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DIMENSIONAL INSTABILITY OF ALUMINUM ALLOYS FOR EXTREME LOW TEMPERATURE CYCLING APPLICATIONS
(GGV MATERIAL INSTABILITY PROBLEM)

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TECHNOLOGY REPORT

DIMENSIONAL INSTABILITY OF ALUMINUM ALLOYS FOR EXTREME LOW TEMPERATURE CYCLING APPLICATIONS

(GGV MATERIAL INSTABILITY PROBLEM)

M-1 ENGINE PROGRAM

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

The problem of critical permanent dimensional changes in grades 6061 and 7075 aluminum alloy valve bodies that occurred during cryogenic thermal cycling is described in this report. A special fabrication process to reduce the distortions within tolerable design levels was developed and applied to test hardware.

Test data confirmed that the special process reduced distortions in both aluminum alloys, but the degree of distortion was dependent upon body shape.

author

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I. INTRODUCTION

The dimensional instability experienced in the M-1 aluminum valve bodies which was caused by relaxation of residual stress during cryogenic thermal cycling was investigated. The results of this investigation are delineated in this report.

The investigation was to determine the causes of critical dimensional changes in the forged-aluminum valve bodies as well as to develop fabrication methods to provide a stabilized material that would reduce or eliminate distortions.

A metallurgical discussion concerning the residual stresses associated with forged parts is included along with the methods devised to minimize the effects, by redistribution, of the residual stresses.

Comparisons are made between the actual test data from unprocessed and processed valve bodies.

Recommendations based upon the results of this study are included.

Although this report deals primarily with 6061 and 7075 aluminum forged materials, it appears that the problems presented and the solutions offered are applicable to other aluminum forging materials for cryogenic applications.

II. SUMMARY

The dimensional instability of the 6061-T6 and 7075-T6 and -T73 M-1 gas generator and start system control valve bodies was investigated. This instability was found to be caused by the relaxation of residual stresses that occurred during cryogenic thermal cycling of the valve. The residual stresses resulted primarily from heat treatment (quenching) and machining operations.

A special fabrication process, incorporating a reheat treatment to relieve machining stresses and a pressure stabilizing operation to reverse the stress pattern resulting from the quenching operation, was applied to the test hardware. This test hardware, along with the standard processed valve bodies, was subsequently subjected to cryogenic thermal cycling. Diametral change versus thermal cycle data were obtained. A comparison of the data showed the specially processed valve bodies experienced less distortion during the thermal cycling.

III. TECHNICAL DISCUSSION

A. DEVELOPMENT TESTING

During development tests with the gas generator oxidizer valve body, a dimensional instability problem occurred after cooling the body to liquid nitrogen temperatures and then warming it to ambient temperatures. During this testing, the inlet and outlet flange joints were effectively sealed at ambient temperatures and also during the first leak tests at liquid nitrogen temperatures.

However, after the joints were returned to ambient temperatures, excessive leakage was experienced. Critical diametral dimensions were changing during the temperature cycle and were not returning to the dimensions recorded prior to the cycle. No definite pattern in the dimensional changes from part to part or for a particular part subjected to a number of temperature cycles was established. In some cases, the diameters increased; in others, they decreased. Subsequent testing verified that both the -T6 and -T73 conditions of the gas generator oxidizer valve 7075 aluminum alloy forging were subject to this instability. Similar tests conducted with the 6061-T6 start valve body and the 7075-T6 gas generator fuel valve body proved that the problem existed with all of these aluminum-forged parts. Dimensional changes were noted even after 24 temperature cycles.

An accelerated program was initiated to discover the cause of the instability phenomenon and to arrive at an optimum solution to the problem.

B. METALLURGICAL

1. Alloys and Heat Treatment for Gas Generator Valve Bodies

Aluminum alloys, grades 7075 (Al-5.5Zn-2.5Mg-1.5Cu-0.3Cr-0.2Mn), and 6061 (Al-1.0Mg-0.6Si-0.25Cu-0.25Cr) are used in the M-1 gas generator valve bodies.

The heat treatments applied to the grade 7075 alloys are either the -T6 or -T73 tempers. The latter treatment was developed by the Aluminum Company of America and is used for the prevention of stress-corrosion cracking; the -T6 temper is used for grade 6061 alloy. The heat treatments require a solution treatment prior to aging to obtain age-hardening response. For grade 7075 alloy, solution treatment is performed at a temperature of 860°F to 930°F and is followed by a quench in water at a temperature of 150°F to 212°F. In the case of grade 6061 alloy, the solution-treatment temperature is slightly higher, 960°F to 1010°F, and is also followed by a similar water quench. Aging follows solutioning treatments. The -T6 age for grade 6061 is performed at 345°F to 355°F for 6 to 10 hr. For grade 7075 alloy, the -T6 age is performed at 245°F to 255°F for 24 to 28 hr; slightly higher aging temperature results in the -T73 temper for grade 7075. The cooling rate from the aging temperatures to ambient temperatures is not critical, and still air cooling is the standard practice.

2. Residual Stresses in Gas Generator Valve Bodies

An adverse result of the quenching operation during the solution-treatment cycle is the drastic thermal and strain gradients that occur causing residual stresses in the gas generator valve bodies. The normal pattern of the residual stresses is one of compression in the outer surface fibers and tension in the core. However, variations from this pattern are possible because of the particular geometrical design.

A second source of residual stresses is machining. The stress is introduced into the forgings during rough machining of the part from a rough forging or bar stock, and remains in the part if not removed by an adequate thermal stress relief or a reheat treatment.

Other sources of residual stresses are fabrication and assembly. These stresses are usually of smaller magnitude than those caused by either quenching or machining stresses.

3. Effect of Residual Stresses and Metallurgical Instability

The effect of residual or "locked-in" stresses is that they are the main-driving force in producing distortion in the gas generator valve bodies. Relaxation of residual stresses at ambient temperature or during cryogenic cycling is manifested as a plastic deformation of the valve bodies.

Distortion can also occur from metallurgical instability(1), the gradual and continued precipitation of the dispersion phases from solid solution, leading to a decrease of the lattice parameter causing shrinkage. The degree of dimensional change reported for aluminum alloys from the aspect of metallurgical precipitation reaction is in the order of 5 to 25 microin./in. per year. The distortion experienced with the gas generator valve bodies is far in excess of this amount. Thus, it can be concluded that the large dimensional changes in these parts do not result from metallurgical instability alone, but also from relaxation of residual stresses.

4. Processes for Relieving Residual Stresses

The many processes available for relieving residual stresses include autofrettage, thermomechanical stress relief, mechanical stress relief, and thermal stress relieving. Autofrettage and thermal stress relief were selected because they are the most promising and they were incorporated into the special processing for the gas generator valve bodies.

The autofrettage process involves expansion of the body so that the inner surface layers are residually compressed and the outer surface layers are stressed in tension by internal pressurization. Basically, this process reverses the stress pattern resulting from the quenching operation.

Thermal stress relief involves thermal treatment after rough machining to minimize the extent of distortion occurring during subsequent fabrication operations. The thermal stress relief is a second heat treatment introduced into the fabrication sequence after rough machining and prior to autofrettage. This process not only eliminates most machining stresses but ensures compressive stresses on the valve body surfaces. An important factor related to rough machining and stress relieving is determining the amount that each dimension should be left

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(1) Dimensional Stability of Aluminum Alloys, Battelle Memorial Institute Letter Report, February 1964.

oversize as a result of the degree of possible distortion which might occur during the main heat-treating operation. The situation encountered with the gas generator valve bodies required an oversize of 0.050-in. on all surfaces. This oversize resulted in a sufficient mass of material to account for any distortion that might occur during stress-relieving, reheat treatment, and autofrettage. It also provides for clean-up in subsequent finish machining operations.

C. SELECTED PROCESSES

It was noted during thrust chamber valve development testing that the thrust chamber valve body was apparently stable. This body is made by welding two 6061-T6 body halves together. The difference in processing this body and the gas generator valves and start valve bodies is that the thrust chamber valve body is subjected to a heat treat and pressure stabilization after the welding is completed. The thrust chamber valve body was processed in the following manner. The two halves were welded together, then they were rough machined, reheat treated (solution treated and aged per MIL-H-6088) to the -T6 condition, proof and leak tested, and finish-machined.

As a basis for comparison, the gas generator valves and start valve bodies were processed to the following standard process condition. They were heat treated to the -T6 or -T73 condition for 7075 aluminum, or -T6 condition for 6061 aluminum, and then completely machined.

It was concluded that the dimensional instability problem was caused by residual stresses that remain in the part after the heat-treat quench and heavy machining. These stresses were apparently removed from the thrust chamber valve body by the special process outlined above. Therefore, the fabrication process selected to stabilize the forged gas generator valve and start valve bodies consisted of the following five basic steps.

1. Heat treat the rough forging by normal processes to the desired final heat-treat condition (-T73 for 7075 and -T6 for 6061).

2. Rough machine to within 0.050-in. of the final dimensions.

3. Again, solution heat treat and age to the desired final temper condition.

4. Pressure stabilize at approximately 1.3 times proof pressure of the finished part.

5. Machine to the final blueprint dimensions.

The special process was selected based upon the following analysis. Removal of a relatively thick layer of material (0.25-in.) during rough machining upsets the balance of residual stresses that remain in the part from quenching.

The second heat-treat cycle balances the quench stresses, with compressive stresses on all surfaces. Pressurizing the body at a pressure level above the proof pressure prior to finish machining should eliminate any possibility of the part distorting during the valve proof test. In addition, if the part does receive a permanent distortion at this point, the residual stresses will have been lowered, which would help eliminate the instability problem. Subsequent finish machining removes only the surface layer of material, and should not penetrate into the tensile-stressed core.

IV. TEST PROCEDURES

Thermal cycling tests were conducted with finish-machined valve bodies to determine the dimensional changes (permanent distortions) that occurred during the cycling. The bodies tested included both those that received only the standard heat-treat process and those that received the previously described selected process. The methods used in conducting these tests are discussed below.

A. INITIAL DIMENSIONAL INSPECTION

Critical diameters were selected at each port on the valve body and actual dimensions were recorded at three or four equally spaced positions (0 degrees, 60 degrees, 120 degrees, or 0 degrees, 45 degrees, 90 degrees, and 135 degrees) on the diameters. The same diameters and positions were used in all subsequent dimensional inspections. All dimensions were recorded with the valve body at room temperature (68 ± 5°F).

B. LOW TEMPERATURE THERMAL CYCLE

The valve body was submerged in a container filled with liquid nitrogen (-320°F) until the body temperatures stabilized. The valve body was then removed from the liquid nitrogen (-320°F) bath and permitted to return to room temperature (68 ± 5°F).

C. FINAL DIMENSIONAL INSPECTION

The dimension inspection of the diameters was repeated and the body recycled for 24 cycles or until no dimensional changes could be detected, whichever occurred first.

V. TEST RESULTS

A. STANDARD PROCESS

Initial tests were conducted using four different forged body configurations. These valve bodies were processed using the following standard fabrication process. They were heat treated to the -T6 or -T73 condition for 7075 aluminum alloy, and to the -T6 condition for 6061 aluminum alloy and then they were finished-machined. The purpose of these tests was to ascertain any apparent effects caused by the body shape. The bodies that were tested and the associated heat treatment and materials are indicated in the following tabulation.

Body Configurations	Part No.	Serial No.	Material and Heat Treat
1. M-1 GG Oxidizer Valve Body	273868-9	0000003	7075-T6
2. M-1 GG Oxidizer Valve Body	273868-9	0000010	7075-T73
3. Titan II TC Fuel Valve Body	250220-9	0000140	7075-T73
4. M-1 6-in. Dual Seal Test Cell	263689-9	0000008	7075-T6
5. M-1 GG Fuel Valve Body	273802-9	0000005	7075-T6
6. M-1 Start Valve Body	277998-9	0000013	6061-T6

The configuration of the gas generator oxidizer valve body is shown in Figure 1. This unit contained three flanges, two of which had close tolerance dimensions (the inlet and outlet flanges). Two different standard heat treats were tested on this 7075 aluminum body configuration (-T6 and -T73). The changes on the inlet port diameters of the 7075-T6 body are shown in Figure 2 and the changes on the outlet port diameters are shown in Figure 3. The changes on the inlet port diameters of the 7075-T73 body are shown in Figure 4 and the changes on the outlet port diameters are shown in Figure 5. The different positions plotted for each diameter coincides with the planes shown in Figure 1.

The configuration of the Titan II thrust chamber fuel valve body is shown in Figure 6. This unit contains three flanges with close tolerance dimensions. The standard heat treatment for this 7075 aluminum body is -T73. The diametral changes during thermal cycling for this unit are shown in Figure 7. The different positions plotted for each diameter coincide with the planes shown in Figure 6.

The 6-in. dual seal test cell was a simulated system joint with perfectly cylindrical shape and with stub tubular sections attached to the flange as shown in Figure 8. The results of the thermal cycling tests on this configuration are shown in Figure 9. The different positions plotted for each diameter coincide with the planes shown in Figure 8.

The configuration of the gas generator fuel valve body is shown in Figure 10. This unit contains four flanges, all of which had close tolerance dimensions (the inlet, outlet, actuator, and pilot valve flanges). The standard heat treatment for this 7075 body was -T73. The changes of the inlet, outlet, actuator, and pilot valve port diameters are shown in Figures 11, 12, 13, and 14 respectively.

The configuration of the start valve body is shown in Figure 15. This unit contains four flanges, all of which have close tolerance dimensions. The standard heat treatment for this 6061 aluminum body is -T6. The changes of the inlet and outlet flange diameters are shown in Figure 16. The changes on the retainer and cover flanges are shown in Figure 17.

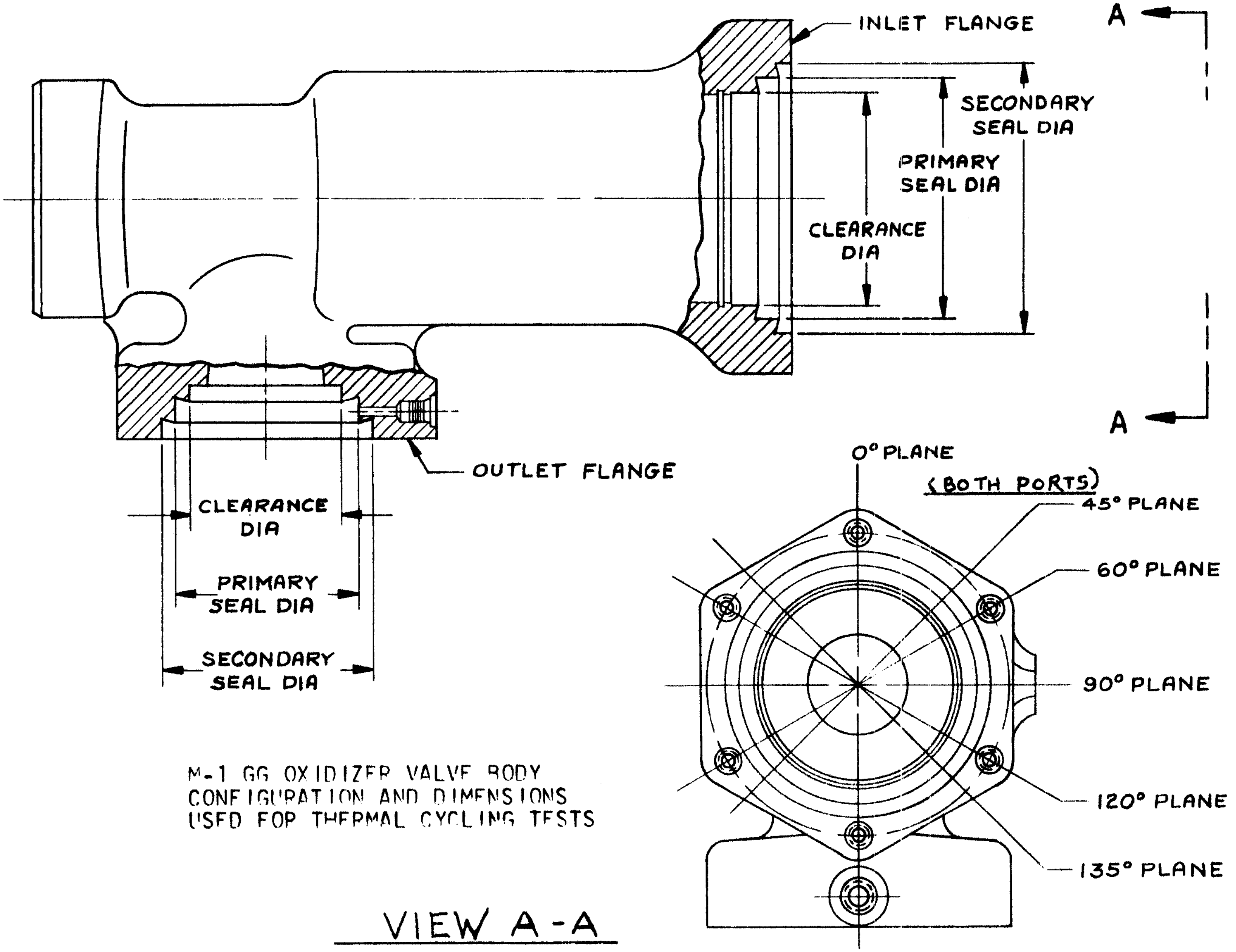


Figure 1

GAS GENERATOR OXIDIZER VALVE BODY CONFIGURATIONS

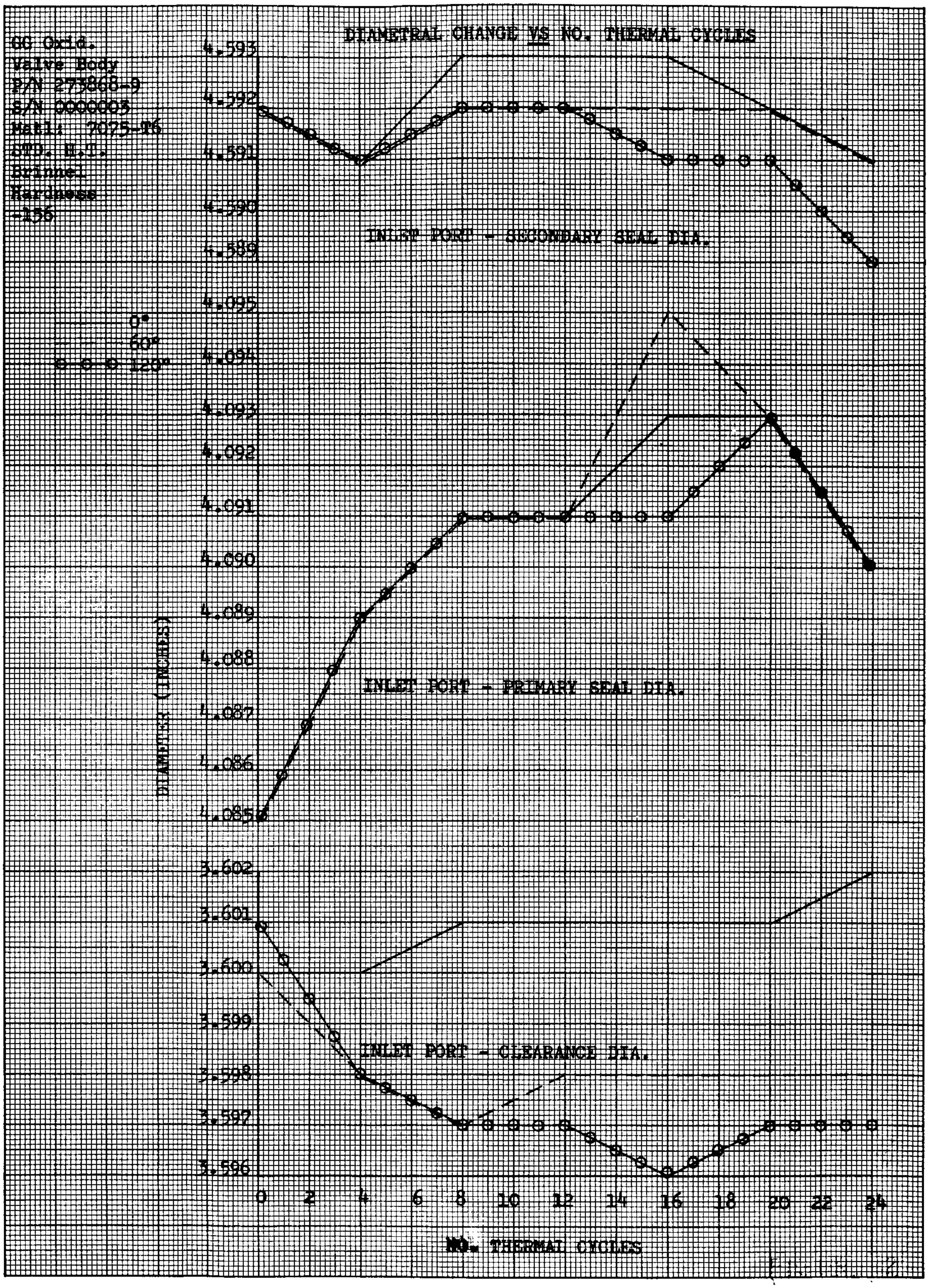


Figure 2

INLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

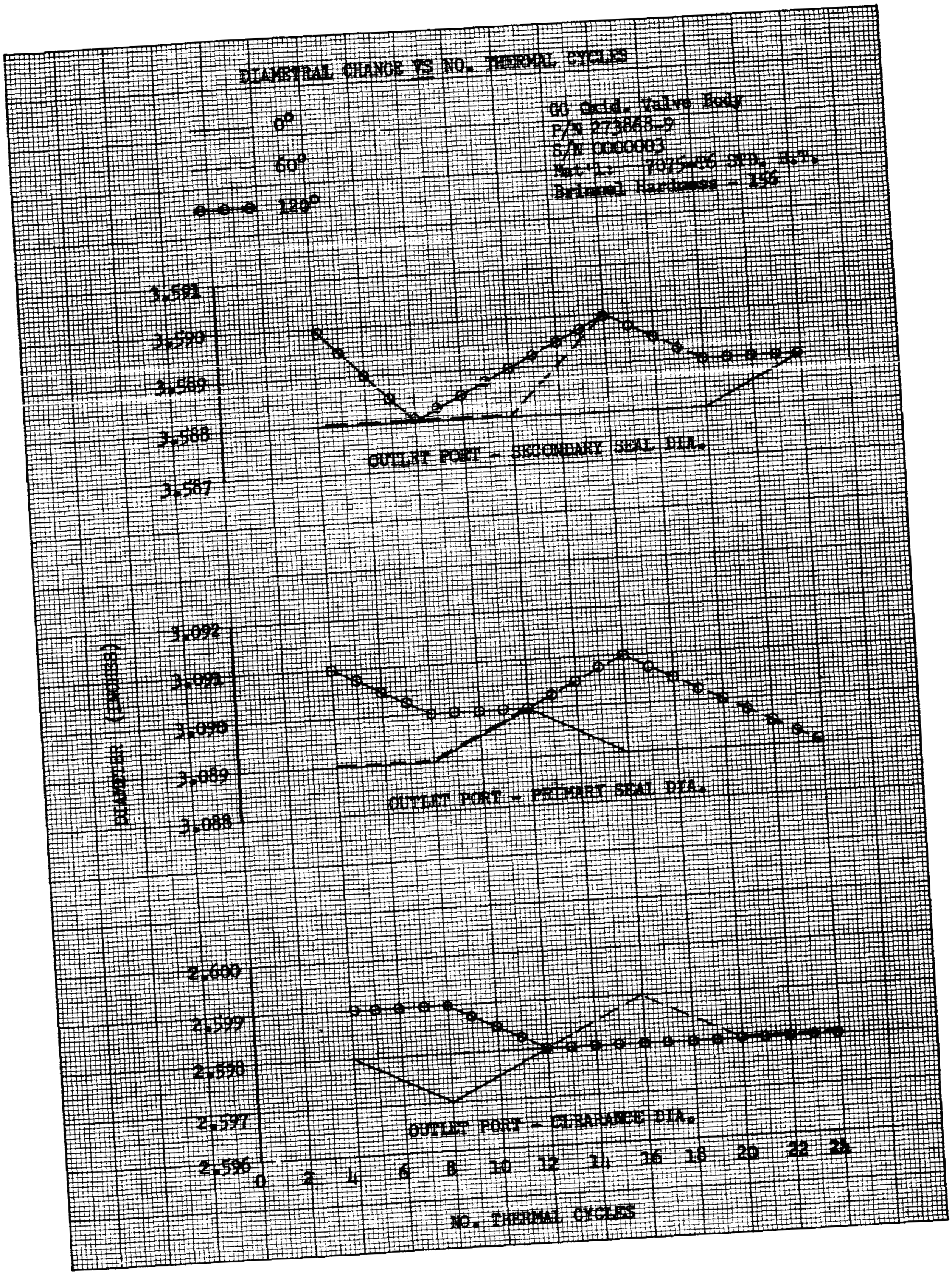


Figure 3

OUTLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

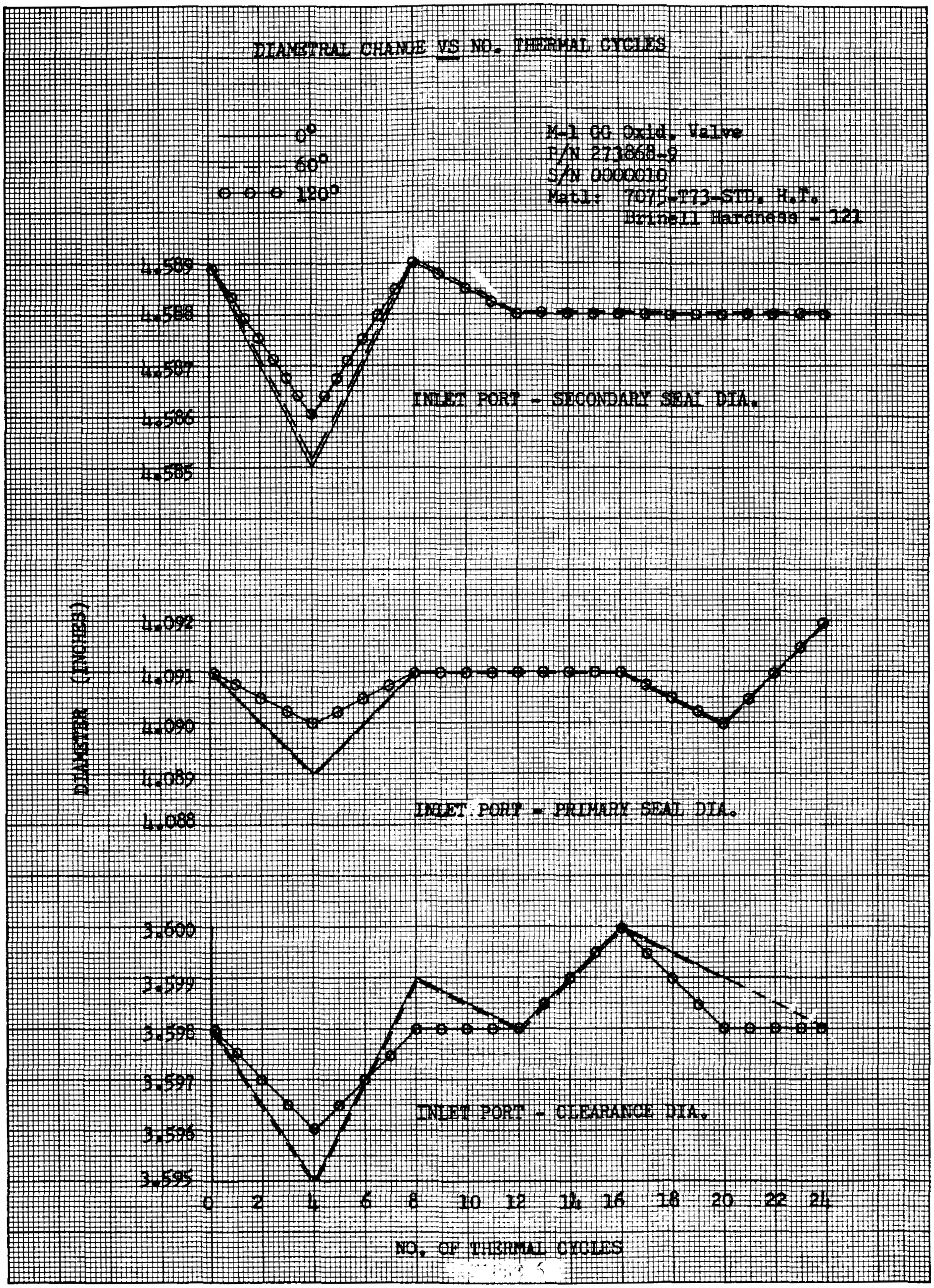


Figure 4

INLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

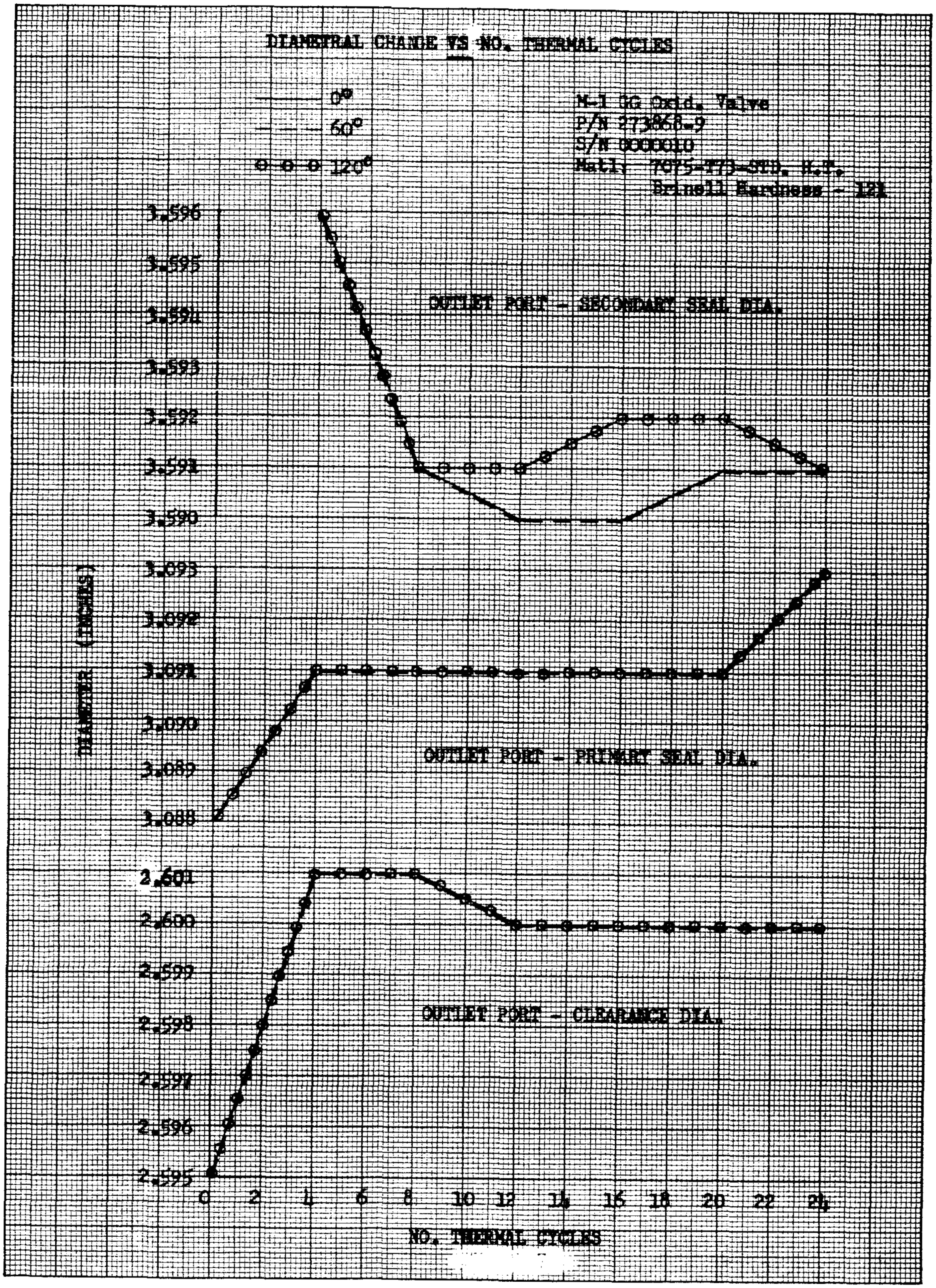


Figure 5

OUTLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

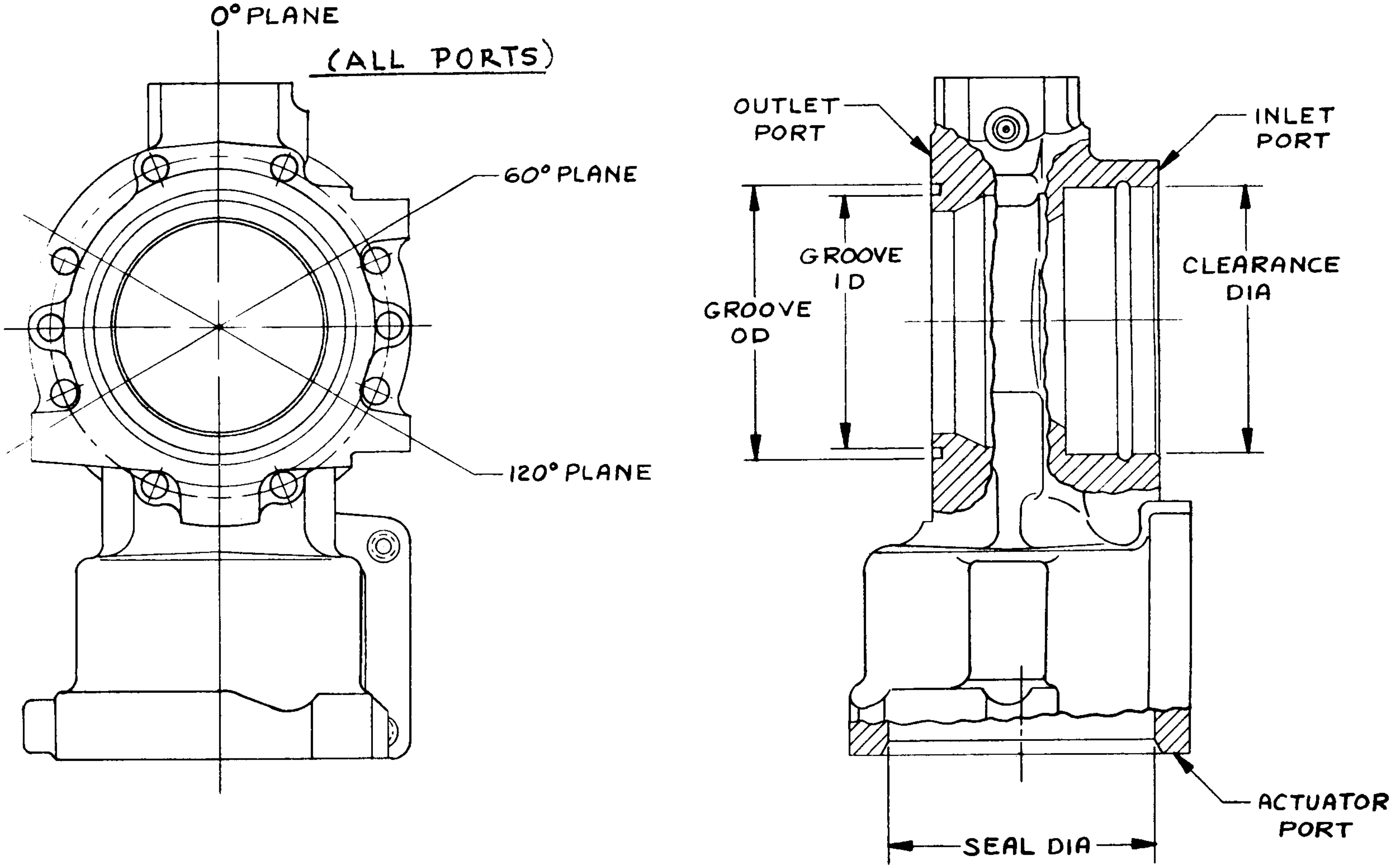


Figure 6

TITAN II THRUST CHAMBER FUEL VALVE BODY CONFIGURATION

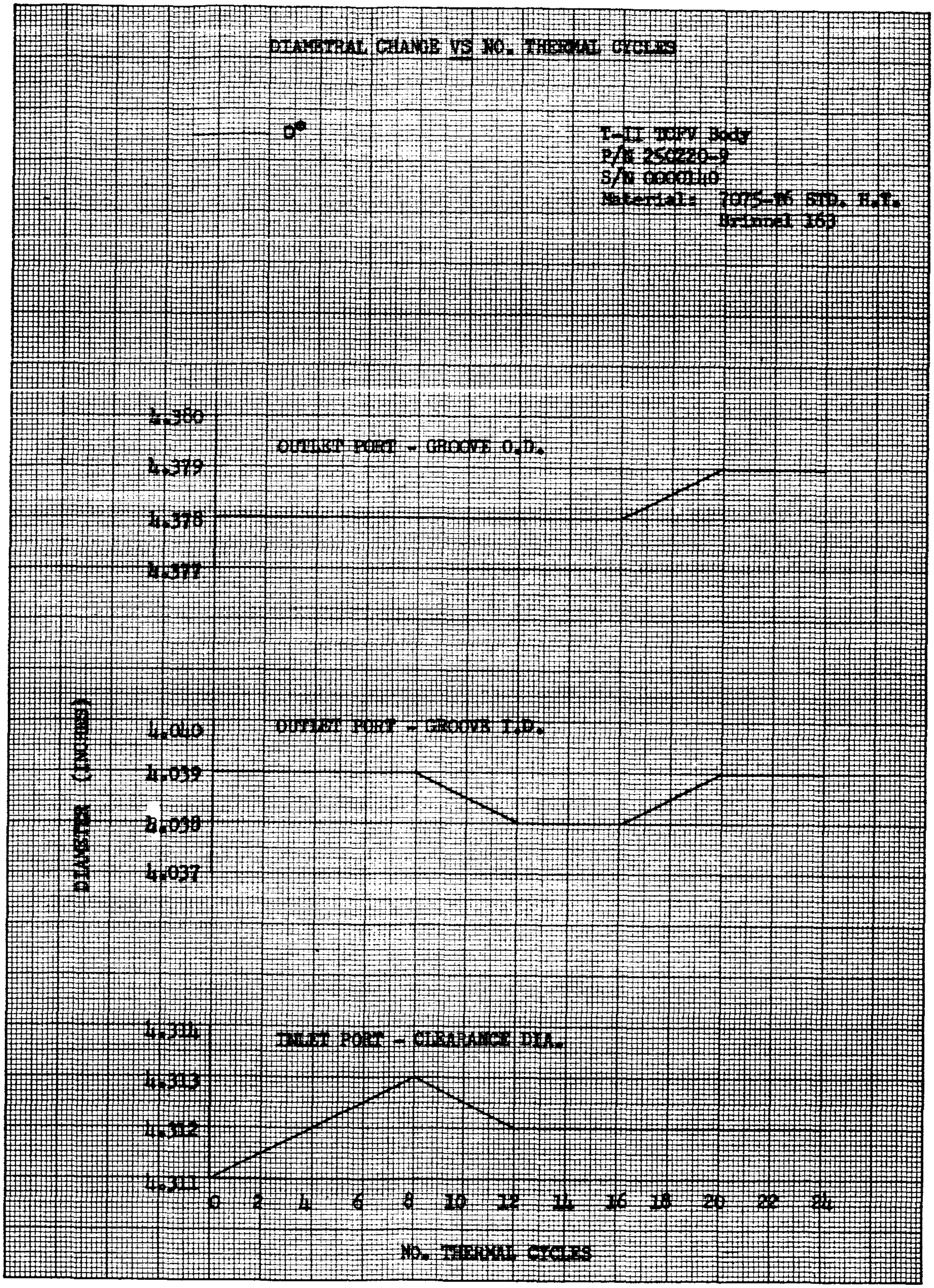


Figure 7

OUTLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

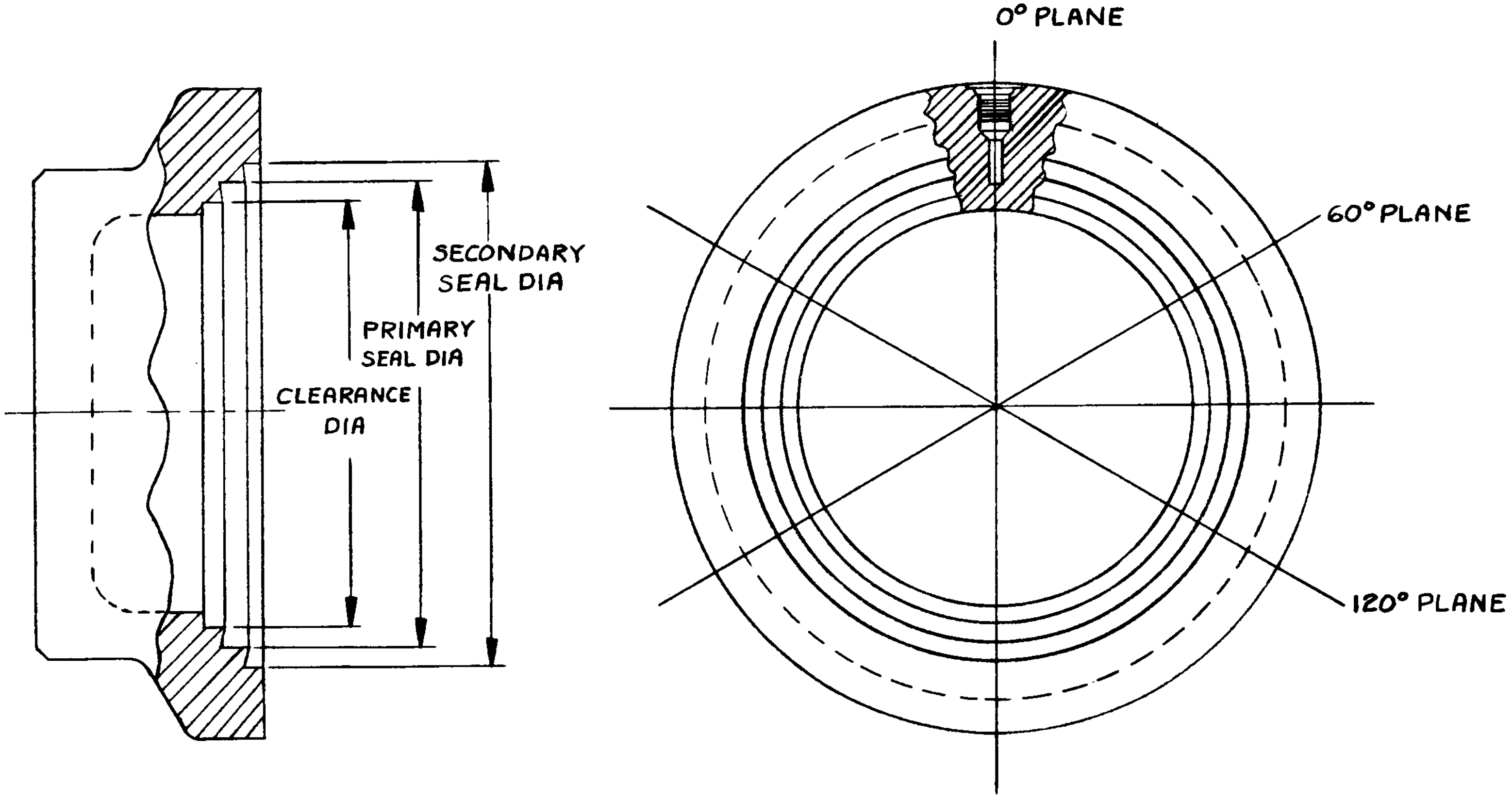


Figure 8

6-IN. DUAL SEAL TEST CELL CONFIGURATIONS

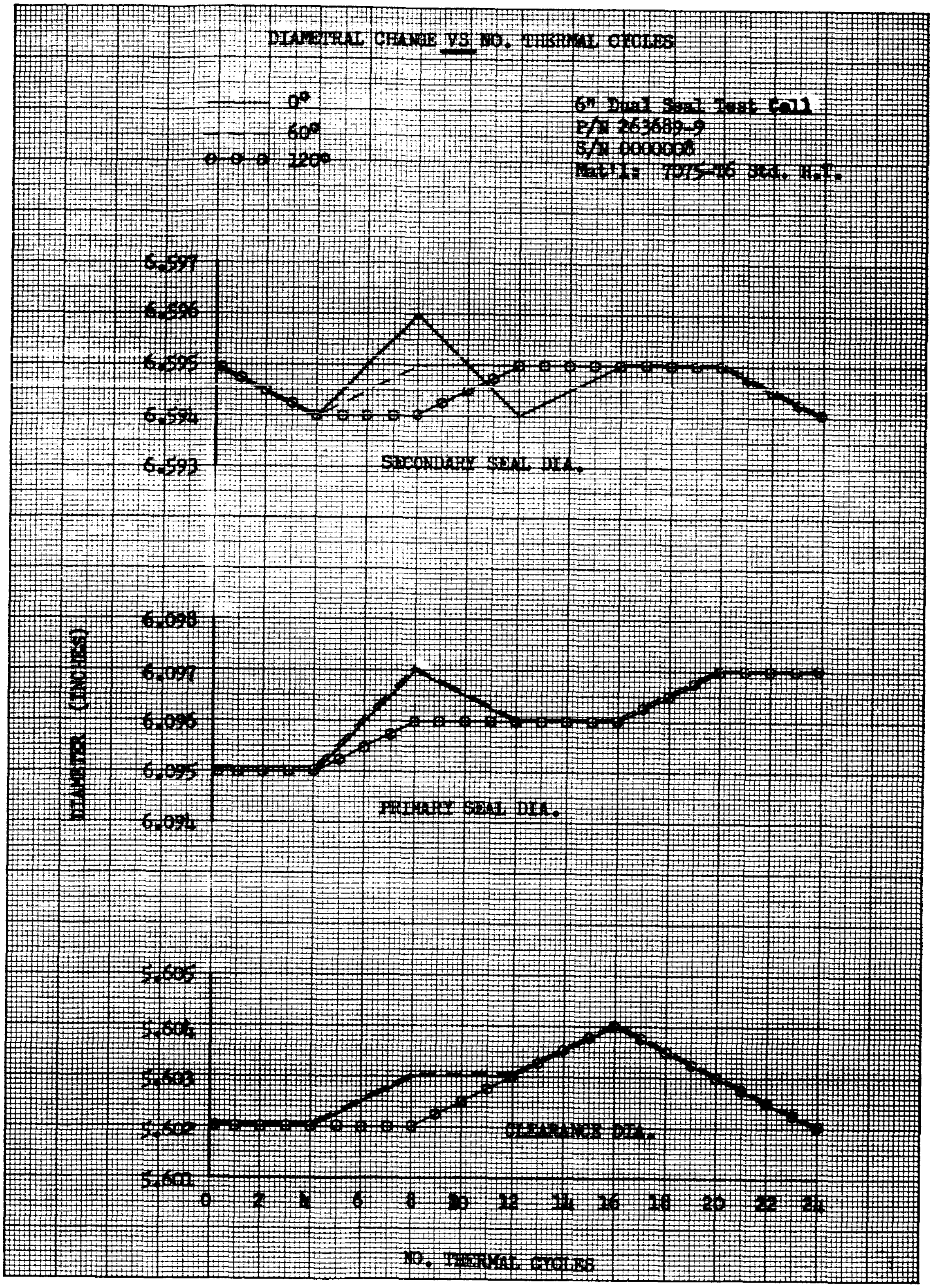
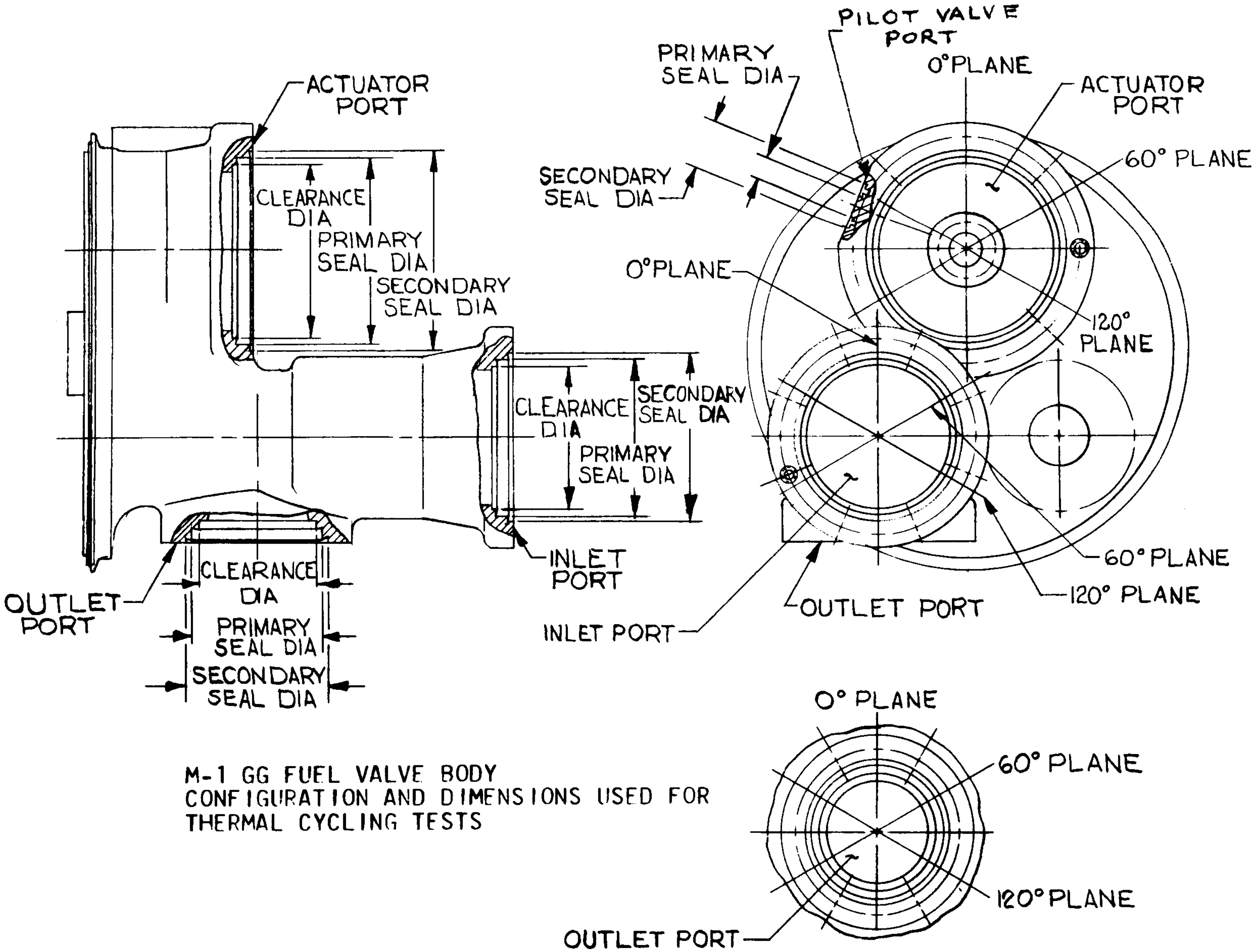


Figure 9

DIAMETRAL CHANGE VERSUS NO. THERMAL CYCLES



M-1 GG FUEL VALVE BODY
CONFIGURATION AND DIMENSIONS USED FOR
THERMAL CYCLING TESTS

Figure 10

GAS GENERATOR FUEL VALVE BODY CONFIGURATION

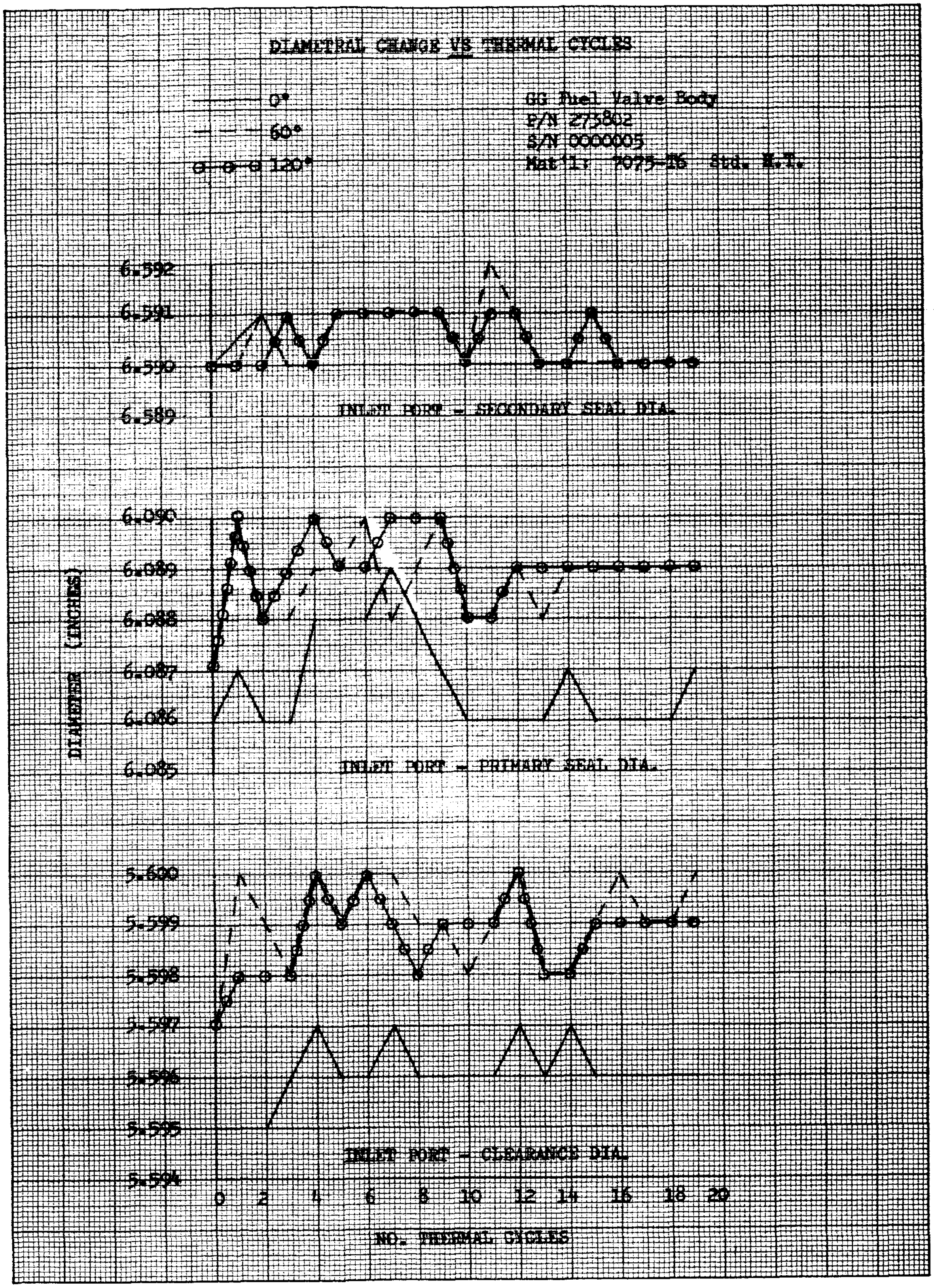


Figure 11

INLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

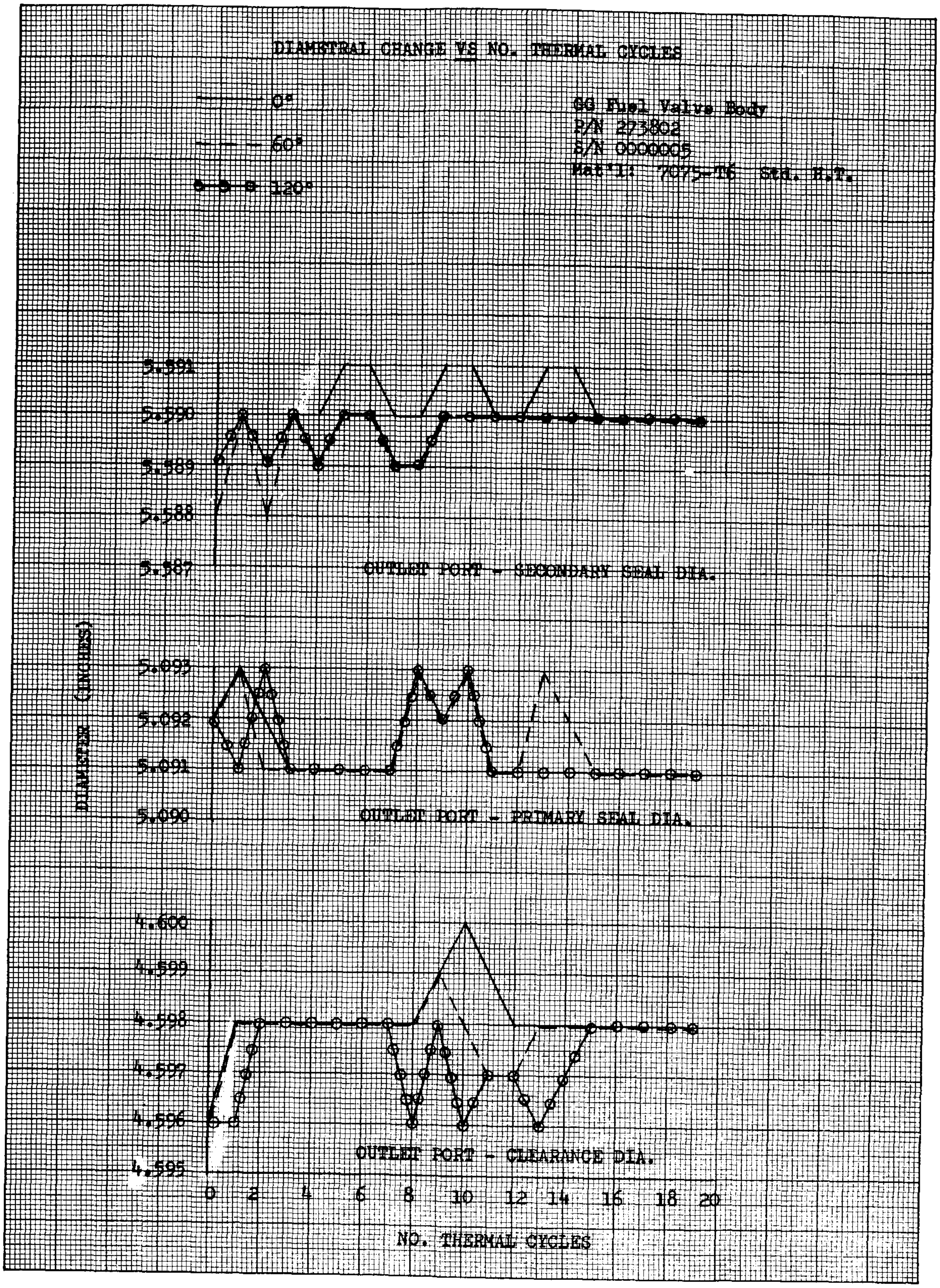


Figure 12

OUTLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

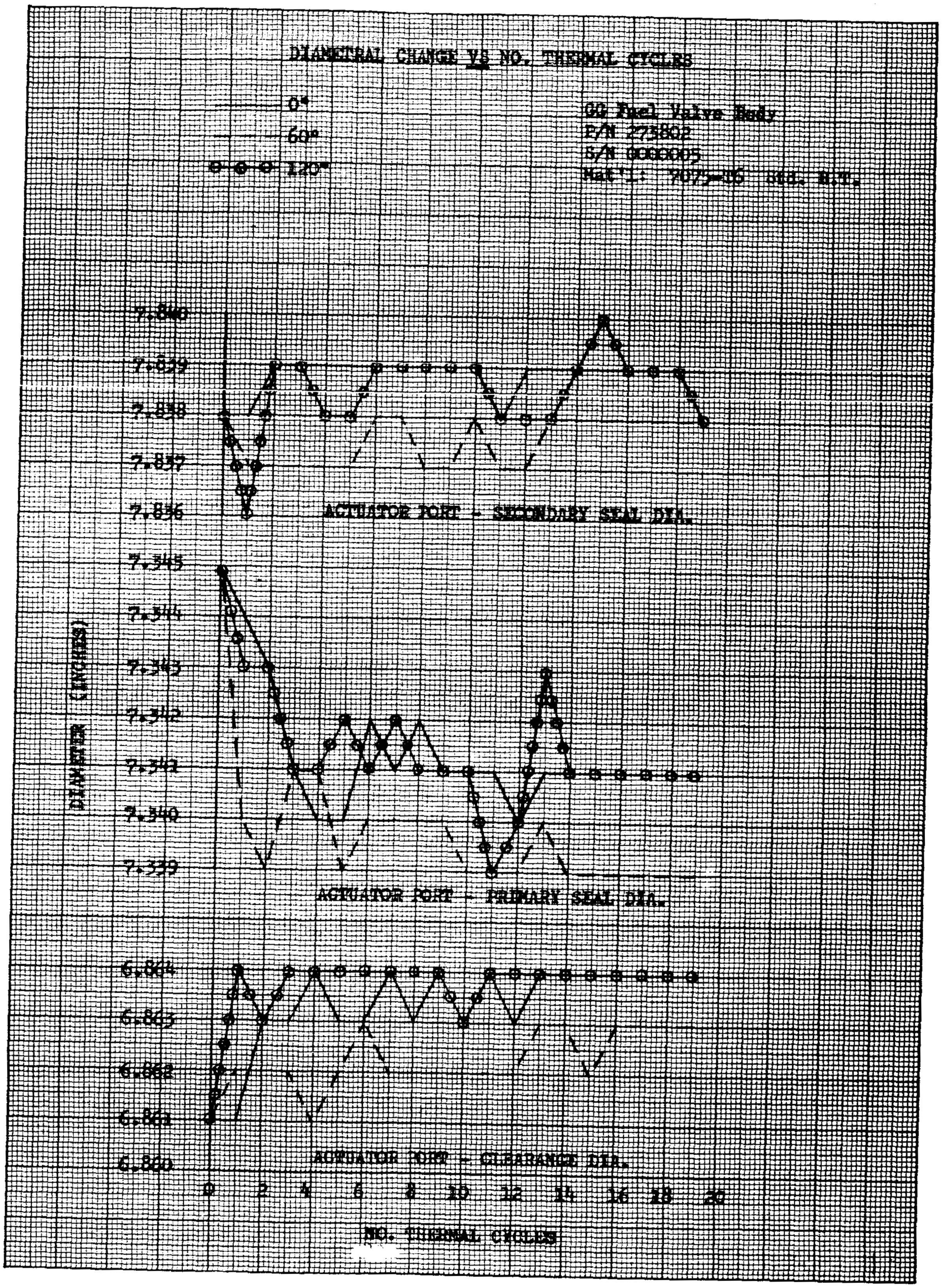


Figure 13

ACTUATOR PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

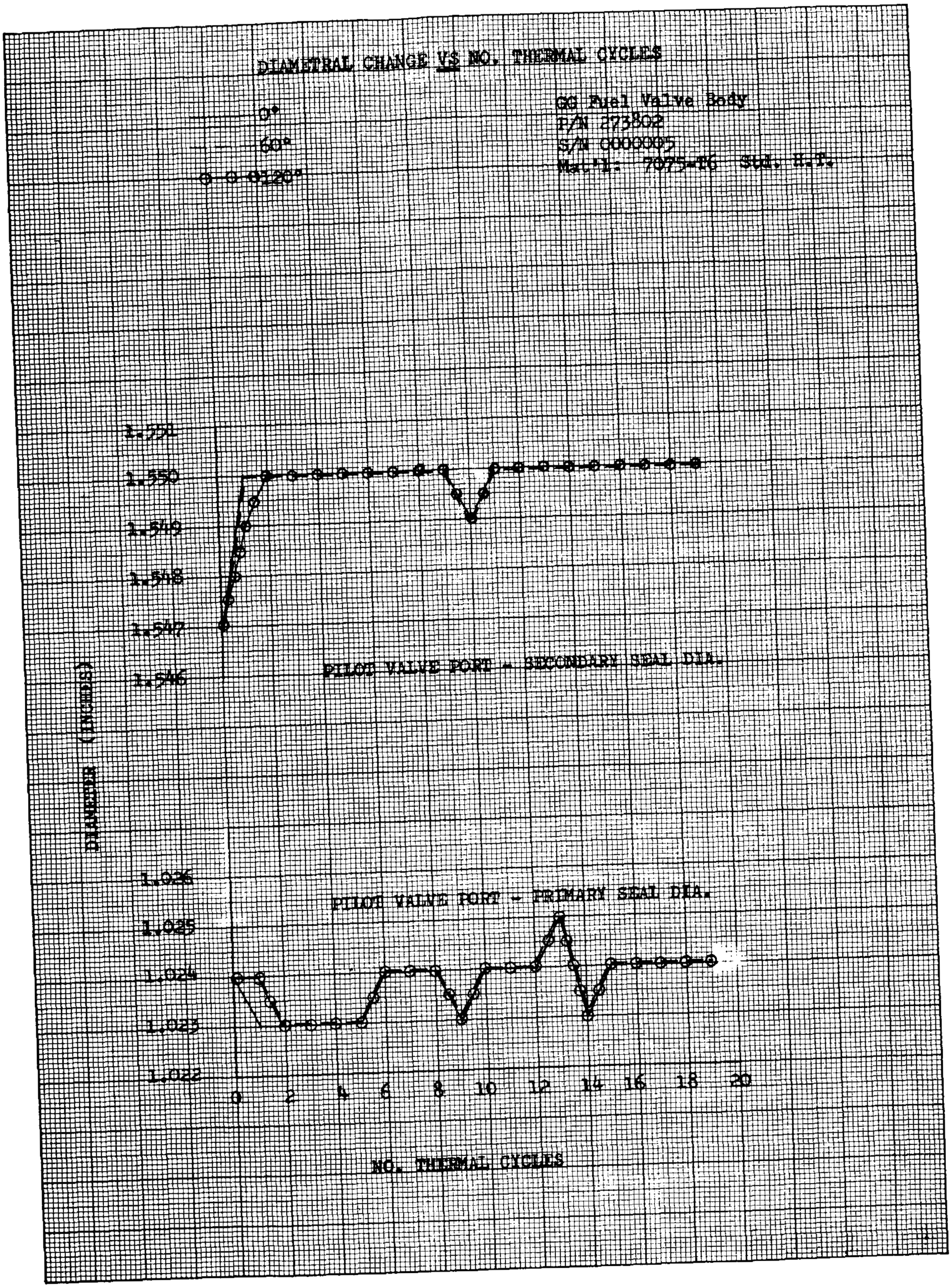
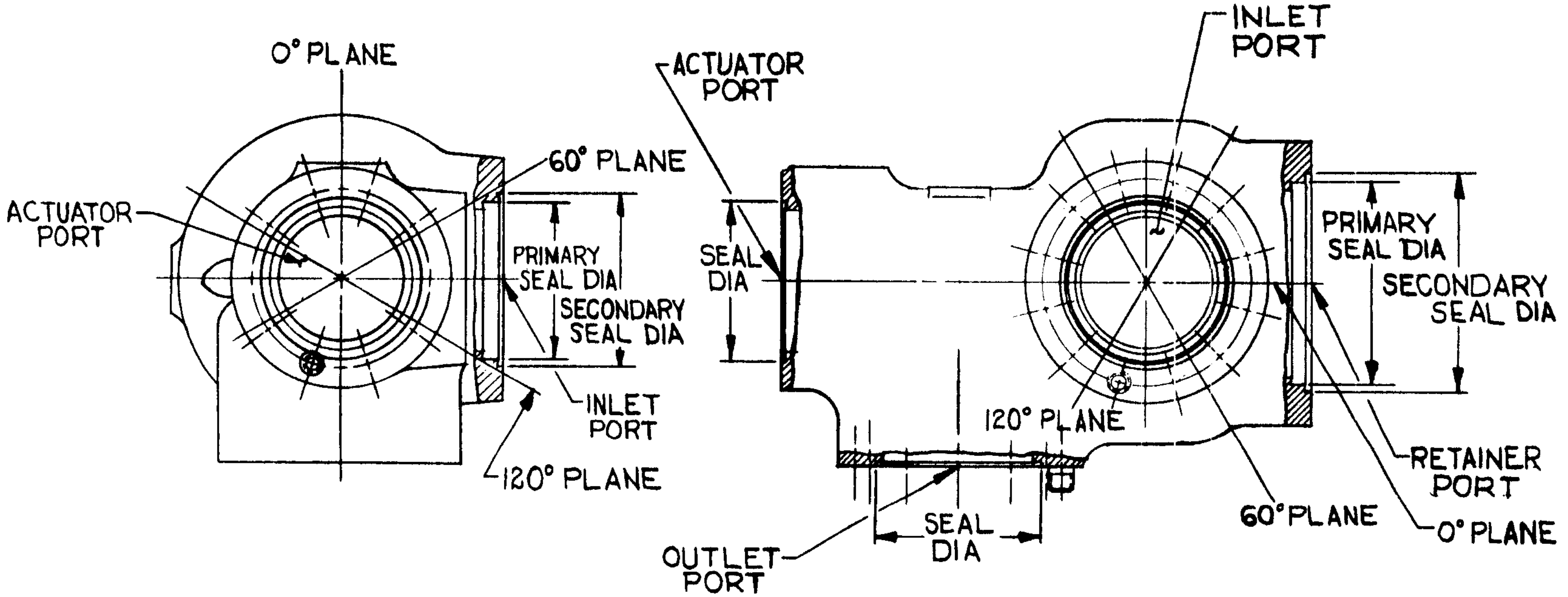


Figure 14

PILOT VALVE PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES



M-1 START VALVE BODY CONFIGURATION
AND DIMENSIONS USED FOR THERMAL
CYCLING TESTS

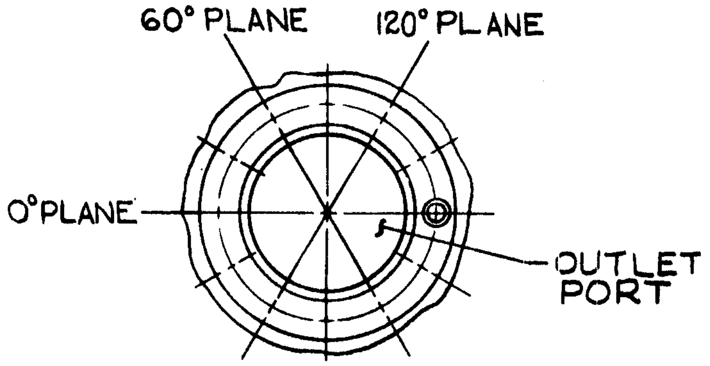


Figure 15

START VALVE BODY CONFIGURATION

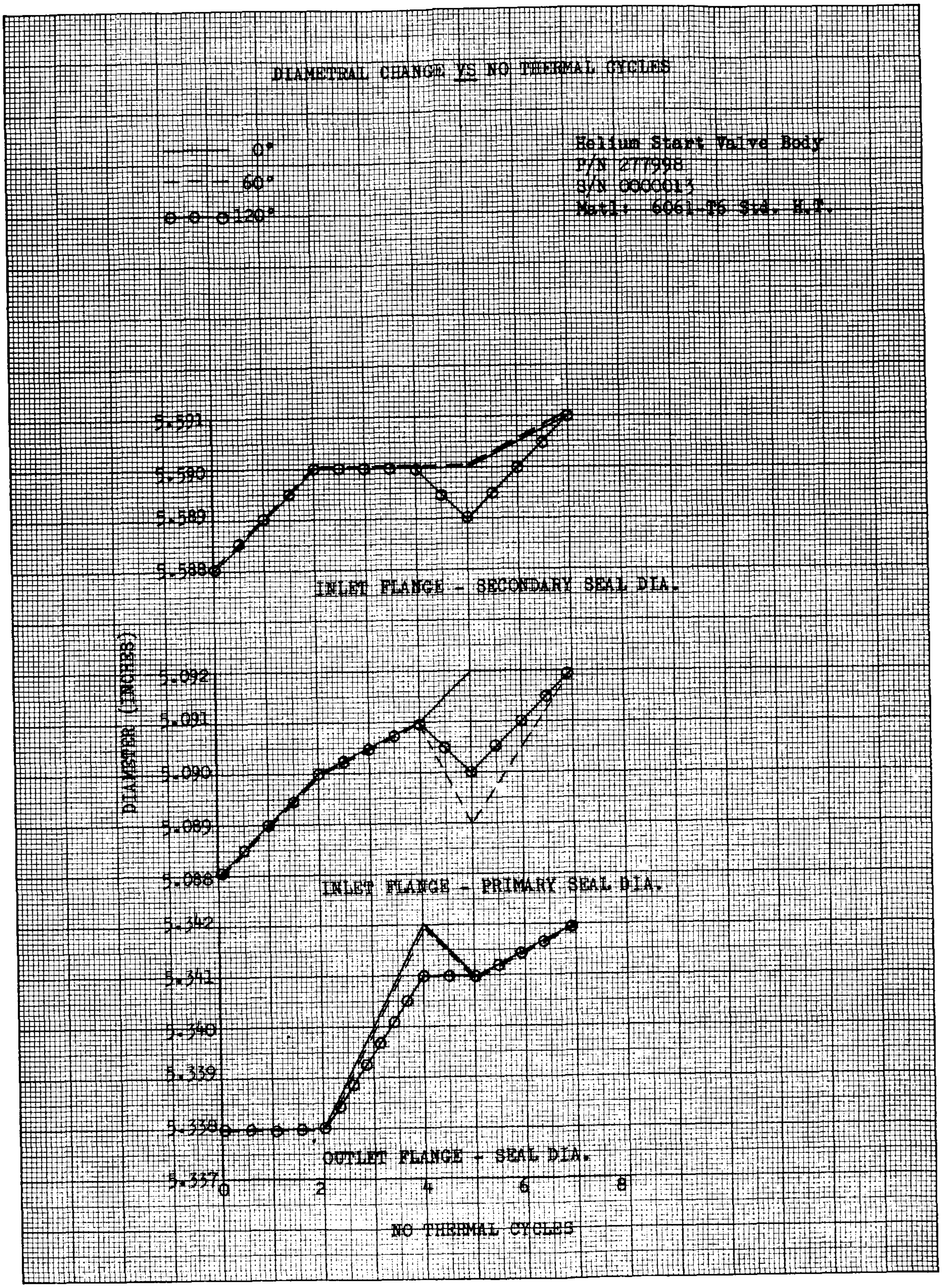


Figure 16

INLET FLANGE DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

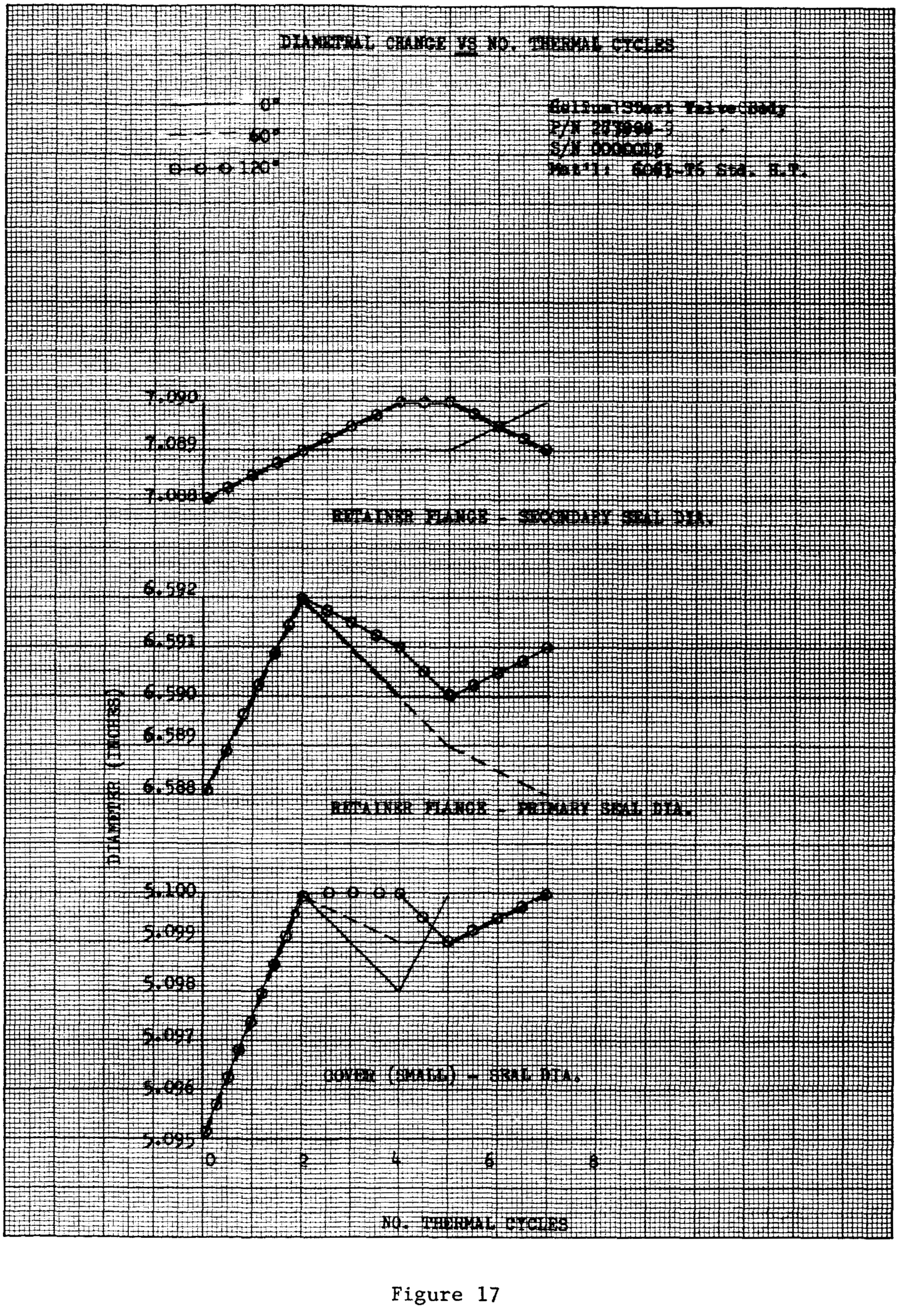


Figure 17

RETAINER FLANGE DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

B. SPECIAL PROCESS (STABILIZED)

Thermal cycling tests were performed using two different body configurations; the M-1 gas generator oxidizer valve body and the Titan II thrust chamber fuel valve body. Two of the M-1 gas generator oxidizer valve bodies were tested. One unit was forged from 7075 aluminum, heat treated to the -T73 condition and then stabilized. The other unit was forged of 6061 aluminum, heat treated to the -T6 condition, and then stabilized. The Titan II thrust chamber fuel valve body was forged from 7075 aluminum, heat treated to the -T73 condition, and then stabilized. The following units were tested.

Body Configuration	Part No.	Serial No.	Material and Heat Treat
M-1 GGOV Body	273868-9	0000018	7075-T73
M-1 GGOV Body	707546-9	0000041	6061-T6
Titan II TCFV Body	250220-5	0000233	7075-T73

The results of the test with the 7075-T73 stabilized gas generator oxidizer valve body are shown in Figures 18 and 19. The results of the test with the 6061-T6 stabilized gas generator oxidizer valve body are shown in Figures 20 and 21. The thrust chamber fuel valve 7075-T73 stabilized body test results are shown in Figure 22.

C. TEST DATA SUMMARY

A complete summary of the maximum to minimum and average distortions experienced with each of the body configurations is presented in Table 1. Detailed discussions of these data with respect to body configuration effects, materials, and heat-treat process effects, etc., follow.

1. Configuration Effects

The data concerning the effects of the body configuration using only the standard heat-treat processed bodies are summarized below.

Body Configuration	Port	Total Distortions (in./in. Diameter)	Range of Change (in./in. Diameter)
GGOV Body	Inlet	4.3 to 24.5×10^{-4}	20.2×10^{-4}
GGOV Body	Outlet	2.8 to 6.5×10^{-4}	3.7×10^{-4}
M-1 6-in. Test Cell		1.5 to 3.6×10^{-4}	2.1×10^{-4}
GGFV Body	Inlet	1.5 to 5.3×10^{-4}	3.8×10^{-4}
GGFV Body	Outlet	1.8 to 8.7×10^{-4}	6.9×10^{-4}

TABLE I

SUMMARIZED TEST DATA

DISTORTION (INCHES/INCH DIA)

Body	Port	7075-T6 Std H.T.	7075-T73 Std H.T.	6061-T6 Std H.T.	7075-T73 Stabilized	6061-T6 Stabilized
GGOV	Inlet	4.3 to 24.5×10^{-4} Range = 20.2×10^{-4} Avg = 13.4×10^{-4}	2.4 to 13.9×10^{-4} Range = 11.5×10^{-4} Avg = 7.9×10^{-4}		4.5 to 23.5×10^{-4} Range = 19.0×10^{-4} Avg = 10.7×10^{-4}	4.9 to 5.6×10^{-4} Range = 0.7×10^{-4} Avg = 5.2×10^{-4}
	Outlet	2.8 to 6.5×10^{-4} Range = 3.7×10^{-4} Avg = 4.5×10^{-4}	13.9 to 23.1×10^{-4} Range = 9.2×10^{-4} Avg = 17.7×10^{-4}		9.0 to 11.5×10^{-4} Range = 2.5×10^{-4} Avg = 10.2×10^{-4}	3.6 to 6.5×10^{-4} Range = 2.9×10^{-4} Avg = 4.0×10^{-4}
Start Valve	Inlet			5.1 to 7.8×10^{-4} Range = 2.7×10^{-4} Avg = 6.45×10^{-4}		
	Retainer			2.8 to 6.1×10^{-4} Range = 3.3×10^{-4} Avg = 4.45×10^{-4}		
	Actuator			9.8 to 9.8×10^{-4} Range = ~ 0 Avg = 9.8×10^{-4}		
	Outlet			7.5 to 7.5×10^{-4} Range = ~ 0 Avg = 7.5×10^{-4}		

TABLE I (cont.)

		DISTORTION (INCHES/INCH DIA)				
Body	Port	7075-T6 Std H.T.	7075-T73 Std H.T.	6061-T6 Std H.T.	7075-T73 Stabilized	6061-T6 Stabilized
TCFV (Titan II)	Inlet	4.6×10^{-4} Range = Unknown Avg = Unknown			4.6 to 7.4×10^{-4} Range = 2.8×10^{-4} Avg = 6.6×10^{-4}	
	Outlet	2.3×10^{-4} Range = Unknown Avg = Unknown			4.9 to 9.1×10^{-4} Range = 4.2×10^{-4} Avg = 6.3×10^{-4}	
6-Inch Test Cell	---	1.5 to 3.6×10^{-4} Range = 2.1×10^{-4} Avg = 2.85×10^{-4}				
GGFV	Inlet	1.5 to 5.3×10^{-4} Range = 3.8×10^{-4} Avg = 4.0×10^{-4}				
	Outlet	1.8 to 8.7×10^{-4} Range = 6.9×10^{-4} Avg = 4.5×10^{-4}				
	Actuator	1.3 to 8.1×10^{-4} Range = 6.8×10^{-4} Avg = 4.7×10^{-4}				
	Pilot Valve	19.4 to 19.5×10^{-4} Range = 0.1×10^{-4} Avg = 19.45×10^{-4}				

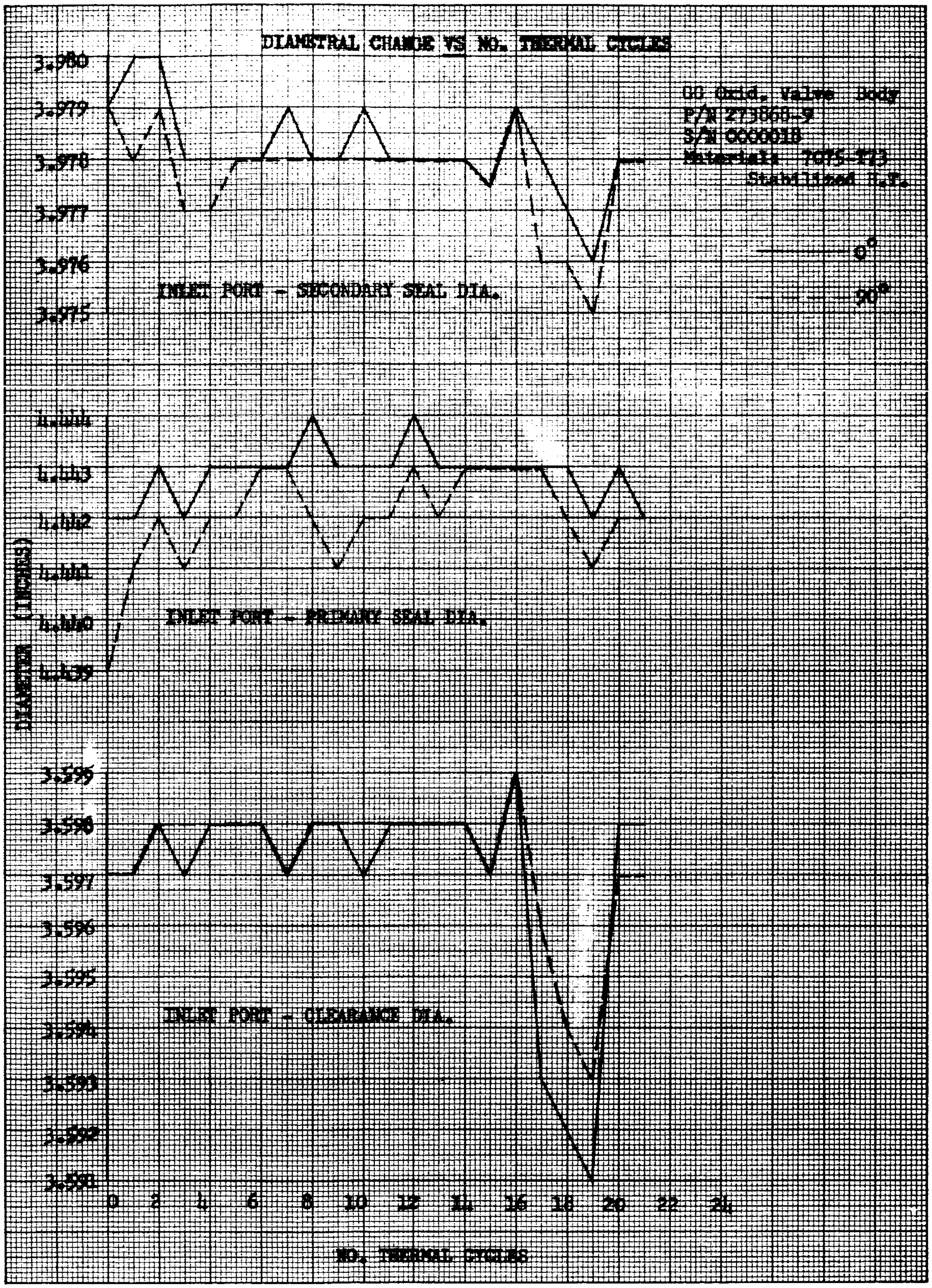


Figure 18

INLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

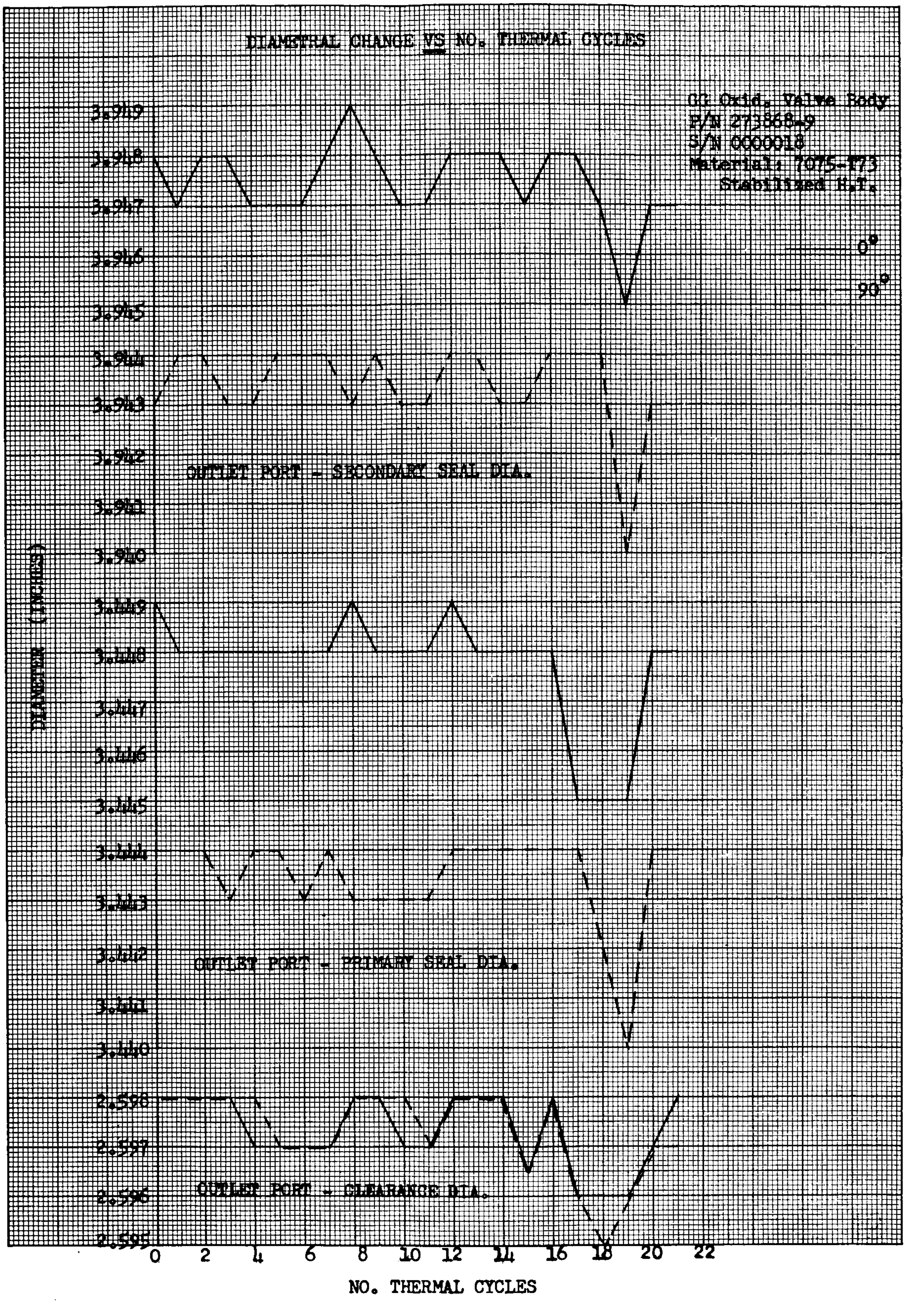


Figure 19

OUTLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

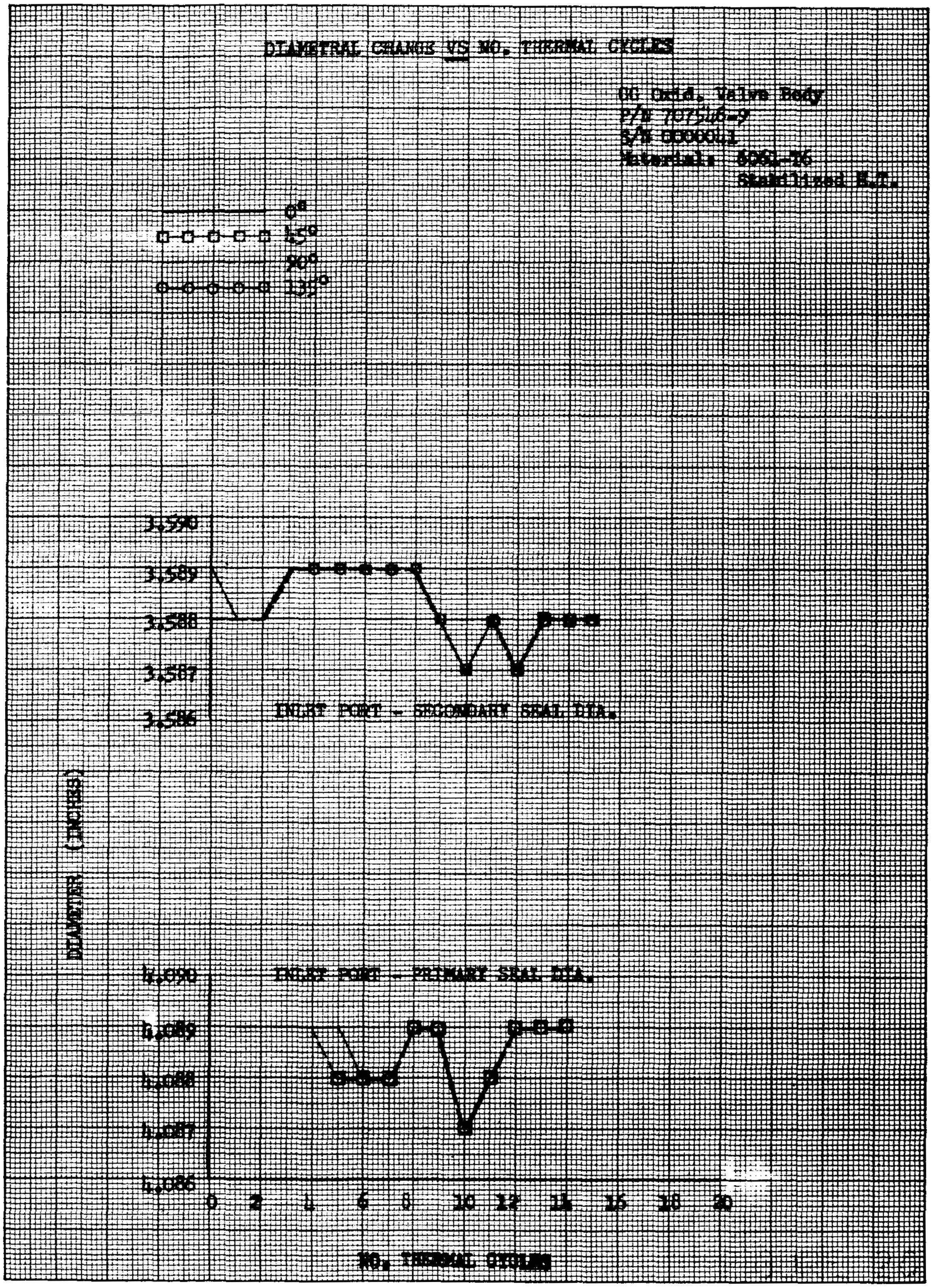


Figure 20

INLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

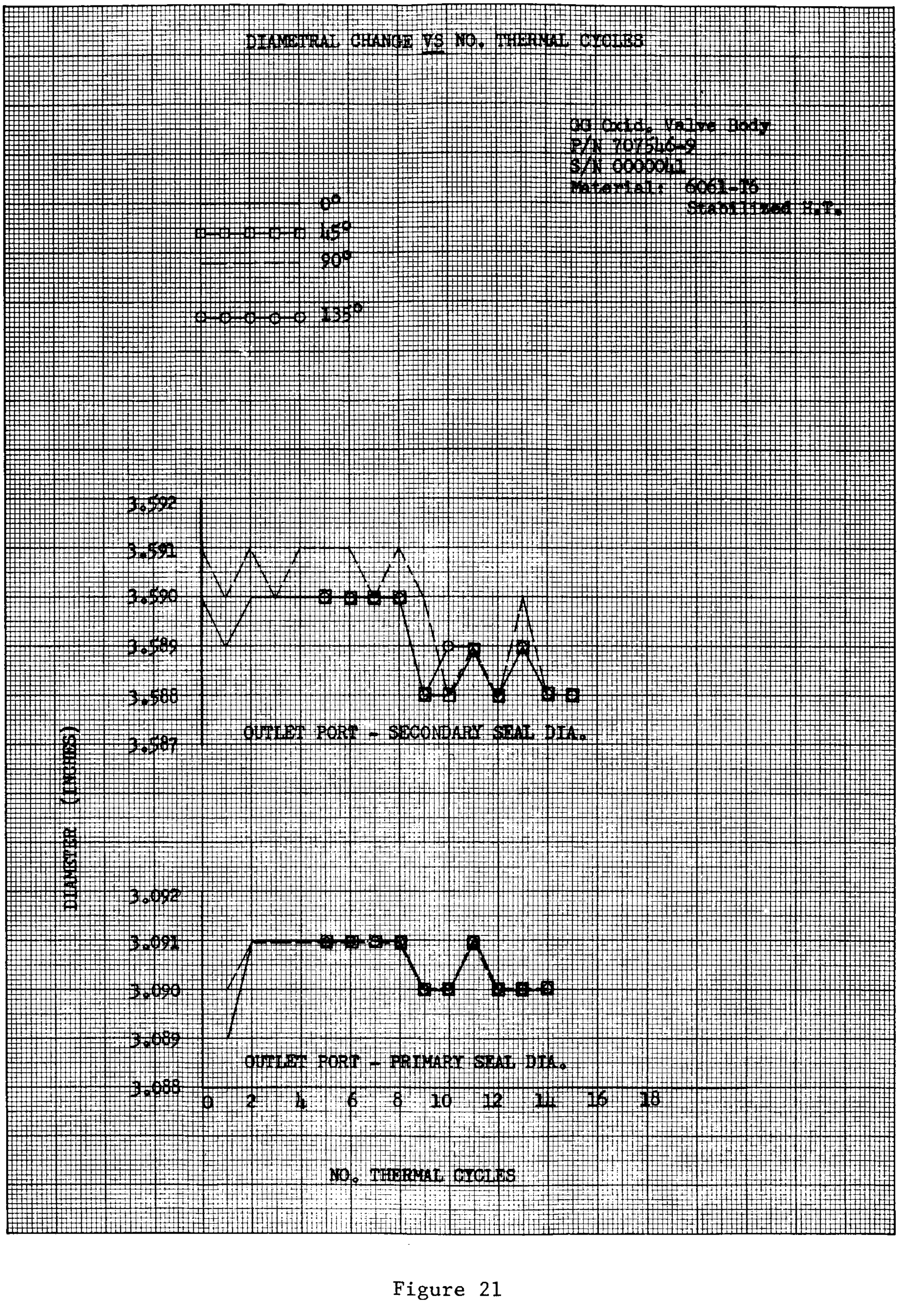


Figure 21

OUTLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

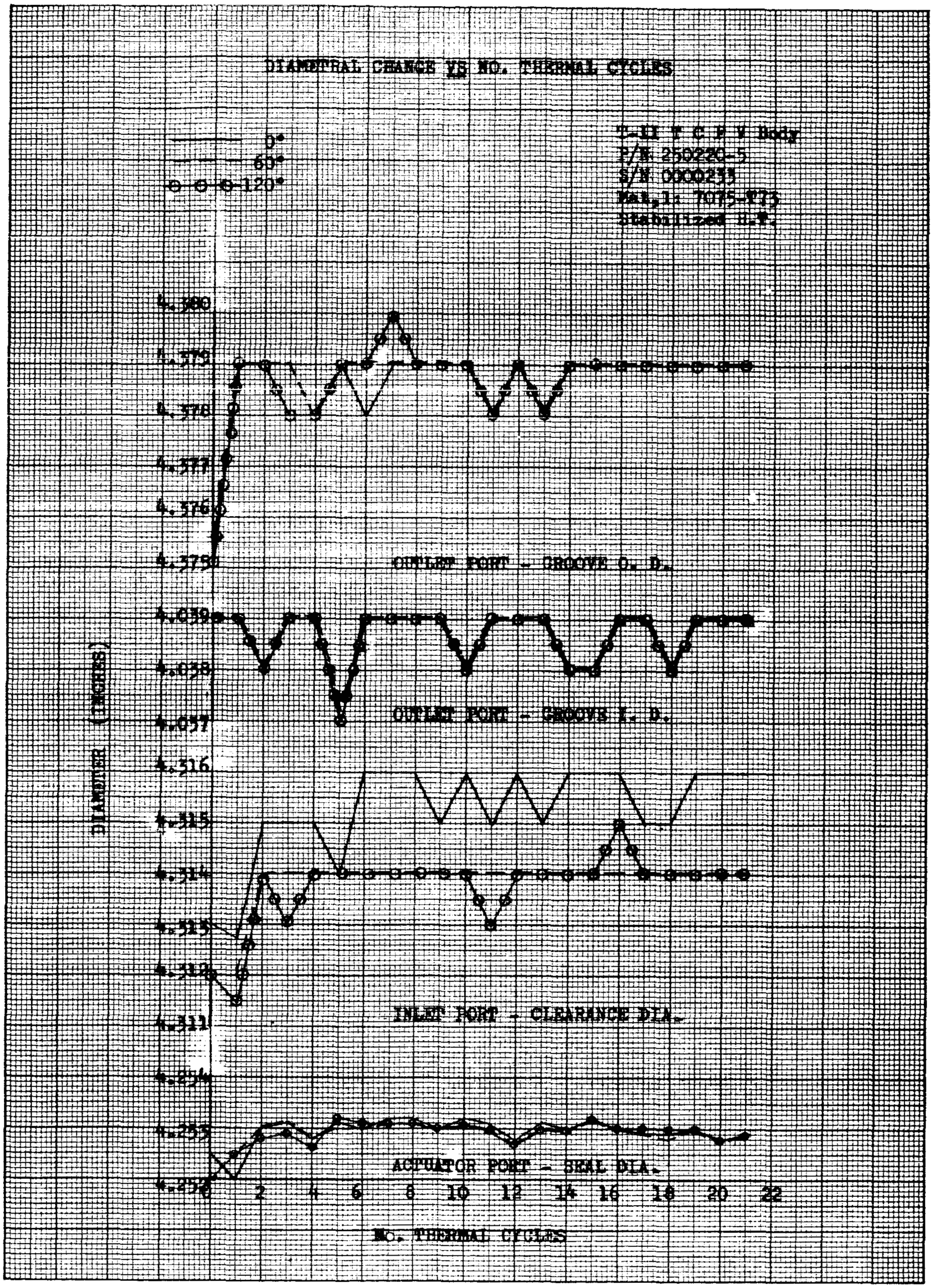


Figure 22

OUTLET PORT DIAMETRAL CHANGE
VERSUS NO. THERMAL CYCLES

Body Configuration	Port	Total Distortions (in./in. Diameter)	Range of Change (in./in. Diameter)
GGFV Body	Actuator	1.3 to 8.1 x 10^{-4}	6.8 x 10^{-4}
GGFV Body	Pilot Valve	19.4 to 19.5 x 10^{-4}	0.1 x 10^{-4}
Start Valve Body	Inlet	5.1 to 7.8 x 10^{-4}	2.7 x 10^{-4}
Start Valve Body	Retainer	2.8 to 6.1 x 10^{-4}	3.3 x 10^{-4}
Start Valve Body	Actuator	9.8 to 9.8 x 10^{-4}	Approx. 0
Start Valve Body	Outlet	7.5 to 7.5 x 10^{-4}	Approx. 0

As expected, the range of change (difference between maximum and minimum distortions) in the diameters (the tendency towards distorting out-of-round) was a function of the shape of the flange and surrounding or adjoining material. The closer the flange and adjoining material was to a true cylindrical shape, the less the tendency was to distort out-of-round. In this case, the range of change was relatively small and the total change was small. Also, if the diameters were located within, or surrounded by, a relatively massive section, the range of change was smaller, though the total change was relatively large. The 6-in. dual seal test cell (a true cylindrically-shaped flange with cylindrical adjoining material) exhibited the smallest total distortions with a relatively small range of change. The pilot valve port in the gas generator fuel valve body (diameters located in a heavier mass of material) exhibited relatively large total distortions, but a small range. The outlet port on the gas generator oxidizer valve body (close to a cylindrically shaped flange with nearly cylindrically shaped adjoining material) also exhibited relatively small total distortions and small range. The outlet and actuator ports on the start valve body (also near a cylindrical shape) exhibited relatively large total distortions but with a small range.

There is no apparent correlation between the direction of distortion (expansion or contraction) and the location of the diameter with respect to the inner or outer fibers (or the center) of the forged section. To reach a condition of equilibrium stress, the following assumption is made: diameters located near the inner fibers (residual compressive stresses) would tend to contract and diameters located near the outer fibers (also residual compressive stresses) would tend to expand to relieve the residual stresses. Apparently, the shape of the section is the predominant governing factor.

2. Materials and Heat-Treat Effects on GGOV Body

The average distortion experienced with the standard heat-treated 7075 aluminum forgings for the gas generator oxidizer valve body was approximately 13.0 x 10^{-4} in./in. diameter, while the average distortion experienced in the stabilized 7075 aluminum forging was approximately 10.5 x 10^{-4} in./in. diameter; an average reduction of 19%. The average distortion experienced with the stabilized 6061 aluminum forging was approximately 4.5 x 10^{-4} in./in. diameter; a reduction of 73% over the standard heat-treated 7075 aluminum forgings and 57% over the stabilized 7075 aluminum forgings.

3. Comparison of Heat Treatments on 6061 Aluminum Forgings

The average distortions experienced with the standard heat-treated 6061 aluminum start valve body forging was 7.0 x 10^{-4} in./in. diameter. The average distortions experienced with the stabilized 6061 aluminum gas generator oxidizer valve body forging was 4.5 x 10^{-4} in./in. diameter. The calculated reduction of distortion in the 6061-T6 forging processed by the special fabrication method is 29%.

VI. CONCLUSIONS

Permanent distortions (dimensional instability) encountered in the aluminum forgings during cryogenic thermal cycling was caused by residual stresses. The re-heat treatment and pressure stabilization process reduced the distortions by approximately 20% in the 7075 aluminum forgings and approximately 30% in the 6061 aluminum forging. It is doubtful that a process could be devised that would completely eliminate permanent distortions of the aluminum forgings.

The degree of dimensional instability was dependent upon the mass and shape of the finish-machined forging. Total distortions and the range of distortions (maximum to minimum) were smaller in forgings having cylindrically shaped configurations. Total distortions of areas adjacent to and located in massive sections tended to be large, but the range of distortions were small (tends to maintain roundness, flatness, parallelism, etc.). Odd-shaped sections tended to experience large total distortions and a large range of distortions (distorts out-of-round, out-of-flat, etc.).

The 6061 aluminum forgings appeared more stable for low-temperature thermal cycling applications than the 7075 aluminum forgings.

VII. RECOMMENDATIONS

The re-heat treatment and the pressure stabilization process described herein should be incorporated in the fabrication process to minimize dimensional instability in valve bodies and other parts intended for low temperature service. This is particularly important for valve bodies, housings, and actuators that require close tolerance dimensions for sealing and proper fit.

The advantages of a low temperature stress relief treatment after final machining should be investigated to further reduce the residual stress level in the valve bodies. A treatment at 200°F for 24 hours has been found suitable for certain aluminum alloy forgings(2). This may be required for very close tolerances in parts where the stabilization process alone does not reduce distortions within tolerable limits.

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(2) Dimensional Stability of Aluminum Alloys, Battelle Memorial Institute Letter Report, February 1964

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