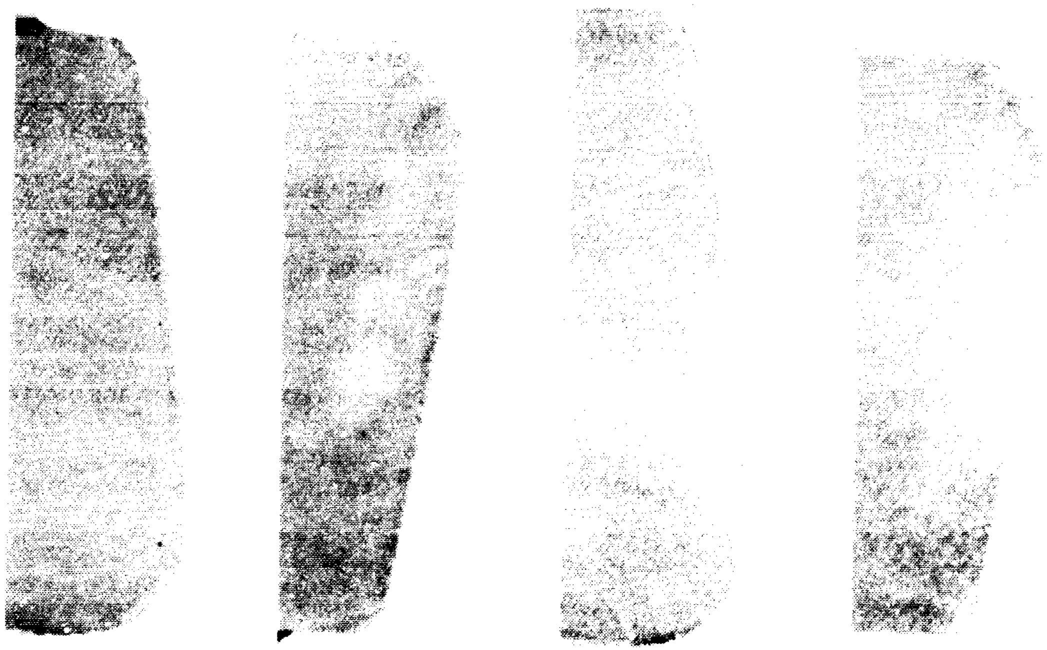

INSERT No.1 INSERT No.2 INSERT No.3 INSERT No.4

Figure 22. Insert cutting edges of T-rib cutter used to machine all delivered panels.

4-1.1. 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 1.25-in. diameter roughing and finishing cutters (Figs. 10 to 13) and 8,000 rpm for the 4-in. diameter T-rib cutter (Figs. 14 and 15).

4-1.2. 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 high-speed machining of the tank panels were 5,890 sfpm for the 1.25-in. diameter cutter and 8,378 sfpm for the 4-in. diameter cutter.

4-1.3. Table Feed

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 LMSC Machine) were used for the 1.25-in. diameter roughing and finishing cutters, and from 40 to 100 ipm for the 4-in. diameter T-rib cutter.

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TABLE 7. 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 20 HP 40,000 WITH 40 HP 12,000 WITH 100 HP
CUTTING SPEED (SFPM)	5,890	3,600 (2–INCH DIA. CUTTER)	4,000 – 10,000 CURRENTLY BELIEVED TO BE MOST EFFICIENT. (20,000 NOW USED ON LARGE DIA. FACE MILLS)
TABLE FEED (IPM)	200	150 (300 AVAILABLE FROM CINCINNATI MILACRON)	400 (1500 WITH 20 HP)
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 75 HP	400 EXPECTED WITH 100 HP (UP TO 450 NOW USING LARGE DIA FACE MILLS)
HORSEPOWER	13.4	75 AT 7200 RPM	100 AT 12,000 RPM
CUTTING EFFICIENCY (CU IN./MIN/HP)	4.0	4.0	4.0 OR BETTER
UNIT HP (HP/CU IN./MIN)	0.25	0.25	.25 OR LESS
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 (BASED ON CINCINNATI MILACRON DATA USING 75 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.

4-1.4 Chip Load

Chip load is the chip thickness that each flute or cutting edge removes as the cutter turns through one revolution as the workpiece is fed against it. Chipload 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 0.0025 to 0.0032 in. for the roughing cutter, stayed constant at 0.0032 in. for the finishing cutter, and varied from 0.0016 to 0.0032 in. for the T-rib cutter. These relatively small chiploads helped to achieve the fine surface finish required by the part.

4-1.5. Depth of Cut

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 varied from 0.070 to 0.300 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 0.370-in. fillet radius of the part. Therefore, both axial and radial depths of 0.370-in. were used. Axial depths from 0.075 to 0.635 in. and radial depths from 0.025 to 0.550 in. were utilized with the T-rib cutter.

4-1.6 Metal Removal Rate

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

4-1.7. Horsepower

Available power, or horsepower, to turn the cutter is the most limiting parameter where larger volumes of metal are to be removed. The Bryant 18,000 rpm spindle motor used was rated at 16.6 hp at the full 18,000 rpm. Horsepower readings, as recorded in Tables 3, 4, 5, and 6, 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 T-rib cutter (Tool No. 04) drew a maximum of approximately 5.1 hp which was near the 5.5 hp maximum available at 8,000 rpm at which the spindle was operating.

4-1.8 Cutting Efficiency

Cutting efficiency is often expressed as cipm/hp. Using the values already cited in paragraphs 4-1.6 and 4-1.7 to calculate cutting efficiency for the maximum metal removal rate, we find that 56 cipm divided by 13.4 hp yields a cutting efficiency of 4.18 cipm/hp.

Cutting efficiency is the mathematical reciprocal of unit horsepower which is expressed as horsepower per cubic inch of metal removed per minute; e.g., the unit horsepower equivalent to the 4.18 cipm/hp given above is 0.24 hp/cipm.

4-1.9 Time to Machine 4-Foot Long Panel Section

The actual machining, or chip cutting, time for high-speed machining the 4-ft long panel sections is presented in Table 7. The 2.019 hr listed is the time generated by the NC tape and was found to be reasonably accurate in actual operation. This time does not include such activities as part loading and unloading and tool changes.

4-1.10 Time to Machine 8-Foot Long Panel Section

As with the 4-ft long panel, the 3.49 hr listed in Table 7 was generated by the Lockheed NC program. This computer calculated time for high-speed machining the 8-ft long panel was also found to be reasonably accurate.

4-2. Projected Time to Machine Full-Size 11-ft x 20-ft Barrel Panel

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 an entire full-sized 11-ft x 20-ft panel from which the sample section was taken. The total estimated time (as given in Table 7) is 27.256 hr. As only 13.4 hp was employed in machining the 8-ft sample panel, it is 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, the rates attainable on the available Lockheed equipment were not optimal for machining full-sized tank panels.

4-3. Projections of Optimum HSM Parameters and Times

High-speed machining is presently in a dynamic state of development. 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 7 in addition to the "actual" values utilized during this demonstration project.

4-3.1. Projections Based on Proven Data

The first set of optimum parameter values projected for high-speed machining ET barrel 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 7 is readily available today.

As presented in Table 7, the impressive volume of 300 cipm 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 0.010 in. and cutting speed of only 3,600 sfpm was acceptable for a roughing operation. However, to produce less tool side-pressure and better surface finish, which would be required for the T-rib section 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 needed to maintain a proper chip load.

*See Bibliography No. 36.

Using the HSM parameter values available as shown in this example, the projected time to machine a full-size 11-ft x 20-ft panel was computed by two methods, which 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 the 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 hr 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 hr.

The second method employed to predict cutting time for a full-size 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 50,183 in.^{3} of metal to be removed, the 16.6 hp Lockheed spindle with a maximum metal removal rate of 56 cipm at actual developed hp of 13.4 could be expected to machine the full panel in 14.9 hr. However, the actual projected NC program time to machine the panel using the 16.6 hp spindle was 27.3 hr (Table 7). 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 hr calculated for the 75 hp spindle by this 1.83 factor, a more logical projected machining time of 5.1 hr was determined. As noted above, either of these projected machining times would suggest considerable potential savings in machining time.

4-3.2. 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 ET barrel panels is a compilation of information from various sources. Most of these capabilities are available singly now. However, the exact combination of all "optimum" parameter values desirable for high-speed machining ET tank panels has probably not 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 ET barrel 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 7 is the largest currently known (October 82) 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 7, it would be able to remove 400 cipm. This would equate to a 2.5-in. diameter 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 in.^{2}, an entire pocket between T-ribs could be machined in four pases 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 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.

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, it is not known if any proven magnetic bearing spindles are available with the horsepower level recommended for machining tank panels.

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

SECTION 5. SUMMARY AND CONCLUSIONS

5-1. Summary

High Speed Machining of ET LH_2 barrel panels has been successfully demonstrated by Lockheed Missiles and Space Company, under Contract NAS8-34508, to the George C. Marshall Space Flight Center.

Subsections of one drawing of the latest light weight (LW) barrel panel design were selected as the parts to be machined. Three 38-in. x 46.5-in. panels and one 38-in. x 96.5-in. panel were high-speed machined at spindle speeds of up to 18,000 rpm, and feed rates of up to 200 ipm; these rates being the maximum capable on the Lockheed Milling Machine (Sundstrand Model OM4 modified with a Bryant 18,000 rpm, 16.6 hp spindle). With this limited capability, up to 56 cipm (approximately 3X a comparable conventional machining rate) of the 2219-T87 aluminum alloy was removed with a 1.25-in., three-fluted end mill at a cutting efficiency of 4.18 cipm/hp. Large gantry milling machines are available that are capable, on a production basis, of machining full size (approximately 11-ft x 20 ft) ET LH_2 barrel panels at metal removal rates of 400 cipm. It is conservatively estimated that HSM can reduce conventional machining times on ET barrel panels by 25 percent or $85,000.00 per tank; more exact estimates will be available at the conclusion of an ongoing economic assessment.

5-2. Conclusions

ET LH_2 barrel panels can be easily machined by HSM techniques and processes. HSM times will be less than conventional machining times; final estimates of reduced machining time will be available in late 1983. Based upon the LMSC study, it is projected that full size (11-ft x 20-ft) panels can be high-speed machined from 1.75-in. solid plate in as little as 6-hr with currently available HSM equipment.

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