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DEVELOPMENT OF HOT ISOSTATICALLY PRESSED RENE' 95 TURBINE PARTS

General Electric Company
Aircraft Engine Group
1000 Western Ave.
Lynn, MA 01910

May 1977

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EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
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EUSTIS DIRECTORATE POSITION STATEMENT

This report provides the details of a program that has developed a production manufacturing process for fabricating T700 engine gas generator turbine disks and cooling plates by Hot Isostatic Pressing (HIP) Rene' 95 alloy powder to the approximate shape of each part. These program details include extensive heat treatment investigations and mechanical property evaluations to ensure production of high-quality, high-strength hardware with this simplified, cost-effective process. It must be understood that this report provides specific processing for this material and hardware configuration and only insight into possible processes for other poweder metallurgy materials and geometries.

Jan M. Lane of the Propulsion Technical Area, Technology Applications Division, served as Project Engineer for this effort.

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To arrest the increasing cost of materials and fabrication techniques for high-strength gas turbine components, a contract was awarded to the General Electric Company to develop a reliable, low-cost, reproducible powder metallurgy production process for manufacturing premium quality HIP Rene'95 T700 gas generator turbine disks and cooling plates. The work to accomplish this objective was subdivided into four tasks.

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20. ABSTRACT (Continued)

In the first (Task I) of the four tasks, the effects of powder mesh size and particle size distribution, compaction temperature and pressure, and post-compaction heat treatment were studied utilizing the powder and processing methods of two independent subcontractors. The finer mesh powder appeared to have no advantage over the -60 mesh powder, which offered ease in handling. A compaction temperature of 2050°F at 15 ksi compacting pressure provided uniform, fine-grain microstructure with desired γ' morphology. A heat treatment consisting of a solution temperature 30°F below the γ' solvus, a 1000°F salt quench, and double aging resulted in the required final microstructure and mechanical properties.

The powder treatment, container (material, shape and production process), and container filling and evacuation procedures were also established by both subcontractors to produce the turbine disks and cooling plate shapes. Both steel and ceramic have demonstrated their suitability as container materials. It was determined that the disks would be fabricated individually, while the cooling plates would be fabricated in multiples using hollow cylindrical containers.

A preliminary quality plan integrating the activities of the subcontractors and General Electric manufacturing, engineering, quality control, and shop operation functions was also developed to insure that customer requirements are met consistently and economically. A complete process definition consisting of manufacturing process parameters, the preliminary quality plan and a cost analysis was established.

Task II was aimed at conducting a more detailed mechanical property evaluation of the T700 As-HIP Rene'95 production process selected in Task I. Included in the evaluation, in addition to test specimen data, were four spin pit burst tests to determine the integrity and predictability of As-HIP Rene'95.

A total of three turbine disk shapes and three cooling plate configurations were produced by each of the two independent subcontractors using process parameters defined in Task I. The cooling plates and two turbine disks from each subcontractor were sectioned and machined into test specimens. The mechanical property evaluation consisted of tensile, stress rupture, creep, notched tensile, crack propagation, cyclic rupture (SPLCF) and low-cycle fatigue testing at several different conditions. All properties were approximately equivalent to those achieved in PM HIP + forged T700 production hardware with the exception of tensile strength.

Spin pit burst tests were also conducted on two turbine disk shapes from each subcontractor. The disks were machined to two different T700 model configurations and tested to destruction at room temperature in an evacuated chamber. All disks failed at speeds predicted by a semiempirical formula developed at General Electric, although one disk contained a preexisting flaw that reduced its burst speed significantly. It was concluded that the burst characteristics of As-HIP Rene'95 at room temperature can be predicted using the General Electric semiempirical method.

During Task III,several lots of turbine disks and cooling plates were fabricated by each subcontractor as part of a pilot-production program. Previously established processing parameters and quality procedures were used. Rigorous nondestructive testing and an extensive mechanical property evaluation were conducted. A set of two turbine disks and three cooling plates was machined to final part configuration. The finish machined hardware was submitted for an engine test in Task IV using an engine from the UTTAS engine development program as a vehicle. The parts successfully completed 150 endurance hours in the maturity hardware assurance test. Following the disassembly, these were nondestructively evaluated and found to be sound and identical to the parts with similar test history.

FOREWORD

This final report summarizes the work done under the U.S. Army Contract DAAJ02-73-C-0106 during July 1973 and August 1976.

Dr. P.S. Mathur was the Program Manager and Principal Investigator of this project. He provided the overall supervision for this work. The responsible engineer, Dr. J.L. Bartos, contributed to the testing and evaluation and is the coauthor of this report.

The technical direction for the program was provided by Mr. G. Easterling (in the first half) and Mr. J. Lane (in the second half) of the U.S. Army Air Mobility Research and Development Laboratory, Eustis Directorate. Dr. R.L. Dreshfield of NASA Lewis Research Center provided helpful and timely technical assistance. Their help and cooperation is greatly appreciated.

The guidance and encouragement of Mr. J.I. Hsia, Manager Technical Resource Operation, is gratefully acknowledged.

The diligent work, patience and enthusiasm of personnel at Crucible Materials Research Center and Carpenter Technology Corporation Research and Development Center were key factors in the success of this program.

This project was accomplished as part of the U.S. Army Aviation Systems Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U.S. Army Aviation Systems Command, Attn: AMSAV-Ext, P.O. Box 209 St. Louis, Missouri 63166.

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INTRODUCTION

Rene' 95 is a highly alloyed, precipitation-strengthened, Nickel-base superalloy, which is used to make two turbine disks and the four turbine cooling plates of the T700 engine.

The current method of manufacturing Rene' 95 turbine hardware is comprised of forgings made from powder compacts or the cast ingot. Because of high alloy content, and thus the strength, Rene' 95 is difficult and expensive to produce by these conventional methods. The largest cost element is the forging cycle itself. The development of a successful, forgeless, hot isostatic pressing (HIP) process has a significant cost savings potential and could also develop properties comparable to forging with more homogeneity and reproducibility. This work, performed under U.S. Army Contract DAAJ02-73-C-0106 (Phase II), was directed toward this goal. The objective was to develop a reliable, low-cost, reproducible, powder metallurgy production process for manufacturing premium quality hot isostatically pressed (As-HIP) T700 engine turbine hardware.

The program consisted of the following five tasks:

Task I	Process Refinement Definition
Task II	Fabrication and Evaluation of Lab Test Specimens
Task III	Fabrication of Engine Test Hardware
Task IV	Test and Evaluation
Task V	Technical Data Package

An additional task, Task VI – Heat Treat Study, was added to the program but will be a separate report.

Two vendors, A and B, were selected to participate as the subcontractors to supply the material to develop the shape-making technology and institute quality control procedures.

The objective of Task I, comprised of three subtasks (IA, IB and IC), was to define a process for the production of hot isostatically pressed (As-HIP) turbine disks and cooling plates to a shape near the ultrasonic inspection envelope.

The specific objective of Subtask IA, HIP Process Definition, was to determine processing parameters including powder mesh size, HIP compaction parameters and heat treatment necessary to produce mechanical properties equivalent to those of current HIP + forge hardware. The property goals were as follows:

Tensile Properties

Room Temperature				1200°F				Stress-Rupture 1200°F/150 ksi	
0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Life (hr)	EL (%)
180	230	10	12	167	207	8	10	50	3

Subtask IB, Shape Definition, was directed toward developing a process to manufacture As-HIP T700 turbine disks and cooling plate shapes. It included the identification of powder treatment, container material, shape-making process and container filling and evacuation procedures.

The objective of Subtask IC, Complete Process Definition, was to incorporate the processing parameters and quality consideration of Subtasks IA and IB into a complete manufacturing process definition.

Task II was aimed at conducting a more detailed mechanical property evaluation of the limited turbine hardware (disk and cooling plates) made in accordance with the production process established in Task I. In addition, it included plans to conduct four overspeed spin pit burst tests to determine the integrity and predictability of As-HIP Rene' 95 hardware.

The objective of Task III was to fabricate several lots of disks and cooling plates by each vendor in a pilot production program using previously established processing parameters and quality control procedures. Extensive mechanical and metallurgical evaluation of the hardware was planned, along with a rigorous non-destructive inspection in order to insure conformance to the material release criteria for a new turbine disk material. A complete set of turbine hardware (two disks and four cooling plates) was then to be machined to final part configuration. These parts were to be submitted for test and evaluation during scheduled engine test of the UTTAS engine development program in Task IV.

Upon completion of all the testing and inspection, a technical data package (Task V) was to be prepared and submitted to the contracting officer.

TASK I – PROCESS REFINEMENT DEFINITION

INITIAL STUDIES

An initial study designed to define process parameters and to provide direction for Task I was completed by both the vendors. Independent studies were conducted at two vendors (A and B) to investigate the effect of hot isostatic pressing (HIP) compaction parameters (compaction cycle, pressure, temperature, and the solution treatment temperature) on the microstructure, density, and mechanical properties of powder metallurgy Rene' 95. Each vendor used powder of the same mesh size and particle size distribution as to be used for Task I studies.

Two compacts, 2½ inches in diameter and 15 inches long, of each mesh size/HIP temperature combination were prepared by Vendor A according to the plan given in Table 1, using an autoclave; compacts, prepared using additional cold wall compaction techniques, were added to the study to determine if this technique had potential for producing As-HIP engine hardware. Density measurements of the As-HIP compacts, given in Table 2, indicate that all compacts achieved approximately 100 percent density. Chemistry variations are believed to be responsible for the lower densities of the -200 mesh compacts, since the two mesh size powders were atomized from different alloy heats.

The effect of compaction temperature on microstructure for the As-HIP conditions presented in Table 1 is shown in Figures 1 and 2. Prior particle outlining is very evident in the 1950° and 2000°F compacts. Consolidation at these temperatures apparently results in preferential precipitation of γ' at the highly mismatched prior particle surfaces. Although most particles have recrystallized to a very fine grain structure (ASTM 8 to 10), a number of particles retain the dendritic structure inherent in argon-atomized powders. Consolidation at 2050°F eliminated most of the prior particle outlining. A few particles recrystallized during compaction into a relatively small number of large grains, making them easily identifiable in the fine-grained matrix. This phenomenon appears slightly more pronounced in the material compacted by cold-wall compaction. Also, the uniformly finer microstructure of -200 mesh powder reflects the finer particle size.

Following compaction, 3-inch-long sections were cut from the compacts and heat treated utilizing the standard Rene' 95 heat treatment.* Tensile and stress-rupture properties are presented in Tables 3 and 4. Room temperature tensile properties increased with decreasing HIP compaction temperature in -60 mesh compacts, although no compact achieved the program goal. Two of the four -200 mesh compacts cracked during heat treatment, leaving only the 2050° material available for evaluation. The room temperature property goal was achieved by the finer mesh size compact prepared in the autoclave, while the compact prepared by the cold-wall technique exhibited low ductility, which reduced the ultimate strength significantly.

Tensile properties at 1200°F showed the same general trends as those at room temperature, with the -200 mesh compact prepared in the autoclave achieving program goal properties.

Tensile properties of the -60 mesh compacts were generally lower than those required. This is believed to be heat treat section size effect, since the data for proposed goals were obtained using specimens heat treated as small (5/8-inch diameter) blanks. The heat treat section size used in the initial study could again result in lower mechanical properties, since the 2½-inch-diameter samples represent a larger section size than the actual engine hardware.

Stress-rupture properties became more erratic and exhibited lower ductility at lower compaction temperatures. The -60 and -200 mesh compacts prepared in the autoclave at 2050°F and the -60 mesh compact prepared by

*1650°F/4 hours, 2000°F/1 hour/OQ, + 1400°F/16 hours/AC.

TABLE 1. INITIAL STUDY CONDITIONS EVALUATED BY VENDOR A

Type	HIP Temperature (°F)		
	1950	2000	2050
Powder Mesh Size Autoclave compacted			
−60	X	X	X
−200	X	X	X
Cold-wall compacted			
−60	–	–	X
−200	–	–	X

TABLE 2. AS-HIP DENSITIES OF INTIAL STUDY COMPACTS FROM VENDOR A

Powder Mesh Size	HIP Temperature (°F)			
	Autoclave Compacted			Cold Wall Compacted
	1950	2000	2050	2050
−60	0.2986*	0.2984	0.2985	0.2985
	0.2984	0.2985	0.2985	
−200	0.2977	0.2976	0.2977	0.2974
		0.2976	0.2977	

*All densities expressed as lb/in.^{3}

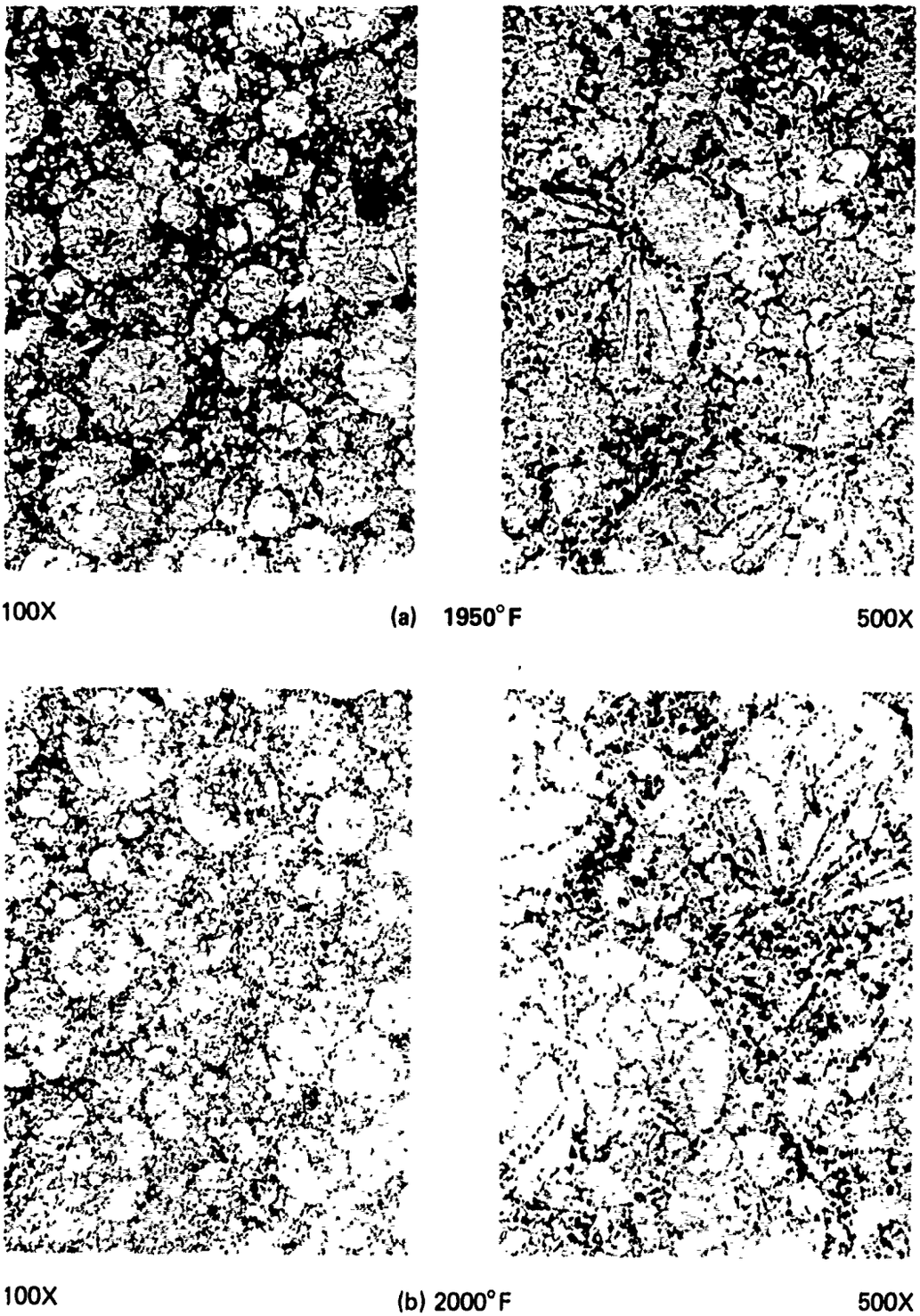
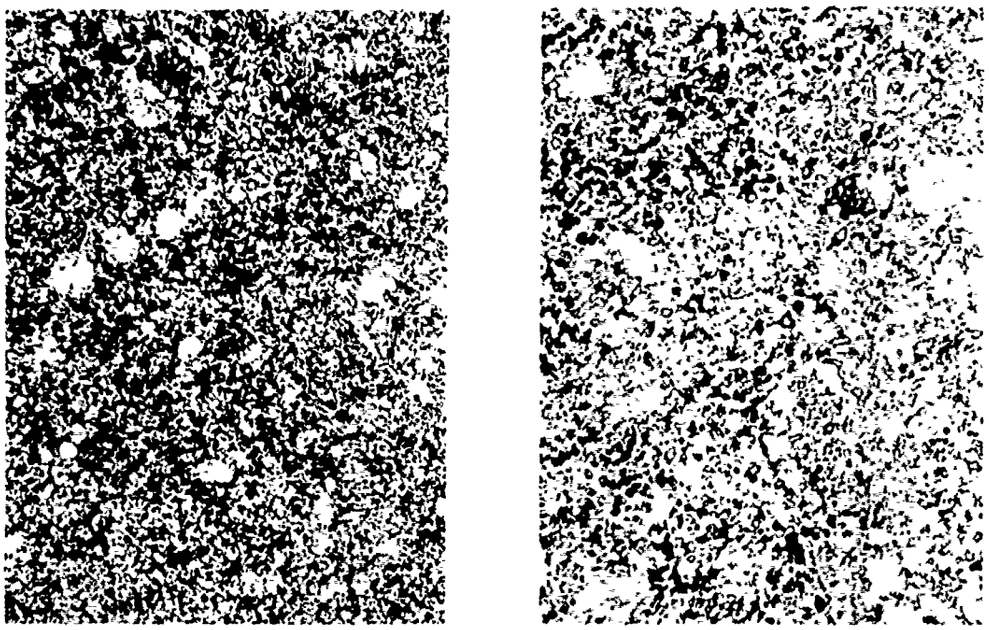


Figure 1. As-HIP Microstructures of Vendor A's Initial Study, -60 Mesh Compacts Fabricated at: (a) 1950°F and (b) 2000°F (Sheet 1).



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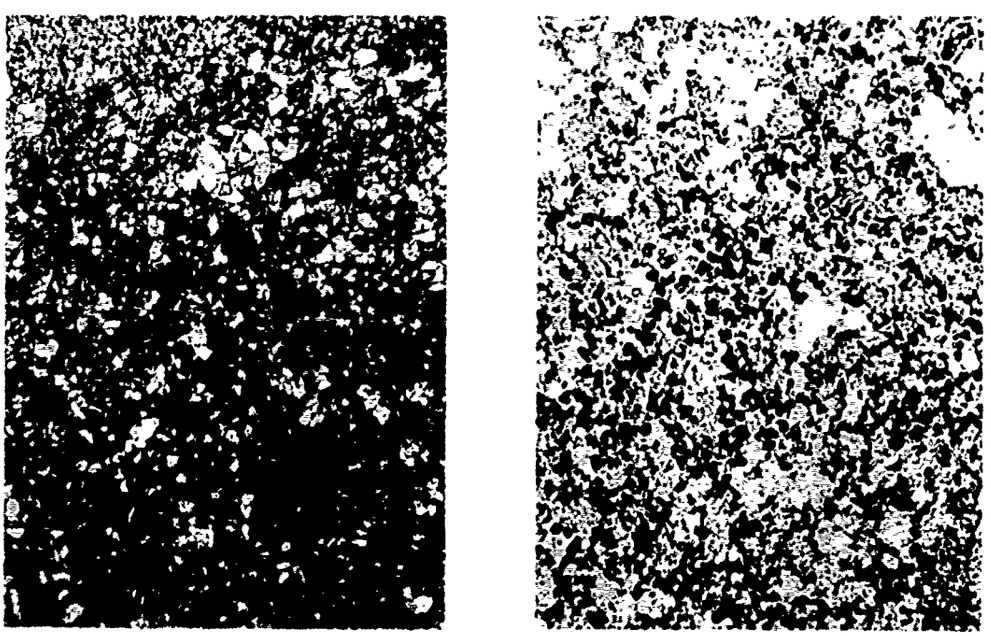
(c) 2050°F



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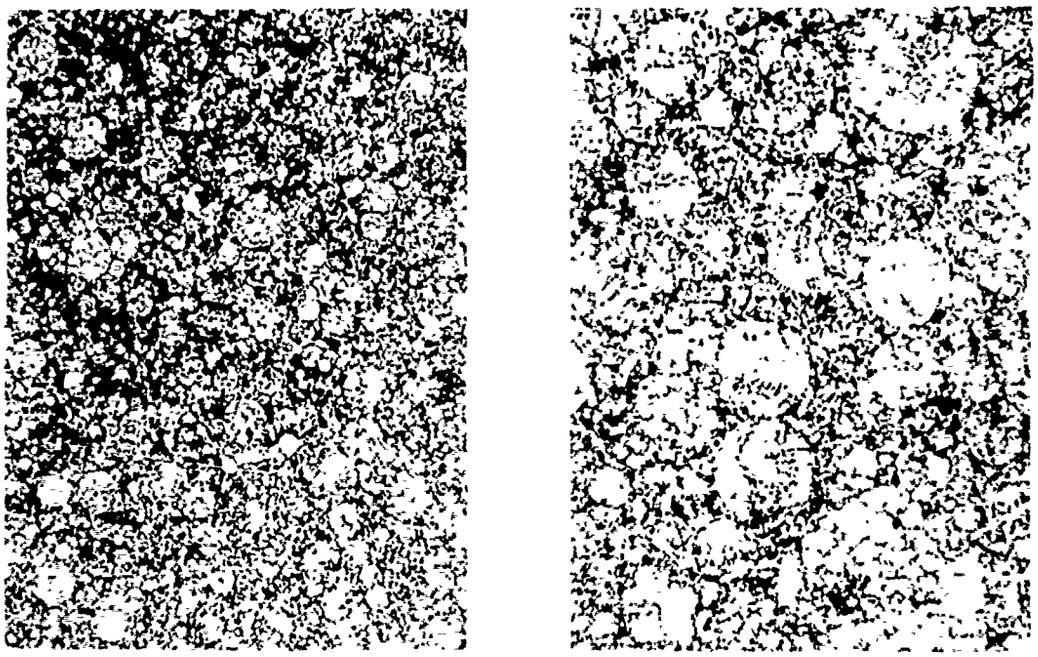
(d) 2050°F

Figure 1. As-HIP Microstructures of Vendor A's Initial Study, -60 Mesh Compacts Fabricated at: (c) 2050°F, and (d) 2050°F by Cold Wall Techniques (Sheet 2).



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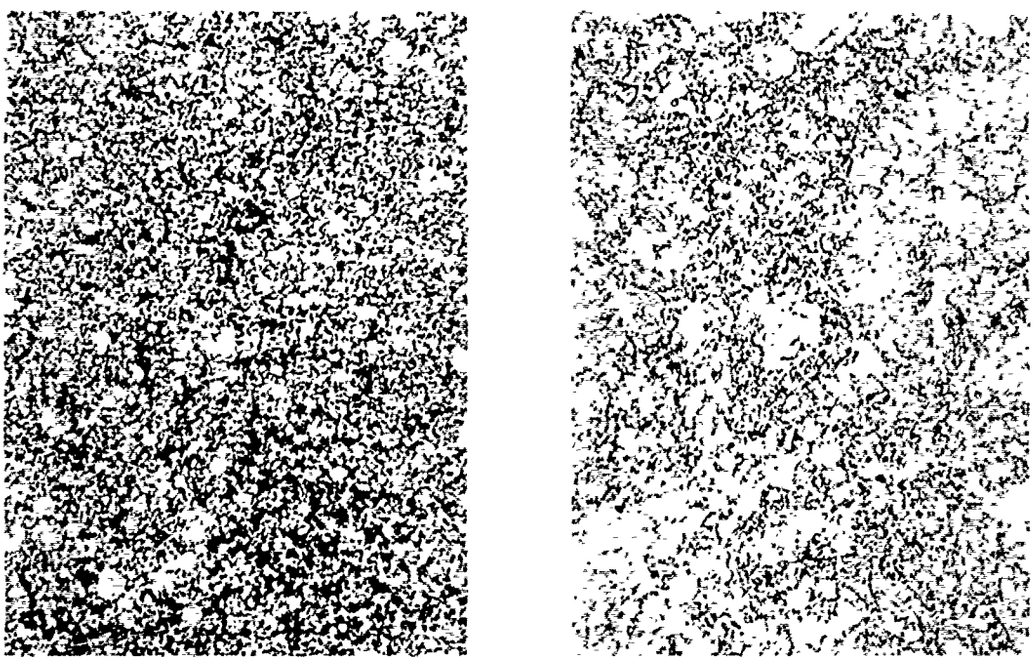
(a) 1950°F



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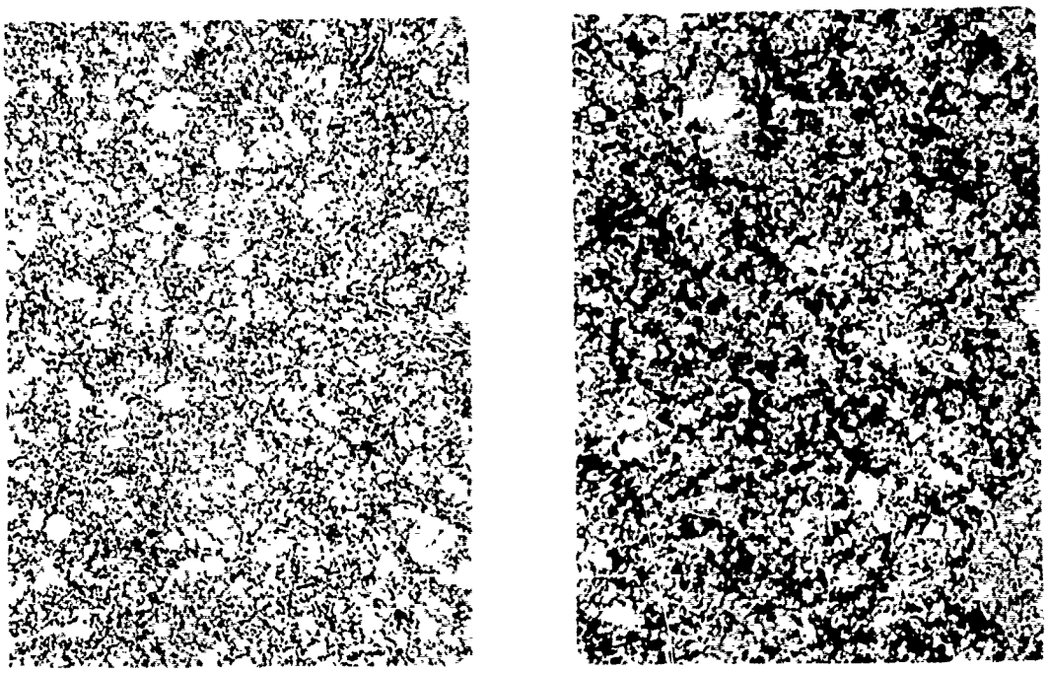
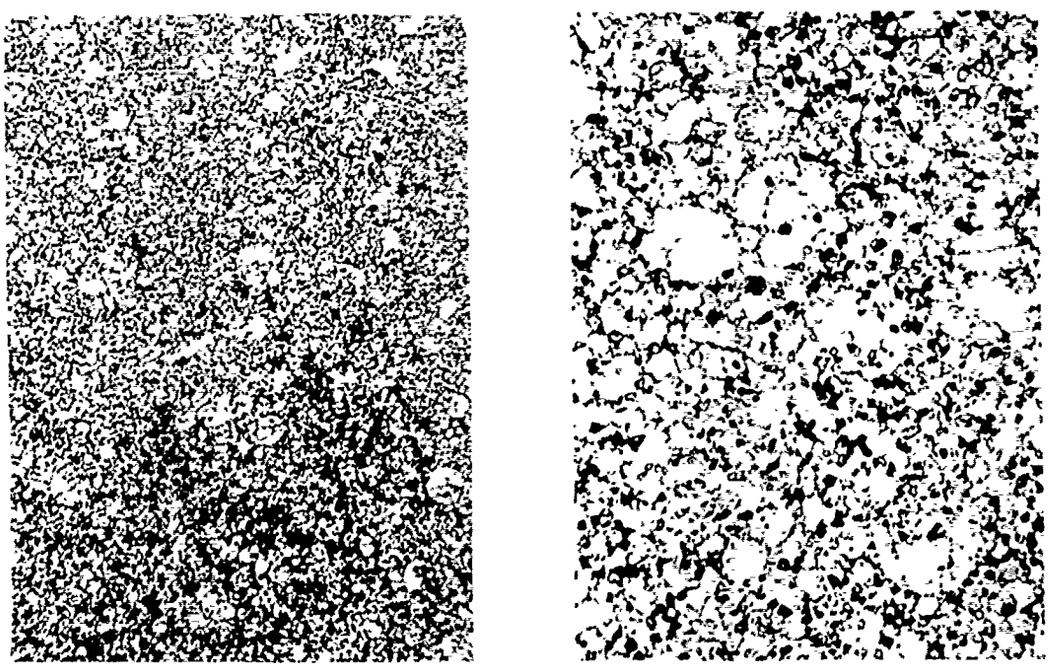
(b) 2000°F

Figure 2. As-HIP Microstructures of Vendor A's Initial Study, -200 Mesh Compacts Fabricated at: (a) 1950°F and (b) 2000°F (Sheet 1).



500X 100X

(c) 2050°F



100X 500X

(d) 2050°F

Figure 2. As-HIP Microstructures of Vendor A's Initial Study, -200 Mesh Compacts Fabricated at: (c) 2050°F by Autoclave, and (d) 2050°F by Coldwall Technique (Sheet 2).

TABLE 3. TENSILE PROPERTIES OF INITIAL STUDY COMPACTS – VENDOR A

RT Tensile

Powder Size	HIP Temperature (°F)				Program Goals	
	Autoclave			Coldwall		
	1950	2000	2050	2050		
−60	177	174	170	168	180	YS (ksi)
	236	234	228	233	230	TS (ksi)
	14	14	13	15	10	E1 (%)
	19	18	18	20	12	RA (%)
−200	–	–	180	177	180	YS (ksi)
	–	–	231	204	230	TS (ksi)
	–	–	11	4	10	E1 (%)
	–	–	15	11	12	RA (%)

1200°F Tensile

Powder Size	HIP Temperature (°F)				Program Goals	
	Autoclave			Coldwall		
	1950	2000	2050	2050		
−60	169	161	– 155	155	167	YS (ksi)
	210	208	209, 209	209	207	TS (ksi)
	7	10	11, 15	14	8	E1 (%)
	9	11	16, 17	18	10	RA (%)
−200	–	–	170	161*, 166	167	YS (ksi)
	–	–	214	162*, 212	207	TS (ksi)
	–	–	10	1*, 14	8	E1 (%)
	–	–	15	4*, 17	10	RA (%)

*Specimen cracked

Heat Treatment – (2-1/2 x 3 in. blanks) 1650°F/4 hr 2000°F/1 hr/OQ + 1400°F/16 hr/AC

TABLE 4. STRESS-RUPTURE PROPERTIES OF INITIAL STUDY COMPACTS – VENDOR A

1200°F/150,000 psi Stress Rupture

Powder Size	HIP Temperature (°F)				Program Goals	
	Autoclave			Cold Wall		
	1950	2000	2050	2050		
–60	8, 78	147, 16	73, 59	137, 134	50	Life (hr)
	1, 2	2, 2	2, 4	2, 2	3	E1 (%)
	2, 6	7, 5	6, 6	6, 4		RA (%)
–200	–	–	257, 136	64, 12	50	Life (hr)
	–	–	2, 2	3, 2	3	E1 (%)
	–	–	3, 4	6, 3		RA (%)

Heat Treatment – 1650°F/4 hr 2000°F/1 hr/OQ + 1400°F/16 hr/AC

cold wall compaction met the stress-rupture life goal but fell short of the desired elongation. This lack of stress-rupture ductility, which generally indicates marginal low-cycle fatigue resistance, was considered the primary problem to be faced in Task IA.

The examination of the As-HIP microstructures and mechanical properties indicates that retention of prior particle identity may have a deleterious effect on ductility. Prior powder particle outlining with resultant lack of ductility is thus an undesirable condition and should be avoided. A thorough evaluation of its impact, however, was not the goal of this program. The grain growth across prior particle boundaries decreased the tensile properties slightly in the -60 mesh compacts, but the associated ductility improvements more than compensate for this strength loss.

These results suggested that a 2050°F compaction temperature should be used on both -60 and -200 mesh powder. The "cold wall" process appears to have potential and should be investigated further.

To investigate the effect of increased solution treatment temperature (above 2000°F) on microstructure and mechanical properties, a higher solution temperature was considered to be potentially useful, since studies* have indicated a γ' solvus temperature of 2125° through 2150°F for As-HIP powder metallurgy Rene' 95. This is significantly higher than the 2075° through 2090°F solvus temperature generally observed for cast + wrought Rene' 95.

Three mesh size/compaction temperature combinations were exposed at 2000° and 2100°F solution annealing temperature followed by a 1400°F/16-hour/AC aging heat treatment prepared by Vendor A.** Test results given in Table 5 indicated that the 2100°F solution treatment improved room temperature tensile and 1200°F stress-rupture properties in the -60 and -200 mesh powder compacts. The improvement in tensile properties is more pronounced in the -60 mesh powder compacts. With the 2100°F solution annealing temperature, the effect of mesh size on tensile properties is greatly reduced.

Stress-rupture results, also shown in Table 5, indicated a significant improvement in rupture life of the -60 mesh compacts with no loss of rupture ductility. The increased solution temperature appears to have reduced the average rupture life of -200 mesh powder compacts slightly with no apparent effect on ductility.

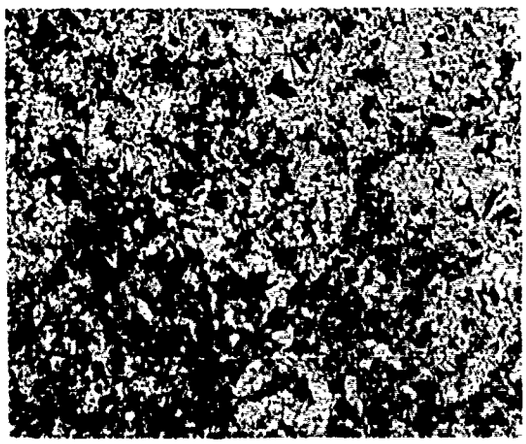
The effect of solution temperature on microstructure of the three compacts investigated is illustrated in Figures 3, 4, and 5. The behavior of -60 mesh compact consolidated at 2000°F in an autoclave was typical of that observed in all compacts (Figure 3). The large quantity of very coarse, unsolutioned γ' present after the 2000°F treatment was reduced substantially by the 2100°F exposure. The absence of grain growth and the presence of a few large, agglomerated γ' particles after the higher solution treatment verify that the γ' solvus temperature is above 2100°F. The dendritic structure retained during the 2000°F compaction cycle was reduced but not quite eliminated by the 2100°F treatment. Grain size appears to range from ASTM 8 to 11 independent of solution temperature.

The beneficial effect of the 2100°F solution treatment was more obvious in the -60 mesh compact consolidated at 2050°F (Figure 4). The dendritic structure has been eliminated by the higher consolidation temperature. As in Figure 3, the 2100°F treatment reduces the amount of coarse γ' without increasing the grain size. Both samples appear to contain essentially the same grain size noted in Figure 3 (ASTM 8 to 11), although most grain boundaries are covered by γ' particles after the 2000°F solution. The substantial improvement in tensile and stress-rupture properties of this compact after the 2100°F treatment is primarily due to the increased quantity of solutioned γ' available for precipitation during the subsequent aging treatment. The increased volume

*Private Communication Vendor A.
**Heat treat section size was 2½ inches in diameter by 3 inches long.

TABLE 5. EFFECT OF SOLUTION TREATMENT ON MECHANICAL PROPERTIES OF INITIAL STUDY COMPACTS – VENDOR A

Mesh Size	Compaction Temperature (°F)	Solution Treatment	Room Temperature Tensile 0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	1200°F/150 ksi Stress Rupture Life (hr)	El (%)	RA (%)
							147	2.0	7.0
−60	2000	2000°F/1 hr/OQ	174	234	14	18	16	2.0	5.0
							164	2.0	6.0
−60	2000	2100°F/1 hr/OQ	180	244	16	19	372	2.0	5.0
							73	2.0	6.0
−60	2050	2000°F/1 hr/OQ	170	228	13	18	59	4.0	6.0
							166	3.0	6.4
−60	2050	2100°F/1 hr/OQ	186	239	10	14	314	3.0	7.0
							237	2.0	3.0
−200	2050	2000°F/1 hr/OQ	180	231	11	15	136	2.0	4.0
							111	3.0	4.0
−200	2050	2100°F/1 hr/OQ	186	239	12	15	120	1.0	4.0
Program Goals (min.)			180	230	10	12	50	3.0	



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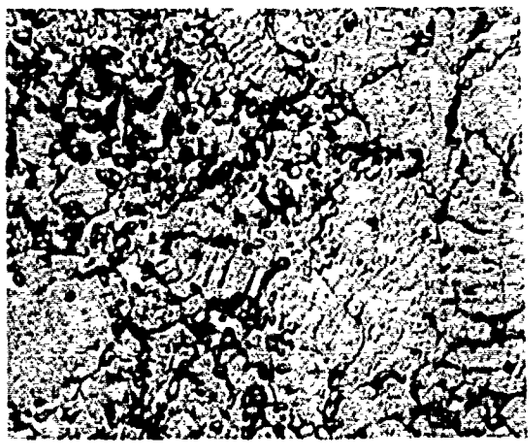

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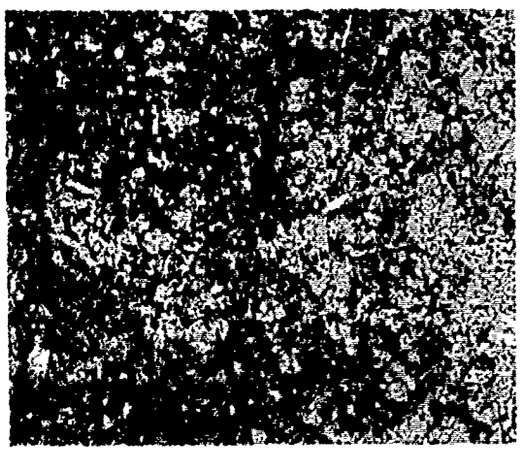
2000°F/1 hr/CQ Solution Treatment



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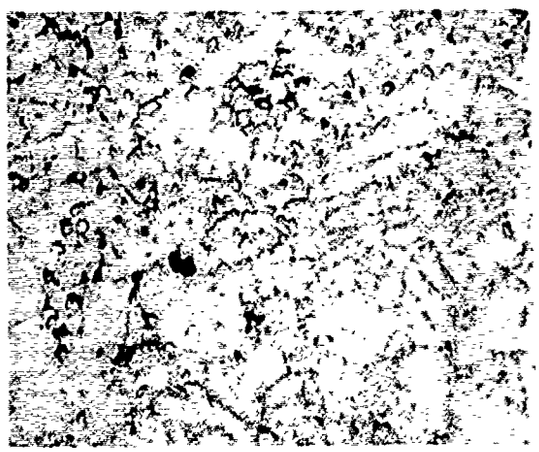
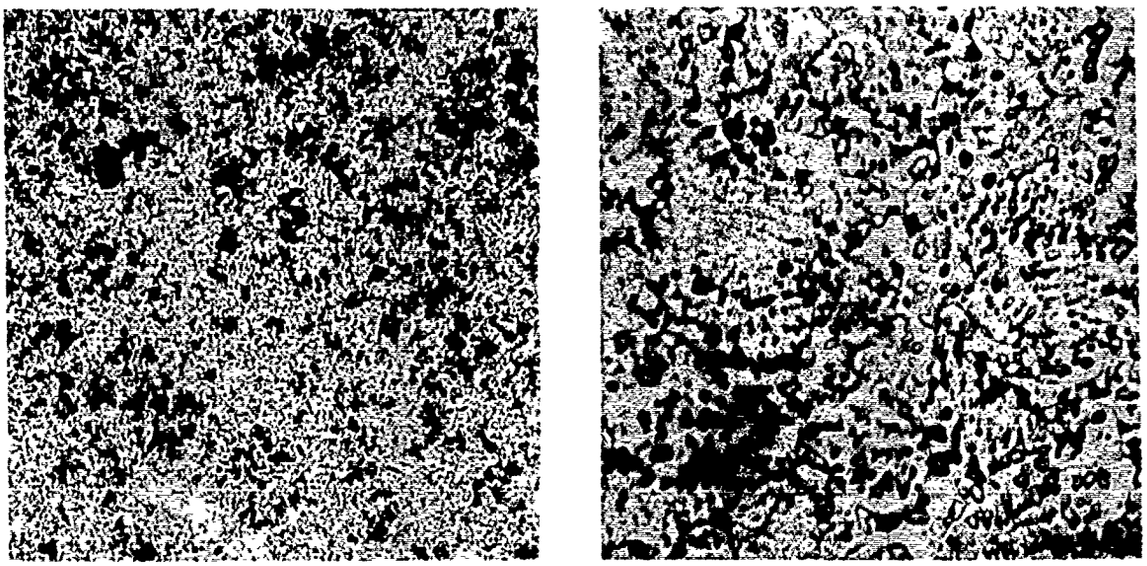


1000X

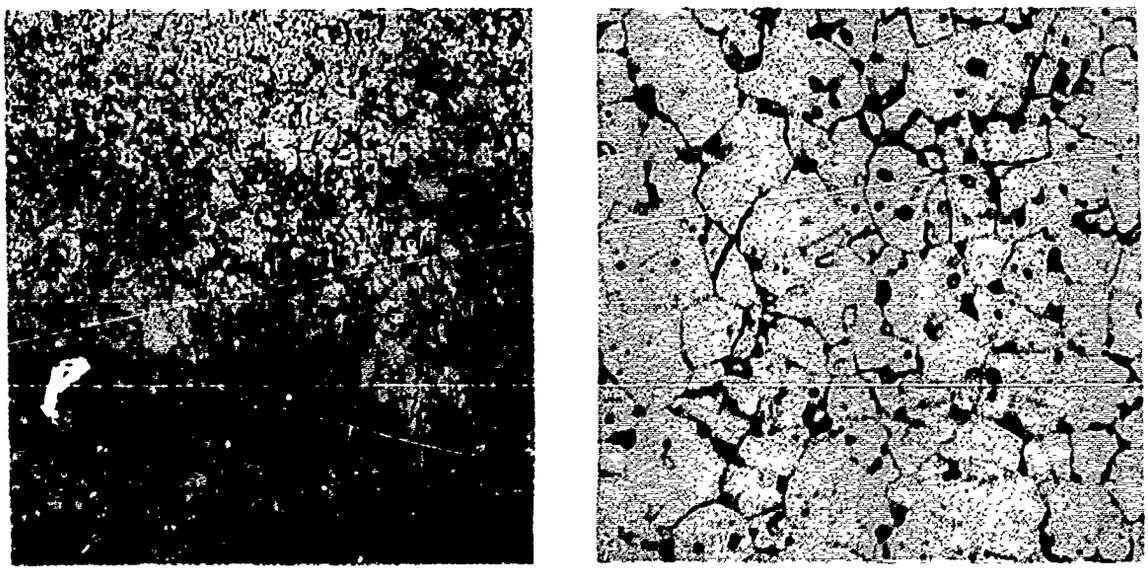
2100°F/1 hr/OQ Solution Treatment

Figure 3. Effect of Solution Treatment Temperature on Microstructure of Vendor A Initial Study -60 Mesh Compact Consolidated at 2000°F.



100X 1000X

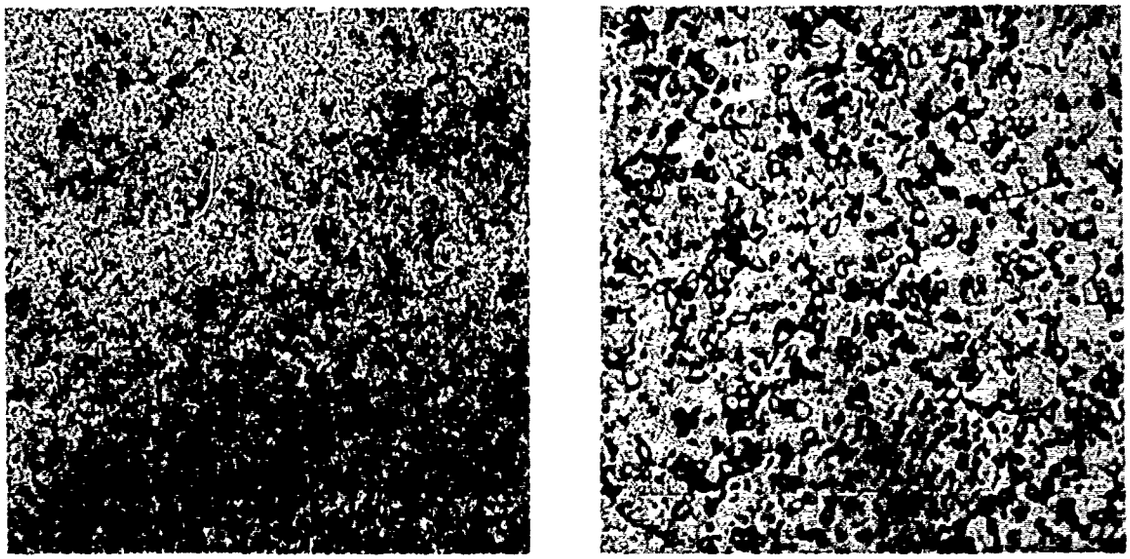
2000°F/1 hr/OQ Solution Treatment



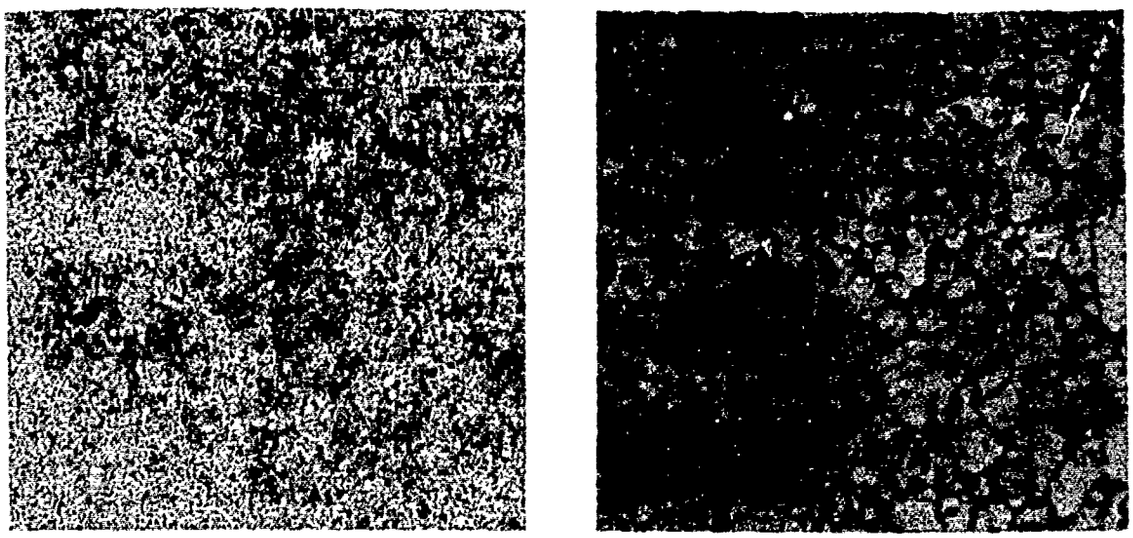
100X 1000X

2100°F/1 hr/OQ Solution Treatment

Figure 4. Effect of Solution Treatment Temperature on Microstructure of Vendor A Initial Study -60 Mesh Compact Consolidated at 2050°F.



100X 2100°F/1 hr/OQ Solution Treatment 1000X



100X 2000°F/1 hr/OQ Solution Treatment 1000X

Figure 5. Effect of Solution Treatment Temperature on Microsturcture of Vendor A Initial Study -200 Mesh Compact Consolidated at 2050°F.

fraction and decreased interparticle spacing of γ' precipitated during aging after the 2100°F solution produced the observed increase in mechanical properties.

The reaction of the -200 mesh compact consolidated at 2050°F to the solution treatments was virtually identical to that of the -60 mesh compact. The principal difference in the compacts was the finer grain size inherent in -200 mesh powder. The grain size of the -200 mesh compacts, shown in Figure 5, is ASTM 10 to 13 after either solution treatment. The presence of a considerable amount of intermediate size γ' particles after the 2100°F solution was unexpected, since they were not detected in the -60 mesh compact after the 2100°F treatment (Figure 4).

It can be concluded that a 2100°F/1-hour/OQ solution treatment improved room temperature tensile properties significantly relative to the standard 2000°F/1-hour/OQ treatment currently applied to wrought Rene' 95. This conclusion applies to -60 mesh powder consolidated at 2000° or 2050°F and -200 mesh powder consolidated at 2050°F. Stress-rupture lives of the -60 mesh compacts were also improved by the higher solution temperature, whereas the life exhibited by the -200 mesh material appeared to be degraded slightly.

Vendor B investigated the effects of HIP compaction temperature and pressure on density, microstructure and mechanical properties.

One compact, 3 inches in diameter and 6 inches long, of each HIP temperature/pressure combination described in Table 6 was filled with -60 mesh powder and compacted. Following compaction, specimen blanks 3 inches long and 5/8 inches in diameter were cut and subjected to the standard Rene' 95 heat treatment. The larger section size of engine hardware would, however, require faster quench rates to achieve similar properties.

Results of density measurements on As-HIP plus heat treated samples are presented in Table 7. It appears that several samples, compacted primarily at the lower temperature, deviate by maximum of ±0.01 percent from this heat's assumed theoretical density of 0.2995 ±.0001 pound/inch^3 (typical measuring accuracy).

The effects of compaction temperature and pressure on microstructure for the HIP conditions presented in Table 6 are shown in Figure 6. Photomicrographs of the -60 mesh compacts appear in Figure 6. Consolidation at lower temperature produced the same type of prior particle outlining observed in the Vendor A compacts.

Tensile properties of the heat-treated compacts, shown in Table 8, seem to indicate no significant effect of compaction temperature variation. Increasing compaction pressure seems to improve properties slightly. Nearly all specimens achieved the program goals at room temperature, but several exhibited low ductility at 1200°F.

Results of the stress-rupture testing at 1200°F/150 ksi are presented in Table 9. The data indicates the same erratic behavior and low rupture ductility as seen in the Vendor A compacts. The problem appears somewhat more severe in the Vendor B samples, since rupture lives as well as ductilities are very low in many cases.

In order to further investigate the effect of HIP cycle parameters on microstructure and mechanical properties, six additional 3-inch-diameter compacts were fabricated. Compacts containing -60 mesh and -100 mesh powder were consolidated using the following three different HIP cycles.

Cycle 1: Alumina grain fill used as insulation in HIP chamber. Very low pressure (500 psi) initially applied at room temperature and maintained until temperature stabilizes at 2050°F and then pressurized as rapidly as possible to 15,000 psi, held for 2 hours, and then the temperature and pressure are reduced as quickly as possible.

TABLE 6. INITIAL STUDY CONDITIONS EVALUATED BY VENDOR B

HIP Pressure (ksi) / HIP Temperature (°F)	15 ksi	30 ksi
1900	X	X
1950	–	X
2000	X	X
2050	X	–

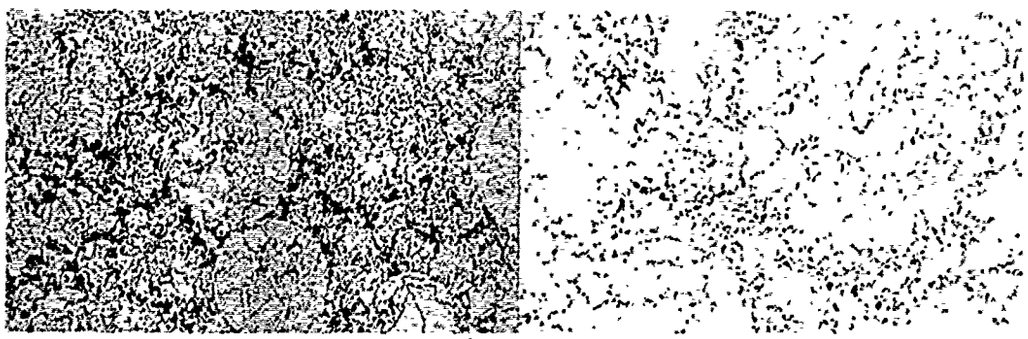
TABLE 7. AS-HIP DENSITIES OF INITIAL STUDY COMPACTS OF VENDOR B

HIP Compaction Pressure (ksi)	HIP Compaction Temperature (°F)			
	1900	1950	2000	2050
15	0.2991*		0.2991	0.2996
30	0.2992	0.2995	0.2993	

*All densities expressed as lb/in.^{3}

100K 1900°F/15 ksi 500X

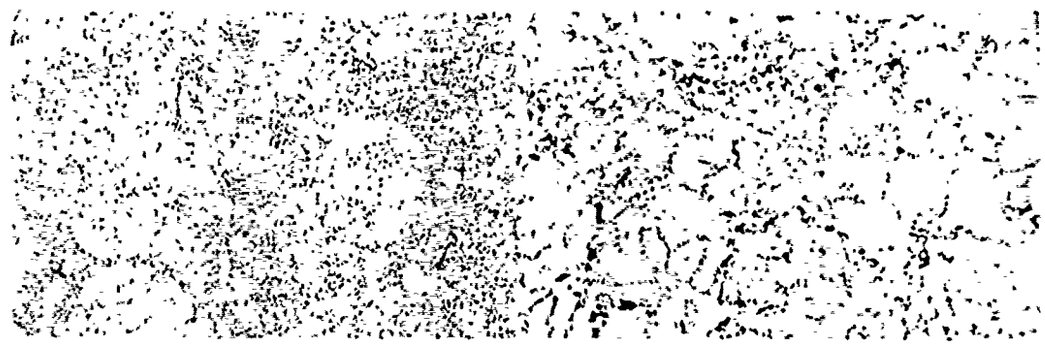
100X 1900°F/30 ksi 500X



100X 1950°F/30 ksi 500X

Figure 6. Microstructures of -60 Mesh Vendor B Initial Study Compacts – (Sheet 1).

100X 2000°F/15 ksi 500X



100X 2000°F/30 ksi 500X

100X 2050°F/15 ksi 500X

Figure 6. Microstructures of -60 Mesh Vendor B Initial Study Compacts – (Sheet 2).

TABLE 8. TENSILE PROPERTIES OF INITIAL STUDY COMPACTS – VENDOR B

Room Temperature

HIP Compaction Pressure (ksi)	HIP Compaction Temperature (°F)				Program Goal	
	1900	1950	2000	2050		
15	187		182	181	180	0.2 YS (ksi)
	240		233	238	230	UTS (ksi)
	16.2		14.3	17.1	10	E1 (%)
	18.2		13.8	14.6	12	RA (%)
30	190	189	189		180	0.2 YS (ksi)
	227	241	232		230	UTS (ksi)
	10.0	16.1	11.4		10	E1 (%)
	13.8	16.7	12.3		12	RA (%)

1200°F

HIP Compaction Pressure (ksi)	HIP Compaction Temperature (°F)				Program Goal	
	1900	1950	2000	2050		
15	169		168	168	167	0.2 YS (ksi)
	212		214	219	207	UTS (ksi)
	7.7		8.6†	11.5†	8	E1 (%)
	10.3		11.6†	11.6†	10	RA (%)
30	171	171	170		167	0.2 YS (ksi)
	216	205	208		207	UTS (ksi)
	8.0	*	6.3		8	E1 (%)
	9.4	*	5.9		10	RA (%)

*Fixtures failed – no fracture
†Specimen failed in fillet radius

TABLE 9. STRESS RUPTURE PROPERTIES OF INITIAL STUDY COMPACTS – VENDOR B

Test Conditions – 1200°F/150 ksi

HIP Compaction Pressure (ksi)	HIP Compaction Temperature (°F)				Program Goal	
	1900	1950	2000	2050		
15	41.9, 20.7 0.0, 0.0 0.0, 0.0		20.9, 10.6 0.3, 0.0† 0.0, 0.0†	28.2, 14.0 1.0, 0.6 0.0, 0.0	50 3.0 –	Life (hr) E1 (%) RA (%)
30	26.9, 19.2 0.6, 1.9 2.0, 4.4	68.0, 128.5 1.1, 1.6 3.2, 4.6	152.4, 3.0 2.2, 0.8 4.4, 3.2		50 3.0 –	Life (hr) E1 (%) RA (%)

†Specimen failed in fillet radius

Cycle 2: Same procedure as Cycle 1 without alumina grain fill.

Cycle 3: Alumina grain fill is not used. Maximum pressure (15,000 psi) at room temperature is applied and then heated as rapidly as possible to 2050°F, maintaining 15,000 psi pressure at all times by bleeding off gas as the temperature increases. Compacts are held for 2 hours after stabilizing at 2050°F, and then the temperature and pressure are reduced as quickly as possible.

Density results of consolidated samples presented in Table 10 indicate that the compacts consolidated using HIP Cylces 1 and 3 were essentially fully dense, while compacts from Cycle 2 contained a very slight amount of porosity (0.1 percent). Thermally induced porosity (TIP) testing to determine the amount of argon gas remaining revealed that the -60 mesh compact from Cycle 1 contained large amounts of argon. The remaining compacts contained acceptably low quantities of argon.

Tensile properties, given in Table 11, were obtained at room temperature and 1200°F on heat-treated* -60 and -100 mesh compacts. Tensile strengths are lower than those obtained in the previous compacts; a contributing factor may be the larger section size of the heat treat specimen. The 3-inch-diameter HIP cycle study compacts were heat treated prior to machining the specimens, whereas 0.625-inch-diameter machined specimen blanks were treated and tested initially. The data indicate that powder mesh size has little effect on room temperature strength. Various HIP cycles appeared to produce similar results, although the ductility of Cycle 3 was marginal.

Stress-rupture results, presented in Table 12, indicate very low ductilities and only one acceptable life value for all cycles and powder mesh sizes. Thus no conclusions could be reached for an acceptable cycle. The variables investigated in the three cycles appear to have little effect on the heat-treated microstructure shown in Figure 7. The only microstructural feature that would be interpreted as varying with HIP cycle is the amount of residual dendritic structure in the -60 mesh compacts. Heating to the HIP temperature with insulation before pressurizing (Cycle 1) seems to reduce the quantity of dendritic structure retained from the atomized powder relative to Cycles 2 and 3, which probably is a measure of the total temperature/time exposure.

Initial studies thus indicated that 2050°F is the recommended compaction temperature and the compaction pressure of 15 ksi should be adequate. The HIP cycle does not seem to have any conclusive effect. However, Cycle 2 should be avoided. A higher solution temperature treatment (2100° versus 2000°F) improved mechanical properties and should be further investigated. The lack of adequate stress-rupture ductility, however, remains the problem to be faced in Task IA.

*Heat Treatment – 1650°F/4 hours/AC + 2000°F/1 hour/OQ + 1400°F/16 hours/AC.

TABLE 10. EFFECT OF HIP CYCLE ON DENSITY OF COMPACTS – VENDOR B

HIP Cycle* No.	Powder Mesh Size	Density		
		As Consolidated	After TIP Exposure**	% Change
1	−60	0.2988	0.2921	−2.24
	−100	0.2990	0.2986	−0.13
2	−60	0.2986	0.2984	−0.07
	−100	0.2987	0.2985	−0.07
3	−60	0.2989	0.2984	−0.17
	−100	0.2988	0.2986	−0.07

*1 – Pressurized at temperature – use insulating material
2 – Same as (1) w/o insulating material
3 – Same as (2) but pressurized at RT

**TIP (Thermal Induced Porosity) Exposure = 2200°F/4 hr/AC

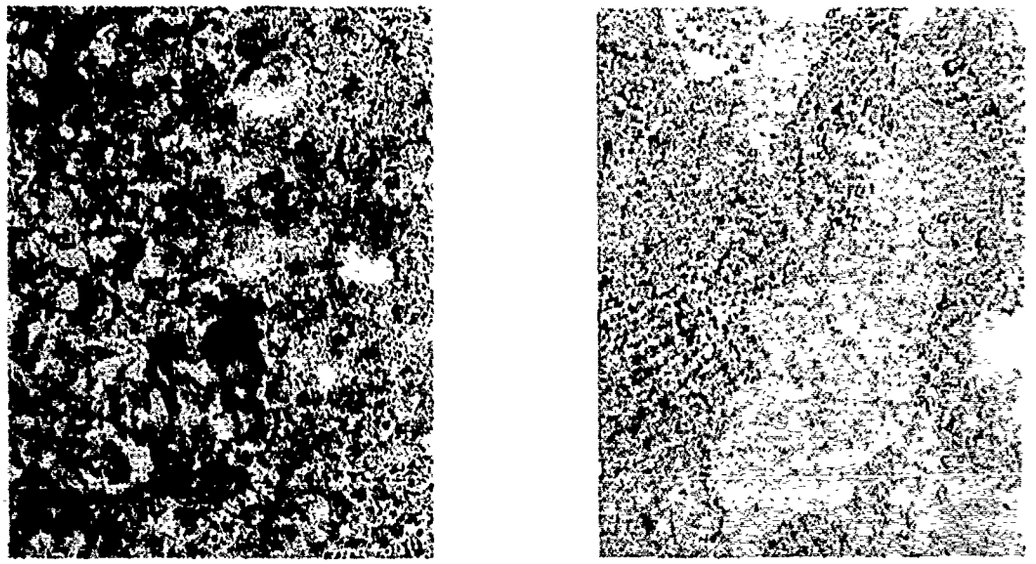
TABLE 11. EFFECT OF HIP CYCLE ON TENSILE PROPERTIES OF INITIAL STUDY COMPACTS – VENDOR B

HIP Cycle No.	Powder Mesh Size	Test Temp. (°F)	0.2% YS (ksi)	UTS (ksi)	Elong. (%)	RA (%)
1	–60	RT	Argon contamination			
	–100			234	13	15
2	–60		178	230	15	17
	–100		177	232	14	15
3	–60		184	229	12	14
	–100		182	236	13	14
1	–60	1200	Argon contamination			
	–100		160	216	12	14
2	–60		161	208	10	12
	–100		161	199	6	10
3	–60		170	197	4	11
	–100		164	187	3	10
Program Goals		RT	180	230	10	12
		1200	167	207	8	10

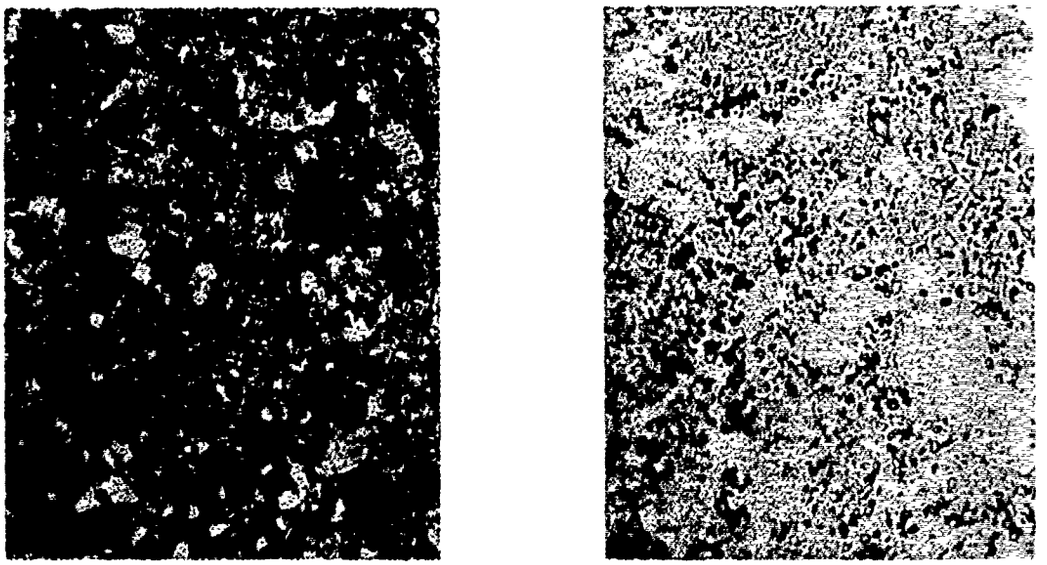
TABLE 12. EFFECT OF HIP CYCLE ON 1200°F/150 KSI STRESS RUPTURE PROPERTIES OF INITIAL STUDY COMPACTS – VENDOR B

HIP Cycle No.	Powder Mesh Size	Rupture Life (hr)	Elong. (%)	RA (%)
1	–60 –100	 3	Argon Contamination 0	 0
2	–60 –100	5.9 4.4	1.4 0	1.2 0
3	–60 –100	107 3.3	1.3 0	1.3 0
Program Goals		50	3	

HIP Cycle #1



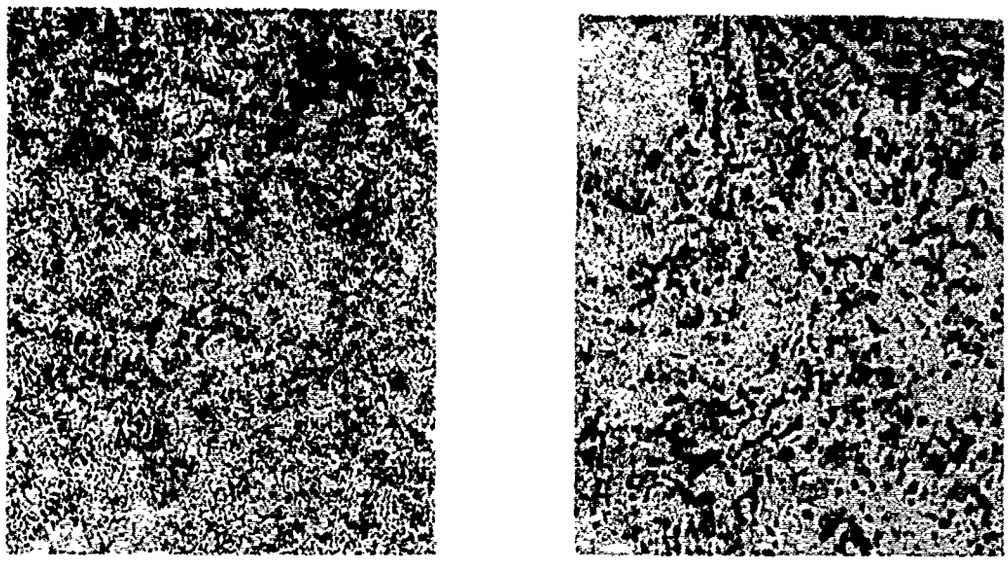
100X -60 Mesh 500X



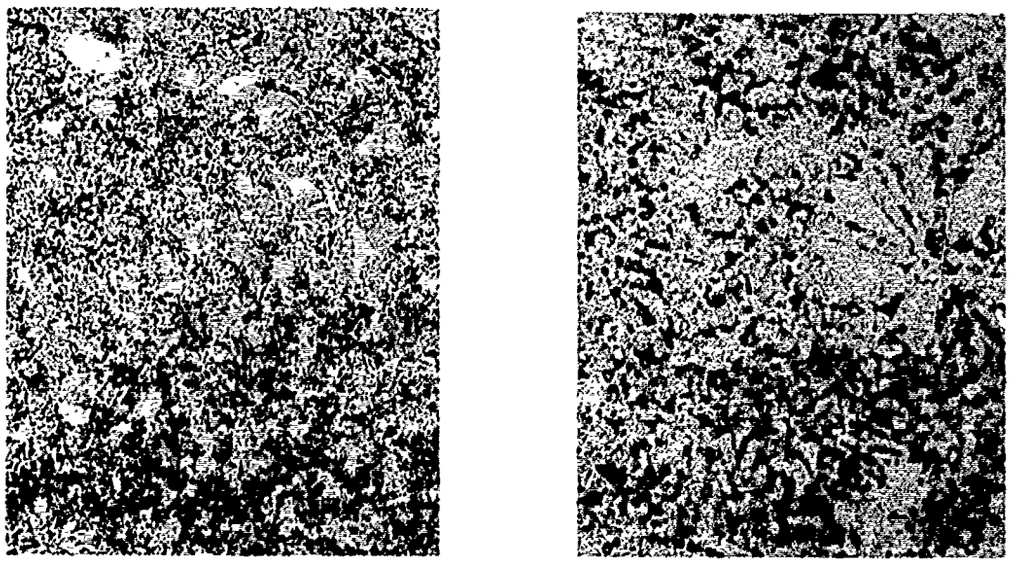
100X -100 Mesh 500X

Figure 7. Effect of HIP Cycle on Microstructure of Vendor B Initial Compacts (Cycle #1 – Pressurized at 2050°F with Insulating Material) (Sheet 1).

HIP Cycle #2



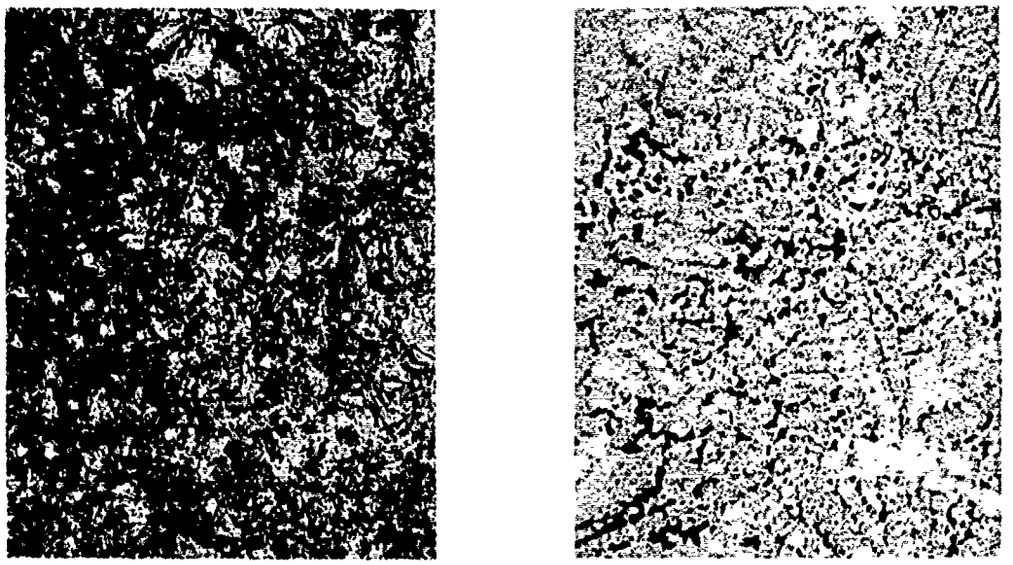
100X -60 Mesh 500X



100X -100 Mesh 500X

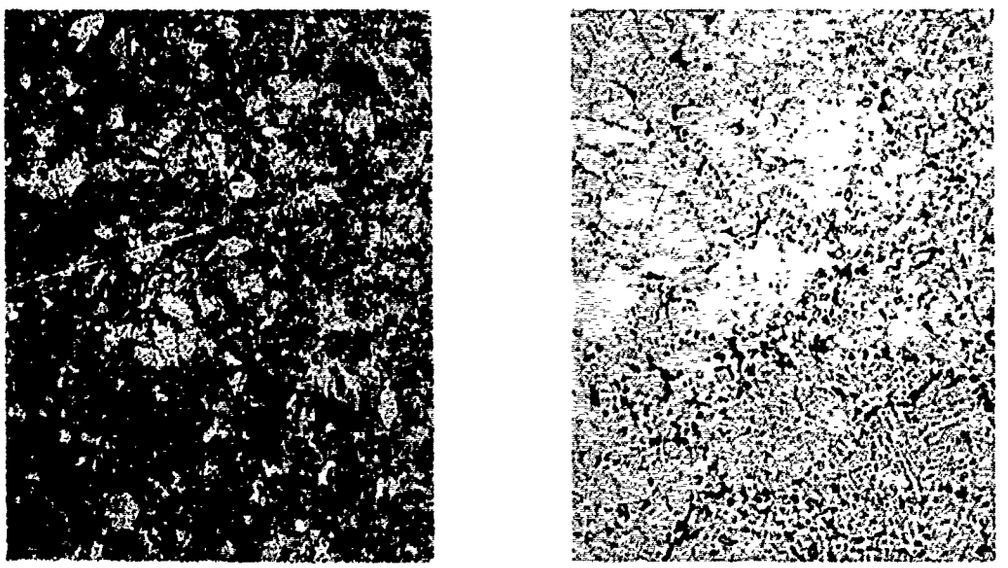
Figure 7. Effect of HIP Cycle on Microstructure of Vendor B Initial Compacts (Cycle #2 – Pressurized at 2050°F with Insulating Material) (Sheet 2).

HIP Cycle #3



100X 500X

-60 Mesh



100X 500X

-100 Mesh

Figure 7. Effect of HIP Cycle on Microstructure of Vendor B Initial Compacts (Cycle #3 Pressurized at 2050°F with Insulating Material) (Sheet 3).

TASK IA – HIP PROCESS DEFINITION

The primary objective of Task IA was to develop the processing parameters necessary to produce the program goal properties in As-HIP Rene' 95. Each of the powder vendors addressed the problem, utilizing the flow diagram shown in Figure 8.

Master powder blends of each of the two mesh size powders selected by the vendor were prepared. Vendor A used -60 and -200 mesh powder, while Vendor B selected -60 and -100 mesh powder for evaluation. Certified chemical analyses of powders from both vendors are presented in Tables 13 and 14.

The scanning electron micrographs shown in Figures 9 and 10 indicate that the -60 mesh powders from Vendors A and B are virtually identical in size, shape and satellite formation. Other than the expected lack of large particles in the finer mesh powders, the morphologies of Vendor A's -200 mesh and Vendor B's -100 mesh powders are very similar to their -60 mesh products.

Each powder vendor fabricated hollow cylindrical billets from -60 mesh and their finer mesh powders. The powders were encapsulated in mild steel and hot isostatically pressed at 2050°F. Final dimensions of the cylinders were approximately 6.5 inches outside diameter by 2.75 inches inside diameter by 20 inches in length. Compacted cylinders, when cut into 2-inch-thick slices, were prototypes of the cooling plate shapes.

Density and thermally induced porosity (TIP) measurements were completed on billets A and B from Vendor B and billets B107 and B111 from Vendor A to determine the relative amount of entrapped argon in each compact. The determination consisted of density measurements on samples in the As-HIP and As-HIP + heat treated (2200°F/4 hours) conditions. The observed decrease in density is proportional to the quantity of argon remaining in the compact. Results, given in Tables 15 and 16, indicate that all areas of both vendor's billets conform to GE's specification C50TF64, Paragraph 3.6, requirements (0.2 percent change maximum).

All the As-HIP compacts were subjected to metallographic examination. Microstructure of Vendor A's-60 mesh and -200 mesh billets (B111 and B107 respectively) confirmed the desired fine grain structure (Figures 11 and 12). Vendor B's billet A (Figure 13) has a uniform microstructure suggesting uniform heating. The microstructure of billet B (Figures 14a and 14b) showed increased grain size and preferential precipitation of large γ' at prior particle boundaries near the top of the compact indicating possible overheating in this region. To determine the longitudinal penetration of overheating, two slices (2 inches thick) were cut from the top of compact B. Optical metallography of samples (Figure 15) from top and bottom of these slices suggested that less than 2.5 inches of the total length was overheated. Only the material cut from below the overheated section of billet B was used in Task IA.

SCREENING TEST EVALUATION

A number of 2-inch-thick slices from -60 mesh powder billets were prepared for the heat treatment study. The plan for the heat treatment study is described in Table 17. The two principal variables in this study were solution temperature and aging treatment. The hollow cylinders were quartered after solutioning so that four different aging treatments could be examined on each cylinder. A typical slice is shown in Figure 16 after it had been solutioned and sectioned into quarter segments prior to application of the experimental aging treatments.

Each vendor solution treated two cylinders (1 and 2) using the standard (wrought) Rene' 95 solution temperature (2000°F) and applied eight different aging treatments to the quarter sections. In addition to establishing a reference condition of the standard heat treatment with the 1400°F/16-hour age, several overaging treatments

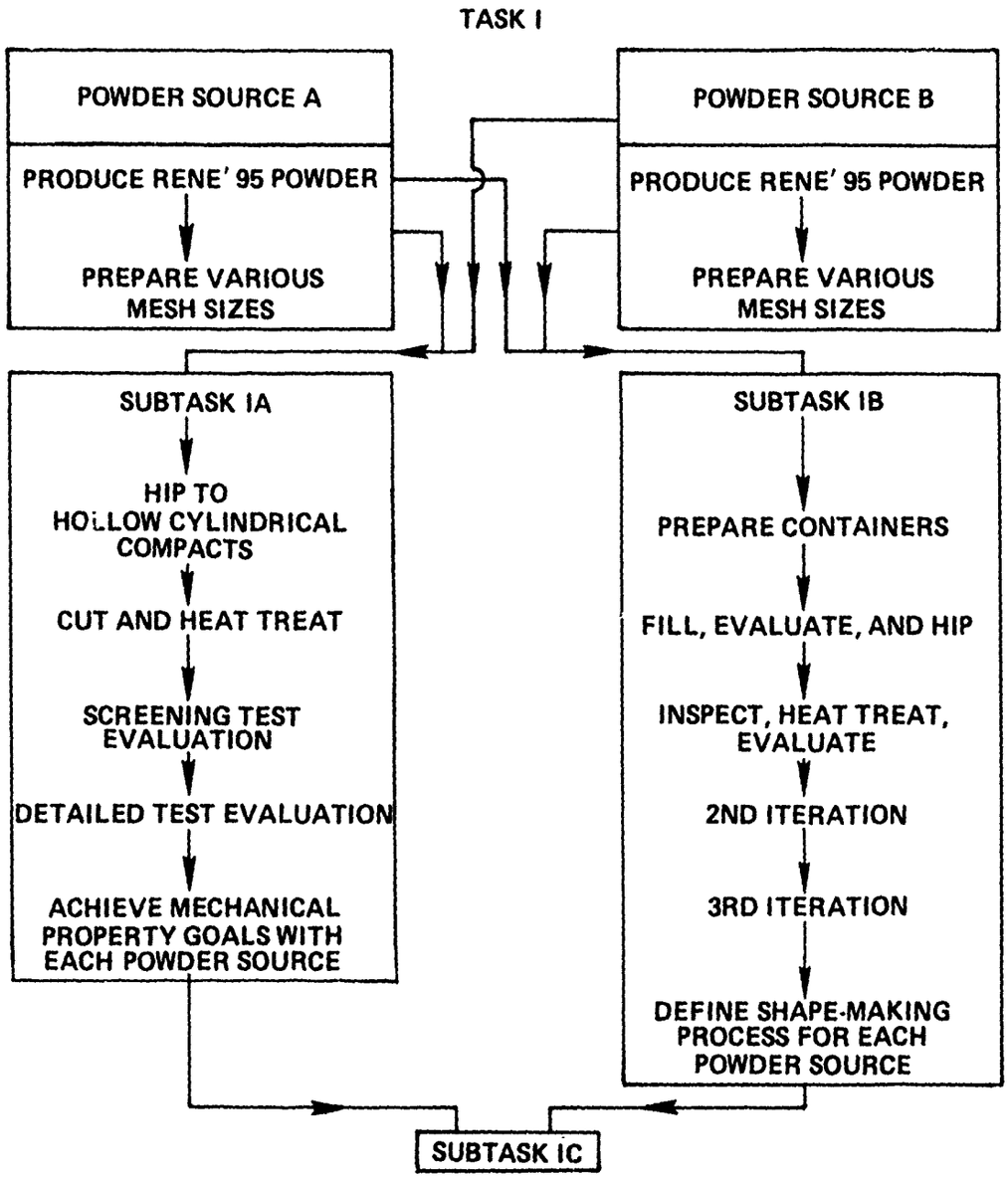


Figure 8. Flow Chart for Task I.

TABLE 13. CHEMISTRY OF TASKS I AND II RENE' 95 POWDER – VENDOR A

Heat Code	Powder Type	Elemental Content (Wt. %)														
		C	Mn	S	Si	P	Cr	Co	Cb	Mo	W	Ti	Al	B	Zr	Fe
MB009	– 60 Mesh	0.059	<0.01		0.15		12.84	8.17	3.55	3.51	3.35	2.60	3.60	0.009	0.04	0.08
MB010	–200 Mesh	0.058	0.01	0.004	0.11	0.003	13.00	8.25	3.49	3.53	3.27	2.59	3.53	0.009	0.05	0.18

Heat Code	Powder Type	O_2	N_2	H_2
MB009	– 60 Mesh	50*	27*	3*
MB010	–200 Mesh	89*	34*	3*

*Parts Per Million

TABLE 14. CHEMISTRY OF VENDOR B TASK I AND II RENE' 95 POWDER

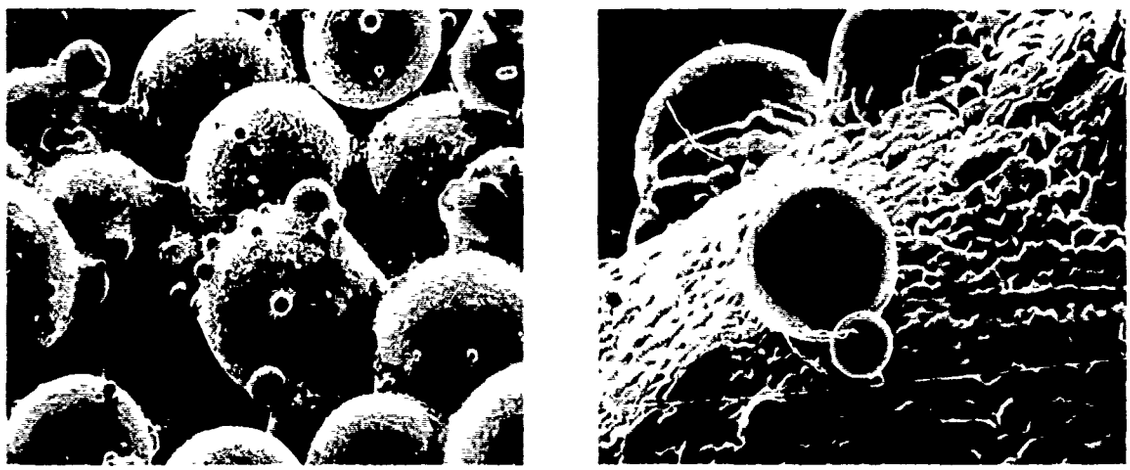
MAJOR ELEMENTS (Wt. %)

Powder Blend	C	Cr	Mo	Co	Ti	Al	Cb	W	Zr	B
−60 Mesh	0.072	13.19	3.50	8.14	2.55	3.48	3.51	3.49	0.056	0.011
−100 Mesh	0.072	13.09	3.37	8.07	2.54	3.60	3.48	3.44	0.056	0.012
C50TF64	0.04–0.09	12–14	3.3–3.7	7–9	2.3–2.7	3.3–3.7	3.3–3.7	3.3–3.7	0.03–0.07	0.006–0.015

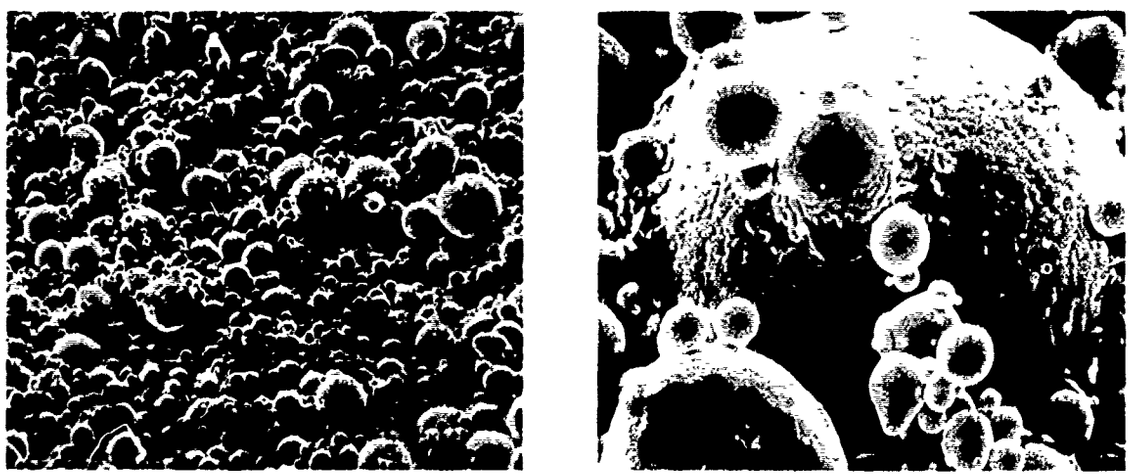
OTHER ELEMENTS

Powder Blend	Mn	Si	P	S	Ta	Fe	O	N	H
−60 Mesh	0.01	0.02	<0.005	0.002	<0.02	0.08	40*	10*	3*
−100 Mesh	0.01	0.03	<0.005	0.002	<0.02	0.08	44*	10*	4*
C50TF64	0.15 Max.	0.2 Max.	0.015 Max.	0.015 Max.	0.2 Max.	0.5 Max.	150* Max.	50* Max.	10* Max.

*Parts per million

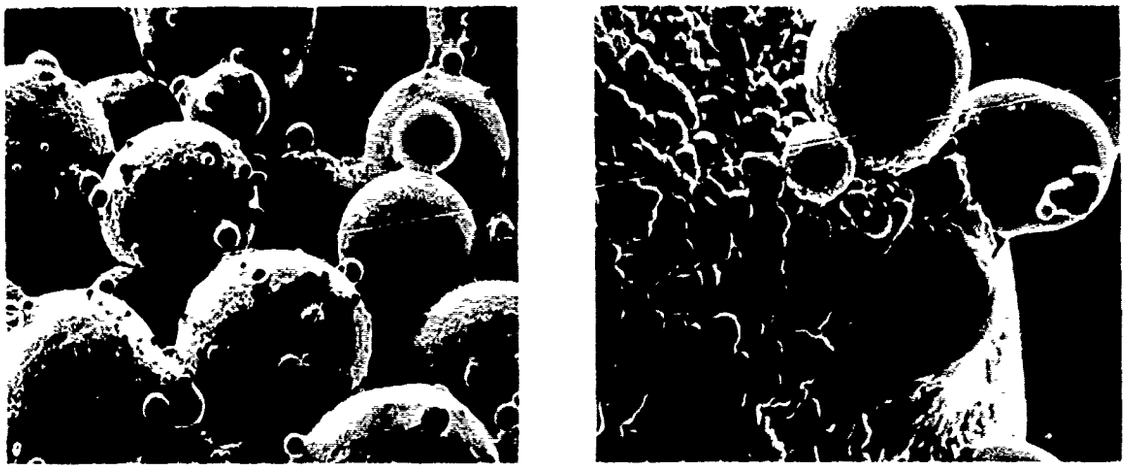


110X -60 Mesh 1100X

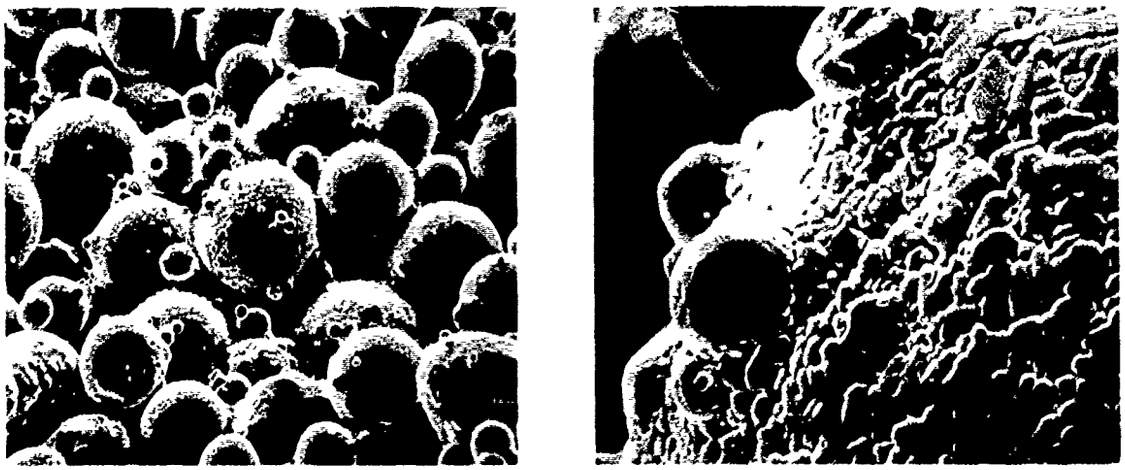


110X -200 Mesh 1100X

Figure 9. Scanning Electron Micrographs of Powder Used in Task 1 -- Vendor A.



110X -60 Mesh 1100X



110X -100 Mesh 1100X

Figure 10. Scanning Electron Micrographs of Powder Used in Task I - Vendor B

TABLE 15. THERMALLY INDUCED POROSITY MEASUREMENTS ON TASK IA BILLETS – VENDOR A

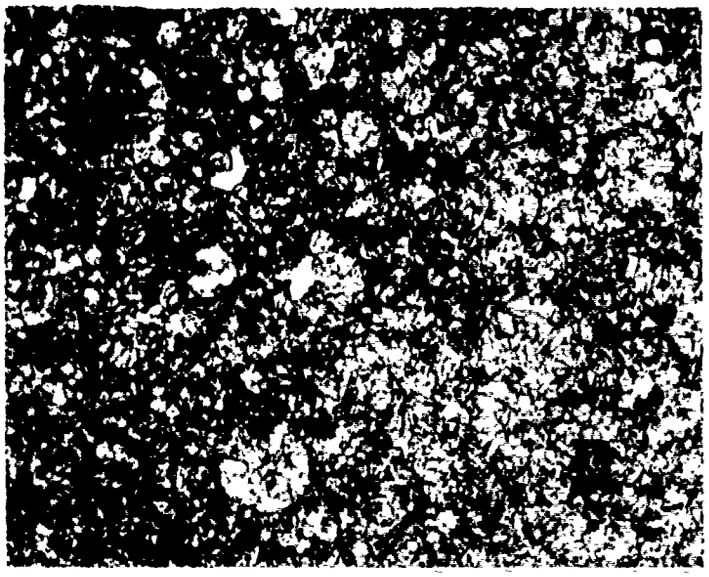
Billet No.	Powder Mesh Size	Density ($lb/in.^3$)		Density Change (%)
		As-HIP	TIP*	
B107	–200	0.2981	0.2974	0.23
B107	–200	0.2983	0.2975	0.28
B111	–60	0.2982	0.2975	0.21
B111	–60	0.2983	0.2975	0.29

*TIP Treatement – 2200°F/4 hr/AC

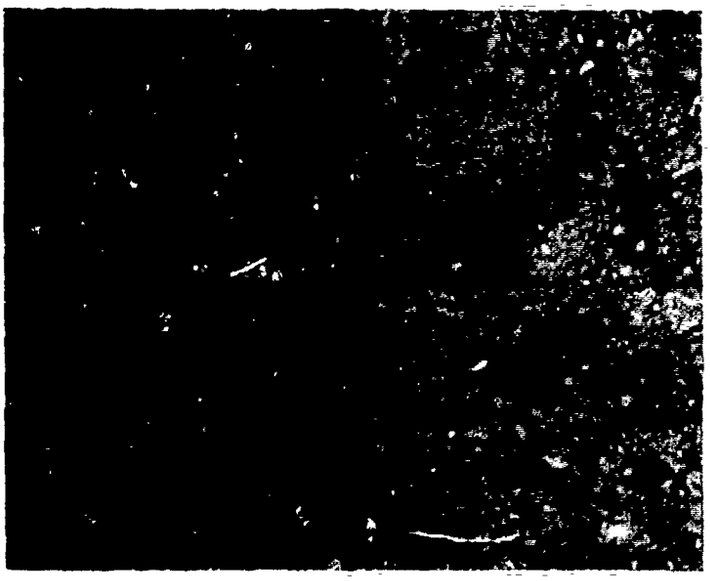
TABLE 16. THERMALLY INDUCED POROSITY MEASUREMENTS ON TASK IA BILLETS – VENDOR B

Billet	Billet End	Location	As-HIP Density (lb/in.^{3})	TIP* Density (lb/in.^{3})	Density Change (%)
A	Top	OD[1]	0.2992	0.2989	-0.11
	Top	Mid Radius	0.2991	0.2990	-0.05
	Top	ID[2]	0.2992	0.2992	-0.00
	Bottom	O.D.	0.2992	0.2984	-0.24
	Bottom	Mid Radius	0.2992	0.2986	-0.19
	Bottom	I.D.	0.2992	0.2986	-0.19
B	Top	O.D.	0.2991	0.2989	-0.09
	Top	Mid Radius	0.2992	0.2990	-0.09
	Top	I.D.	0.2993	0.2989	-0.13
	Bottom	O.D.	0.2991	0.2986	-0.18
	Bottom	Mid Radius	0.2991	0.2985	-0.21
	Bottom	I.D.	0.2992	0.2985	-0.23

*TIP Treatment – 2200°F/4 hr/AC
[1]OD – Outside diameter of hollow cylinder
[2]ID – Inside diameter of hollow cylinder

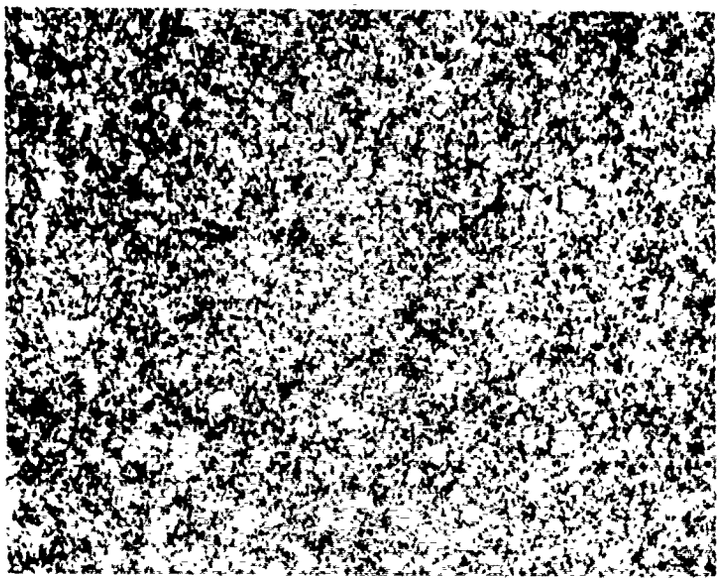


100X



1000X

Figure 11. Microstructure of Task IA -60 Mesh Billet B111 -- Vendor A.



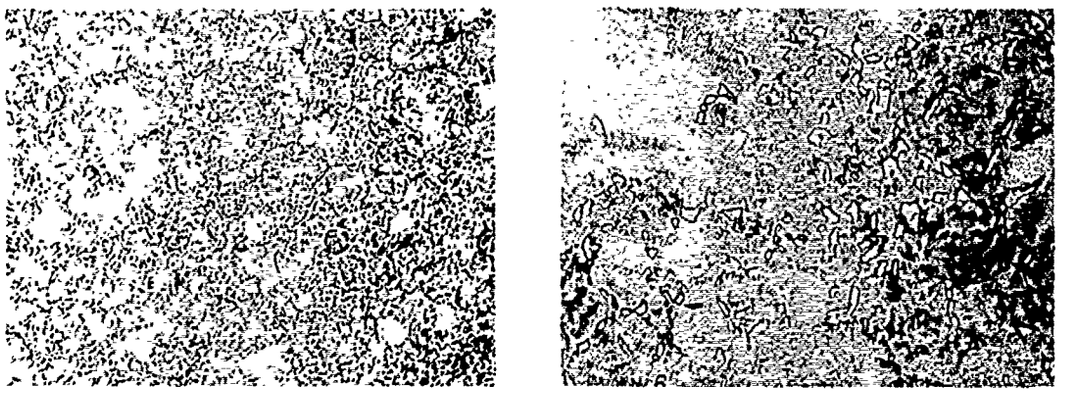
100X

1000X

Figure 12. Microstructure of Task IA -200 Mesh Billet B107 – Vendor A.

100X 500X

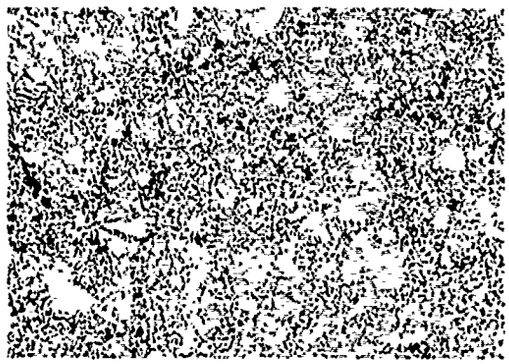
a) Top Surface at Inside Diameter



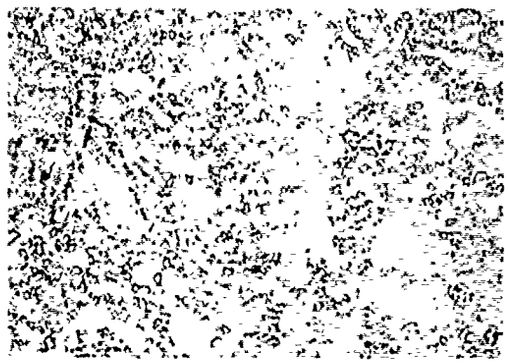
100X 500X

b) Top Surface at Outside Diameter

Figure 13. Metallographic Survey of Task IA -60 Mesh Billet A – Vendor B (Sheet 1).

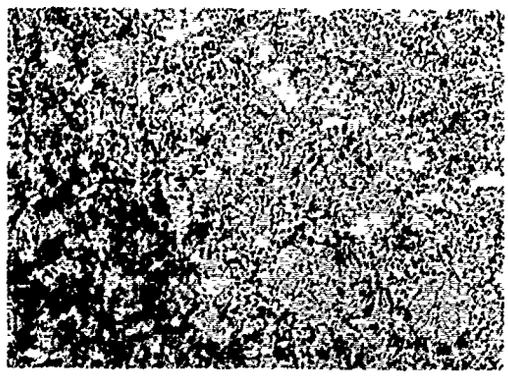


100X



500X

c) Bottom Surface at Inside Diameter

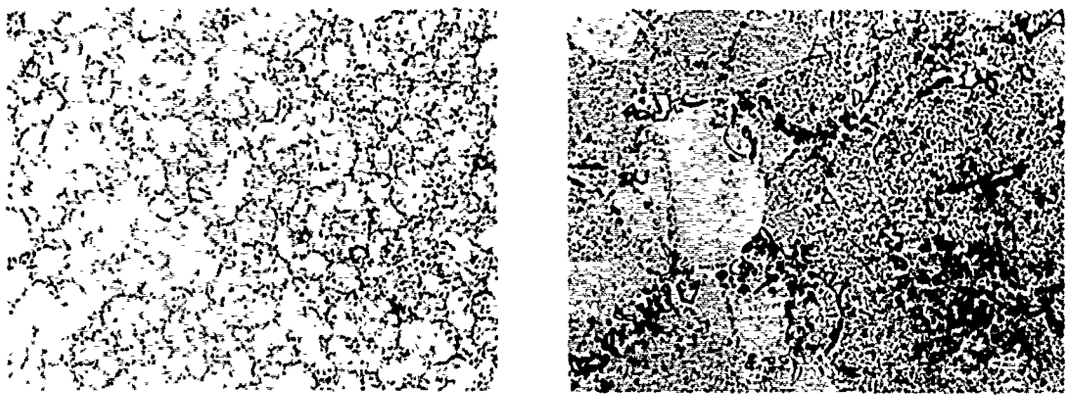


100X

500X

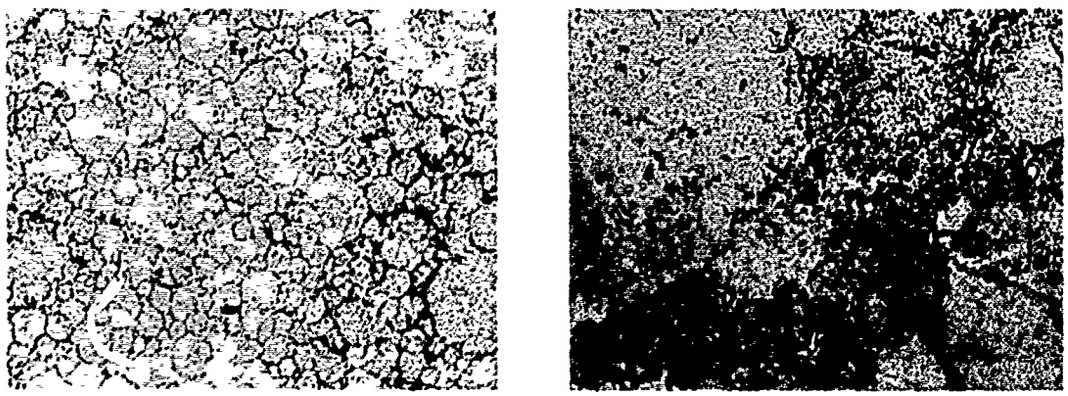
d) Bottom Surface at Outside Diameter

Figure 13. Metallographic Survey of Task IA -60 Mesh Billet A – Vendor B (Sheet 2).



100X 500X

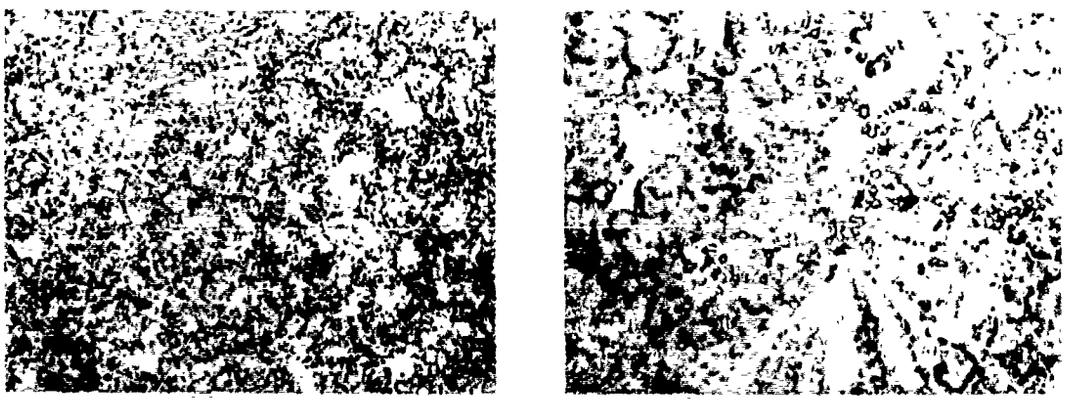
a) Top Surface at Inside Diameter



100X 500X

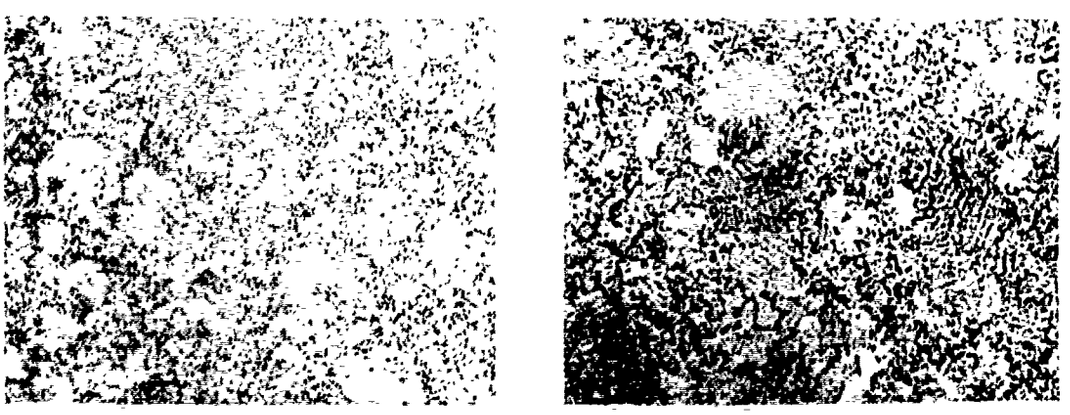
b) Top Surface at Outside Diameter

Figure 14. Metallographic Survey of Task IA -60 Mesh Billet B – Vendor B (Sheet 1).



100X 500X

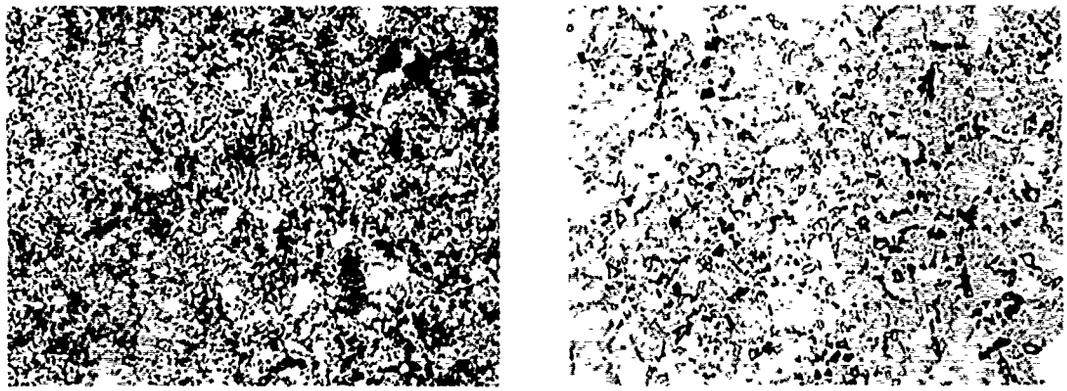
c) Bottom Surface at Inside Diameter



100X 500X

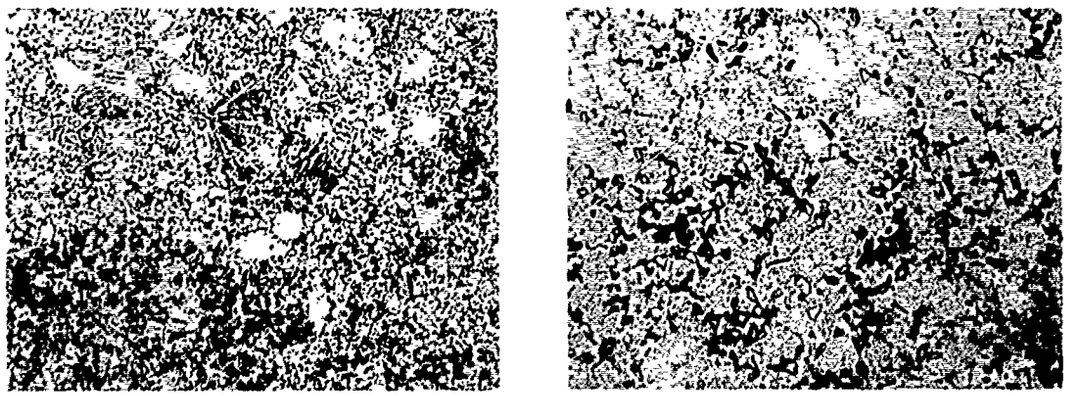
d) Bottom Surface at Outside Diameter

Figure 14. Metallographic Survey of Task IA -60 Mesh Billet B – Vendor B (sheet 2).



100X 500X

2-1/2 in. from Top



100X 500X

b) 4-1/2 in. from Top

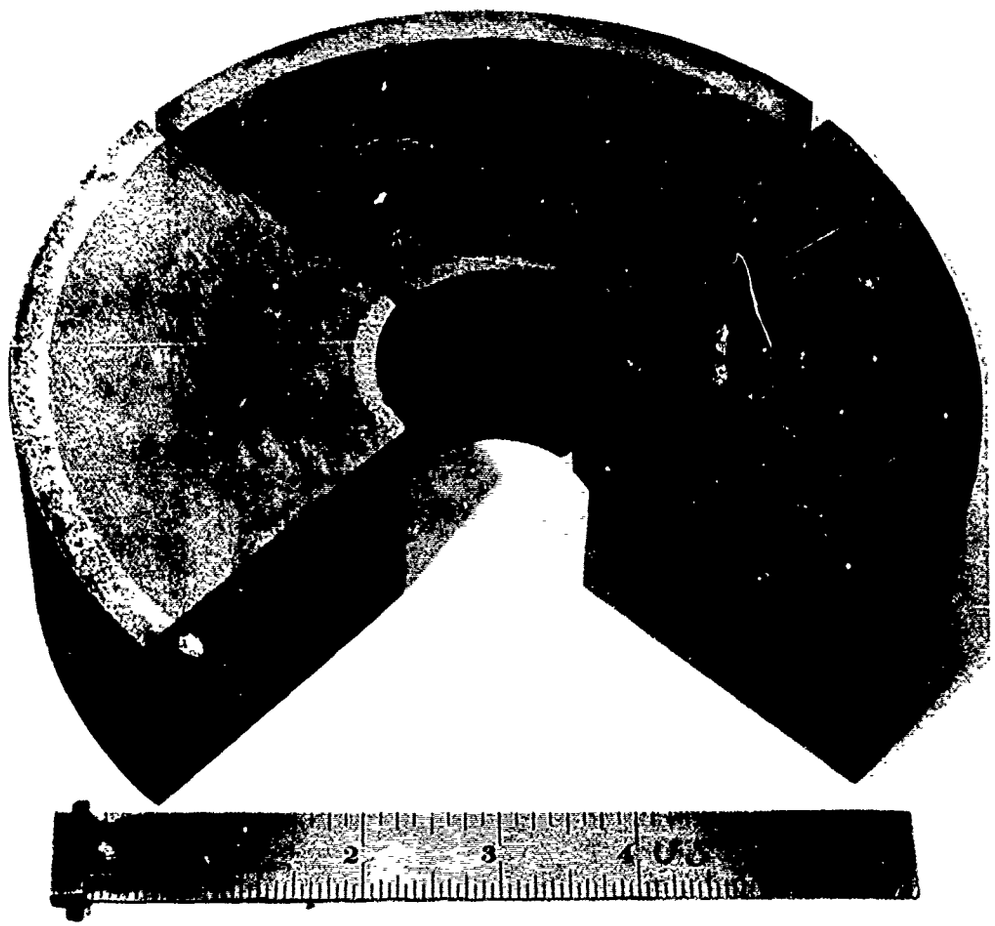
Figure 15. Microstructure Samples of Task IA -60 Mesh Billet B – Vendor B.

TABLE 17. TASK IA HEAT TREATMENT STUDY (-60 MESH POWDER)

Hollow Cylinder No.	1 and 2	3 and 4	5 and 6	7	8	9
Solution Treatment	2000°F/1 hr/OQ	T_s^*-40°F/1 hr/OQ	T_s^*-40°F/1 hr/1000°F Salt Q	T_s^*+50/1 hr/1500°F Salt/4 hr/AC	T_s^*+50°F/1 hr/RAC	Undesignated
Aging Treatments ↓	1. 1400°F/16 hr/AC 2. 1400°F/32 hr/AC 3. 1400°F/64 hr/AC 4. 1500°F/4 hr/AC 5. 1500°F/4 hr/AC + 1200°F/24 hr/AC 6. 1600°F/1 hr/AC 7. 1600°F/1 hr/AC + 1200°F/24 hr/AC 8. Undesignated	Same as Cylinders 1 and 2	Same as Cylinders 1 and 2	1. None 2. 1400°F/16 hr/AC 3. 1200°F/24 hr/AC 4. Undesignated	1. 1500°F/4 hr/AC 2. 1500°F/4 hr/AC + 1200°F/24 hr/AC 3. 1400°F/16 hr/AC 4. Undesignated	Undesignated

T_s^* = 2115 for Vendor B Material

T_s^* = 2135 for Vendor A Material



Task IA
Vendor B Heat Treat Study

Figure 16. Typical Hollow Cylindrical Slice Used in Task IA Screening Test Evaluation.

at 1400°, 1500° and 1600°F were evaluated. Two double ages were also included to determine if a 1200°F/24-hour treatment after an initial overage has any beneficial effect on mechanical properties. The aging treatment for the undesignated quarter segment was to be based on information generated by the first seven segments.

The potential of higher solution temperatures was further investigated on cylinders 3 and 4 by Vendor A. In the initial study it was indicated that higher temperatures would tend to increase the γ' in solution prior to the quenching cycle. The two vendors used different solution temperatures, since the initial studies indicated that their γ' solvus temperatures differed by 20°F. The aging treatments were identical to those evaluated with the 2000°F solution temperature.

The possibility of encountering quench cracking during oil quenching was the primary reason for employing a 1000°F salt quench on hollow cylinders 5 and 6. The solution temperatures and aging treatments were similar to those used on cylinders 3 and 4.

Cylinders 7 and 8 were used to determine the effect of solution treating at a temperature above the γ' solvus. This procedure could produce grain growth, along with dissolution of all large γ' formed during consolidation. Since oil quenching from these temperatures (2165° to 2185°F) could result in severe quench cracking, two slower cooling treatments were used. Cylinder 7 was quenched into 1500°F salt and held for 4 hours. This condition was evaluated, along with two secondary aging treatments designed to produce much finer precipitates. Cylinder 8 was rapid air cooled from the same solution temperature as cylinder 7. A 1500°F/4-hour age was then applied to one segment to compare with the as-quenched segment from cylinder 7. The other two aging treatments were also included for comparative purposes. One segment from each cylinder remained undesignated pending analysis of the planned data. Each vendor kept the undesignated cylinder 9 for further optimization of the best of the initial planned heat treatments.

The heat-treated compacts were subjected to optical metallography, tensile, and stress rupture testing. Test specimens used for the evaluation are shown in Figure 17. Specimen locations from each quarter section are illustrated in Figure 18. In addition to the tangential specimens, one specimen in the axial orientation was machined from several quarter sections to determine mechanical property isotropy. Heat-treat section size was maintained at 2 inches during all solution treatment.

Test results from both vendors are tabulated, along with appropriate heat-treat conditions, in Tables 18 and 19. Typical microstructures produced by each of the solution treatments are shown in Figures 19 and 20. Differences due to the various aging treatments could not be discerned using optical metallography.

The standard 2000°F/1 hour/OQ solution treatment produced a fine grained structure with a large quantity of coarse, unsolutioned γ' remaining after solutioning (Figures 19a and 20a). Mechanical property results from both vendors indicated the tensile yield strength to be slightly below program goals, although ultimate strengths and ductilities were excellent at both test temperatures. Stress-rupture ductilities were generally low for all aging treatments.

The 2075°F/1 hour/OQ solution applied to Vendor B material produced the best combination of properties observed to date in As-HIP Rene' 95. All test points exceeded program goals in quarter sections A3C and A4C. Properties of A4A were also excellent with the exception of slightly low stress rupture ductility. The microstructure produced by this solution treatment, shown in Figure 20b, had approximately the same grain size as the 2000°F/1 hour/OQ material but the quantity of undissolved γ' was significantly reduced. The 2100°F/1 hour/OQ solution applied to Vendor A material produced even higher tensile yield and ultimate strengths than those observed in the Vendor B specimens. These high-tensile properties were generally accompanied by somewhat lower stress rupture ductilities than previously obtained in the Vendor B material solutioned at 2075°/1 hour/OQ. The microstructure, after 2100°F/1 hour/OQ, shown in Figure 19b, indicates

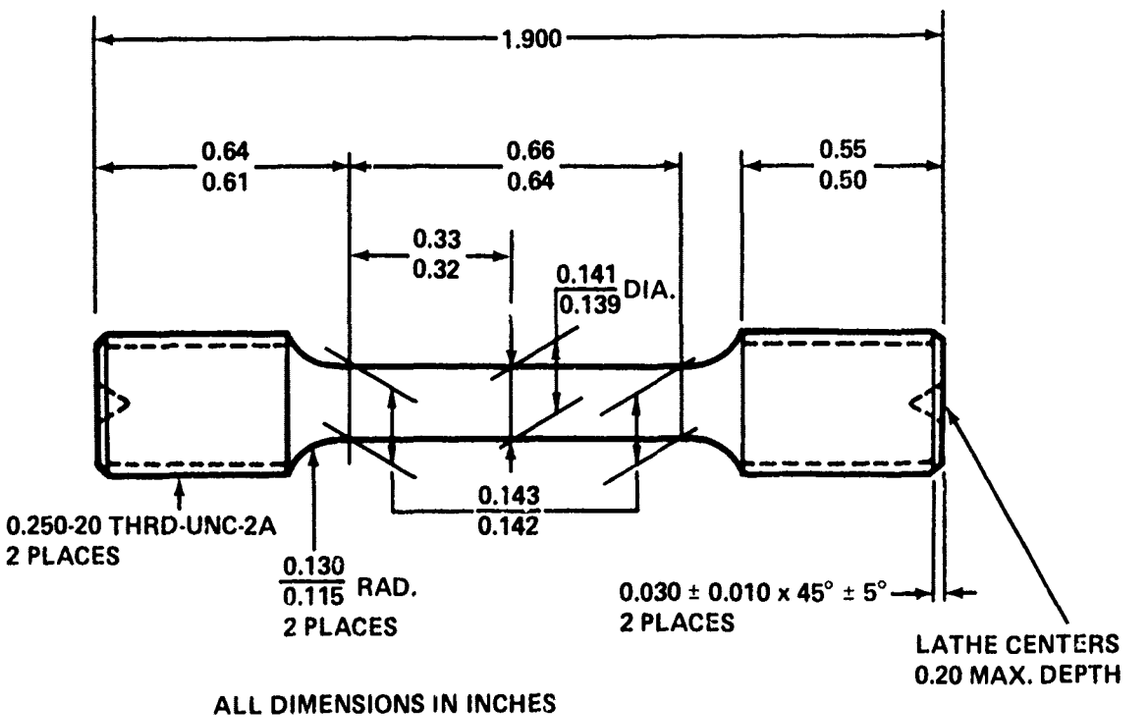
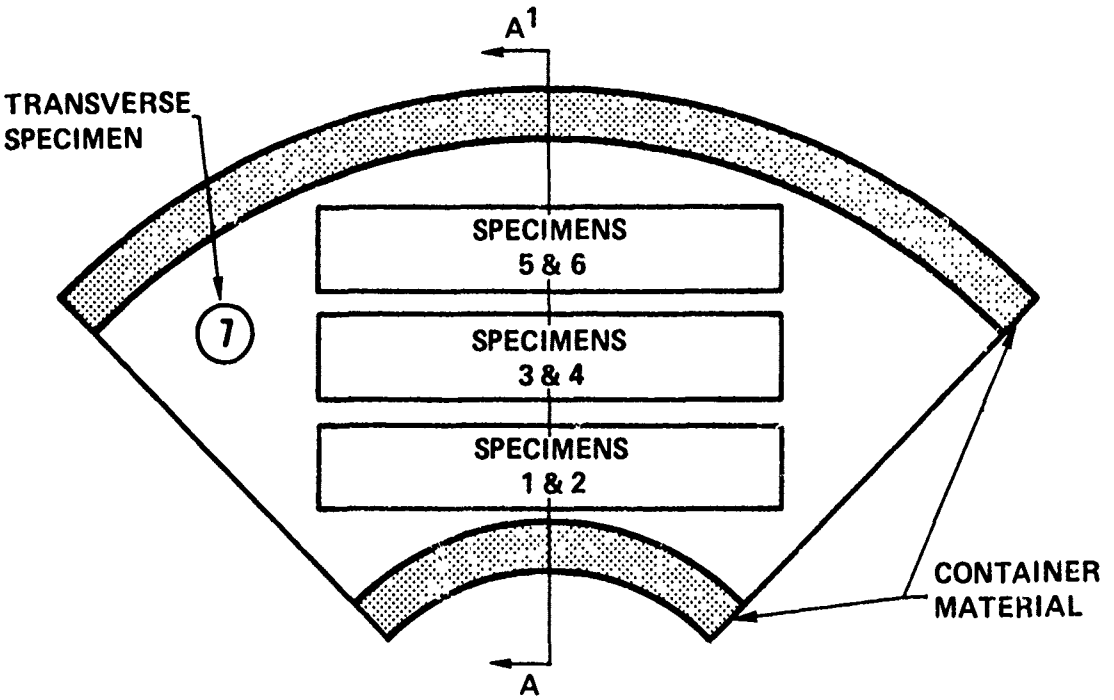
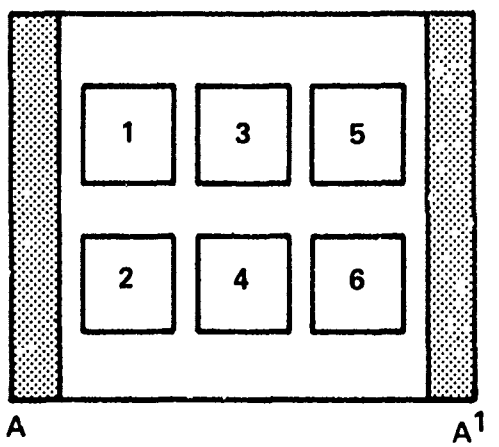


Figure 17. Smooth Bar Specimen Used for Task IA Screen Evaluation – Tensile and Stress-Rupture Tests.





SPECIMEN TYPE	LOCATION
ROOM TEMP. TENSILE	3 & 5
1200°F TENSILE	4, 6, & 7
1200°F/150 KSI STRESS RUPTURE	1 & 2

Figure 18. Test Specimen Location for Task IA Heat-Treatment Screening Evaluation.

TABLE 18. INITIAL TASK IA SCREENING TEST RESULTS ON VENDOR A MATERIAL (SHEET 1)

Disk Quarter Identity No.	Solution Treatment	Aging Treatement	Tensile Properties								Stress-Rupture Properties		
			Room Temperature				1200°F				1200°F/150 ksi		
			0.2% YS (ksi)	UTS (ksi)	% El	% R of A	0.2% YS (ksi)	UTS (ksi)	% El	% R of A	Time (hr)	% El	% R of A
1-B	2000°F/1 hr/OQ	1400°F/16 hr/AC	175.1	240.7	21.1	26.5	167.3	215.1	13.5	13.7	28.9	0.5	0.8
1-B			167.4	242.6	17.9	24.2	168.6	213.7	13.4	15.5	116.6	3.3	8.4
1-C	2000°F/1 hr/OQ	1400°F/32 hr/AC	171.6	239.1	23.3	25.6	168.5	217.2	14.5	18.8	75.3	3.2	7.6
1-C			176.2	240.2	20.6	26.3	165.8	212.2	17.5	22.1	83.5	3.3	8.3
1-D	2000°F/1 hr/OQ	1400°F/64 hr/AC	170.6	236.5	20.2	29.4	164.5	212.3	17.2	20.8	61.2	3.8	11.0
1-D			173.5	239.8	22.2	24.1	164.4	209.2	15.5	20.2	57.4	3.8	6.3
2-E	2000°F/1 hr/OQ	1500°F/4 hr/AC	177.9	233.2	15.1	20.8	167.2	216.5	15.5	21.3	89.1	4.7	10.0
2-E			177.7	241.1	16.3	17.7	164.6	181.0	4.9	9.6	91.0	5.5	9.6
							*165.7	212.5	16.9	20.2			
2-F	2000°F/1 hr/OQ	1500°F/4 hr/AC†	173.2	243.9	16.8	22.1	168.0	216.0	14.3	21.5	133.3	3.0	11.4
2-F		1200°F/24 hr/AC	177.1	242.9	19.1	23.3	170.8	216.6	13.1	21.0	86.6	3.8	12.5
2-G	2000°F/1 hr/OQ	1600°F/1 hr/AC	170.2	236.8	21.7	28.9	160.8	207.6	16.8	22.8	150.5	4.1	8.3
			169.2	234.4	18.9	21.9	160.5	208.2	16.5	21.3	119.0	5.2	9.0
2-H	2000°F/1 hr/OQ	1600°F/1 hr/AC†	174.2	240.2	19.5	25.1	166.7	213.5	15.7	21.0	142.2	3.3	8.0
2-H		1200°F/24 hr/AC	177.6	244.0	19.7	26.4	168.1	215.6	15.4	17.8	87.3	2.7	7.6
3-B	2100°F/1 hr/OQ	1400°F/16 hr/AC	185.8	248.7	15.1	21.9	182.1	232.1	10.6	15.2	145.7	2.6	5.9
3-B			183.8	239.7	13.5	18.2	177.4	230.7	13.8	16.4	0.7	2.4	7.6
3-C	2100°F/1 hr/OQ	1400°F/32 hr/AC	*185.8	248.9	14.5	21.3	*176.7	231.6	10.8	17.7	*125.7	2.7	6.0
3-C			*183.9	245.6	15.1	23.8	*178.1	231.3	12.9	16.3	*104.4	3.7	11.1
3-D	2100°F/1 hr/OQ	1400°F/64 hr/AC	*183.5	246.5	14.9	23.3	*180.6	235.2	12.0	19.0	*124.9	4.4	8.3
3-D			*185.8	248.4	15.5	24.6	*175.5	228.7	13.7	17.6	*134.8	4.3	8.3
4-E	2100°F/1 hr/OQ	1500°F/4 hr/AC	178.1	241.8	16.9	21.3	177.7	232.6	12.4	19.0	136.4	3.4	5.1
4-E			181.9	240.6	12.3	13.9	177.7	234.7	11.7	16.7	84.9	2.3	4.5
							*176.0	228.4	10.4	18.4			
4-F	2100°F/1 hr/OQ	1500°F/4 hr/AC†	189.3	241.5	11.1	14.9	183.9	236.7	12.0	15.2	93.6	2.2	3.8
4-F		1200°F/4 hr/AC	193.9	252.9	11.7	14.7	178.4	234.9	12.9	16.4	19.5	1.5	3.8
4-G	2100°F/1 hr/OQ	1600°F/1 hr/AC	*179.3	243.3	15.4	21.5	*177.3	231.7	11.2	16.5	*202.9	3.2	8.3
4-G			*180.7	244.4	16.3	20.1	*173.0	230.0	14.1	20.1	*169.7	3.1	4.6
4-H	2100°F/1 hr/OQ	1600°F/1 hr/AC†	183.6	247.2	16.2	24.2	173.1	225.5	8.6	19.6	172.3	3.5	4.7
4-H		1200°F/24 hr/AC	184.2	239.4	12.6	13.7	173.9	221.3	12.6	14.9	77.6	2.4	8.3

*Axial Orientation
†-60 mesh

TABLE 18. INITIAL TASK IA SCREENING TEST RESULTS ON VENDOR A MATERIAL (SHEET 2)

Disk Quarter Identify No.	Solution Treatment	Aging Treatment	Tensile Properties: Room Temperature 0.2% YS (ksi)	UTS (ksi)	% El	% R of A	Tensile Properties: 1200°F 0.2% YS (ksi)	UTS (ksi)	% El	% R of A	Stress Rupture Properties: 1200°F/150 ksi Time (hr)	% El	% R of A
5-B	2100°F/1 hr/1000°F	1400°F/16 hr/AC	180 6	246 3	17 1	20 2	173 1	226 8	13 5	14 4	81 2	3 0	10 0
5 B	Salt Q/5 min/AC		179 3	243 5	15 5	22 2	171 8	225 8	14 5	18 4	143 4	2 9	4 1
5-C	2100°F/1 hr/1000°F	1400°F/32 hr/AC	181 9	245 8	16 8	20 8	173 1	226 4	1. 1	21 0	103 4	3 1	4 5
5-C	Salt Q/5 min/AC		176 6	241 5	16 0	16 4	172 8	224 5	13 1	20 2	70 4	4 1	8 3
5-D	2100°F/1 hr/1000°F	1400°F/64 hr/AC	179 3	245 6	17 1	24 1	170 2	219 9	18 3	25 3	45 3	3 5	9 2
5-D	Salt Q/5 min/AC		176 7	241 5	15 7	21 0	172 1	221 5	14 5	18 4	58 8	3 8	6 3
							166 7	218 8	16 0	19 8			
6-E	2100°F/1 hr/1000°F	1500°F/4 hr/AC	177 5	240 9	14 5	20 1	178 2	231 4	13 4	16 6	108 2	3 8	11 6
6-E	Salt Q/5 min/AC		178 4	242 8	16 8	21 3	169 4	222 6	12 9	17 0	/5 9	2 1	3 9
6-F	2100°F/1 hr/1000°F	1500°F/4 hr/AC+	180 0	243 7	15 4	20 2	171 6	217 0	14 6	22 4	106 1	5 4	8 3
6-F	Salt Q/5 min/AC	1200°F/24 hr/AC	179 4	242 6	14 6	17 0	174 0	222 5	17 4	21 6	100 3	7 2	15 4
6-G	2100°F/1 hr/1000°F	1600°F/1 hr/AC	175 2	242 9	17 1	21 2	168 6	222 9	13 7	17 7	132 6	3 5	8 3
6-G	Salt Q/5 min/AC		176 2	243 8	17 5	22 6	167 6	224 2	12 8	19 0	198 7	3 7	5 6
6-H	2100°F/1 hr/1000°F	1600°F/1 hr/AC+	181 6	246 2	16 9	20 5	170 1	224 4	13 8	16 0	155 8	4 9	6 5
6-H	Salt Q/5 min/AC	1200°F/24 hr/AC	181 6	242 3	13 8	14 1	171 6	225 4	16 3	21 8*	104 5	5 8	8 3
7-EE	2175°F/1 hr/1500°F	None	174 0	232 4	13 2	23 0	159 8	220 1	11 7	17 6	127 3	3 7	9 9
7-EE	Salt Q/4 hr/AC		168 1	222 5	12 9	13 9	155 9	217 2	12 6	19 1	126 7	4 3	6 9
7 FF	2175°F/1 hr/1500°F	1200°F/24 hr/AC	172 3	220 3	11 4	13 0	162 1	219 6	11 8	17 7	201 9	3 3	7 7
7-FF	Salt Q/4 hr/AC		170 6	226 4	13 4	13 7	161 4	220 7	12 5	17 6	111 0	5 8	9 7
7-II	2175°F/1 hr/1500°F	1400°F/16 hr/AC	164 2	229 0	14 8	22 1	163 1	222 9	9 7	16 4	153 7	4 6	8 3
7-II	Salt Q/4 hr/AC		170 1	225 5	12 1	13 7	161 8	221 7	10 3	18 8	141 6	5 0	6 9
							162 4	217 7	11 4	15 1			
8-B	2175°F/1 hr/RAC	1400°F/16 hr/AC	163 7	228 7	16 9	22 8	156.7	224 8	17 2	21 1	80 1	4 2	8 3
8-B			165 3	230 3	15 7	17 6	161 1	216 1	13 4	24 5	82 8	5 3	9 3
							152 3	211 9	15 1	20 8			
8 E	2175°F/1 hr/RAC	1500°F/4 hr/AC	161 9	227 7	19 7	23 3	154 8	216 8	14 8	19 6	89 8	6 4	10 7
8 E			180 4	244 3	15 8	22 8	152 6	214 6	12 3	20 4	89 3	6 1	8.6
8-F	2175°F/1 hr/RAC	1500°F/4 hr/AC	166 3	230 7	18 0	21 5	152 7	212 5	14 1	19 4	90 8	7 0	11 1
		1200°F/24 hr/AC	164 9	228 4	17 4	21 0	153 5	213.5	12 6	20 3	96 9	9 1	11 9

*Axial Orientation

TABLE 19. INITIAL TASK IA SCREENING TEST RESULTS ON VENDOR B MATERIAL (SHEET 1)

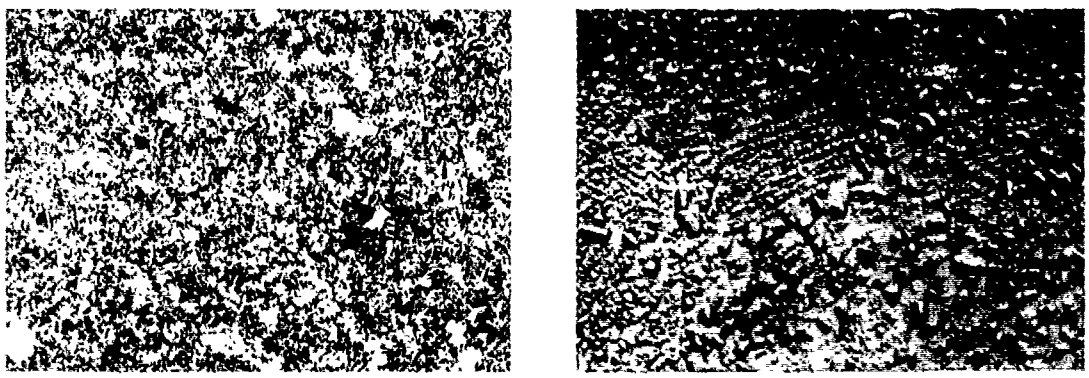
Disk Quarter Identify No	Solution Treatment	Aging Treatment	Tensile Properties: Room Temperature 0.2% YS (ksi)	UTS (ksi)	% El	% R of A	Tensile Properties: 1200°F 0.2% YS (ksi)	UTS (ksi)	% El	% R of A	Stress Rupture Properties: 1200°F/150 ksi Time (hr)	% El	% R of A
A1A	2000°F/1 hr OQ	1400°F/16 hr/AC	174 4	242 5	17 0	21 0	163 9	206 5	8 6	11 8	41 5	2 6	5 6
A1A			174 0	241 9	16 9	23 0	169 3	218 6	12 6	17 7	82 5	1 5	2 8
A1B	2000°F/1 hr/OQ	1400°F/32 hrs/AC	175 8	237 5	13 3	17 7	167 2	213 4	11 1	15 8	69 9	1 8	4 7
A1B			170 0	238 6	19 5	23 0	165 3	208 2	10 9	18 8	54 7	2 8	5 6
A1C	2000°F/1 hr/OQ	1400°F/64 hrs/AC	177 7	241 9	17 3	20 8	171 1	216 2	10 2	15 2	39 3	3 1	5 6
A1C			176 1	240 7	18 1	24 1	169 1	220 5	15 1	16 5	55 2	5 8	8 3
A1D	2000°F/1 hr/OQ	1500°F/4 hrs/AC	174 0	240 6	18 8	19 1	167 5	217 5	13 1	20 1	54 1	2 0	5 6
A1D			171 7	231 3	14 0	15 1	165 7	217 0	15 3	20 2	76 5	4 6	7 7
							166 4	216 9	12 3	16 5			
A2A	2000°F/1 hr/OQ	1500°F/4 hrs/AC +	179 9	240 8	13 6	18 4	172 5	219 0	13 0	13 7	110 7	2 0	5 6
A2A		1200°F/24 hrs/AC	176 7	240 4	16 5	21 5	168 8	221 7	13 8	14 9	75 6	4 2	8 3
A2B	2000°F/1 hr/OQ	1600°F/1 hr/AC	158 9	226 1	20 7	27 7	166 6	214 3	11 5	12 3	84 5	2 9	4 2
A2B			168 4	235 2	17 6	22 1	164 3	213 3	13 9	20 1	77 2	2 8	4 2
A2C	2000°F/1 hr/OQ	1600°F/1 hr/AC	169 5	236 3	20 0	23 5	165 7	213 5	11 6	19 0	76 0	4 3	8 5
A2C		1200°F/24 hrs/AC	172 8	235 2	13 3	16 4	164 7	213 1	14 8	19 0	75 2	1 7	2 8
A3A	2075°F/1 hr/OQ	1400°F/16 hrs/AC	174 8	238 1	14 0	20 2	169 2	227 4	10 9	13 1	63 4	1 9	3 5
A3A			181 6	240 8	13 8	15 8	172 9	222 6	11 4	15 7	31 6	1 5	4 2
A3B	2075°F/1 hr/OQ	1400°F/32 hrs/AC	180 6	245 9	15 7	22 8	174 5	223 5	12 1	14 4	71 7	4 6	5 6
A3B			181 9	247 9	*8 3	20 5	172 8	234 0	13 8	17 7	62 8	1 2	2 8
A3C	2075°F/1 hr/OQ	1400°F/64 hrs/AC	182 3	245 0	15 8	21 3	175 0	223 1	13 4	15 9	65 7	4 5	7 0
A3C			180 0	243 1	18 5	23 5	172 6	219 4	9 2	15 7			
							*172 6	219 5	9 2	14 3			
A3D	2075°F/1 hr/OQ	1500°F/4 hr/AC	178 8	241 1	17 1	26 1	171 4	222 8	12 3	16 5	114 5	3 7	6 4
A3D			176 6	242 0	16 4	19 8	169 3	225 8	9 6	12 4	75 4	5 9	9 8
							*169 8	222 0	12 6	14 9			
A4A	2075°F/1 hr/OQ	1500°F/4 hrs/AC +	184 6	242 6	12 2	16 5	178 7	230 0	14 4	17 7	66 9	3 0	7 0
A4A		1200°F/24 hrs/AC	183 3	245 5	16 1	26 8	175 1	228 7	11 9	19 0	107 7	2 7	7 0
A4B	2075°F/1 hr/OQ	1600°F/1 hr/AC	173 0	236 6	18 8	29 2	161 5	213 2	14 4	17 8	71 3	1 8	4 4
A4B			170 6	236 1	17 2	24 4	158 9	214 9	15 2	21 6	97 2	5 6	9 8
							*164 1	219 0	12 9	19 0			
A4C	2075°F/1 hr/OQ	1600°F/1 hr/AC +	183 3	242 6	16 5	20 4	173 0	228 1	15 2	16 5	108 6	4 7	7 0
A4C		1200°F/24 hrs/AC	180 3	241 6	14 8	15 2	173 3	228 7	*3 1	20 1	116 9	4 2	7 0

*Axial Orientation
1-80 Mesh

TABLE 19. INITIAL TASK IA SCREENING TEST RESULTS ON VENDOR B MATERIAL (SHEET 2)

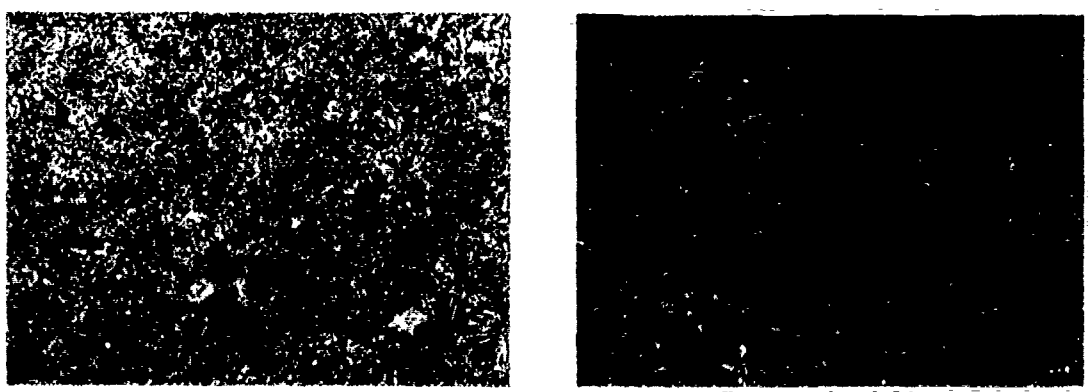
Disk Quarter Identity No.	Solution Treatment	Aging Treatment	Tensile Properties: Room Temperature 0.2% YS (ksi)	UTS (ksi)	% El	% R of A	Tensile Properties: 1200F 0.2% YS (ksi)	UTS (ksi)	% El	% R of A	Stress-Rupture Properties: 1200F/150 ksi Time (hr)	% El	% R of A
A5A	2165°F/1 hr /1500°F	1400°F/16 hrs/AC	162 4	229 4	14 6	20.2	155 3	219.7	10 7	12 3	75 9	6 0	9 8
A5A	Salt Q/4 hrs/AC		158 8	227 1	17 2	21 6	157 4	222.5	10 7	18 4	77 6	6 3	10 1
							*157 0	221.0	11 3	14 9			
A5B	2165°F/1 hr/1500°F	1200°F/24 hrs/AC	163 5	231 3	17 5	22.1	153.9	220 5	11 1	15 2	91 5	5 4	7 7
A5B	Salt Q/4 hrs/AC		162.8	227 8	15 5	19 1	155 0	219 7	14 0	19 9	106.6	5 3	8 4
A5C	2165°F/1 hr/1500°F	None	159 8	228 4	14.5	18 8	150 3	215 4	10 9	11 2	65.1	3 2	5 6
A5C	Salt Q/4 hrs/AC		156 3	226 5	16 4	23 8	145.7	214 2	12 2	19 1	91 0	4.9	8 3
A6A	2165°F/ 1 hr/RAC	1500°F/4 hrs/AC	155 4	225 2	20 6	25 8	147 5	214 1	16 4	16 4	90 5	6 1	11 2
A6A			155 6	225 8	18 6	20 6	147 8	216 0	13 6	20 2	96 5	4 0	9 1
A6B	2165°F/1 hr/RAC	1500°F/4 hrs/AC	159 4	224 8	19 1	23 3	158 2	223 5	12.9	14 5	93 5	5 7	8 4
A6B		1200°F/24 hrs/AC	161 8	228 7	17 9	20 1	155 8	216 1	14 6	20 8	106 9	8 6	9 8
A6C	2165°F/1 hr/RAC	1400°F/16 hrs/AC	156 9	225 1	19 6	27 9	153 1	215 5	15 3	15 9	78 1	4 2	6 6
A6C			162 5	230 7	17 7	23 0	154 9	213 6	15 7	16 5	66 0	4 5	7 1
							*154 0	215 1	13 4	19 0			
B3A	1075°F/1 hr/1000°F	1400°F/16 hr/AC	167 0	231 3	14.3	21 5	157 1	212 4	11 4	20 1	50 4	4 6	14.5
B3A	Salt Q		164 6	230 3	16 0	23 4	157 0	212 0	14 9	23 8	32.1	3 5	10 5
B3B	2075°F/1 hr/1000°F	1400°F/32 hrs/AC	168 6	236 5	17 5	26 5	164.3	219 1	14 8	20 9	39 0	3 7	12 7
B3B	Salt Q		168 4	236 0	18 6	24 2	156 9	214 5	16 9	24 0	46 4	4 6	11 4
B													
B3C	2075°F/1 hr/1000°F	1400°F/64 hrs/AC	167 2	233 9	16 5	23 9	163 5	216 8	14 8	19 6	33 1	5 5	12 5
B3C	Salt Q		168 7	236 2	14 8	21 6	160 6	219 2	14.1	20 0	36 6	7 2	10 6
							*163 5	218 5	11 1	19 4			
B3D	2075°F/1 hr/1000°F	1500°F/4 hrs/AC	160 2	224 3	13 8	19 6	158 8	217 1	15.1	23 0	56 8	6 0	14.7
B3D	Salt Q		163 4	232 1	18 3	28 4	161 2	216 4	14 6	23 4	55 0	6 4	13.5
B5A	2075°F/1 hr/1000°F	1500°F/4 hrs/AC +	172 3	237 4	14 3	20 8	163 9	217 9	16 9	24 5	79.2	7 2	16 9
B5A	Salt Q	1200°F/24 hrs/AC	172.3	239 4	16 5	20 8	165 9	219 7	16 2	17 1	62 5	5 4	12.7
B5B	2075°F/1 hr/1000°F	1600°F/1 hr/AC	164 2	231 3	18 2	22 1	159 8	217 0	14 5	21.1	51 4	4 1	10 0
B5B	Salt Q		161 9	230 8	9.1	27.2	163 4	219 7	14 1	17 0	65.2	5 8	12 3
B5C	2075°F/1 hr/1000°F	1600°F/1 hr/AC +	164.0	224.5	14.3	15.4	158 3	216 2	15 8	21 0	79 6	5 4	15 9
B5C	Salt Q	1200°F/24 hrs/AC	165 2	230 2	19 1	27 9	154 1	215 2	17 2	25 1	84 8	8 0	16.7

*Axial Orientation
*-60 Mesh



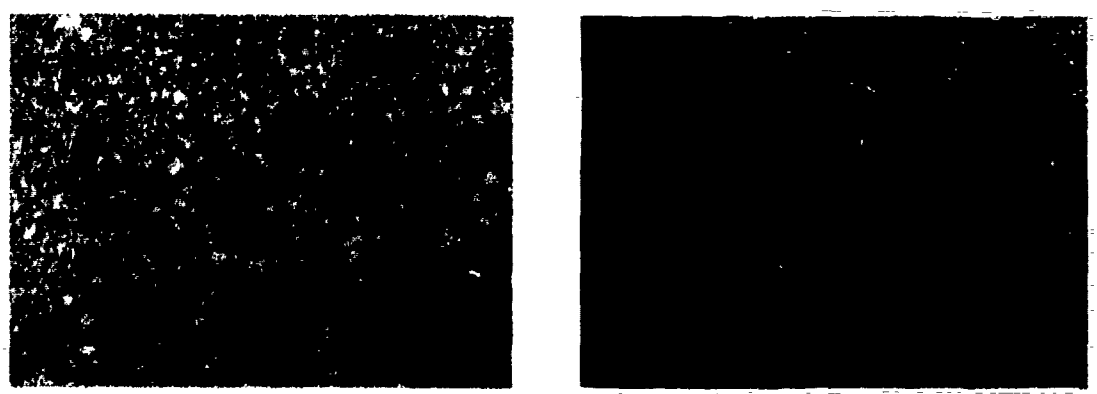
100X 1000X

a) 1650°F/4 hr → 2000°F/1 hr/Oil Quench



100X 1000X

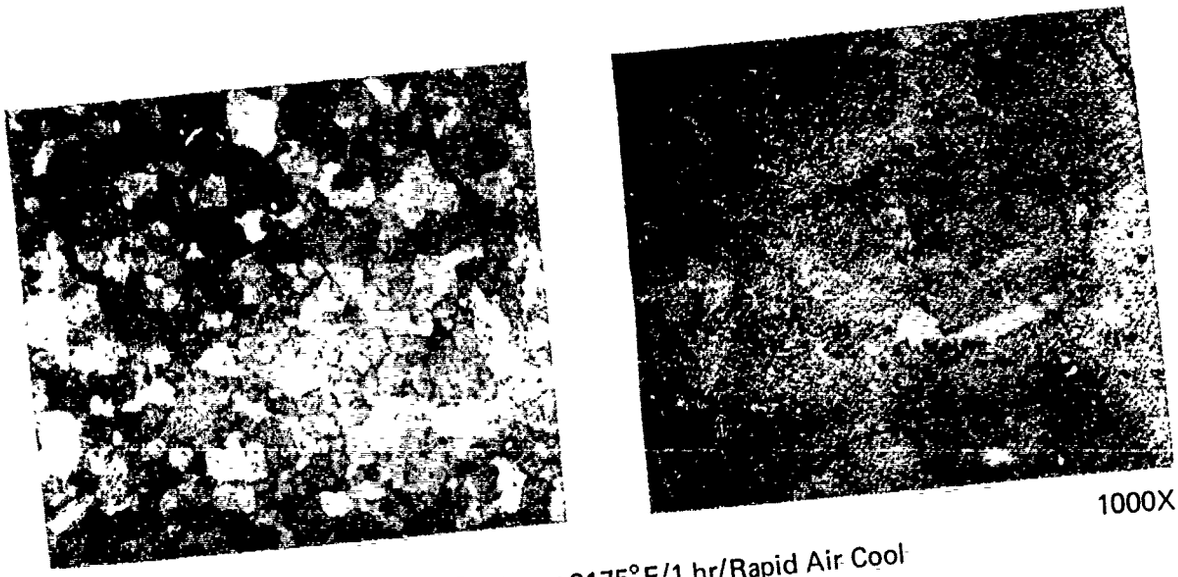
b) 1650°F/4 hr → 2100°F/1 hr/Oil Quench



100X 1000X

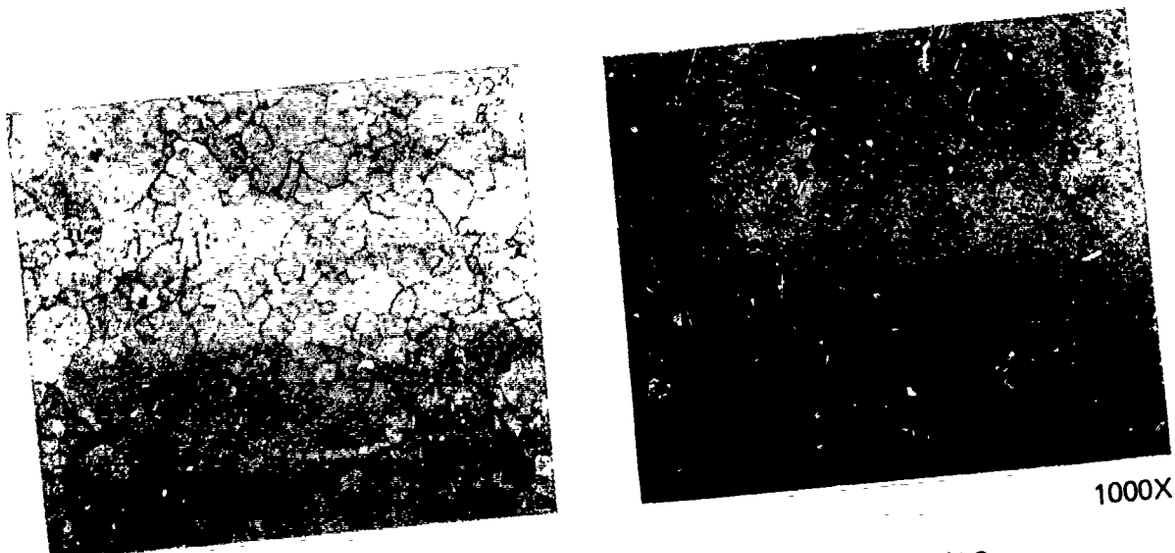
c) 1650°F/4 hr → 2100°F/1 hr/1000°F Salt Quench

Figure 19. Typical Microstructures of Task IA Initial Heat-Treat Evaluation of Quarter Sections After Solution Treatment - Vendor A (Sheet 1).



100X 1000X

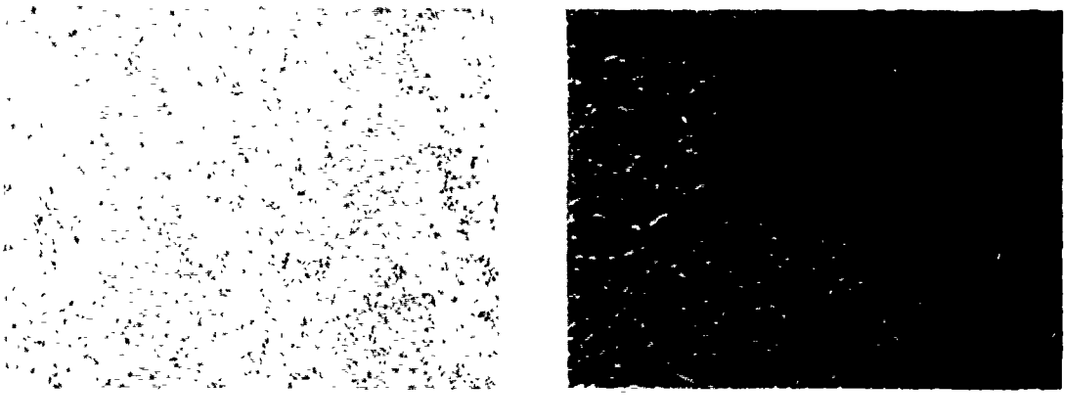
d) 1640°F/4 hr → 2175°F/1 hr/Rapid Air Cool



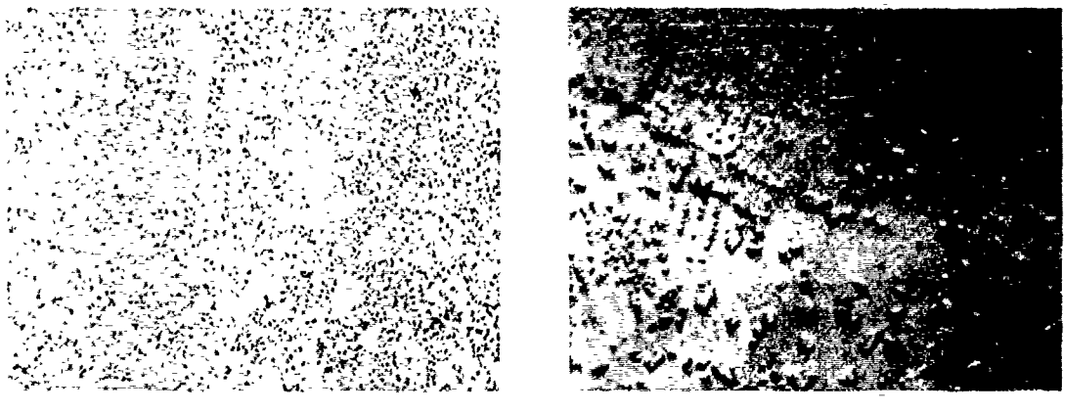
100X 1000X

e) 1650°F/4 hr → 2175°F/1 hr 1500°F Salt/4 hr/AC

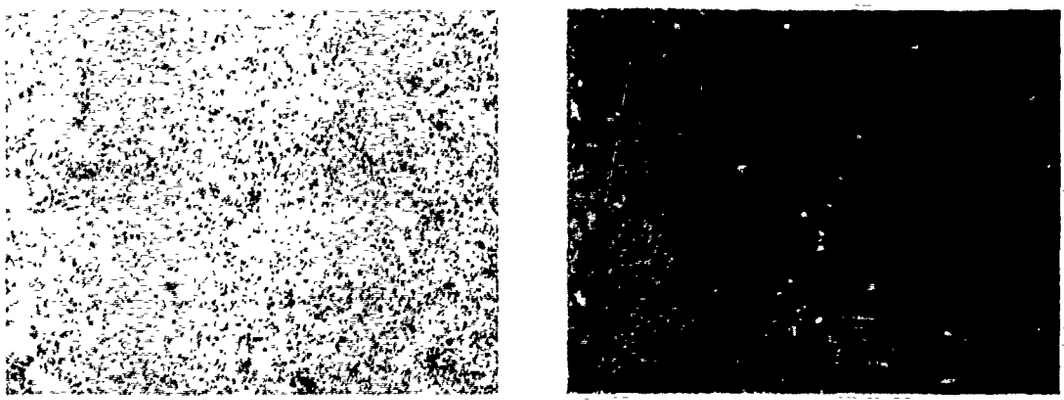
Figure 19. Typical Microstructures of Task IA Initial Heat-Treat Evaluation of Quarter Sections After Solution Treatment – Vendor A (Sheet 2).



100X a) 1650°F/4 hr → 2000°F/1 hr/Oil Quench 1000X

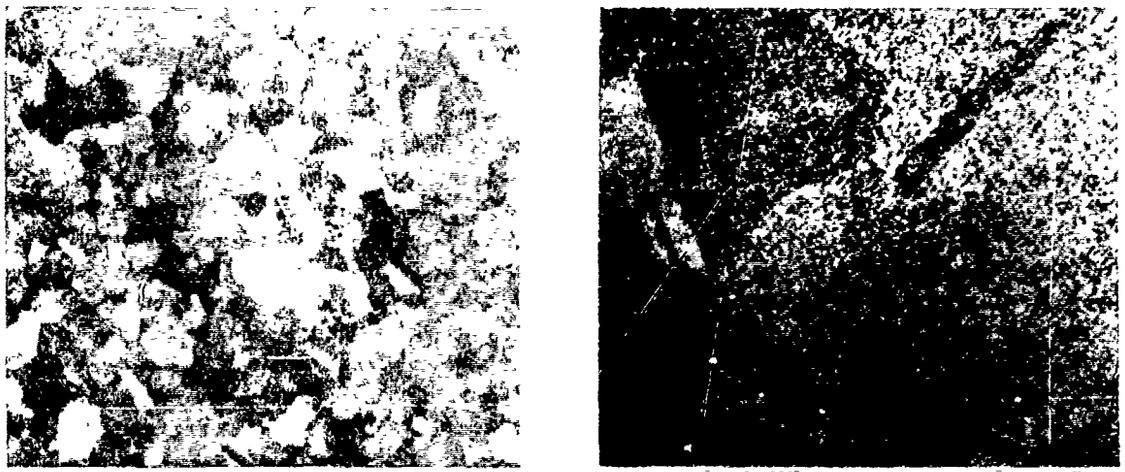


100X b) 1650°F/4 hr → 2075°F/1 hr/Oil Quench 1000X



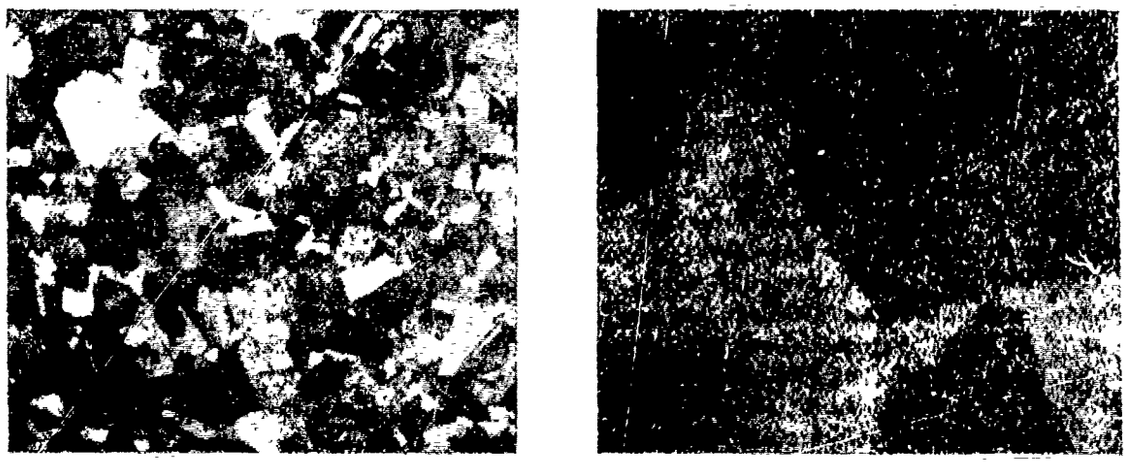
100X c) 1650°F/4 hr → 2075°F/1 hr/1000°F Salt Quench 1000X

Figure 20. Typical Microstructures of Task IA Initial Heat-Treat Evaluation of Quarter Sections After Solution Treatment – Vendor B (Sheet 1).



100X

d) 1650°F/4 hr → 2165°F/1 hr/Rapid Air Cool



100X 1000X

e) 1650°F/4 hr → 2165°F/1 hr → 1500°F Salt Q/4 hr/AC

Figure 20. Typical Microstructures of Task IA Initial Heat-Treat Evaluation of Quarter Sections After Solution Treatment – Vendor B (Sheet 2).

that more recrystallization and a reduced amount of undissolved γ' were produced relative to the Vendor B 2075°F/1-hour/OQ treatment. Of all the aging treatments applied after the 2100°F/1 hour/OQ, only the 1400°F/64-hour/AC produced tensile and rupture properties exceeding the program goals. All specimens for quarter sections 3C, 3D, and 4G were machined in the transverse (axial) orientation due to material cracking during the oil quench from 2100°F.

Mechanical properties after solutioning the Vendor B material at 2075°F/1 hour and quenching into 1000°F salt were lower than the oil quench values. This was expected since the slower cooling rate does not retain as much γ' in solution as the faster oil quench thereby reducing the quantity available for subsequent aging at lower temperatures. This is illustrated in Figure 20c. Although tensile properties and stress rupture lives were reduced, the stress rupture ductilities were generally greater than those observed after the 2075°F/1 hour/OQ solution treatment. The primary purpose of investigating the salt quench was to provide an alternate 2075°F solution treatment in the event the oil quench produced quench cracking in the turbine disk shapes. Resulting properties after solutioning the Vendor A material at 2100°F/1 hour/1000°F salt quench were somewhat lower than the corresponding oil quench values, but significantly higher than the Vendor B material solutioned at 2075°F/1 hour/1000°F salt quench. The microstructure, shown in Figure 19c, reveals approximately the same grain size and degree of recrystallization as observed in the oil quench sample. However, as in the Vendor B material, a greater amount of intermediate γ' was present due to the slower cooling rate produced by the 1000°F salt quench. The slower quench rate reduced the tensile strengths slightly while generally improving stress rupture ductilities. One heat treatment, quarter section 6H, exceeded all program goals, while a second, quarter section 6F, met all goals except room temperature yield strength.

Solution treatments above the γ' solvus produced some grain growth to ASTM 5-6 in Vendor B material, as shown in Figures 20d and 20e, and a larger quantity of γ' precipitated during cooling from the solution temperature due to the slower quenching rates. Rapid air cooling and quenching into 1500°F salt appeared to produce approximately equivalent background γ' sizes and distributions. Tensile strengths were degraded significantly by these solution treatments, but tensile and stress-rupture ductilities were excellent. Vendor A's solution treatments above the γ' solvus resulted in slightly finer grain sizes (ASTM 5-7) than the corresponding Vendor B material. The Vendor A cooling rate from 2175°F appeared to be somewhat higher than Vendor B's, based on the reduced background γ' sizes shown in Figures 19d and 19e. Rapid air cooling and quenching into 1500°F salt and holding for 4 hours produced approximately equivalent background sizes and distributions. As with the Vendor B material, tensile strengths were degraded significantly by these solution treatments, but tensile and stress rupture ductilities were excellent. The extremely high room temperature tensile strength of quarter section 8E remains an anomaly. Metallographic examination of the fractured specimen indicated that the microstructure was consistent with that shown in Figure 19d. Based on these results, several additional heat treatments were specified for the undesignated Task IA material. One-quarter section from the Vendor A 2100°F/1 hour/1000°F salt quench material was aged at 1400°F/64 hours/AC + 1200°F/24 hours/AC in an effort to improve yield strength. The remaining undesignated -60 mesh hollow cylindrical slice was solutioned at 2100°F/1 hour and quenched into 500°F salt to provide a slightly faster cooling rate than the 1000°F salt quench. Aging treatments evaluated included 1400°F/64 hours/AC, 1400°F/64 hours/AC + 1200°F/24 hours/AC, 1500°F/4 hours/AC + 1200°F/24 hours/AC, and 1600°F/1 hour/AC + 1200°F/24 hours/AC. In addition, three -200 mesh slices were solution treated at: (1) 2100°F/1 hour/1000°F salt quench; (2) 2100°F/1 hour/500°F salt quench; and (3) 2075°F/1 hour/OQ and aged using the same four treatments identified for the -60 mesh slice solutioned at 2100°F/1 hour/500°F salt quench. Results of the tensile and stress-rupture evaluation of the additional Vendor A aging treatments are presented in Table 20.

The 500°F salt quench was applied to Vendor A -60 and -200 mesh material to provide a cooling rate between a very fast oil quench and the slightly slower 1000°F salt quench, both of which were applied to -60 mesh material in the initial heat-treat evaluation. The microstructure of the -60 mesh material, shown in Figure 21a, is virtually identical to the oil quenched and 1000°F salt quench materials shown in Figure 19. The differences in γ' size of quenched material cannot be detected by optical metallography. Mechanical properties of the -60

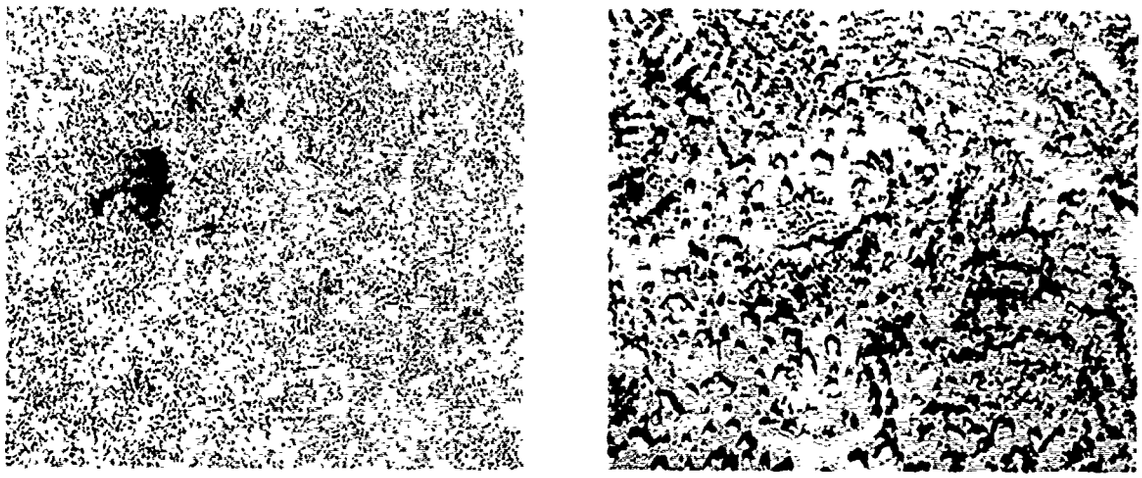
TABLE 20. ADDITIONAL TASK IA SCREENING TEST RESULTS ON VENDOR A MATERIAL (SHEET 1)

Disk Quarter Identity No.	Solution Treatment	Aging Treatment	−200 Mesh Material Tensile Properties								Stress-Rupture Properties		
			Room Temperature				1200°F				1200°F/150 ksi		
			0.2%YS (ksi)	UTS (ksi)	% El	% R of A	0.2%YS (ksi	UTS (ksi)	% El	% R of A	Time (hr)	% El	% R of A
21D	2100°F/1 hr/1000°F Salt Q/AC	1400°F/64 hr/AC	182.3	246 8	13.9	19.1	170 8	221.1	10.5	13.7	51.8	3.5	9.6
			183.1	240.6	11.4	14.9	168.5	216.5	11.1	16 3	35.9	3 8	8.5
21J	2100°F/1 hr/1000°F Salt Q/AC	1400°F/64 hr/AC+ 1200°F/24 hr/AC	187.0	249.4	17.1	[illegible]	172.0	230 6	14.1	14.0	104.4	4.7	10.0
			178.6	239.9	10.5	11.0	167.8	222.0	12.9	24.1	64.8	5.8	14.6
21F	2100°F/1 hr/1000°F Salt Q/AC	1500°F/4 hr/AC+ 1200°F/24 hr/AC	163.5	235.6	11.9	14.7	174.1	227.2	11.4	17.1	53.6	4.1	10.0
			184.4	244.5	13.6	21.4	166.5	226.5	13.7	20.8	87.0	6.7	11.2
21H	2100°F/1 hr/1000°F Salt Q/AC	1600°F/1 hr/AC+ 1200°F/24 hr/AC	179.5	244.0	15.9	24.2	169.5	219.3	11.5	18.4	104.3	8 3	11.1
			183.1	245.2	15 9	24.2	167.5	217.0	9.1	9.6	79.3	9.0	18.4
22D	2100°F/1 hr/500°F Salt Q/AC	1400°F/64 hr/AC	189.7	251.3	14.5	23.7	178.5	216.1	2.7	8.2	160.4	4.0	10.9
			189.3	219.0	6.1	10 8	173.6	227.0	12.0	18.6	37.6	1.6	8.9
							177.4	228.7	12.2	16 6			
22J	2100°F/1 hr/500°F Salt Q/AC	1400°F/64 hr/AC+ 1200°F/24 hr/AC	189.2	252.2	15.2	20.3	181.0	222.3	13 5	21.6	94.1	5.7	10.1
			191.0	252.0	13.4	17.1	173.0	224.5	12.1	15.1	81.9	6.3	12.6
22F	2100°F/1 hr/500°F Salt Q/AC	1500°F/4 hr/AC+ 1200°F/24 hr/AC	180.5	251.6	14.8	20.1	181.0	233.0	12.5	15.1	124.1	4.4	7.7
			189.9	252.5	14.8	19.6	184.0	233.5	8.4	9 6	86 0	6.7	12.5
22H	2100°F/1 hr/500°F Salt Q/AC	1600°F/1 hr/AC+ 1200°F/24 hr/AC	162.6	246.5	16.2	25.2	173 8	231.0	11.0	17.3	144.1	6.3	15.6
			180 3	245.2	13 2	16 6	178.1	231.3	10 5	13.3	100.4	4 0	9 3
23D	2075°F/1 hr/OQ	1400°F/64 hr/AC	183.8	245.9	11.8	15 3	177.6	223.0	13.9	17.3	52.7	7.7	17.1
			177.2	229.4	7.3	9.5	178.2	224.4	14.2	20.9	19.0	3.2	7.8
							170 9	221.5	7.8	8.2			
23J	2075°F/1 hr/OQ	1400°F/64 hr/AC+ 1200°F/24 hr/AC	193.0	248.1	9.2	10.8	178 0	224.5	7.2	9.9	83.3	10.0	14.6
			172.2	206.3	3.2	7.0	180.4	228.5	12.6	19 6	6.3	1.0	5.5
23F	2075°F/1 hr/OQ	1500°F/4 hr/AC+ 1200°F/24 hr/AC	181.4	248.4	14.7	23.7	177.2	226.9	14.7	19.9	105.6	5.8	14.1
			182.3	251.9	12.7	16 5	172 8	224.0	13.8	24.1	5.3	2.6	7.4
23H	2075°F/1 hr/OQ	1600°F/1 hr/AC+ 1200°F/24 hr/AC	184.6	246 8	16.6	26.3	*	223.6	12.3	14.0	38 5	2.4	7.7
			186.5	241.8	12.2	16.4	174.3	222.2	12.8	16 0	82.8	4.0	11.8

*No Data Extensometer Slipped

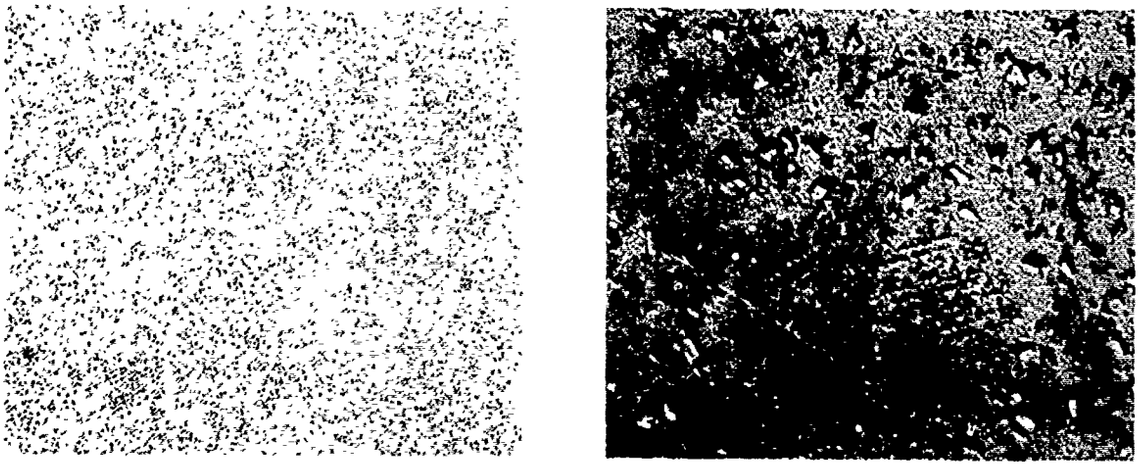
TABLE 20. ADDITIONAL TASK IA SCREENING TEST RESULTS ON VENDOR A MATERIAL (SHEET 2)

Disk Quarter Identify No.	Solution Treatment	Aging Treatment	−60 Mesh Material: Tensile Properties, Room Temperature: 0.2%YS (ksi)	UTS (ksi)	% El	% R of A	Tensile Properties, 1200°F: 0.2%YS (ksi)	UTS (ksi)	% El	% R of A	Stress-Rupture Properties, 1200°F/150 ksi: Time (hr)	% El	% R of A
61D	2100°F/1 hr/500°F Salt Q/AC	1400°F/64 hr/AC	183.5 180.4	246.5 244.3	14.4 16.0	20 4 20.9	174 0 168.6	213.5 222.4	6 5 11.5	5.8 17.3	144.7 82.2	4 6 3.0	9.6 5.5
61J	2100°F/1 hr/500°F Salt Q/AC	1400°F/64 hr/AC+ 1200°F/24 hr/AC	183.5 174.0	246.0 245.2	13.9 12.1	18 9 17.3	175.3 174 5	227.2 225 0	14.5 8 2	17.1 15.3	98.4 86 4	4.7 4 0	8.5 11 5
61F	2100°F/1 hr/500°F Salt Q/AC	1500°F/4 hr/AC+ 1200°F/24 hr/AC	182.4 183.2	246.2 245 3	13 8 14.3	16.4 18 6	171.4 172.8	225 0 227.2	11.5 10.3	14.7 13.3	140 4 172.8	3 0 4.6	6.9 11.6
61H	2100°F/1 hr/500°F Salt Q/AC	1600°F/1 hr/AC+ 1200°F/24 hr/AC	181.1 173.1	241.9 230.1	13.4 9 6	19.9 14.6	173 9 173.6 171.8	224.8 225.2 227.0	14 0 11.6 11.6	17.8 11.3 14.7	138.5 184.7	5.2 5 5	11.7 12.6



100X -60 Mesh Material 1000X

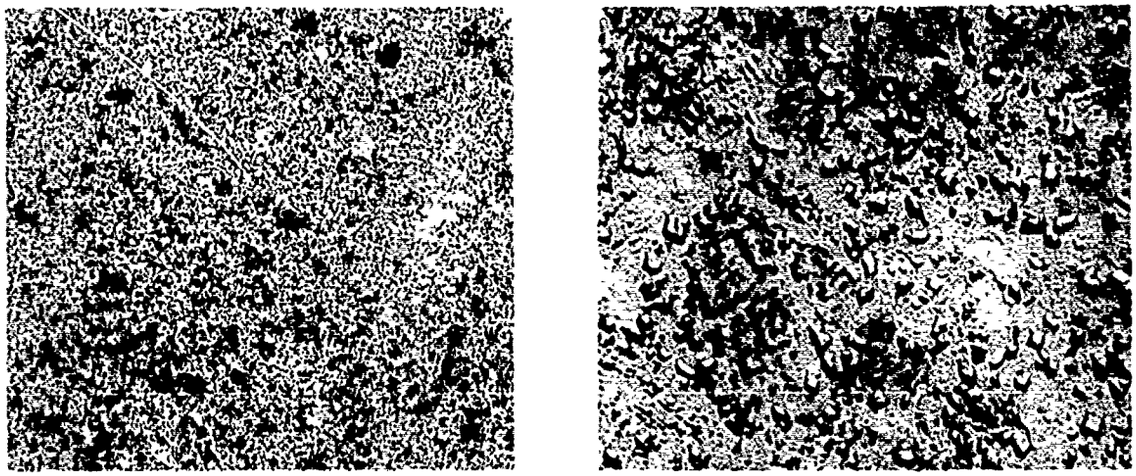
a) 1650°F/4 hr → 2100°F/1 hr/500°F Salt Quench



100X -200 Mesh Material 1000X

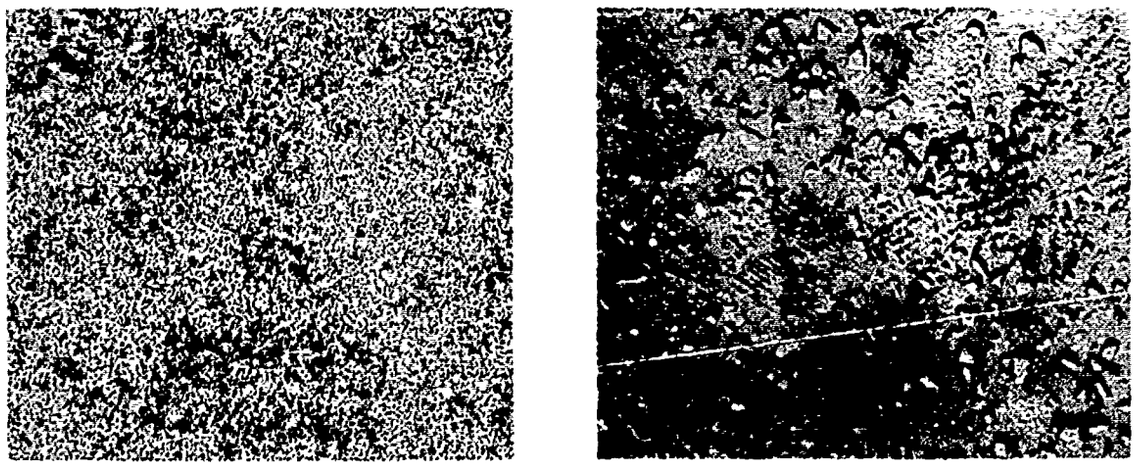
b) 1650°F/4 hr → 2100°F/1 hr/500°F Salt Quench

Figure 21. Typical Microsturctures of Vendor A Task IA Additional Heat-Treatment Quarter Sections After Solution Treatment (Sheet 1).



100X -200 Mesh Material 1000X

c) 1650°F/4 hr → 2100°F/1 hr/1000°F Salt Quench



100X -200 Mesh Material 1000X

d) 1650°F/4 hrs → 1075°F/1 hr/OQ

Figure 21. Typical Microstructures of Vendor A Task IA Additional Heat-Treatment Quarter Sections After Solution Treatment (Sheet 2).

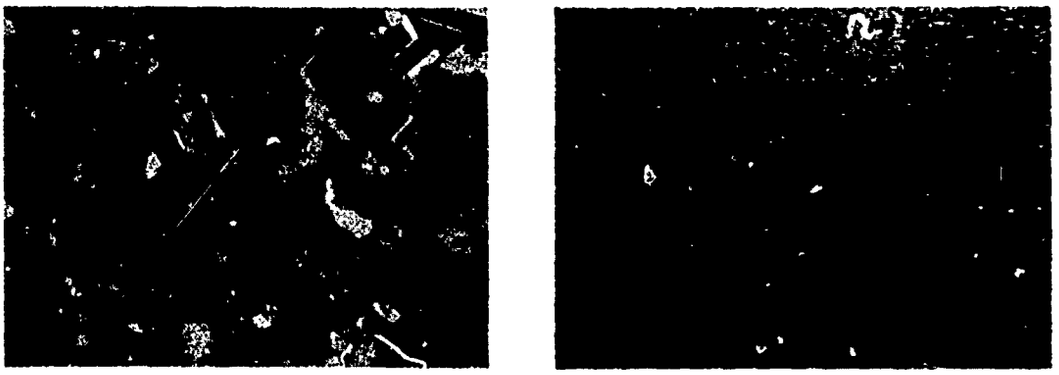
mesh material, when compared to those given in Table 18, indicate that yield and tensile strengths for the 500°F salt quench are slightly below those after oil quench and approximately equivalent to those after 1000°F salt quench. Stress rupture lives and ductilities are generally higher than after oil quenching but again virtually coincident with those obtained after 1000°F salt quenching. The conclusion derived from these data is that the sample size used for this evaluation can be adequately quenched in 1000°F salt and retain sufficient γ' in solution to develop near-maximum properties in subsequent age. The 500°F salt quench develops similar properties for this size bar but may be most useful in developing full properties in heavier sections. For this evaluation, on vendor A material, the 1000°F salt quench appears to be near optimum quench rate.

Application of the 500°F salt quench to -200 mesh powder resulted in the same microstructure (Figure 21b) observed in the -60 mesh material. Tensile and yield strengths were somewhat higher than those obtained on the -60 mesh material. No explanation is currently available for the one very low RT yield strength of disk 22H. The stress rupture properties were approximately equivalent to the -60 mesh material.

The 2100°F/1000°F salt quench was also applied to Vendor A -200 mesh powder material to compare with previously obtained results on -60 mesh material. The microstructure, shown in Figure 21c, is very similar to that of the 500°F salt quench material (21b). Tensile properties of the 1000°F salt quench samples were slightly lower in some cases than corresponding data from the -200 mesh 500°F salt quench material. This difference is most noticeable when 1200°F yield strengths are compared. Again, no reason is available for the one very low room temperature yield strength value in disk 21F. Stress rupture lives appear to be slightly lower than corresponding 500°F salt quench material, while ductilities were at least equivalent to, or, in the case of disk 21H, significantly better than, corresponding disk 22H. Tensile properties of the -200 mesh 1000°F salt quench material were generally equivalent to those obtained on similarly heat treated -60 mesh material (Table 20). Stress rupture lives were slightly lower, while ductilities, except for disk 21H, were equivalent to the -60 mesh material.

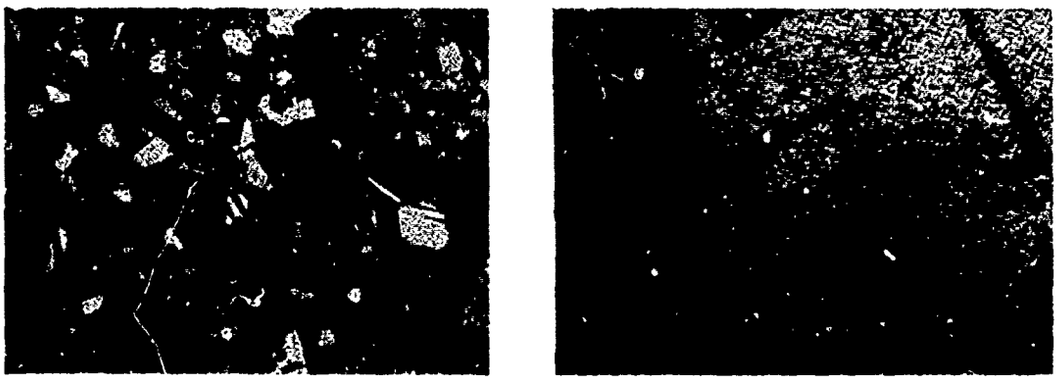
One Vendor A -200 mesh hollow cylindrical slice was solution treated at 2075°F/1 hour/OQ to compare with the initial heat treatment evaluation data on -60 mesh Vendor B material (Table 19). The microstructure after quenching, shown in Figure 21d, was uniformly finer than the -60 mesh Vendor B material (Figure 22a) but contained essentially the same γ' size and distribution. Tensile properties of the -200 mesh Vendor A material were approximately equivalent to those of the -60 mesh Vendor B material. There seems to be a tendency for somewhat lower tensile ductilities in the -200 mesh samples which, in disk 23J, apparently reduced room temperature tensile and yield strengths substantially. Stress rupture properties were very erratic in the -200 mesh material and generally lower than the initial Vendor B -60 mesh data (Table 21). Some of the data scatter in the -200 mesh samples may have been caused by quench cracks. Some cracking was noted visually in one quarter section and, although efforts were made to avoid these areas, some specimens could have contained fine cracks prior to testing.

Several additional heat treatments were also specified for the undesignated Vendor B Task IA material. One quarter section from the 2000°F/1 hour/OQ and 2075°F/1 hour/OQ material was aged at 1400°F/64 hours/AC + 1200°F/24 hours/AC in an effort to improve yield strength. The 1200°F/24 hours/AC age effectively increased strength after the 1500°F/4 hours/AC and 1600°F/1 hour/AC intermediate ages (quarter sections A2A, A2C, A4A, and A4C in Table 19). An attempt was also made to improve the yield strengths of the material solution treated above the γ' solvus by employing a double solution treatment on the undesignated hollow cylindrical slice. The initial 2165°F/1 hour/RAC was followed by a 2075°F/1 hour/OQ treatment to resolve most of the γ' precipitated during the air cooling from 2165°F. The primary intent here was to produce an ASTM 5-6 grain size and make a large quantity of solutioned γ' available for subsequent low temperature aging. The aging treatments evaluated include 1400°F/64 hours/AC, 1500°F/4 hours/AC + 1200°F/24 hours/AC, and 1600°F/1 hour/AC + 1200°F/24 hours/AC. One quarter section remained undesignated pending results of the other three sections.



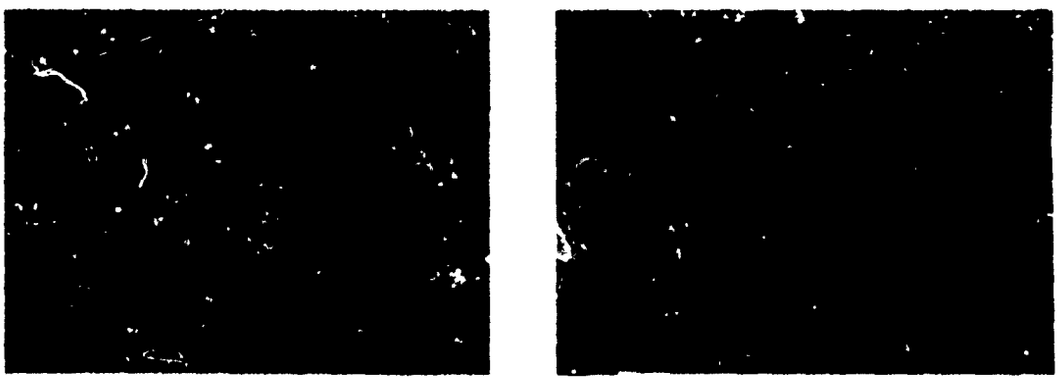
100X -60 Mesh Material 1000X

a) 1650°F/4 hr→2165°F/1 hr/RAC + 2075°F/1 hr/OQ



100X -100 Mesh Material 1000X

b) 1650°F/4 hr→2165°F/1 hr/RAC + 2075°F/1 hr/OQ



100X -100 Mesh Material 1000X

c) 1650°F/4 hr→2075°F/1 hr/OQ

Figure 22. Typical Microstructures of Task IA Additional Heat-Treatment Quarter Sections After Solution Treatment - Vendor B.

TABLE 21. ADDITIONAL TASK IA SCREENING TEST RESULTS ON VENDOR-B MATERIAL (SHEET 1)

			-100 Mesh Material										
			Tensile Properties								Stress-Rupture Properties		
			Room Temperature				1200°F				1200°F/150 ksi		
Disk Quarter Identity No.	Solution Treatment	Aging Treatment	0.2%YS (ksi)	UTS (ksi)	% El	% R of A	0.2%YS (ksi)	UTS (ksi)	% El	% R of A	Time (hr)	% El	% R of A
C4A	2165°F/1 hr/RAC	1400°F/64 hrs/AC	173 4	237.5	17.6	22 8	167.4	219 5	11.7	19 1	114 1	3.7	11.8
C4A	2075°F/1 hr/OQ		179 0	238 0	17 6	25 5	162 1	220 6	13 7	17.7	146.0	34	12.4
C4B	2165°F/1 hr/RAC+	1500°F/4 hrs/AC	180.6	239 1	16 1	20.2	170.3	223 4	12.4	18 5	170 1	36	70
C4B	2075°F/1 hr/OQ	1200°F/24 hrs/AC	180 0	238 0	16 9	21.1	167.3	224.2	13 2	20.2	198 5	63	12.4
C4C	2165°F/1 hr/AC	1600°F/1 hr/AC +	176.1	226 8	11.6	17.7	160 5	214.9	13.1	21 6	274 9	23	55
C4C	2075°F/1 hr/OQ	1200°F/24 hrs/A	178 0	227.7	13 8	16 5	162.4	217.7	12.6	19 0	257.8	9.8	8.3
							159.5	217.2	15.2	21.6			
C5A	2075°F/1 hr/AC	1400°F/16 hrs/AC	180.6	231.3	10 2	13 1	176 0	231.1	12.5	18 5	140.9	31	7.0
			182 6	235 6	17.1	20 5	170 6	229 0	12 2	15.7	118.0	33	83
C5B	2075°F/1 hr OQ	1400°F/32 hrs/AC	179.3	241.4	17.6	22 8	177.4	230.7	15.1	22.8	100 0	3.4	9.7
			182.6	245 6	16.7	22 8	172 2	224 8	14 8	19 0	93 8	4 0	13.0
C5C	2075°F/1 hr/OQ	1400°F/64 hrs/AC	184.9	244.1	12.1	15 1	172.8	220.5	9.1	15.1	60.5	56	9.7
			181.9	246 4	9 0	13 1	177.1	223 8	11 8	15.1	70.6	5.0	83
							165 3	213.5	8 5	15 1			
C5D	2075° F/1 hr/OQ	1400°F/64 hrs/AC +	188 5	243 9	15 8	21.1	170.6	228.7	11.5	17.7	81 0	46	9.0
C5D		1200°F/24 hrs/AC	185 5	247.9	16 0	22 8	169.6	225 5	11 9	17.6	57 4	42	8.3
C6A	2075°F/1 hr/OQ	1500°F/4 hrs/AC	178 7	241 2	15 8	23 5	169 6	227.4	10 6	16 4	132.2	4.7	12.6
			178 7	241 4	17.3	24.1	170 2	225.5	14 5	19 6	90.2	5.9	9.7
C6B	1075°F/1 hr/O.Q.	1500°F/4 hrs/AC +	188 1	249 8	15 8	22.8	171 0	228 6	14.5	15.1	100 9	36	7.0
C6B		1200°F/24 hrs/AC	187.5	248 2	14.0	20.1	173 2	221 9	10.5	14.7	140 6	6.4	9.7
C6C	2075°F/1 hr/OQ	1600°F/1 hr/AC	174 0	237.6	16 8	19 1	166.7	224 2	15 3	16.4	140 7	49	12.4
			171 2	233.4	15.1	16 9	154.3	223 5	14.3	16.4	100 3	43	7.0
C6D	2075°F/1 hr/OQ	1600°F/1 hr/AC +	183 6	242.9	13 4	18 1	172 8	232.6	16.1	21.5	129.3	43	11.0
C6D		1200°F/24 hrs/AC	182.9	242.0	14.5	19 0	172 6	230.0	12.0	19.0	117.3	4.2	9.0

TABLE 21. ADDITIONAL TASK IA SCREENING TEST RESULTS ON VENDOR B MATERIAL (SHEET 2)

			−60 Mesh Material										
			Tensile Properties								Stress-Rupture Properties		
			Room Temperature				1200°F				1200°F/150 ksi		
Disk Quarter Identity No.	Solution Treatment	Aging Treatment	0.2%YS (ksi)	UTS (ksi)	% El	% R of A	0.2%YS (ksi)	UTS (ksi)	% El	% R of A	Time (hr)	% El	% R of A
B2A	2165°F/1 hr/RAC	1400°F/64 hr/AC	179 3	236 2	13.7	20.2	165 5	218.1	11.7	14.3	99.4	3 3	11.1
B2A	2075°F/1 hr/OQ		183 6	231 6	13 2	18 3	161.0	219.0	12.2	19 0	82.4	2.2	4.9
B2B	2165°F/1 hr/RAC	1500°F/4 hr/AC+	190 0	231.6	13.2	18 3	164 5	219 4	13 4	18 3	215 0	4 3	9.7
B2B	2075°F/1 hr/OQ	1200°F/24 hr/AC	181.6	234 6	13 6	20.2	164.1	221.6	13 1	19.0	140.4	3.6	9.7
B2C	2165°F/1 hr/RAC+	1600°F/1 hr/AC+	177.4	222 9	10 7	13.7	166 0	217.0	13 8	21.0	200 4	6.6	9.8
B2C	2075°F/1 hr/OQ	1200°F/24 hr/AC	180 6	229 7	17.1	24.1	157.2	214.1	13.2	20.2	174 4	4 9	14.3
							157.9	213 8	15 7	21.5			

Results of the double solution treatment of Vendor B -60 mesh powder are presented in Table 21. Essentially the same grain size observed in the previous -60 mesh specimens solutioned at 2165°F/1 hour/RAC was produced. However, the γ' size and distributio.. was altered significantly by the second solution treatment (2075°F/1 hour/OQ). Large γ' precipitated at grain boundaries and within the grains during the 1 hour at 2075°F (as shown in Fig. 22a). Much more γ' was available for subsequent aging because of the oil quench from 2075°F. This increased amount of available γ' resulted in increased properties, as can be seen by a comparison of data in Tables 19 and 21. The average increase in yield strength was 20 to 25 ksi at both room temperature and 1200°F. Ultimate strengths and stress rapture lives also improved substantially, while tensile and stress rupture ductilities were degraded slightly. Some quench cracking was detected in one of the quarter sections suggesting that the oil quench may be too severe for the large-grained structure produced by the initial solution.

A 2-inch-thick slice from the -100 mesh Vendor B billet was also given the double solution treatment to determine the effect of powder mesh size. Metallographic and mechanical property evaluation indicated that the response of the -100 mesh material was essentially identical to that of the -60 mesh material. The microstructure, shown in Figure 22b is very similar to the -60 mesh material. Mechanical properties show the same trends as the -60 mesh, although the -100 mesh samples appear to have slightly better room temperature tensile ductilities and less scatter in stress rupture ductility data. The double solution treatment appeared to be a potentially attractive heat treatment, especially for Class C (slightly lower than our goal of Class B) hardware.

The most promising Vendor B solution treatment (2075°F/1 hour/OQ) identified using -60 mesh material was also applied to two -100 mesh slices to determine if any mechanical property improvements could inherently be obtained with a finer mesh size powder. Results indicated that application of the 2075°F/1 hour /OQ solution treatment to -100 mesh material produced microstructures (Figure 22c) and mechanical properties (Table 21) similar to those observed in the -60 mesh material. The only properties significantly affected by the finer mesh size were stress rupture lives and ductilities. These properties were improved substantially for several aging treatments, including 1400°F/16 hours/AC, 1400°F/32 hours/AC, 1500°F/4 hours /AC and 1500°F/ AC + 1200°F/24 hours/AC. Tensile strengths and ductilities deviated very little from the values determined on the -60 mesh disk (Table 21).

DETAILED EVALUATION

Based on the screening test results, a total of eight mesh size/heat treatment combinations (four per powder vendor) were selected for detailed evaluation. Important process parameters of these eight combinations are presented in Table 22. The 2075°F/1 hour 500°F salt quench was applied to one slice of Vendor A -60 mesh material to investigate a more moderate quench rate, while evaluation of the 2075°F/1 hour/OQ solution treatment on a -200 mesh slice allowed a comparison of this heat treatment on three different powder mesh sizes (-60, -100, -200). The 2060°F/1 hour/OQ was evaluated on -60 mesh Vendor B material to determine the mechanical property degradation associated with a slightly lower solution temperature. If acceptable, this solution treatment would reduce any tendency for quench cracking and also increase the margin between the γ' solvus and solution temperatures.

Complete 2-inch-thick cylindrical slices were cut, heat treated to each of the eight conditions, and sectioned to provide material for the detailed evaluation of low-cycle fatigue (LCF) and, in two cases, tensile specimens. Four LCF tests were selected to characterize the properties of As-HIP material relative to conventional cast + wrought and T700 P/M HIP + forge hardware. Important test parameters are described on page 90.

These four tests were intended to provide data at temperatures, notch conditions and stresses typical of the actual operating environment of the T700 engine. Specimen geometries for the four tests are shown in Figures 23 through 26. Specimen locations and orientations in the cylindrical slices are identified in Figure 27. Since tensile or stress-rupture data had not been previously obtained on Vendor A disk 63H or Vendor B disk B-8, six specimens were machined in the axial orientation as shown in Figure 27.

TABLE 22. HEAT-TREAT CONDITIONS SELECTED FOR DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICES

Powder Vendor	Disk	Mesh Size	Solution Treatment	Aging Treatment
A	6H	– 60	2100°F/1 hr/1000°F Salt Q	1600°F/1 hr/AC + 1200°F/24 hr/AC
A	21H	–200	2100°F/1 hr/1000°F Salt Q	1600°F/1 hr/AC + 1200°F/24 hr/AC
A	63H	– 60	2075°F/1 hr/500°F Salt Q	1600°F/1 hr/AC + 1200°F/24 hr/AC
A	23H	–200	2075°F/1 hr/OQ	1600°F/1 hr/AC + 1200°F/24 hr/AC
B	A4A	– 60	2075°F/1 hr/OQ	1500°F/4 hr/AC + 1200°F/24 hr/AC
B	A4C	– 60	2075°F/1 hr/OQ	1600°F/1 hr/AC + 1200°F/24 hr/AC
B	C6D	–100	2075°F/1 hr/OQ	1600°F/1 hr/AC + 1200°F/24 hr/AC
B	B8	– 60	2060°F/1 hr/OQ	1600°F/1 hr/AC + 1200°F/24 hr/AC

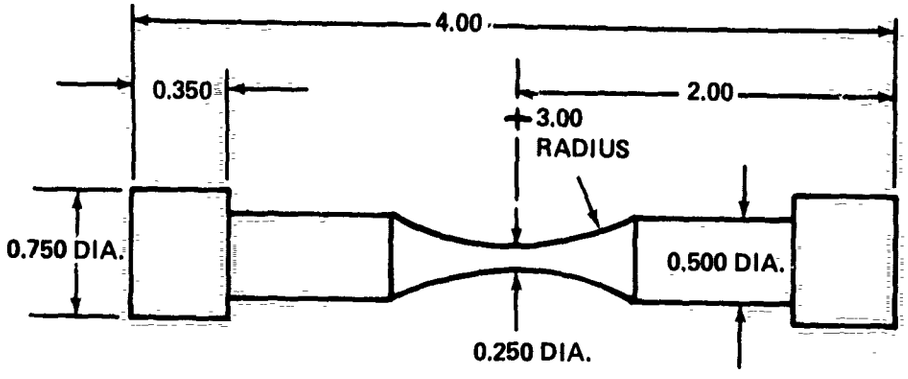


Figure 23. Smooth Bar Low-Cycle Fatigue (Strain Control) Test Specimen.

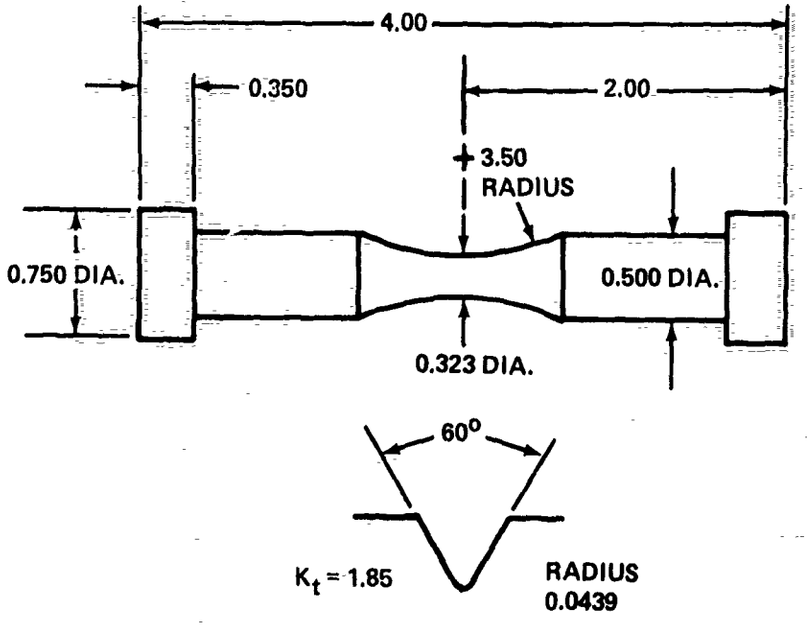


Figure 24. Notched Bar Low-Cycle Fatigue (Load Control) Test Specimen.

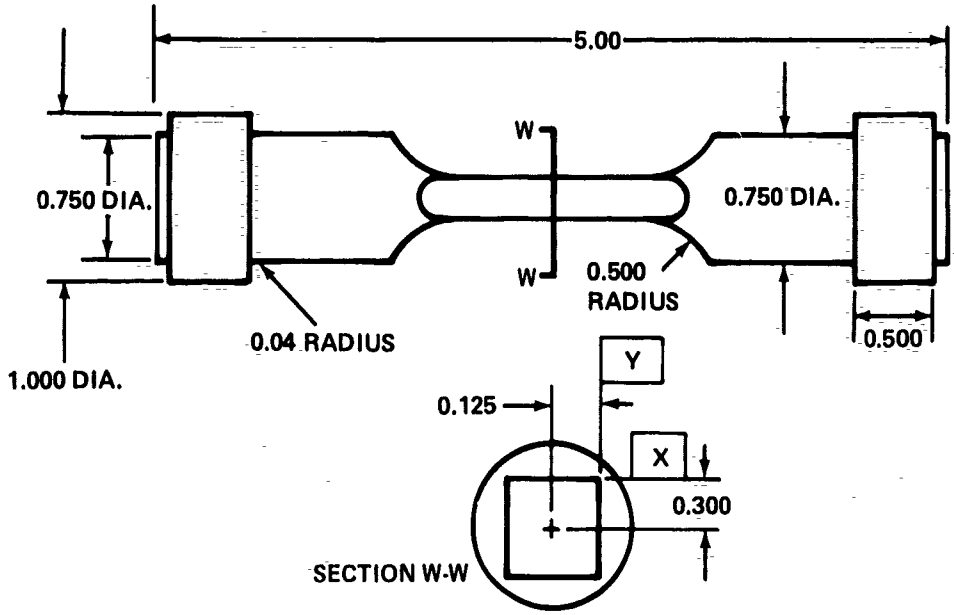


Figure 25. Crack Propagation (K_{P_j}) Test Specimen.

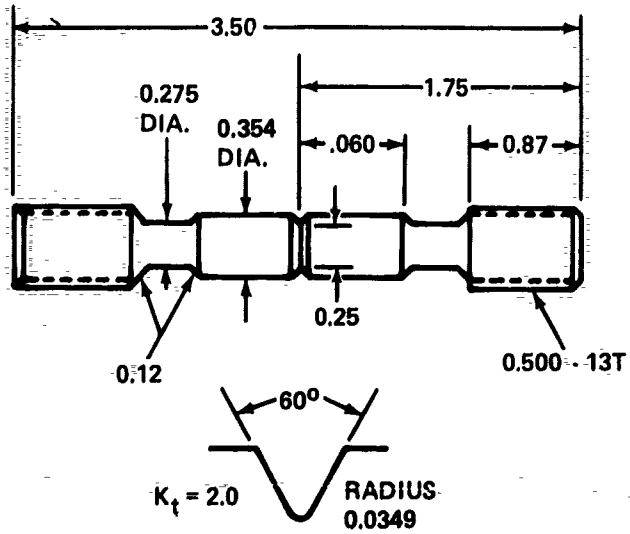


Figure 26. Double Reduce Notched Bar Cycle Rupture (SPLCF) Test Specimen.

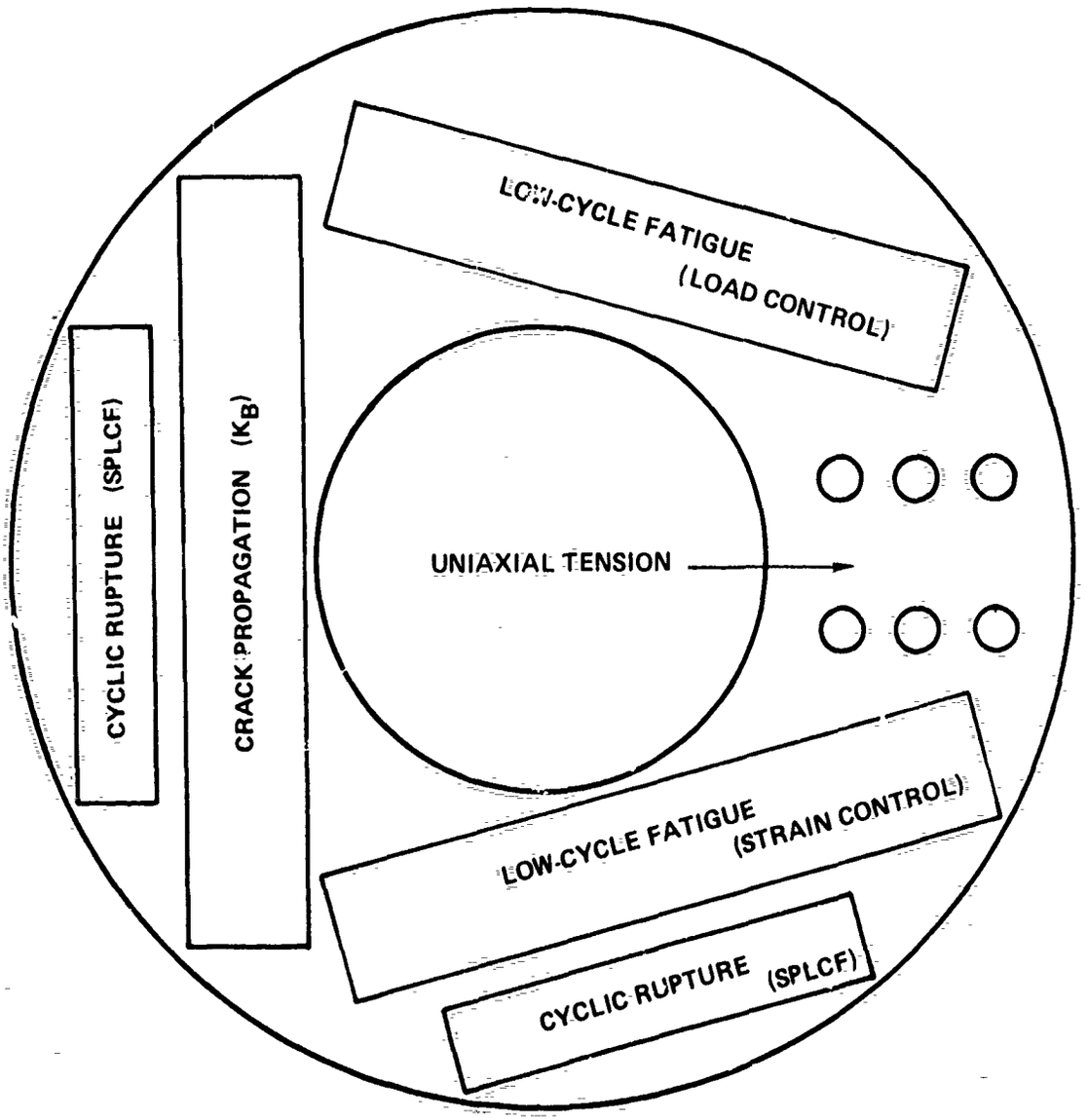


Figure 27. Location of Specimens in Detailed Evaluation of Hollow Cylindrical Slices.

Temperature	Test Type	Stress Ratio	Notch Severity	Maximum Alternate Stress
900°F	PS/N_f*	A = 1	$K_t = 1.0$	150 ksi
1050°F	PS/N_f	A = 1	$K_t = 1.85$	80 ksi
1000°F	Crack Propagation	A = 1	0.020 X 0.060 in. crack	100 ksi
1200°F	SPLCF**	A = 1	$K_t = 2.0$	72.5 ksi

*PS – Pseudo Stress, N_f – Number of Cycles to Failure.
**SPLCF – Sustained Peak Low-Cycle Fatigue which is an LCF test with a superimposed hold time. An actual test cycle is 10 seconds to load to peak stress, 90 seconds at peak stress and 10 seconds to unload.

Each cylindrical slice was examined metallographically after the heat treatment to insure that the proper temperatures had been attained. The results, when compared to previously heat treated quarter sections from the screening test study, indicated that all had been processed properly. Typical microstructures are presented in Figure 28.

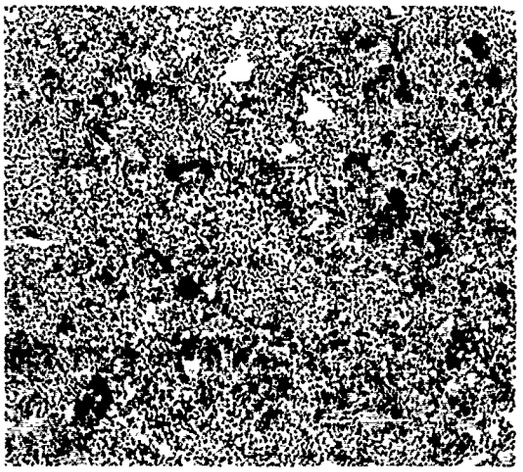
The tensile and stress rupture results on all eight treatments examined in the detailed evaluation are summarized in Table 23. Each data point represents the average of two test results. The overall high quality of the data is exemplified by the fact that only three of the eighty data points determined failed to meet the program goal.

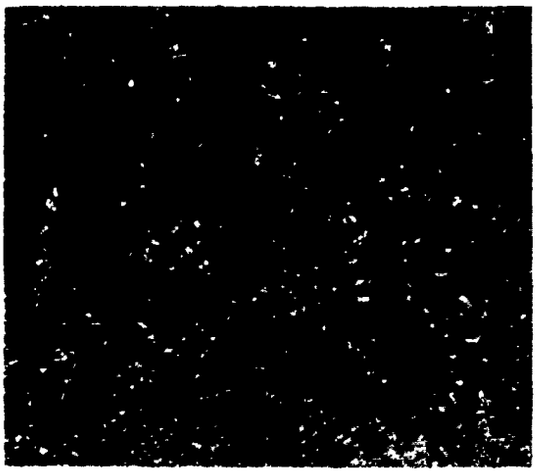
Composite test results of the detailed evaluation low-cycle fatigue testing are given in Table 24. All data were compared to an average value for T700 P/M HIP + forged engine hardware to provide a basis for judgment.

Results of the 900°F LCF testing of a smooth bar specimen ($K_t = 1.0$) indicated that nearly all As-HIP materials evaluated exceeded the average performance of HIP + forged parts. A graphical representation of the data, shown in Figure 29, suggests that the best As-HIP materials are approximately 1σ better than T700 HIP + forge parts.

Evaluation of 1050°F with a notch of $K_t = 1.85$ indicated that the two best As-HIP results were equivalent to HIP + forged average curve, suggesting that As-HIP material can be processed by several methods to produce acceptable 1050°F LCF properties. This is shown graphically in Figure 30.

The 1000°F crack propagation testing was conducted using a precracked K_B specimen (Figure 25). Specimen preparation consisted of electrical discharge machining (EDM) a 0.010-inch-deep by 0.040-inch-wide slot in the center of the gage section. The specimen was then fatigue precracked until the total crack length reached approximately 0.060 inch. The number of cycles to failure of the specimen is intimately associated with the initial size of the precracked slot. In order to reduce the effect of initial crack size on interpretation of results, the cycles to failure have been plotted against initial crack area for As-HIP, HIP + forged, and conventional cast + wrought specimens in Figure 31. Since insufficient data is available on T700 HIP + forged parts to construct a curve, previous cast + wrought results were used to provide a basis for judgment of the As-HIP material. A rectangle enclosing all T700 HIP + forged data was also constructed for comparative purposes. The group of As-HIP data fall on the lower portion of the T700 HIP + forged results and about $1 \pm 0.5\ \sigma$ below that of the cast + wrought material.

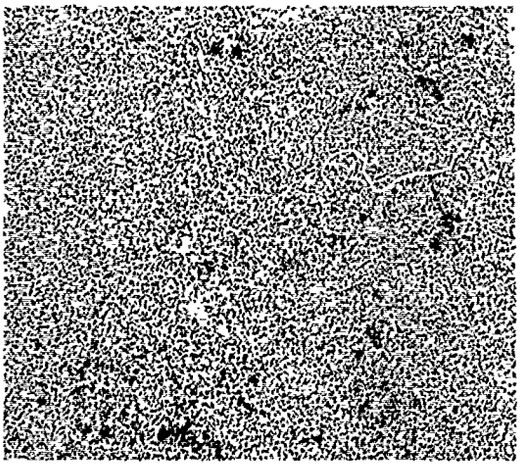


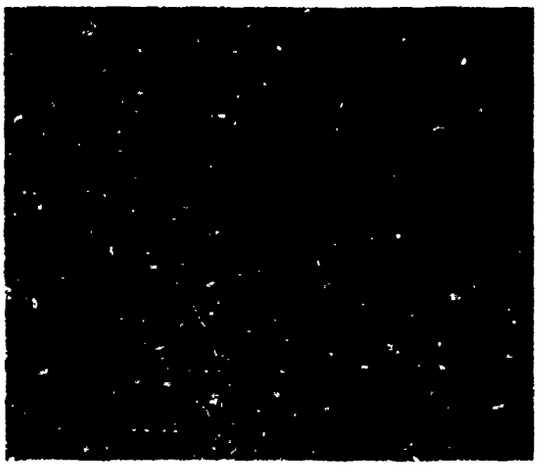


100X 1000X

Vendor A -60 Mesh Material (6H)

a) 1650°F/4 hr → 2100°F/1 hr/1000 Salt Quench + 1600°F/1 hr/AC + 1200°F/24 hr/AC



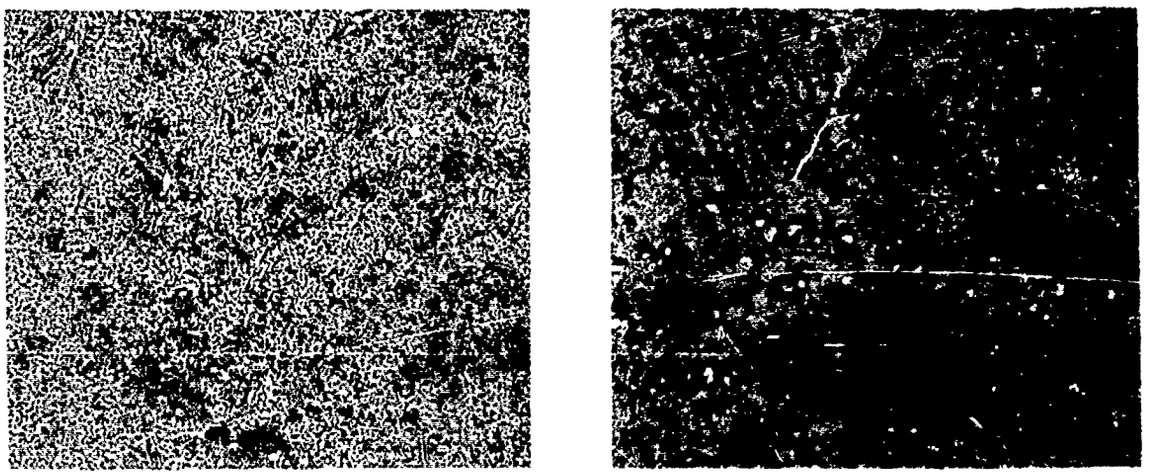


100X 1000X

Vendor A -200 Mesh Material (21H)

b) 1650°F/4 hr → 2100°F/1 hr/1000 Salt Quench + 1600°F/1 hr/AC + 1200°F/24 hr/AC

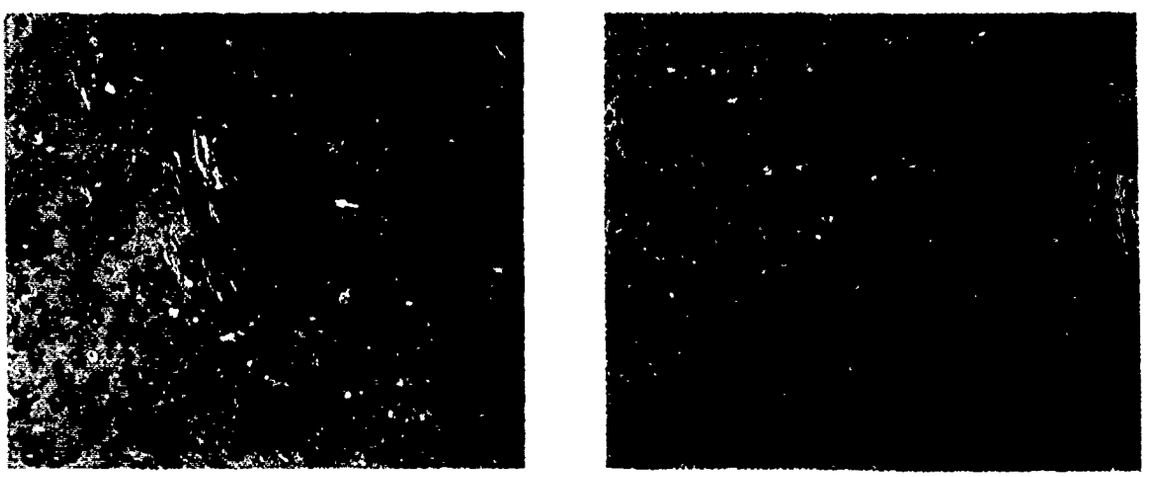
Figure 28. Typical Microstructures of Task IA Detailed Evaluation Hollow Cylindrical Slices After Solution and Aging Treatments – (Sheet 1).



100X 1000X

Vendor A -60 Mesh Material (63H)

c) 1650°F/4 hr → 2075°F/1 hr/500 Salt Quench + 1600°F/1 hr/AC + 1200°F/24 hr/AC

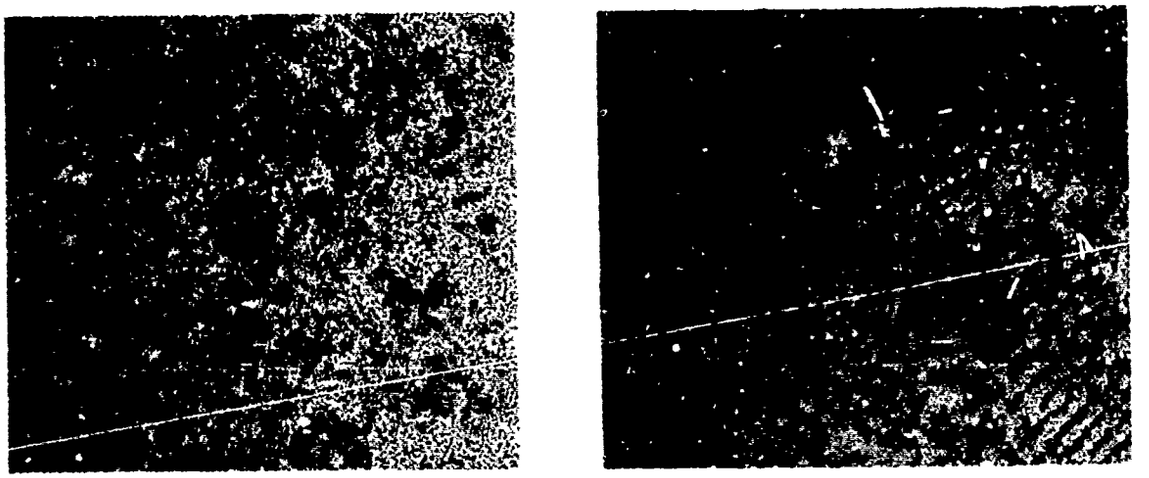


100X 1000X

Vendor A -200 Mesh Material (23H)

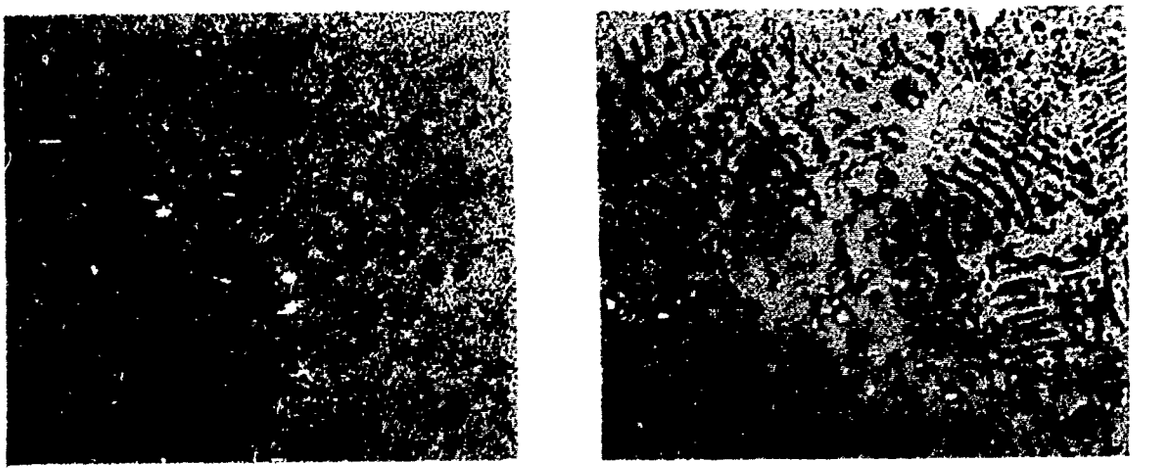
d) 1650°F/4 hr → 2075°F/1 hr/Oil Quench + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Figure 28. Typical Microstructures of Task IA Detailed Evaluation Hollow Cylindrical Slices After Solution and Aging Treatments – (Sheet 2).



100X Vendor B -60 Mesh Material (A4A) 1000X

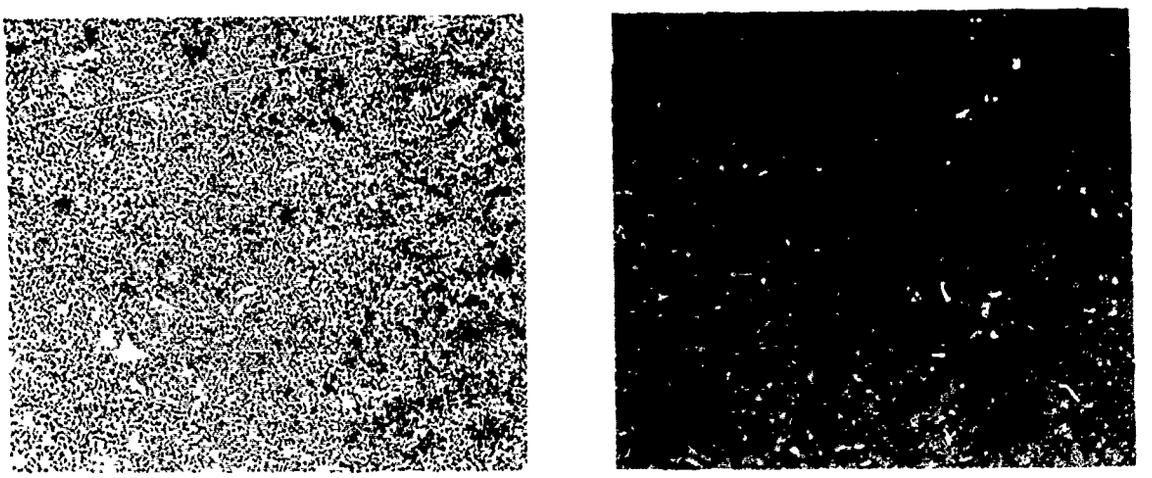
e) 1650°F/4 hr → 2075°F/1 hr/Oil Quench + 1500°F/1 hr/AC + 1200°F/24 hr/AC



100X Vendor B -60 Mesh Material (A4C) 1000X

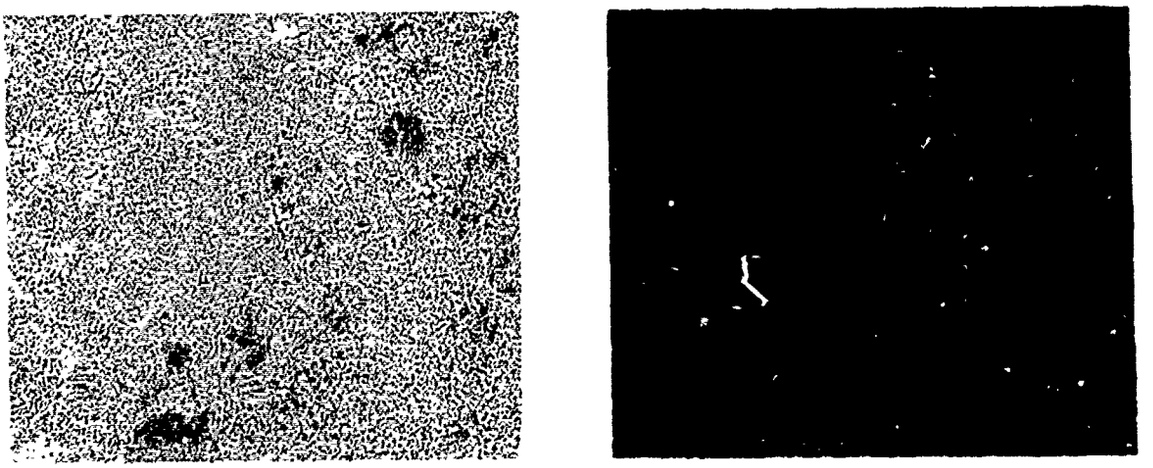
f) 1650°F/4 hr → 2075°F/1 hr/Oil Quench + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Figure 28. Typical Microstructures of Task IA Detailed Evaluation Hollow Cylindrical Slices After Solution and Aging Treatments - (Sheet 3).



100X Vendor B -100 Mesh Material (C6D) 1000X

g) 1650°F/4 hr →2075°F/1 hr/Oil Quench + 1600°F/1 hr/AC + 1200°F/24 hr/AC



100X Vendor B -60 Mesh Material (B8) 1000X

h) 1650°F/4 hr →2060°F/1 hr/Oil Quench + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Figure 28. Typical Microsturctures of Task IA Detailed Evaluation Hollow Cylindrical Slices After Solution and Aging Treatments – (Sheet 4).

TABLE 23. TENSILE AND STRESS RUPTURE RESULTS OF MATERIAL SELECTED FOR DETAILED EVALUATION

Disk	Mesh Size	Tensile Properties								1200°F/150 ksi Stress Rupture	
		Average Room Temp				Average 1200°F					
		0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Life (hr)	EL (%)
Vendor A											
6H	– 60	182	244	15	17	171	225	15	19	130	5.3
21H	–200	181	244	16	24	168	218	10	14	98	8.7
63H	– 60	181	232	16	17	170	224	11	18	105	4.2
23H	–200	185	244	14	20	174	223	12	15	60	3.2
Vendor B											
A4A	– 60	184	244	14	21	177	229	13	18	87	2.9
A4C	– 60	182	242	15	17	173	228	14	18	112	4.5
C6D	–100	183	242	14	18	173	231	14	20	123	4.3
B8	– 60	178	228	12	18	168	222	14	19	78	4.4
Goal		180	230	10	12	167	207	8	10	50	3.0

TABLE 24. LOW-CYCLE FATIGUE RESULTS OF MATERIALS SELECTED FOR TASK IA DETAILED EVALUATION

Powder Vendor	Disk No.	Powder Mesh Size	900°F K_t = 1.0 Alt. Stress = 150 ksi Cycles to Failure	1050°F K_t = 1.85 Alt. Stress = 80 ksi Cycles to Failure	1000°F Crack Propagation Max. Stress = 100 ksi Cycles to Failure	1200°F SPLCF K_t = 2.0 Max. Stress = 145 ksi Cycles to Failure	
A	6H	−60	10044	3919	6383	1111,	884*
A	21H	−200	5316	4222	6166	470*,	664
A	63H	− 60	5199	2984	6694	242*,	785
A	23H	−200	5182**	***	5361	671*,	276*
B	A4a	−60	7000†	2909	7042	1081*,	485*
B	A4C	−60	3885	3132	6720	1698*,	395
B	C6D	−100	4628	2253	6000	689*,	158*
B	B8	−60	6694	2222	6892	287*,	327*
Average HIP + Forge			4500	4000	7100–7900	900	

*Thread Failure
**Thermocouple Weld Failure
***Specimen Fractured During Machining
†Specimen Inadvertently Tested 53,000 Cycles at Alt. Stress = 75 ksi Prior to Actual Test

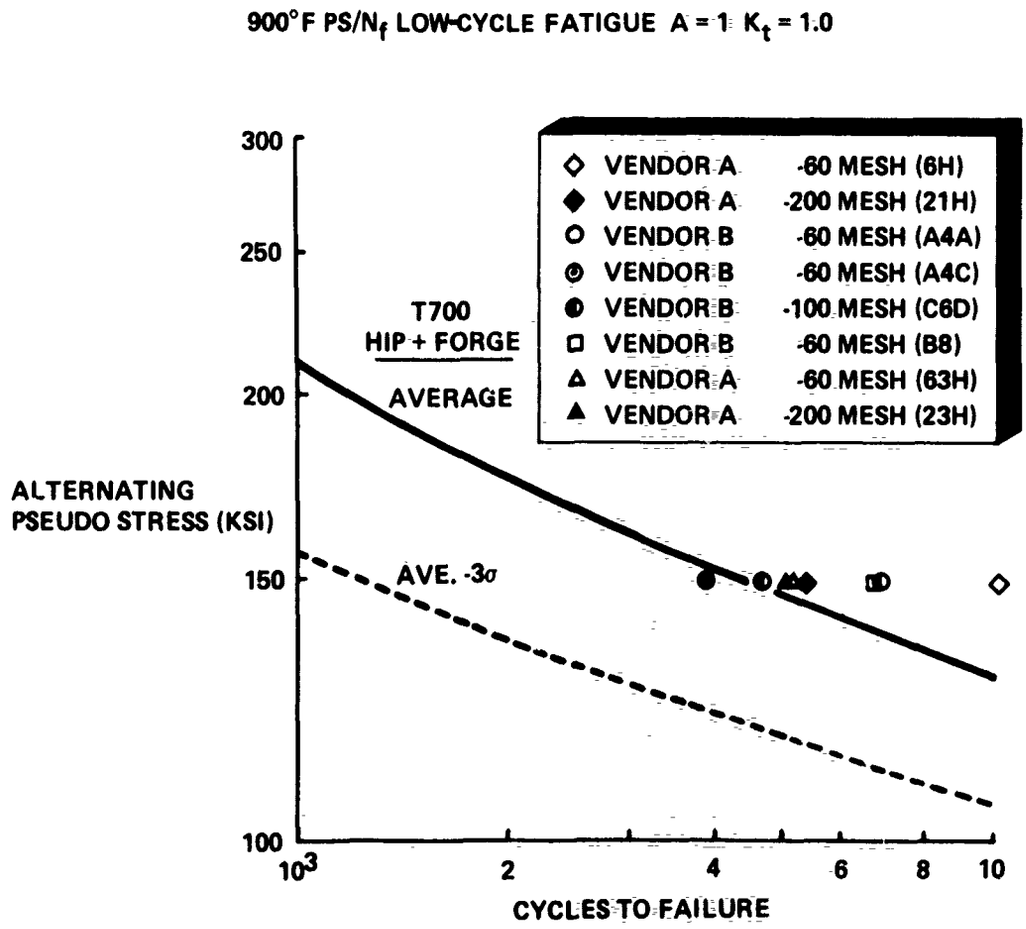


Figure 29. Results of 900°F Low-Cycle Fatigue Testing During the Detailed Evaluation of Hollow Cylindrical Slices Compared to PM HIP + Forged T700 Hardware Data

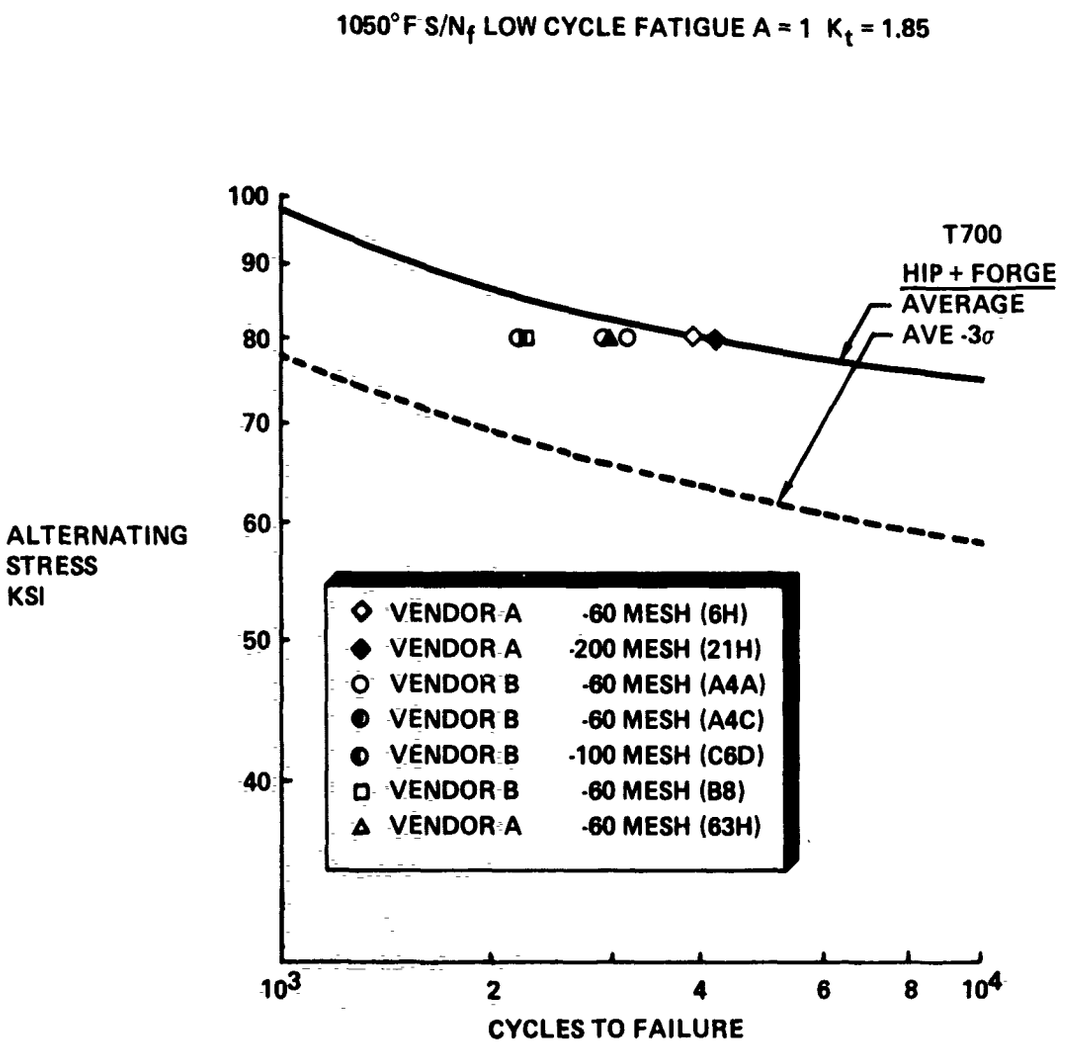


Figure 30. Results of 1050°F Low-Cycle Fatigue Testing During the Detailed Evaluation of Hollow Cylindrical Slices Compared to PM HIP + Forged T700 Hardware Data.

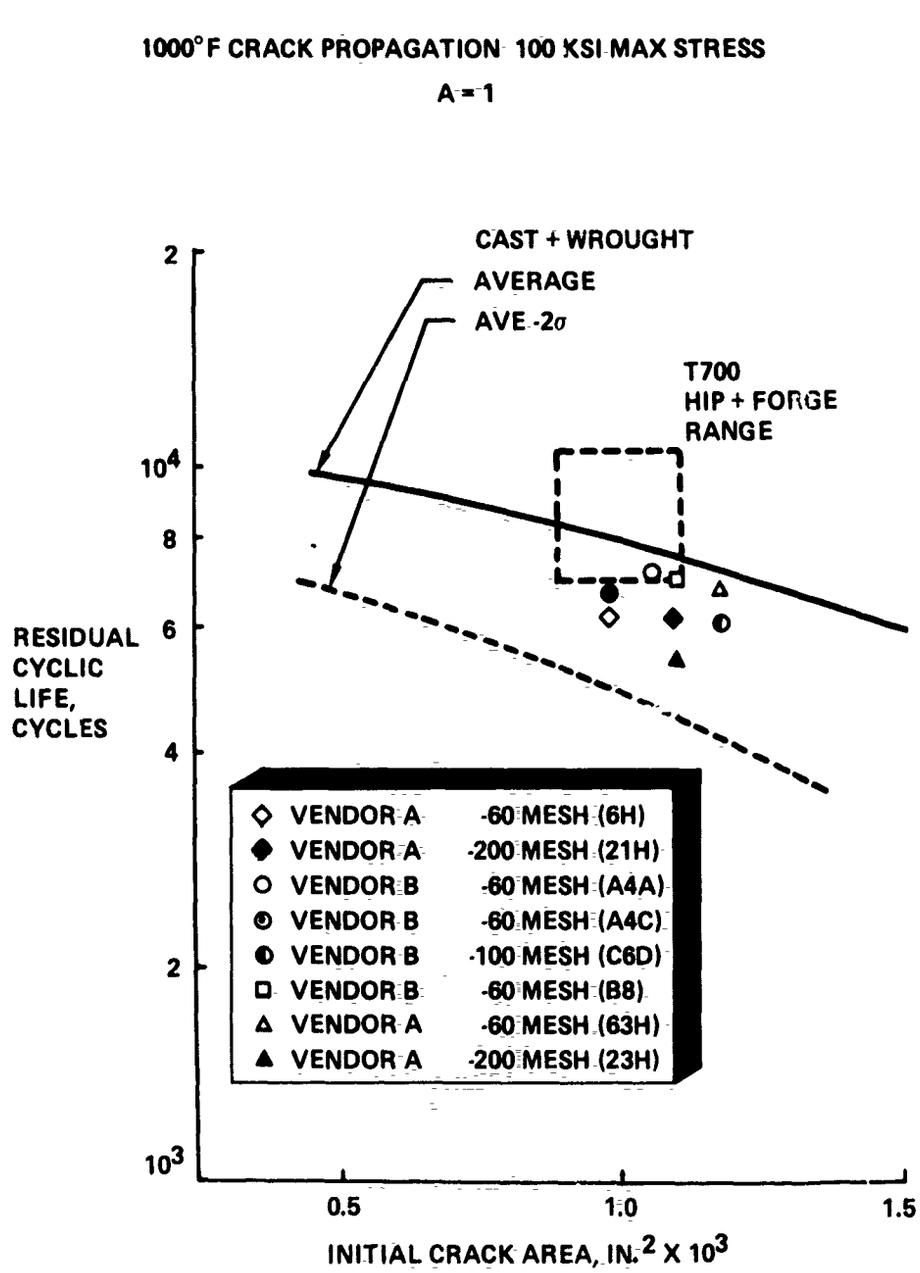


Figure 31. Results of 1000°F Crack Propagation Testing During the Evaluation of Hollow Cylindrical Slices Compared to PM HIP + Forged T700 Hardware Data.

The 1200°F SPLCF test was considered to be the most difficult LCF test for the As-HIP material. The combination of high temperature, high stress, fairly severe notch, and hold time between cycles makes it extremely difficult for fine grained materials, such as the eight As-HIP conditions tested in the detailed evaluation, to perform as well as the coarser grained cast + wrought or T700 HIP + forged parts. Again, Figure 32 indicates that insufficient data was available for definition of a HIP + forged curve. Therefore, the cast + wrought data was used to provide a curve with the indication of the range T700 HIP + forged results. The wide range of HIP + forge data indicates the substantial scatter encountered in the SPLCF test. Results on As-HIP material were clouded by the occurrence of many thread failures, which undoubtedly reduced the cycles to failure. Further investigation into this problem revealed that all As-HIP SPLCF specimens had severe notches at the thread root. These notches, which had K_t = 5-6, were far more severe than those measured on similarly machined HIP + forged specimens ($K_t \cong 3.5$) and were apparently the cause of the premature failures.

In spite of the abundance of premature failures, several As-HIP materials exhibited excellent SPLCF properties. It is conceivable that elimination of the thread failure problem would reveal a number of specimens which produce acceptable SPLCF properties in As-HIP Rene' 95.

A tabular listing of the tensile, stress-rupture, and LCF properties of each of the eight detailed evaluation materials compared to the program goals and average T700 HIP + forged data is presented in Tables 25 through 32. Analysis of each of these tables indicated that the best combination of mechanical properties was produced in Vendor A disk 6H. It would appear that the same heat treatment on Vendor B disk (B5C) yielded lower mechanical properties. The disk B5C however, was solution treated in 2075°F salt bath and then transfered to a 1000°F salt quench tank as opposed to that of Vendor A (6H),which was solution annealed in air. The freezing of high temperature salt around the Vendor B disk (B5C) appears to be responsible for a slower quench rate resulting in the lower properties. Note that the designated heat treatment depends on the γ' solvus temperature of the individual powder blend. This variable solution treatment temperature was specified to allow for heat-to-heat variations in γ' solvus temperatures such as the 20°F difference noted between Vendor A (2135°F) and Vendor B (2115°F) Task I powder blends. These parameters provide the basic framework for achievement of mechanical properties in As-HIP T700 hardware that fulfill the program goal requirements.

In conclusion, the results of Task IA revealed that an optimum combination of compaction and heat treatment parameters yielded desired mechanical properties and microstructure in Hot Isostatically pressed Rene' 95 billets. The finer mesh size powder offers no advantage over the -60 mesh powder,which offers ease in handling. It confirmed 15 ksi and 2050°F to be the suitable HIP parameters. The 2000°F solution temperature used in the heat treatment of forgings appears to be low for HIP compacts and higher solution temperature (but below the γ' solvus to avoid grain growth and low tensile properties) with increased γ' in solution is desirable. The goal of future work would be to achieve similar properties in the compacts with actual hardware configuration.

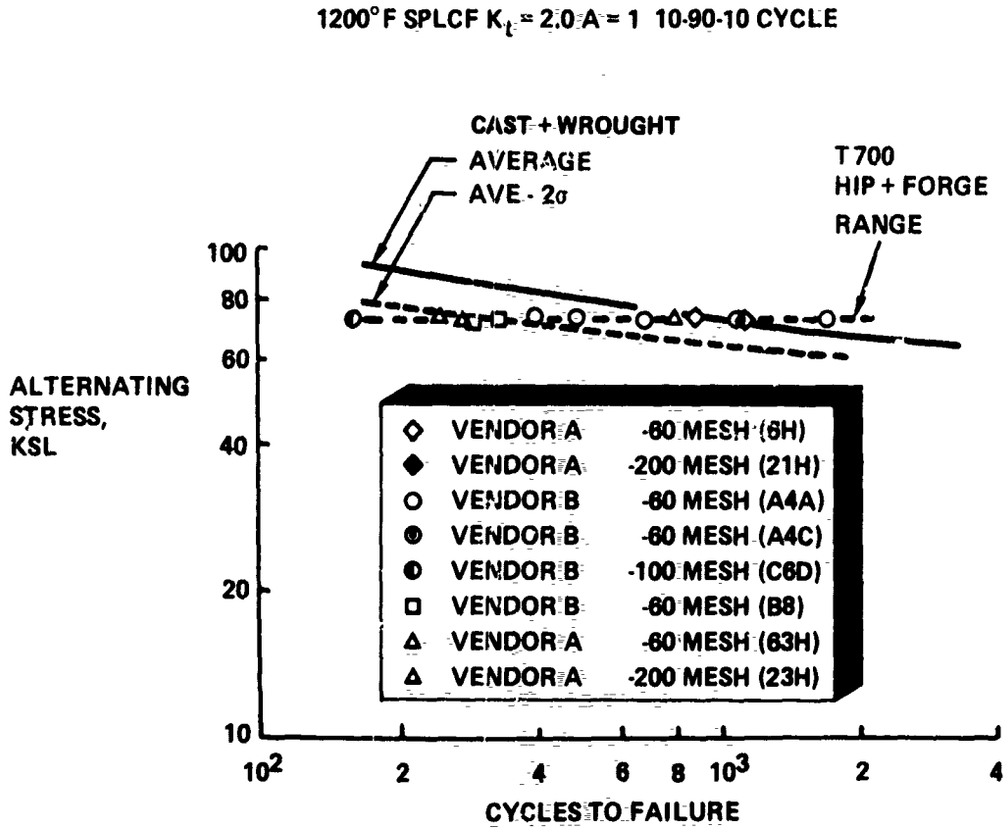


Figure 32. Results of 1200°F Sustained Peak Low-Cycle Fatigue Testing During the Detailed Evaluation of Hollow Cylindrical Slices Compared to PM HIP + Forged T700 Hardware Data.

TABLE 25. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Task IA Results Powder Mesh Size/Heat Treatment Parameters

Powder Vendor..... A. (6H)
Powder Mesh Size ..... -60
Heat Treatment..... 2100°F/1 hr/1000°F Salt Q + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200°F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	181.6	246.2	16.9	20.5	170.1	224.4	13.8	16.0
	181.6	242.3	13.8	14.1	171.6	225.4	16.3	21.8
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL (%)	RA (%)
	155.8	4.9	6.5
	104.5	5.8	8.3
Goal	50	3.0	

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	1000°F 0.021 x 0.059 in. Crack
As-HIP	10044	3919	1111, 884*	6383
HIP - Forge	4500	4000	900	7900

*Thread Failure

TABLE 26. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Powder Vendor ..... A (21H)
Powder Mesh Size ..... -200
Heat Treatment ..... 2100°F/1 hr/1000°F Salt Q + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	179.5	244.0	15.9	24.2	169.5	219.3	11.5	18.4
	183.1	245.2	15.9	24.2	167.5	217.0	9.1	9.6
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL(%)	RA(%)
	104.3	8.3	11.1
	79.3	9.0	18.4
Goal	50	3.0	

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	100°F 0.022 x 0.063 in. Crack
As-HIP	5316	4222	470*,664	6166
HIP + Forge	4500	4000	900	7400

*Thread Failure

TABLE 27. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Powder Vendor ..... A (63H)
Powder Mesh Size ..... −60
Heat Treatment ..... 2075°F/1 hr/500°F Salt Q + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200°F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	182.4 179.0	225.4 237.6	18.7 12.7	16.3 18.6	166.9 173.0	221.1 226.1	12.0 11.3	18.9 17.8
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL (%)	RA (%)
	62.6 147.3	3.0 5.3	5.6 12.9
Goal	50	3.0	–

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	1000°F 0.026 x 0.062 in. Crack
As-HIP	5199	2984	242*, 785	6694
HIP + Forge	4500	4000	900	7100

*Thread Failure

TABLE 28. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Powder Vendor ..... A (23H)
Powder Mesh Size ..... –200
Heat Treatment ..... 2075°F/1 hr/OQ + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	184.6 186.5	246.8 241.8	16.6 12.2	26.3 16.4	** 174.3	223.6 222.1	12.3 12.8	14.0 16.0
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL (%)	RA (%)
	38.5 62.8	2.4 4.0	7.7 11.8
Goal	50	3.0	—

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	1000°F 0.022 x 0.063 in. Crack
As-HIP	5182***	—	671*,276*	5361
HIP + Forge	4500	—	800	7400

*Thread Failure
**No Data Extensometer Slipped
***T/C Weld Failure

TABLE 29. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Powder Vendor ..... B (A4A)
Powder Mesh Size..... −60
Heat Treatment ..... 2075°F/1 hr/OQ + 1500°F/4 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200° F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	184.6 183.3	242.6 245.5	12.2 16.1	16.5 26.8	178.7 175.1	230.0 228.7	14.4 11.9	17.7 19.0
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL (%)	RA (%)
	66.9 107.7	3.0 2.7	7.0 7.0
Goal	50	3.0	–

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	1000°F 0.023 x 0.059 in. Crack
As-HIP	7000*+	2909	1081**,485**	7042
HIP + Forge	4500	4000	900	7600

*Inadvertantly Tested 53,000 Cycles at a Low Stress Prior to Actual Test
**Thread Failure

TABLE 30. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Powder Vendor ..... B (A4C)
Powder Mesh Size..... −60
Heat Treatment ..... 2075°F/1 hr/OQ + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200°F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	183.3 180.3	242.6 241.6	16.5 14.8	20.4 15.2	173.0 173.3	228.1 228.7	15.2 13.1	16.5 20.1
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL (%)	RA (%)
	108.6 116.9	4.7 4.2	7.0 7.0
Goal	50	3.0	–

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	1000°F 0.022 x 0.059 in. Crack
As-HIP	3885	3132	1698*, 395	6720
HIP + Forge	4500	4000	900	7850

*Thread Failure

TABLE 31. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Powder Vendor ..... B (C6D)
Powder Mesh Size..... −100
Heat Treatment .....2075°F/1 hr/OQ + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200°F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	183.6 182.9	242.9 242.0	13.4 14.5	18.1 19.0	172.8 172.6	232.6 230.0	16.1 12.0	21.5 19.0
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL (%)	RA (%)
	129.3 117.3	4.3 4.2	11.0 9.0
Goal	50	3.0	

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	1000°F 0.024 x 0.062 in. Crack
As-HIP	4628	2253	689*,158*	6000
HIP + Forge	4500	4000	900	7100

*Thread Failure

TABLE 32. COMPOSITE DATA FROM DETAILED EVALUATION OF HOLLOW CYLINDRICAL SLICE

Powder Vendor	B (B8)
Powder Mesh Size	–60
Heat Treatment	2060°F/1 hr/OQ + 1600°F/1 hr/AC + 1200°F/24 hr/AC

Tensile Properties

	Room Temp				1200°F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
	179.1 176.4	218.1 238.7	8.6 15.3	15.0 22.4	166.4 169.4	222 221.5	13.[illegible] 13.8	19.7 17.8
Goal	180	230	10	12	167	207	8	10

Stress-Rupture Properties

	Life (hr)	EL (%)	RA (%)
	88.6 68.7	4.6 4.1	15.4 12.6
Goal	50	3.0	–

Low-Cycle Fatigue Properties

	LCF		SPLCF	Crack Propagation
	900°F K_t = 1.0	1050°F K_t = 1.85	1200°F K_t = 2.0	1000°F 0.023 x 0.061 in. Crack
As-HIP	6694	2222	287*,327*	6892
HIP + Forge	4500	4000	900	7400

*Thread Failure

TASK IB – SHAPE DEFINITION

The primary objective of Task IB was to define the processing parameters required to produce a turbine disk shape. This shape, shown in Figure 33, was designed to permit either a Stage 1 or 2 disk to be machined after ultrasonic inspection. The square cornered, parallel-sided design can be inspected using current ultrasonic technology, and represents approximately 50 percent reduction to input weight relative to current shape.

Task IB was divided into three iterations by each vendor in order to incorporate experience gained in initial trials into refined container designs. Although both vendors used -60 mesh powder in the majority of their trials, some finer mesh size disks were fabricated to determine the effect of mesh size on shape definition and handling procedures. Since each vendor employed different techniques, their progress will be reported in separate sections.

A. Vendor A

The first disk, shown in Figure 34, was fabricated using -60 mesh powder consolidated at 2000°F and 15,000 psi. After compaction, the mold was removed by machining and the part was heat treated using a modified Rene' 95 treatment. Following the partial solution treatment of 2000°F/1 hour, the disk was quenched into 900°F salt rather than the room temperature oil normally used. This relatively slow quench was employed to reduce the possibility of quench cracking. The standard 1400°F/16 hours/AC final age was then applied after the salt quench.

Mechanical properties, including tensile, stress rupture and sustained peak low-cycle fatigue tests, are compared with the program goals in Table 33. The results are surprisingly good in spite of the slow salt quench after partial solutioning. Analysis of the shape before and after compaction provided direction for design of the second iteration disks.

Two container materials were examined in the second and third iterations: metal containers shaped by the shear-spin forming technique, and ceramic containers prepared using wax molds. Five disks were prepared for the second iteration. A description of the variables examined in each disk is presented in Table 34, while the target shape for both the second and third iterations is shown in Figure 33.

A typical ceramic shell mold used to fabricate second iteration disks is shown in Figure 35. The two compacts prepared using ceramic molds are shown after consolidation in Figure 36. Figures 37 and 38 illustrate the shape of each compact before and after consolidation relative to the target sonic shape. The concave shape of the bottom surface of each disk is probably due to mold cracking under the weight of the powder. Subsequent compaction studies showed that this effect can be reduced and controlled by a modified mold design and application of more prudent handling techniques prior to consolidation. Mold reaction depth was also a concern with the ceramic containers. The reaction layer resulting from ceramic mold/metal powder interaction was determined to be 0.002 inch thick on the second iteration disks. This is a critical measurement, since production of a thick reaction layer would limit the near-net shape making potential of ceramic molds. The very thin layer indicates that the mold reaction will not limit the shape-making capability of the current ceramic mold material for the T700 applications. These second iteration results were subsequently incorporated in the third iteration ceramic mold configuration.

Spun metal containers were prepared from Type 321 stainless steel and Inconel 601 for the second iteration. A typical stainless steel can prior to assembly is shown in Figure 39. Compacts B112, B113, and B114 are shown after consolidation in Figure 40, while Figure 41 shows compacts B113 and B114 after the container was removed. The shape definition of compacts B113 and B114 relative to the target sonic is illustrated in

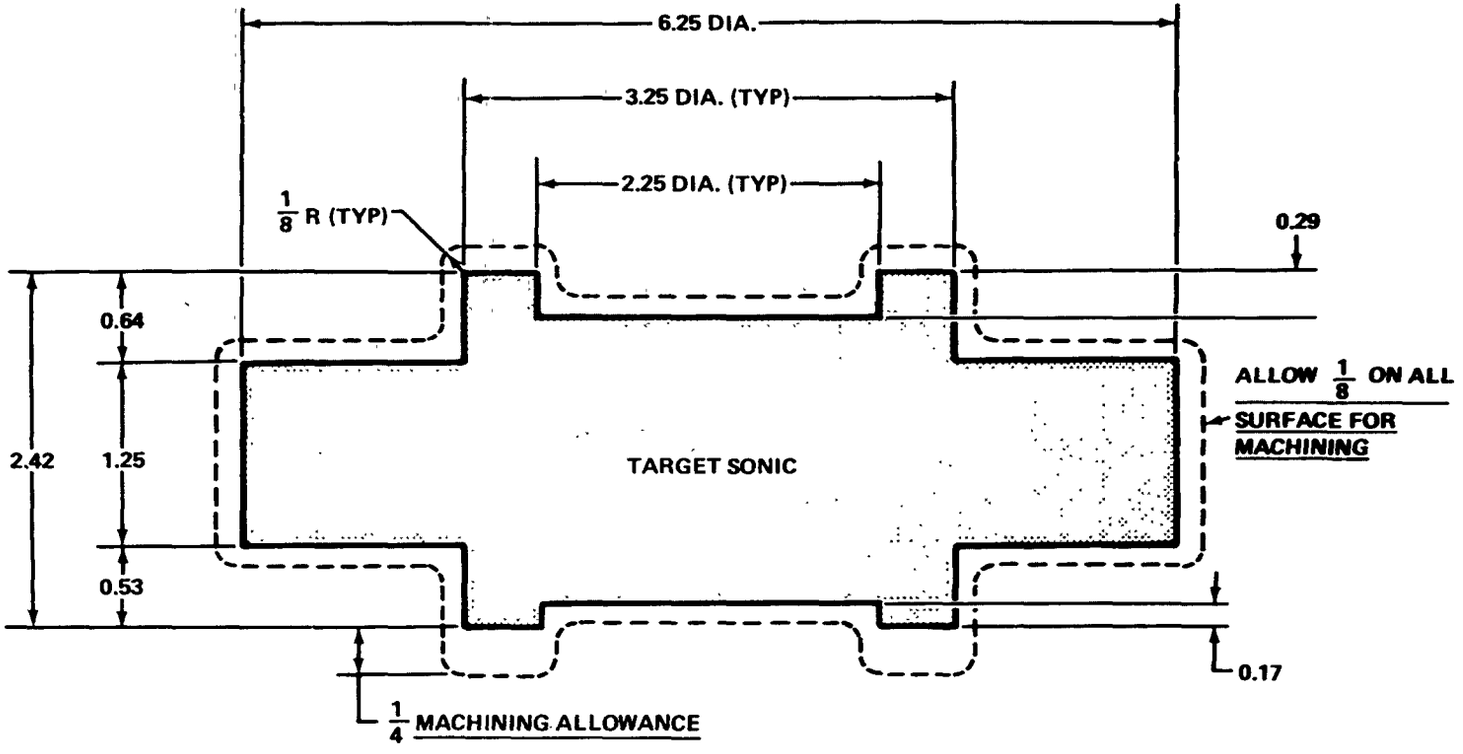


Figure 33. Target Shape – Turbine Disk Sonic.

TABLE 33. MECHANICAL PROPERTIES OF THE FIRST AS-HIP TURBINE DISK OF VENDOR A

Property	As-HIP + Heat Treated* Disk†	Program Goal
Room Temperature Tensile		
0.2% Yield (ksi)	179, 179	180
UTS (ksi)	240, 226	230
Elong. (%)	17, 11	10
RA (%)	19, 15	12
1200°F Tensile		
0.2% Yield (ksi)	167, 166	167
UTS (ksi)	213, 219	207
Elong. (%)	–, 14	8
RA (%)	–, 17	10
1200°F/150 ksi Stress Rupture		
Life (hr)	74, 39	50
Elong. (%)	4, 4	3
RA (%)	5, 6	–
1200°F/145 ksi SPLCF		
Life, cycles	448, 452	–

*Heat treatment – 1650°F/24 hr/AC + 2000°F/1 hr/salt Q + 1400°F/16 hr/AC
†Duplicate test results

Figure 34. First Iteration Disks of Vendor A.

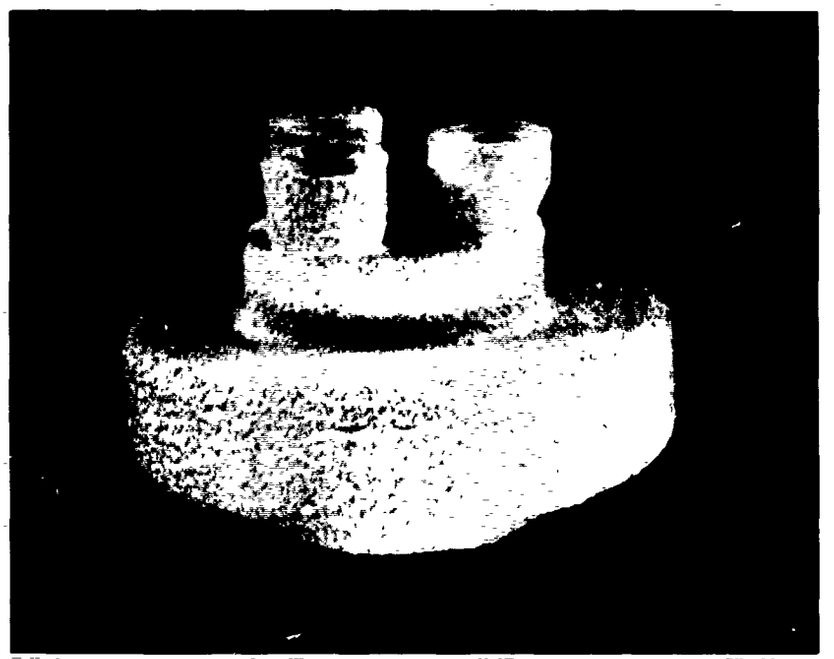


Figure 35. Task IB Ceramic Shell Mold – Vendor A.

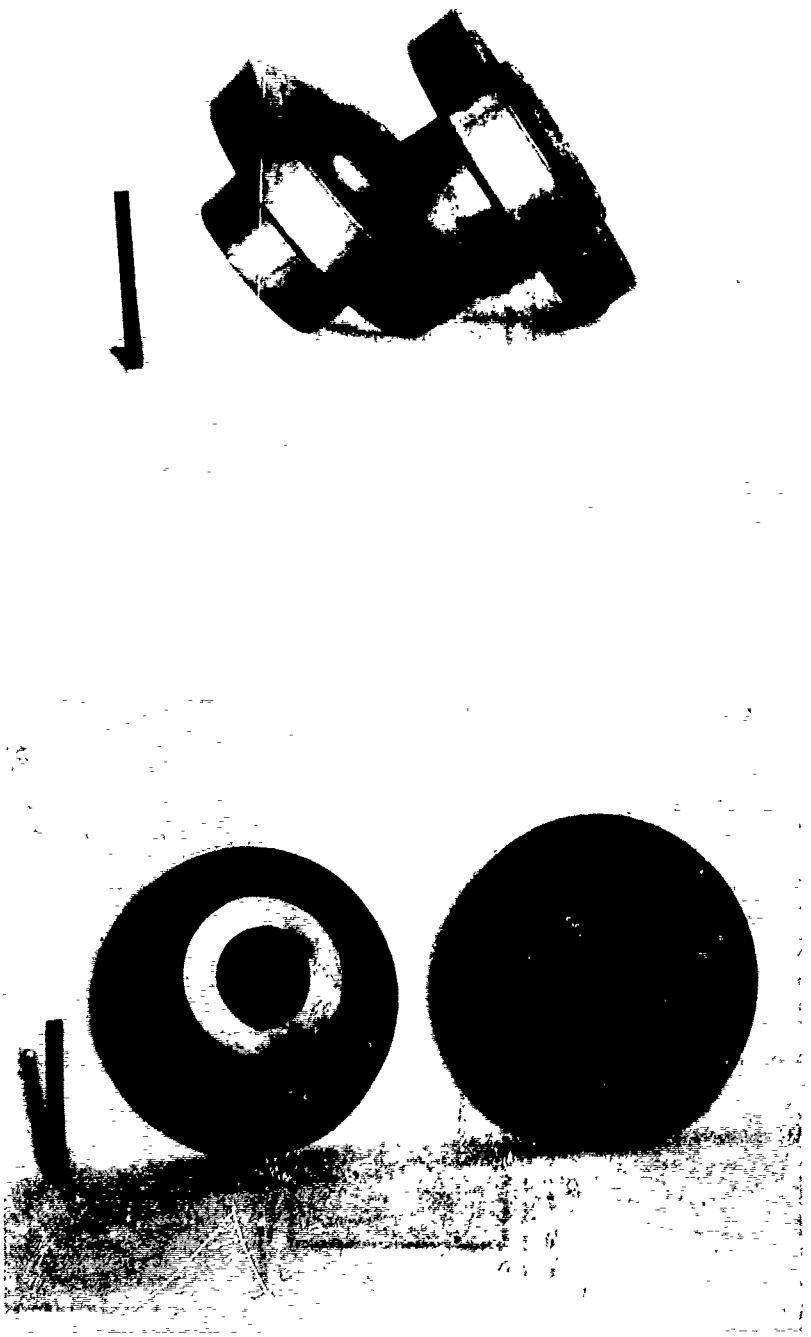


Figure 36. Task 1B Second Iteration Compacts SM-172 and SM-173 After Compaction -- Vendor A.

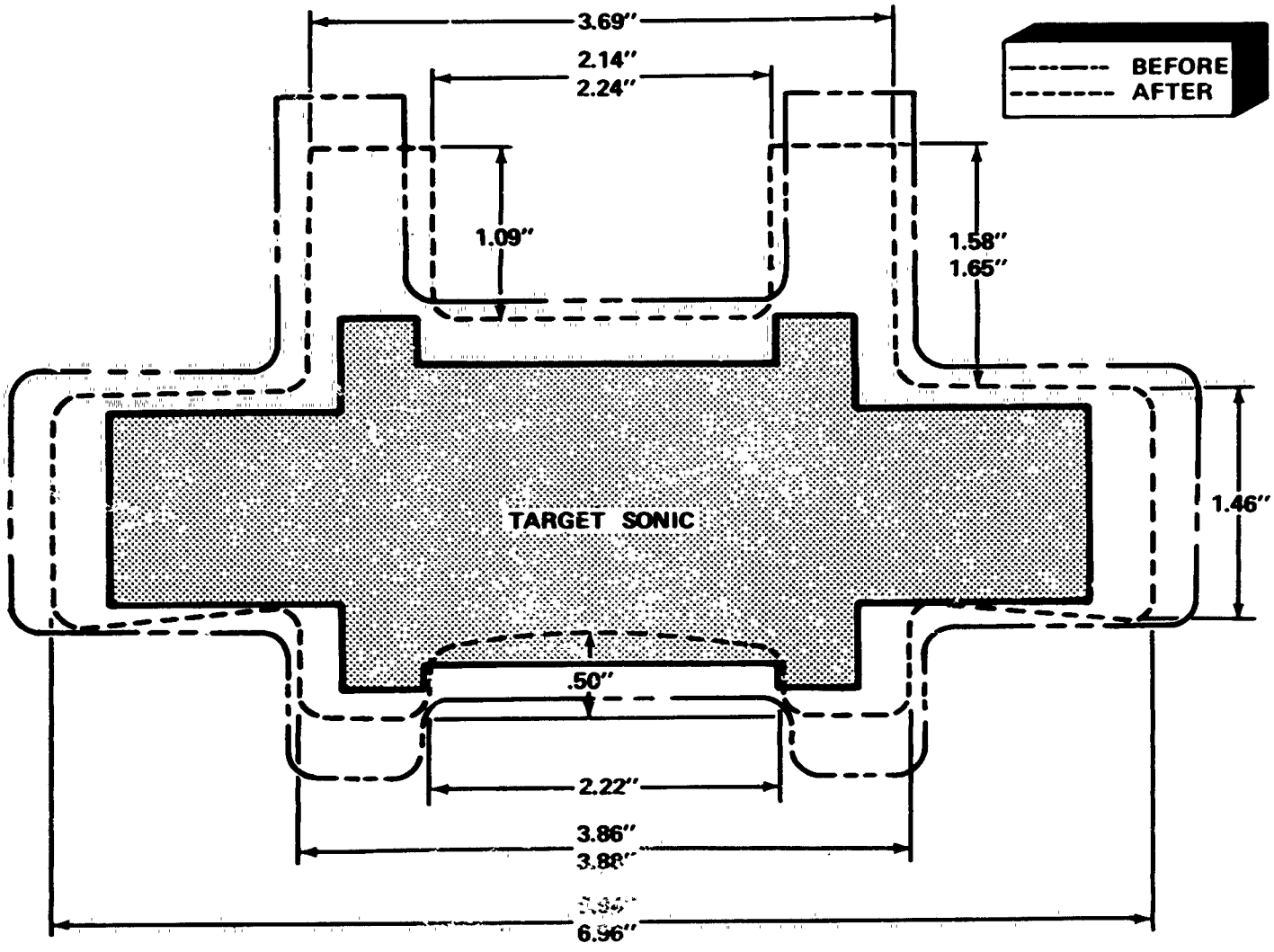


Figure 37. Task IB Second Iteration Shape SM-172 Before and After Compaction (MB009 at -60 Mesh in a Ceramic Mold) – Vendor A.

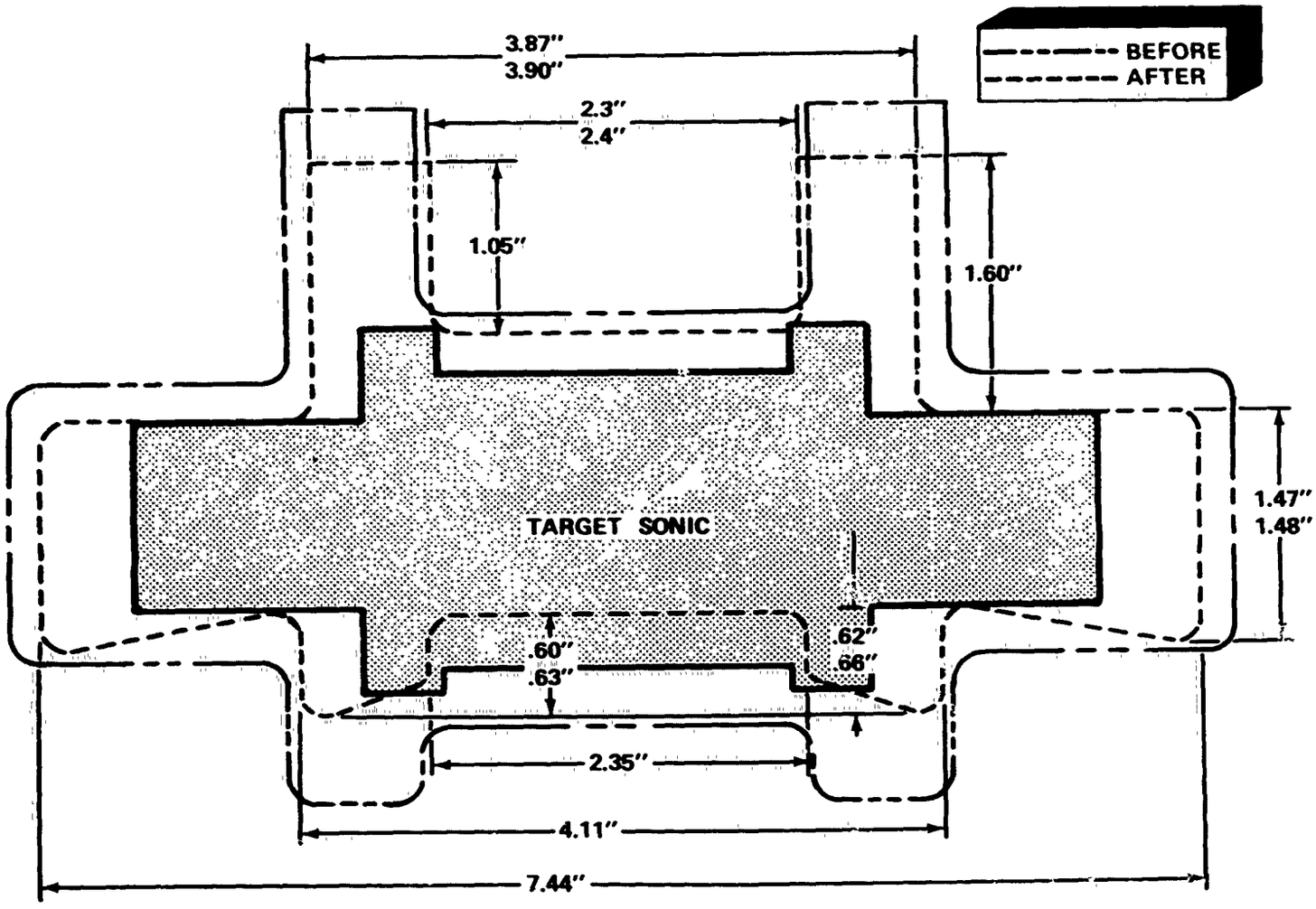


Figure 38. Task IB Second Iteration Shape SM-173 Before and After Compaction (MB010 at -200 Mesh in a Ceramic Mold) – Vendor A.

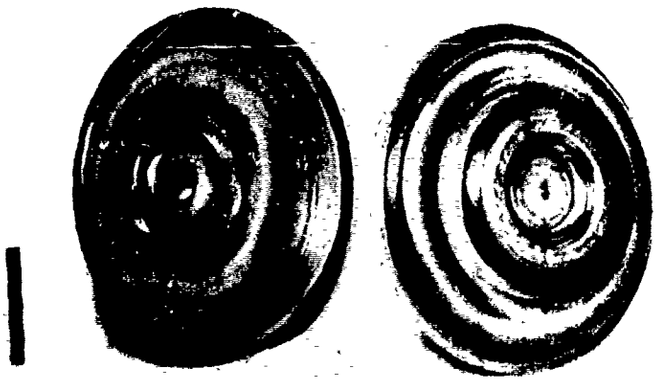


Figure 39. Task IB Spun Stainless Steel Can Halves – Vendor A.

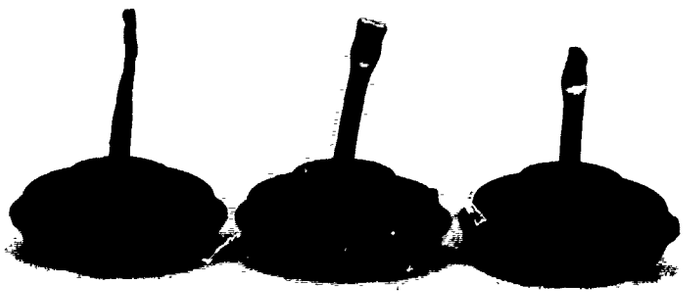


Figure 40. Task IB Second Iteration Shapes Compacted in Spun Metal Cans – From Left to Right B113, B112, B114 – Vendor A.

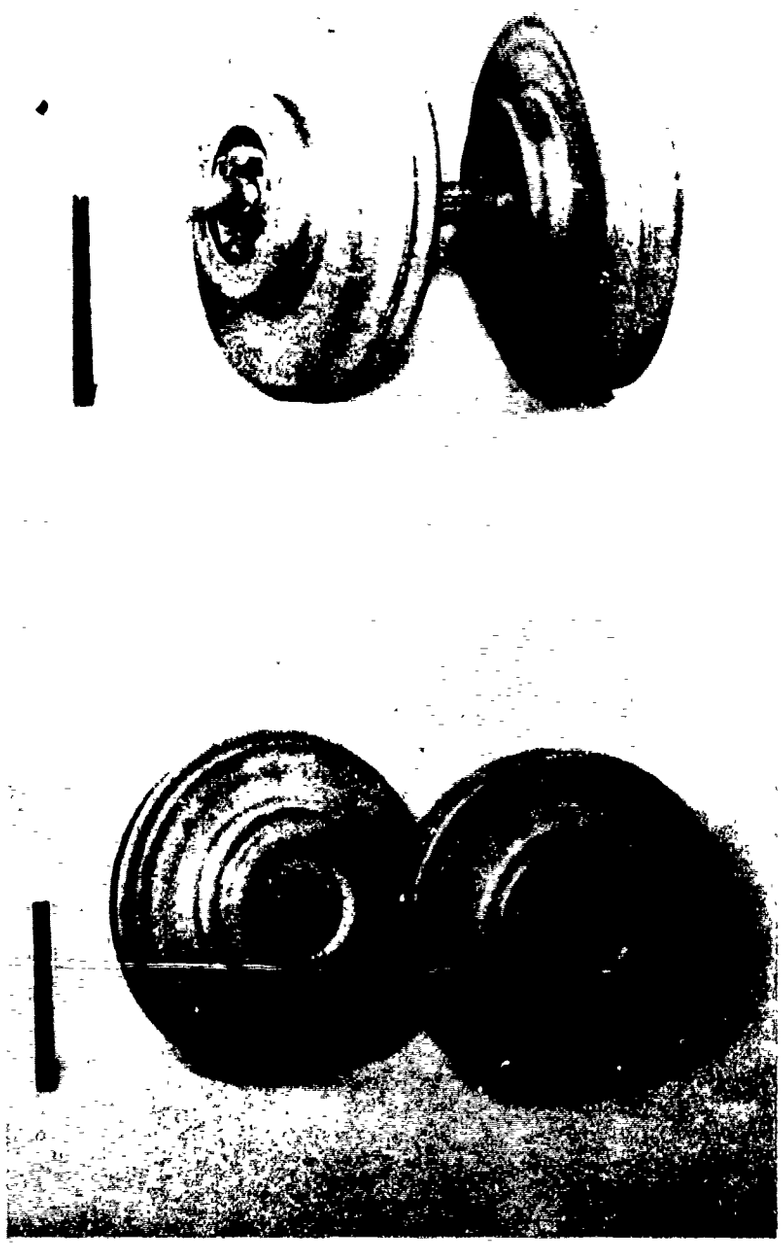


Figure 41. Task IB Second Iteration Compacts B113 and B114 After Decanning – Vendor A.

Figures 42 and 43. Shape control appears to be predictable and reproducible. Dimensional analyses of these disks were used to design container shapes for the third iteration.

Several of the second iteration disks were heat treated to determine the ability of the turbine disk shape to withstand quench cracking. Disk B114 containing -60 mesh powder was heat treated at 2100°F/1 hour/OQ before the mild steel container material was removed. After the disk was machined to an approximate ultrasonic inspection shape, visual and die penetrant inspections were performed. No quench cracking was detected. The 321 stainless steel container was mechanically removed from Disk B113 (containing -200 mesh powder), and a 2100°F/1 hour/oil quench heat treatment was applied to the disk to determine if the as-declad surface was sufficiently smooth to tolerate oil quenching from a high solution treating temperature. Visual inspection after treatment indicated that no cracking occurred during oil quenching.

The third iteration disks were fabricated using both ceramic and spun-steel containers designed on the basis of the second iteration dimensional analyses. A description of the third iteration shape compaction trial is presented in Table 35.

Dimensional analysis of Compact SM-193, shown in Figure 44, indicates that the third iteration ceramic mold shape produced an exceptionally uniform envelope around the target sonic. These results indicate that the third iteration ceramic mold design is adequate to produce the required ultrasonic target shape. Only minor adjustments would be necessary to reduce the envelope around the target sonic to 1/8 inch or less if desired.

Dimensional analyses of -60 and -200 mesh compacts prepared using mild steel containers are presented in Figures 45 and 46. Both shapes conform rather closely to the target sonic and could be fabricated into turbine hardware.

Although it is slightly larger than the -200 mesh, the -60 mesh shape is more reproducible due to the superior flow characteristics of the coarser powder. Only very slight modifications of Compact B-148 container design would be required to reduce the envelope around the target sonic to approximately 1/8 inch or less.

B. Vendor B

Vendor B also employed the shear-spinning method of metal container fabrication to produce three iterations of turbine disk shapes. All of their trial disks were consolidated by a different source than Vendor A.

Their first iteration consisted of two disks, one fabricated from -60 mesh powder and one from -100 mesh powder, consolidated at 2100°F and 15,000 psi to the trial shape shown in Figure 47. These two trial disks were subsequently heat treated using the standard Rene' 95 heat treatment.* This was a severe test of the as-compacted surface finishes, since no preheat treat machining was performed on either disk prior to heat treatment. The disk containing -60 mesh powder, which had a rough surface relative to the disk containing -100 mesh powder, cracked during oil quenching. The -100 mesh powder disk [shown after compaction in the container (Figure 48) and after the removal of the container (Figure 49)] did not crack during the heat treatment.

Dimensional analyses of these first trial disks were incorporated into a new mandrel design to shear spin the containers for the second iteration. Five disks, described in Table 36, were consolidated at 2050°F and 15 ksi. The target shape for these disks was identical to that used by Vendor A (Figure 33). Tabulation of critical dimensions for -60 mesh compact 2 and -100 mesh compacts 3 and 4 is presented in Table 37. Relatively uniform shrinkage occurred throughout the disks, with the maximum variation within any compact being ± 0.7 percent.

*2000°F/1 hour/OQ + 1400°F/16 hours/AC

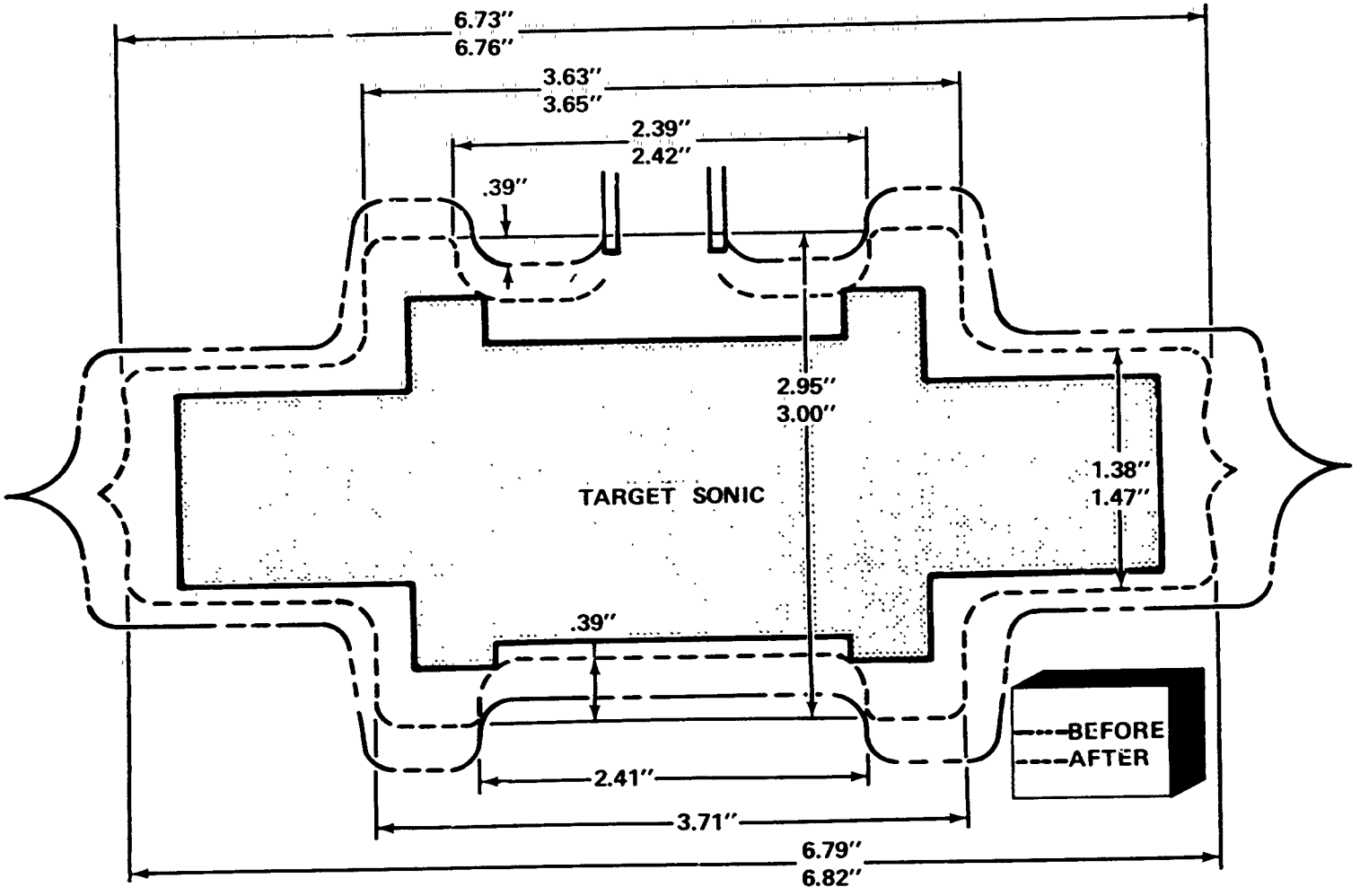


Figure 42. Task IB Second Iteration Shape B113 Before and After Compaction (MB010 at -200 Mesh in a Spun Metal Mold) – Vendor A.

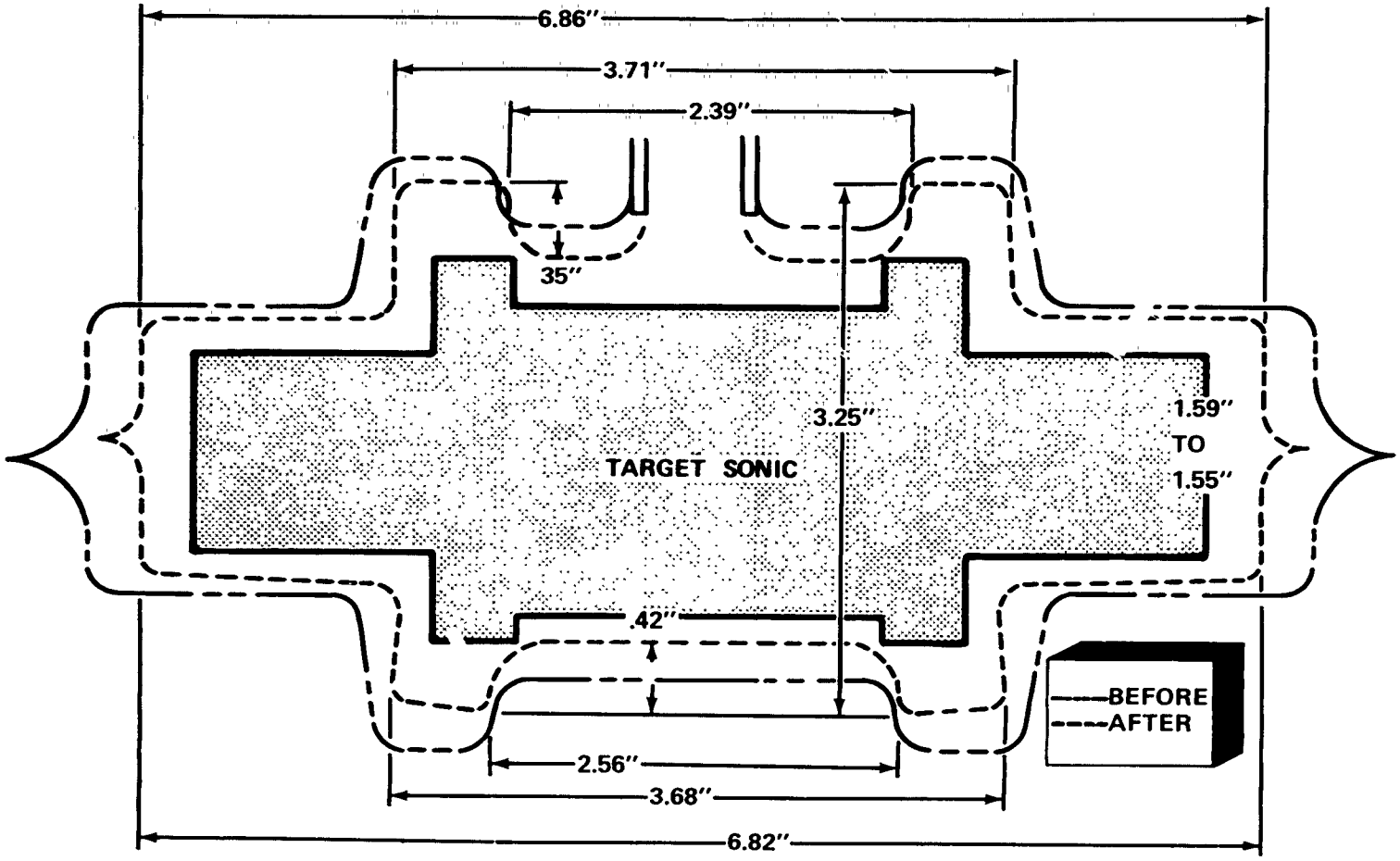


Figure 43. Task IB Second Iteration Shape B114 Before and After Compaction (MB009 at -60 Mesh in a Spun Metal Mold) – Vendor A.

TABLE 34. DESCRIPTION OF TASK 1B SECOND ITERATION SHAPE COMPACTION TRIALS – VENDOR A

Compact Code	Mold Material	Powder Code	Mesh Size
B112	321 S.S.	MB009	– 60
B113	321 S.S.	MB010	–200
B114	Inconel 601	MB009	– 60
SM-172	SiO_2	MB009	– 60
SM-173	SiO_2	MB010	–200

TABLE 35. DESCRIPTION OF TASK 1B THIRD ITERATION SHAPE COMPACTION TRIALS – VENDOR A

Compact Code	Mold Material	Powder Code	Mesh Size
B148	AISI 1020 Steel	MB011	– 60
B142	AISI 1020 Steel	MB010	-200
SM189	SiO_2	MB009	- 60
SM190	SiO_2	MB010	-200
SM193	SiO_2	MB011	- 60

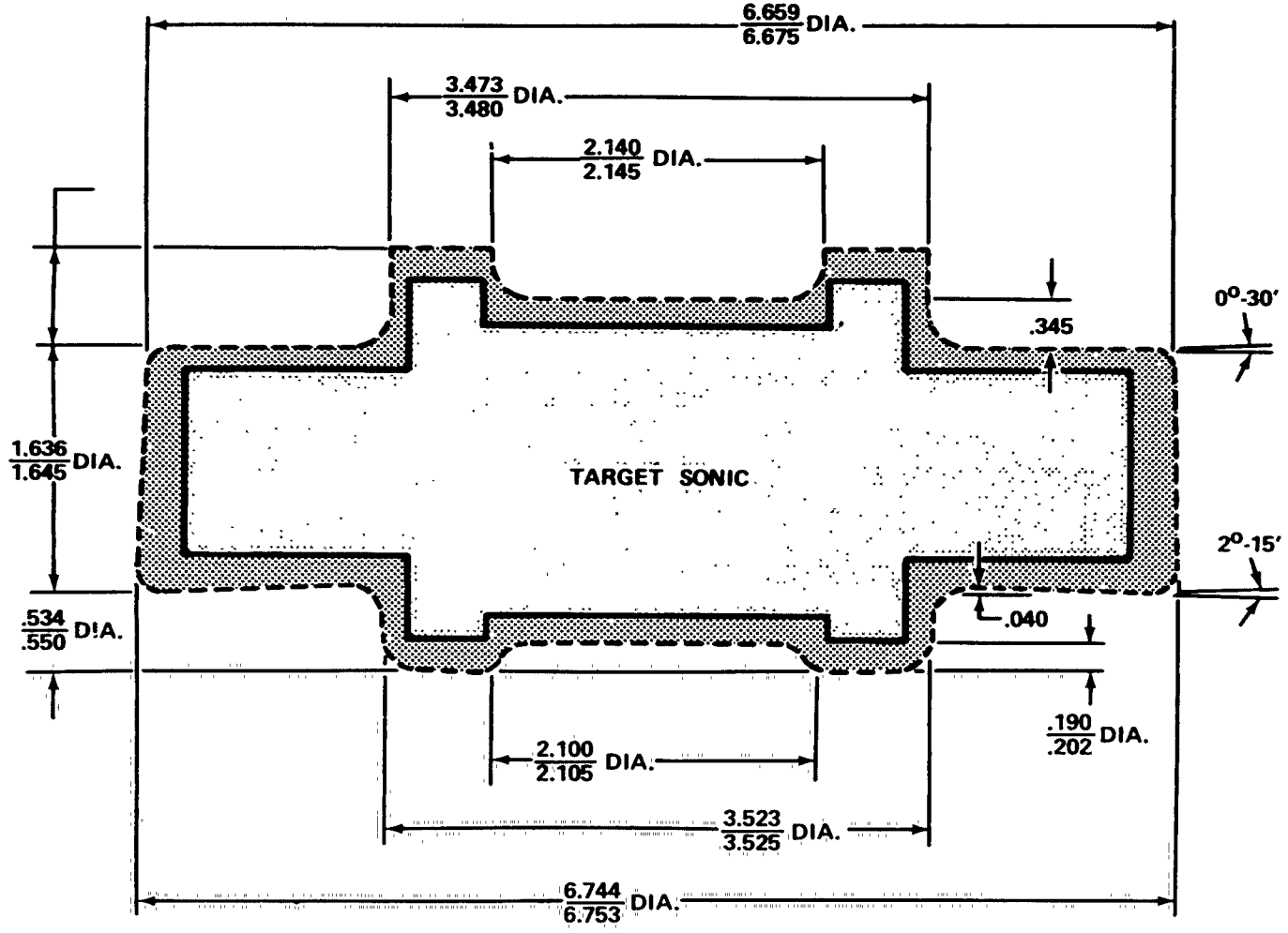


Figure 44. Task IB Third Iteration Shape (SM193) Ceramic Shell Mold, -60 Mesh Rene' 95 Powder Vendor A.

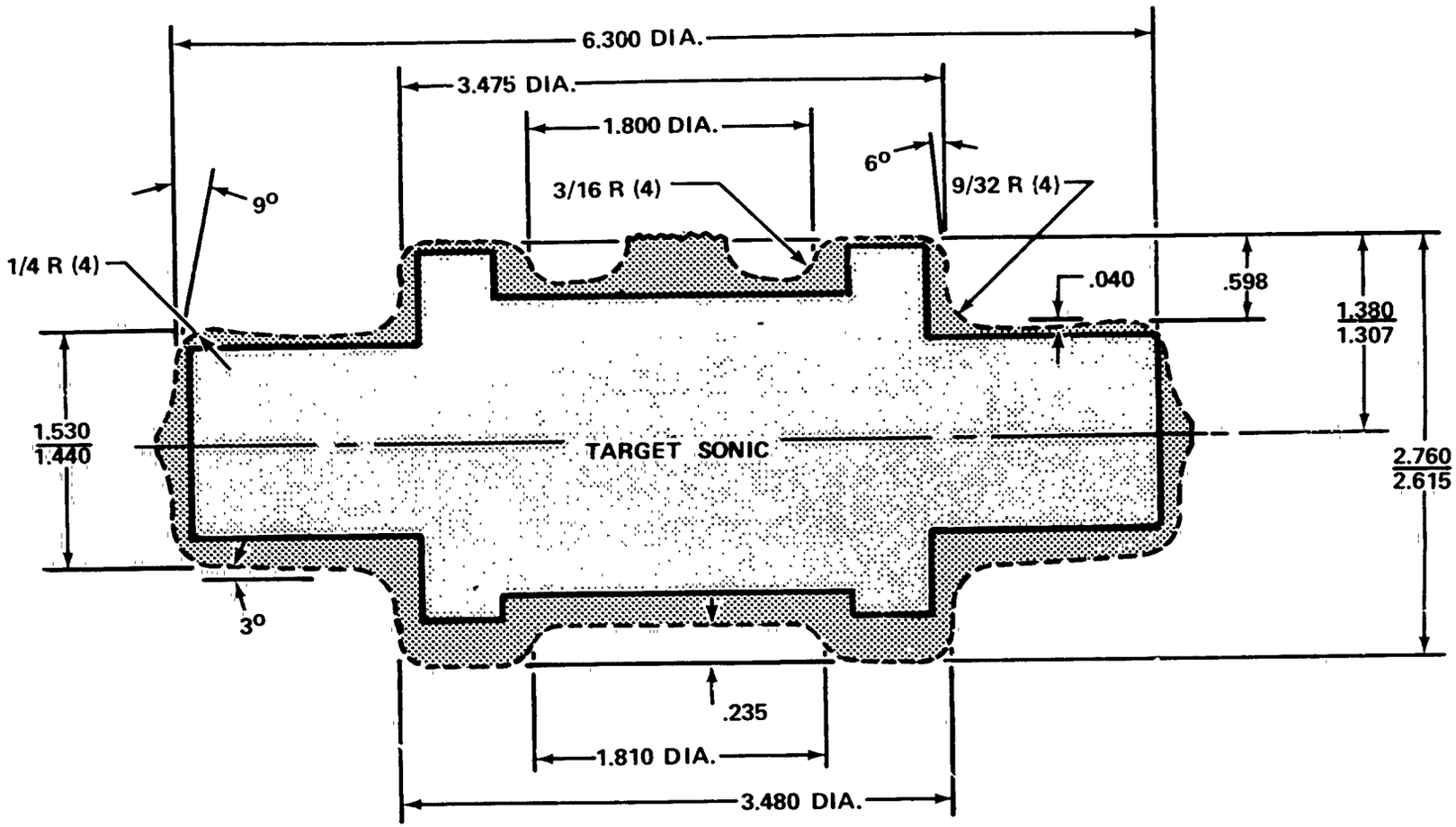


Figure 45. Task IB Third Iteration Shape (B148) Spun Metal Mold, -60 Mesh Rene' 95 Powder Vendor A.

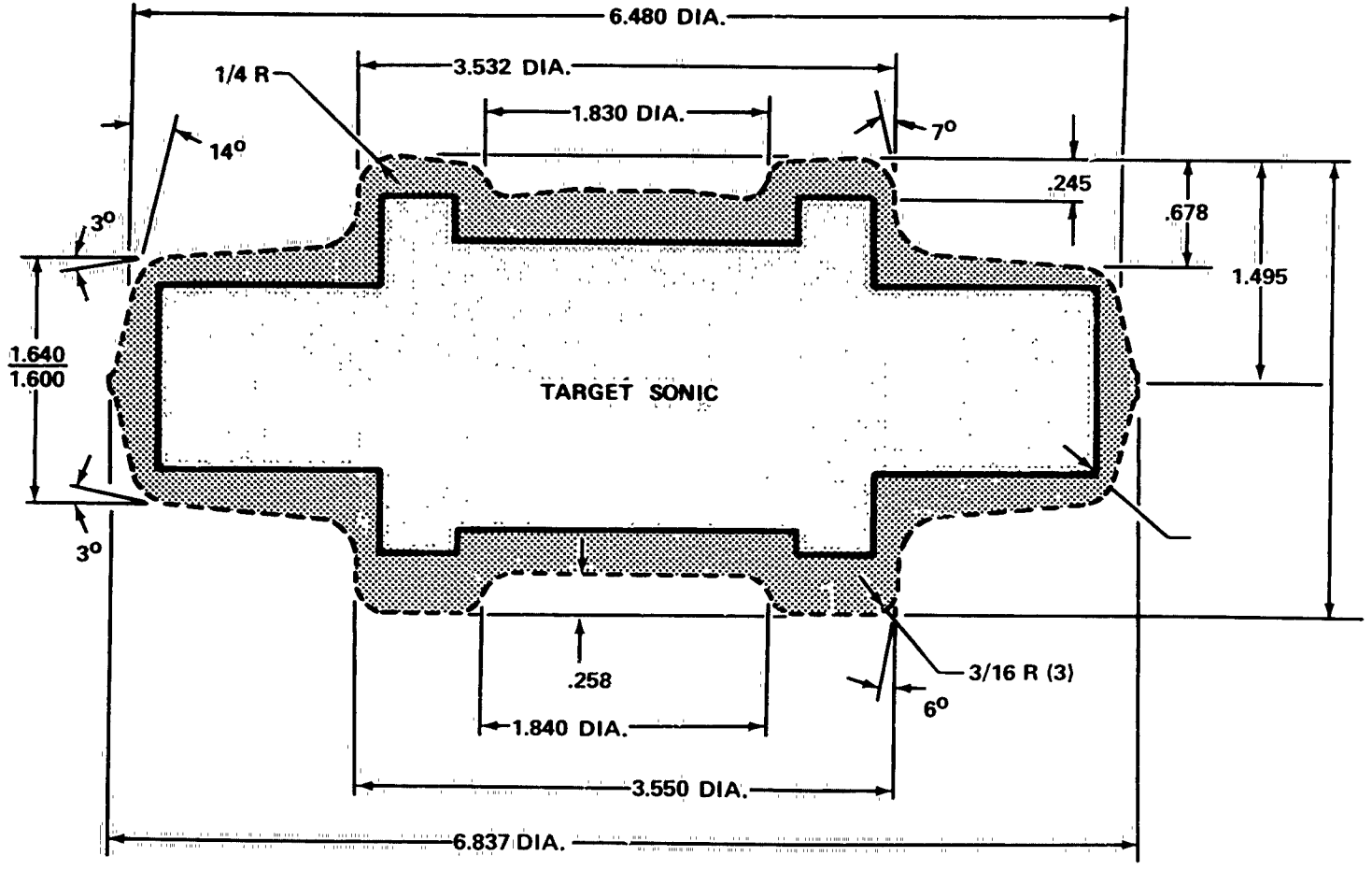


Figure 46. Task IB Third Iteration Shape (B142) Spun Metal Mold, -200 Mesh Rene' 95 Powder Vendor A.

Figure 47. Shear Spun Container Design for First Iteration Disks – Vendor B.

Figure 48. Task IB First Iteration Disk After Hot Isostatic Pressing 2100°F/15 ksi/2 hr – Vendor B.

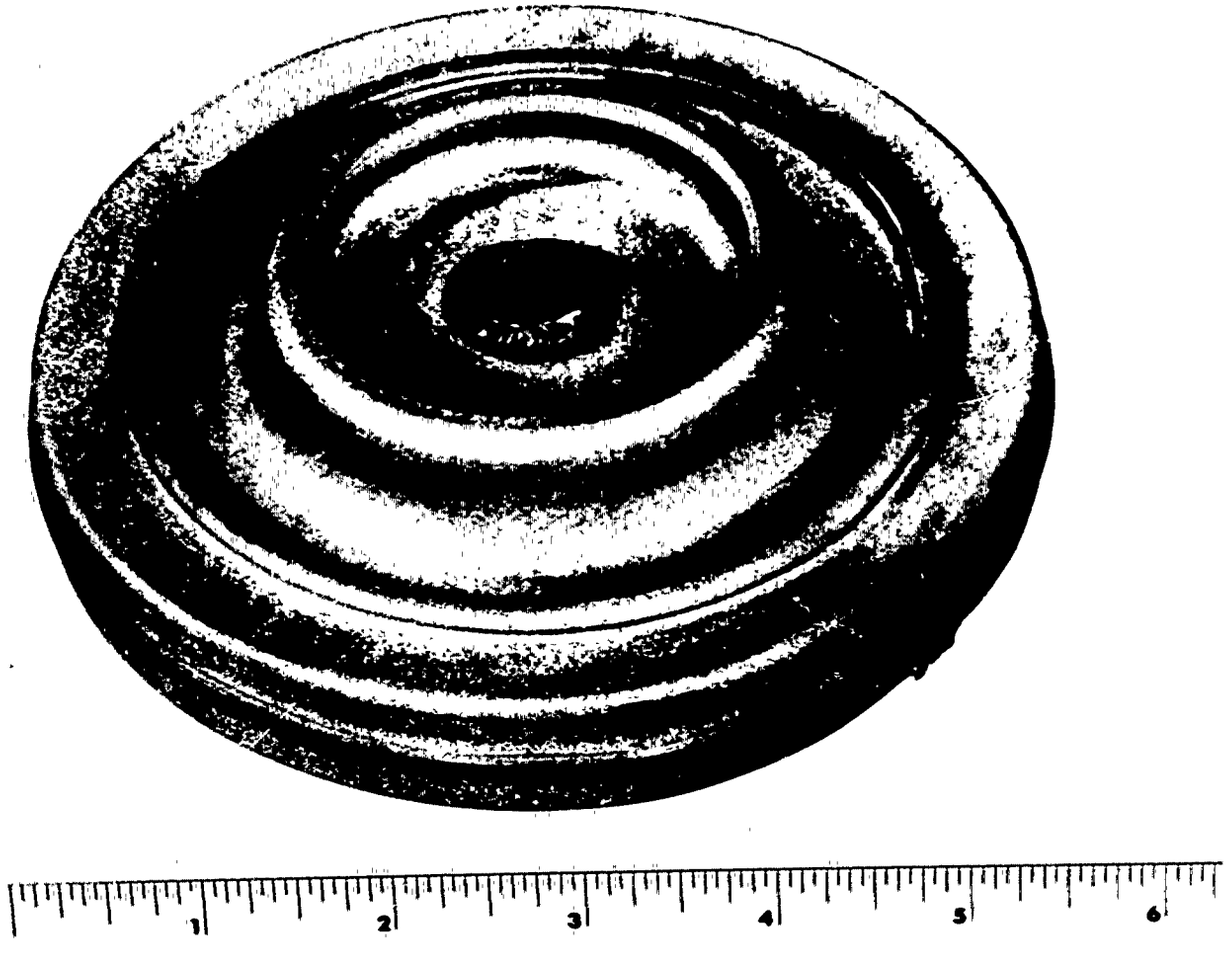


Figure 49. Task IB First Iteration Disk Containing -100 Mesh Powder After Container Removal – Vendor B.

TABLE 36. SUMMARY OF TASK 1B SECOND ITERATION SHAPE MAKING TRIALS – VENDOR B

Compact No.*	Powder Mesh Size	Container Material	Condition Before Heat Treatment	Heat Treatment		Condition After Heat Treatment
1	– 60	Mild Steel	(Leaked During HIP Cycle)			
2	– 60	Mild Steel	Container On	1650°F/4 hr	2000°F/1 hr/OQ	No Cracking**
3	–100	Mild Steel	Container On	1650°F/4 hr	2000°F/1 hr/OQ	No Cracking
4	–100	Mild Steel	Container Pickled Off	1650°F/4 hr	2000°F/1 hr/OQ	No Cracking
5	– 60	Stainless Steel	Container On	1650°F/4 hr	2075°F/1 hr/OQ	No Cracking**

*All Compacts Consolidated at 2050°F in an Autoclave.
**Some Cracking at Fill Tube/Disk Junction (See Text)

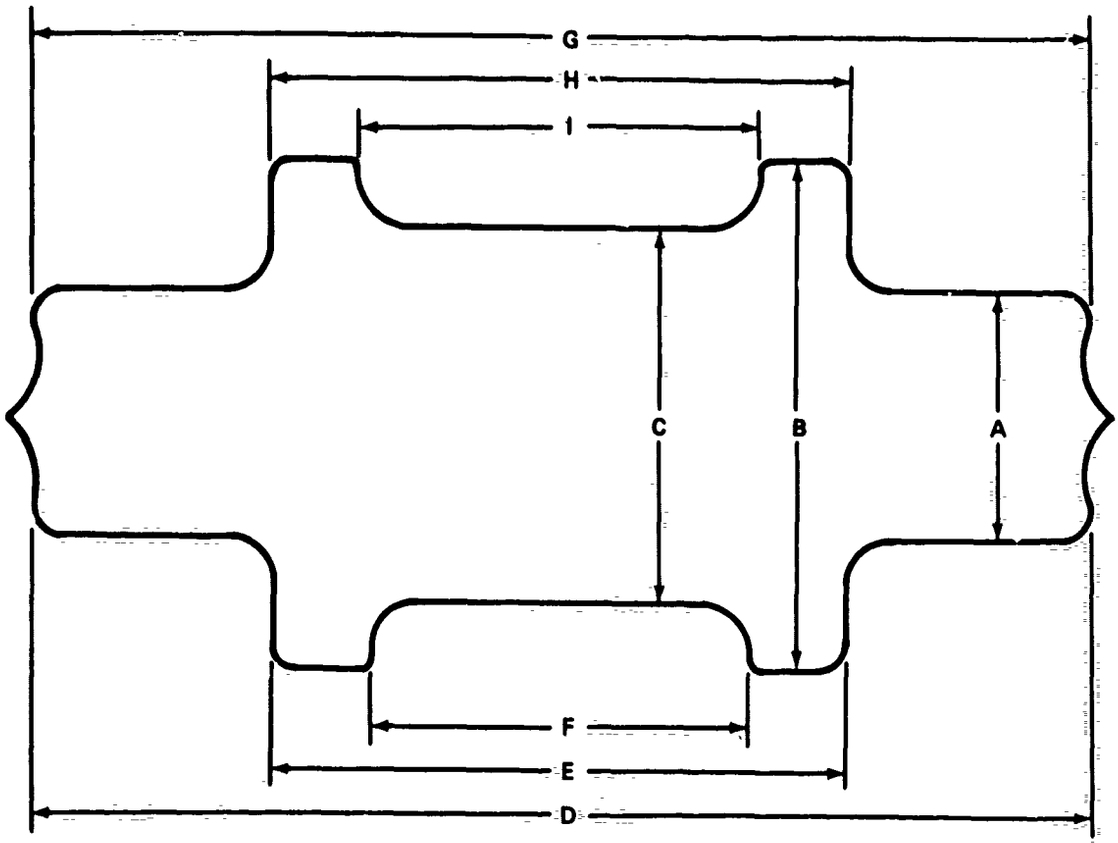


TABLE 37. DIMENSIONAL ANALYSIS OF TASK 1B SECOND ITERATION COMPACTS BEFORE AND AFTER CONSOLIDATION – VENDOR B

Dimension	Compact 2 -60 Mesh			Compact 3 -100 Mesh			Compact 4 -100 Mesh			Variation Between 3 and 4 (in.)
	Before	After	% Shrink	Before	After	% Shrink	Before	After	% Shrink	
A	1.824	1.614	11.5	1.804	1.591	11.8	1.831	1.617	11.6	0.026
B	3.377	2.964	12.2	3.361	2.953	12.1	3.389	2.980	11.9	0.027
C	2.493	2.203	11.7	2.485	2.190	11.8	2.502	2.220	11.2	0.030
D	7.153	6.320	11.6	7.153	6.313	11.7	7.153	6.323	11.6	0.010
E	4.446	3.956	11.0	4.446	3.931	11.5	4.446	3.954	11.0	0.023
F	2.385	2.100	11.9	2.385	2.090	12.3	2.385	2.107	11.6	0.017
G	7.153	6.349	11.2	7.153	6.321	11.6	7.153	6.322	11.6	0.001
H	4.446	3.962	10.9	4.446	3.948	11.2	4.446	3.950	11.1	0.002
I	2.385	2.113	11.4	2.385	2.106	11.6	2.385	2.105	11.7	0.001

Dimensional reproducibility between compacts 3 and 4 was excellent considering the embryonic stage of the shape-making technology. A comparison of the second iteration shape and the target sonic configuration, shown in Figure 50, indicated that only minor modification of the second iteration shape would be necessary in the third iteration. A typical second iteration disk is shown in Figure 51 after the steel container was pickled off.

All the second iteration disks were heat treated, some after the container was removed, to determine their susceptability to quench cracking. Die penetrant, macro-etching, and zyglo inspection of compacts 2, 3, 4 and 5 indicated that no cracking occurred during the heat treatment. Some cracking was detected at the outside diameter of disks 2 and 5: apparently at the fill tube/disk junction. This cracking was probably present prior to heat treatment, although oil quenching from the solution temperature undoubtedly magnified its severity. Steps were taken in the third iteration to eliminate this problem. Dimensional analyses of the second iteration compacts provided the basis for design of the third iteration trials. A description of the third iteration compacts is given in Table 38.

Results of the dimensional analysis of all third iteration disks are presented in Table 39 and Figure 52. Dimensions were determined with the mild steel containers intact. The required target sonic dimensions were adjusted by 0.120 inch to compensate for the container thickness. The data indicates a number of dimensions outside the required range in compacts C216, C217, C218, C219, and C220. However, when disk C220 was sectioned and actual core measurements were taken, a variation in container thickness was discovered which makes all the measurements in Table 39 conservative. Comparison of the target sonic shape with disk C220 cross-section, shown in Figure 53, suggests that the required shape could be machined from all disks except C216 in spite of the seemingly discrepant dimensions reported in Table 39.

An improved container filling technique was also examined in the third iteration in an attempt to improve reproducibility and accuracy. Disks 328, 330, 332 and 333 were prepared using this modified procedure. Although results reported in Table 39 may not accurately reflect core dimensions (in view of the noted variation in container thickness), they do indicate the improved dimensional reproducibility achieved in disks C328-C333 relative to that obtained in disks C216-C220. The container design and modified container filing procedure used to produce disks C328-C333 will be employed to fabricate disks for evaluation in Tasks II and III.

Figures 44, 45, 46 and 53, indicate that both vendors have successfully developed shape-making processes for fabricating T700 turbine disks. Vendor A utilized ceramic and spun metal container materials in their processes, while Vendor B employed only spun metal containers. Both powder vendors have demonstrated their ability to accurately produce the desired turbine disk ultrasonic shape during Task IB.

In conclusion, a successful shape-making technology with adequate reproducibility and accuracy was developed by both vendors in Task IB for more than one container material and powder mesh size. It is noteworthy that at least one material (steel) could be fabricated at reasonable cost for disk shape. The complexity of part shape will, however, determine the future cost effectiveness of the other material. A manufacturing cost analysis also concluded that the cooling plates should be machined from hollow cylindrical compacts similar to those produced in Task IA.

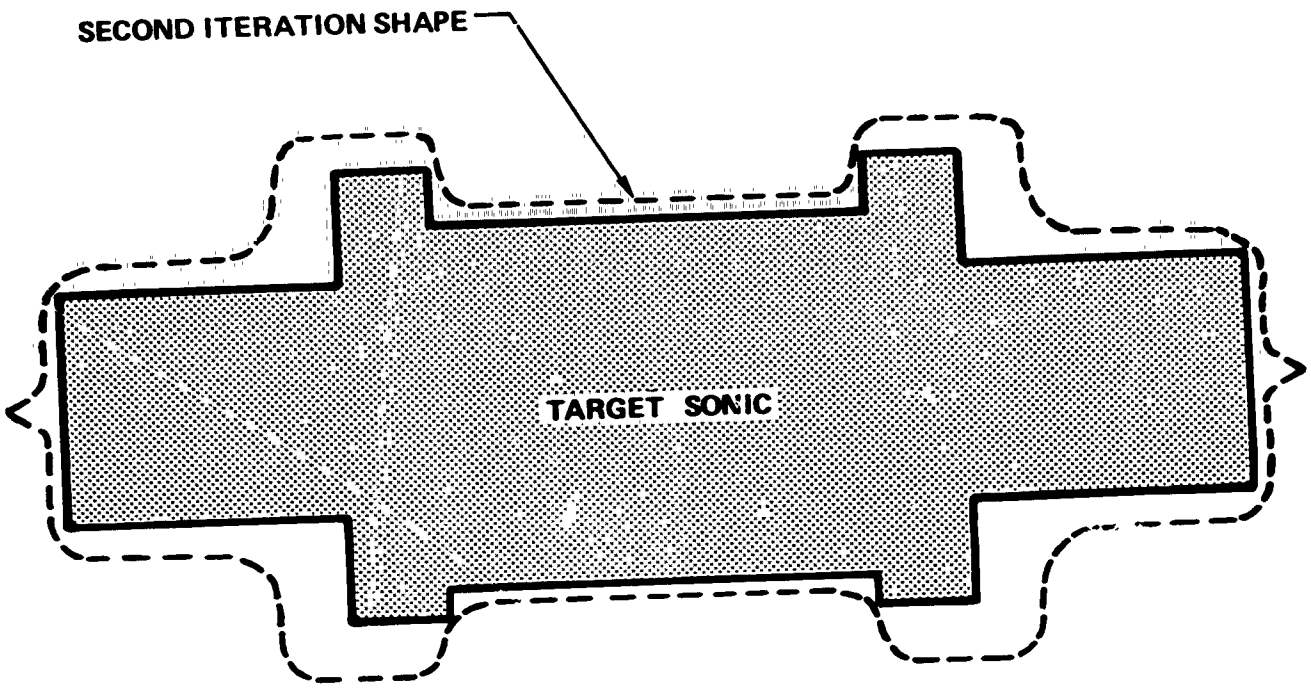


Figure 50. Target Sonic Shape and Task IB Second Iteration Shape – Vendor B.

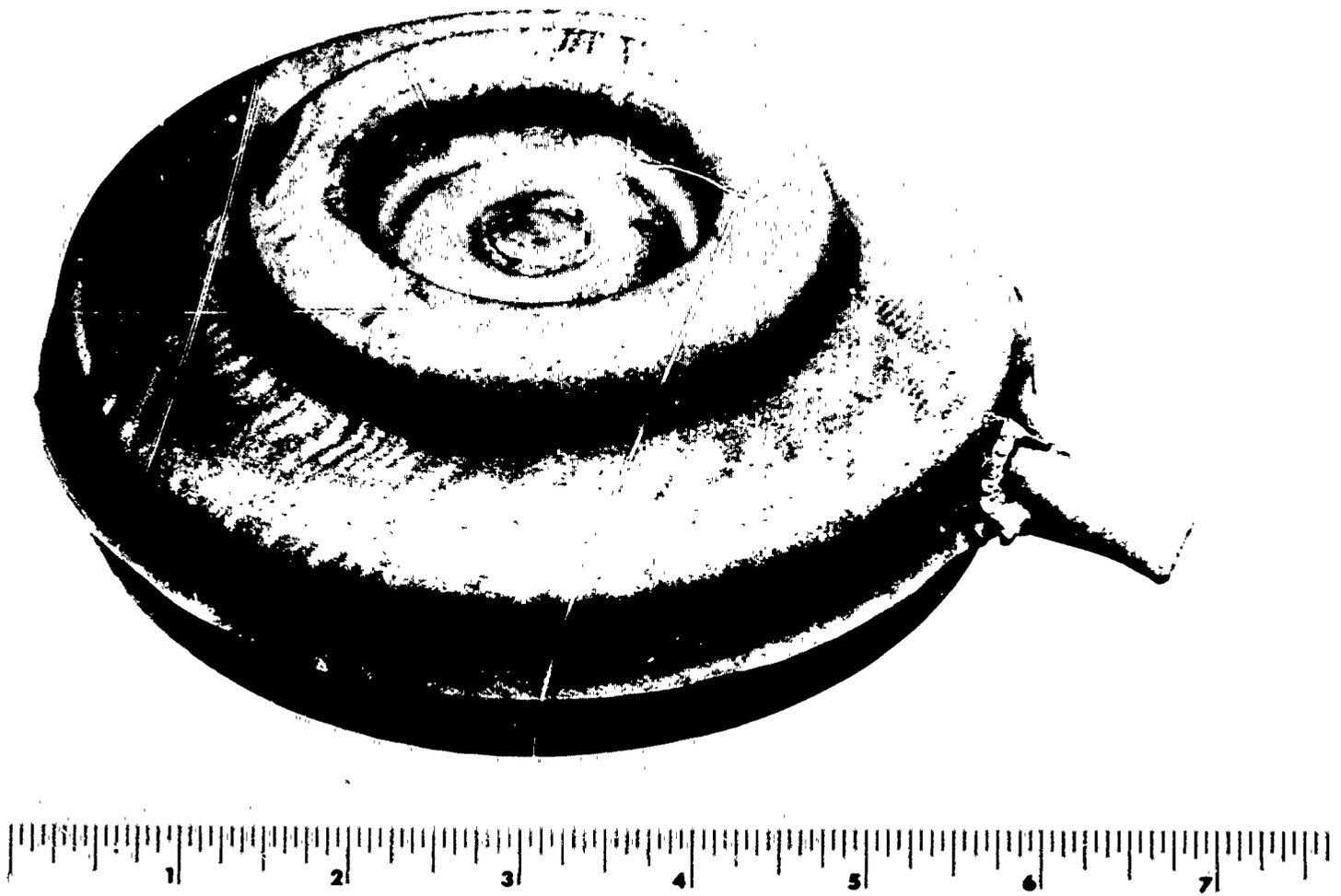


Figure 51. Task IB Second Iteration Shape Disk After Pickling Off the Steel Container – Vendor B.

TABLE 38. SUMMARY OF TASK 1B THIRD ITERATION SHAPE-MAKING TRIALS – VENDOR B

Compact No.	Powder Mesh Size	Container Material
C216	-100	Mild Steel
C217	-100	Mild Steel
C218	-100	Mild Steel
C219	- 60	Mild Steel
C220	- 60	Mild Steel
C328	-100	Mild Steel
C330	- 60	Mild Steel
C332	- 60	Mild Steel
C333	- 60	Mild Steel

TABLE 39. TASK 1B THIRD ITERATION MEASUREMENTS WITH CAN ON – VENDOR B

Dimension[1] (Min. Req.)[2]	C216 (–100)	C217 (–100)	C218 (–100)	C219 (– 60)	C220 (–60)	C328 (–110)	C330 (–60)	C332 (–60)	C333 (– 60)
A (1.364")	1.316"	1.427"	1.430"	1.423"	1.327"	1.452"	1.487"	1.472"	1.483"
B (2.465")	2.375"	2.523"	2.519"	2.521"	–	2.574"	2.604"	2.572"	2.590"
C (1.897")	1.934"	2.019"	2.022"	2.021"	1.936"	2.105"	2.093"	2.062"	2.079"
D (6.388")	6.383"	6.397"	6.355"	6.401"	6.320"	6.394"	6.406"	6.397"	6.419"
E (3.380")	3.483"	3.508"	3.468"	3.488"	3.394"	3.470"	3.496"	3.486"	3.494"
F (2.166")[3]	2.024"	2.005"	2.005"	2.018"	2.020"	1.992"	1.999"	2.007"	2.012"
G (6.388")	6.381"	6.394"	6.320"	6.374"	6.368"	6.385"	6.392"	6.398"	6.404"
H (3.380")	3.475"	3.501"	3.463"	3.465"	3.380"	3.474"	3.490"	3.494"	3.494"
I (2.166")[3]	2.004"	1.993"	1.994"	2.024"	2.014"	2.008"	1.997"	2.000"	2.002"
J (0.496")	0.511"	0.516"	0.517"	0.506"	0.520"	0.518"	0.516"	0.518"	0.517"
K (0.585")	0.570"	0.581"	0.578"	0.592"	–	0.577"	0.579"	0.580"	0.590"
L (0.280")	0.282"	0.302"	0.294"	0.303"	–	0.297"	0.293"	0.301"	0.298"
M (0.172")	0.216"	0.216"	0.205"	0.205"	0.205"	0.210"	0.214"	0.214"	0.216"

(1) See Figure 52 for key
(2) Required dimensions according to General Electric print with 0.120 in. allowed for can thickness
(3) Maximum required

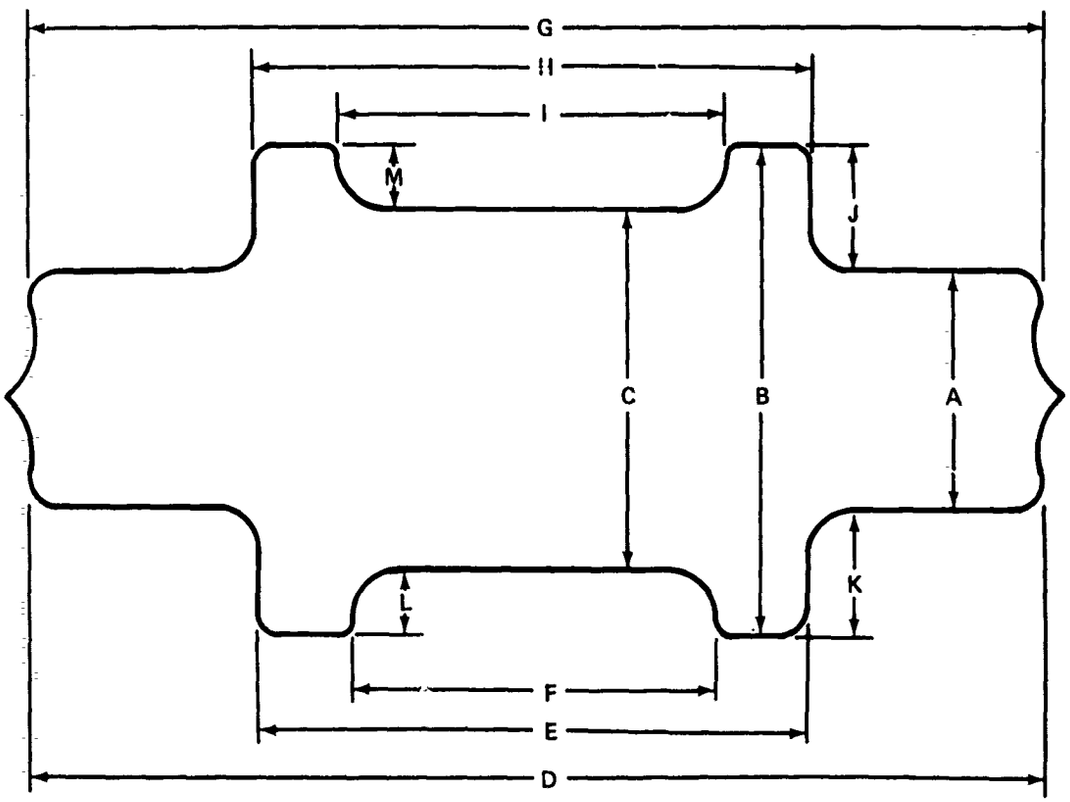


Figure 52. Key for Dimensional Results of Vendor B Task IB Third Iteration Disks in Table 39.

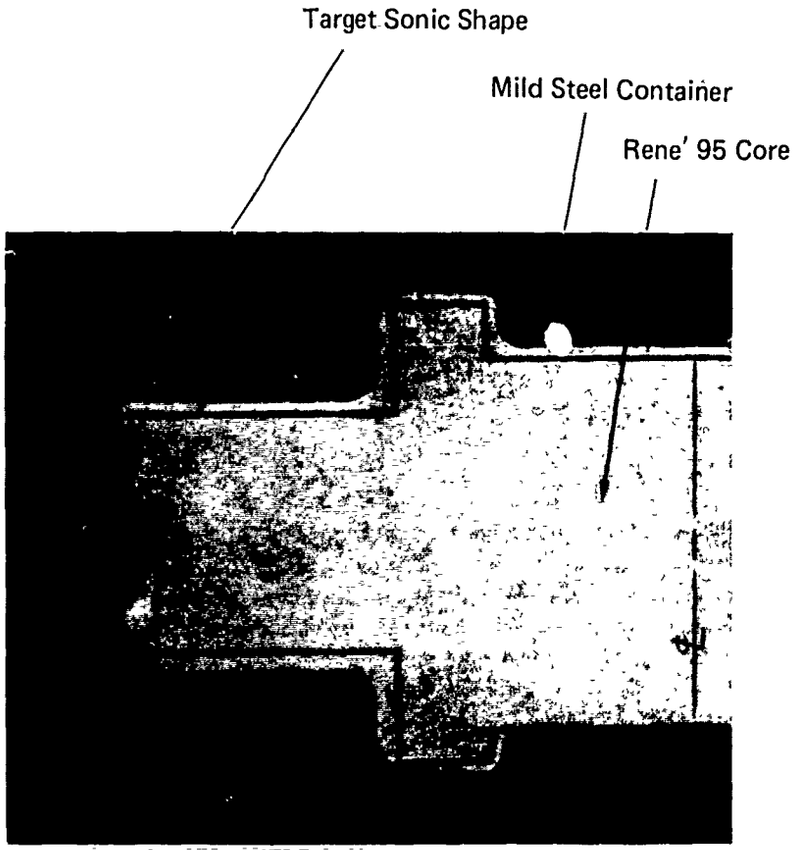


Figure 53. Comparison of Target Sonic Shape with Macroetched Section of Task IB Third Iteration Disk C220 – Vendor B.

TASK IC – COMPLETE PROCESS DEFINITION

The complete process definition emerging from the successful completion of Task IA and Task IB consists of manufacturing processing parameters, a preliminary quality plan, and the Value Engineering Analysis as follows:

PROCESSING PARAMETERS

Important processing parameters selected for hot isostatic pressing and post-compaction treatment of Rene' 95 are given in Table 40. The best combination of tensile and fatigue properties in Task IA was achieved with these variables. The suitable configurations for the shape-making technology resulting from the trials of Task IB are shown in Figures 44 through 46. A process specification, C50TF64, entitled "Premium Quality Powder Metallurgy Rene' 95 Alloy As-HIP Parts" incorporating these and other detailed processing requirements is presented in Appendix I. Two additional process specifications PITF47 "Manufacture of Rene' 95 Alloy powder" and P7TF5 "Containerization and Hot Isostatic Pressing (HIP) of Rene' 95 Alloy powder" have also been issued which cover the powder production and compaction requirements. These specifications are also included in Appendix I.

PRELIMINARY QUALITY PLAN

The quality plan is the overall strategic program integrating the activities of the vendors and General Electric Manufacturing, Engineering, Quality and Shop Operation functions to insure that the customer requirements are met consistently and economically. While the standard quality system usually generates such plans, the unique nature of this development program required that attention be given to additional considerations for Tasks II and III hardware, which was to be incorporated into the system during transition to production. The preliminary quality plan consisted of a specified plan for process control and product acceptance. The preliminary process specification, C50TF64 (Appendix I), is used as a vehicle to define important quality control requirements.

The process control plan consisted of a surveillance program in accordance with General Electric's policy to periodically monitor vendors' conformance to established processing parameters and significant manufacturing procedures. The program personnel, and subsequently field/quality assurance personnel, conducted this monitoring to determine compliance by the vendors to specifications noted in Appendix II (Process Control Plan), including vendor internal specifications, which may be proprietary in nature. After the successful evaluation and approval for the transition to production, the General Electric Source Substantiation System defined and "froze" the details of significant operations not to be changed without prior General Electric approval.

The preliminary product acceptance plan consisted of inspection or testing of the characteristics in Appendix III (Product Acceptance Plan). These characteristics were verified for each compact except the mechanical property evaluation, which consisted of a cut-up of one compact/master powder blend/HIP lot/heat treat lot.

Following transition to production, the frequency of inspection for some characteristics may be reduced. After the hot isostatically pressed parts are accepted per the product acceptance plan, further processing such as machining will be similar to the current method using existing quality plans for T700 turbine hardware.

VALUE ENGINEERING ANALYSIS

The current projected production material cost estimates for the As-HIP hardware for the T700 engine are listed in Table 41. All the costs are in 1976 dollars. The raw material weight refers to configuration ready for ultrasonic inspection. The cooling plate costs assume that the parts are made in long cylinders to be sliced for individual components. The comparable cost of one set of hardware (2 disks and 4 cooling plates) made by the current HIP + forge process is estimated to be $7,075. Thus a raw material cost savings of $4,064/engine is projected using the As-HIP manufacturing process for the T700 turbine hardware.

TABLE 40. SELECTED PROCESSING PARAMETERS

1. Power Mesh Size	—	−60
2. Container Materials	—	Steel or Ceramic
3. HIP Temperature	—	2050°F
4. HIP Pressure	—	15 ksi
5. HIP Time	—	2 hr Minimum
6. Heat Treatment	—	T_s 30°F*/1 hr/1000°F Salt Quench +1600°F/1 hr/AC + 1200°F/24 hr/AC

*Solution temperature based on gamma prime temperature of particular powder blend - individually determined solution temperature should be 30°F below the gamma prime solvus temperature.

TABLE 41. PROJECTED PRODUCTION ESTIMATES

Part	Raw Material Weight (lbs)	Material Cost
Disks		
Stage 1	14	$693
Stage 2	14	$693
Cooling Plates		
Stage 1 Forward	8.8	$437
Stage 1 Rear	9.5	$470
Stage 2 Forward	5.7	$281
Stage 2 Rear	8.8	$437

TASK II – FABRICATION AND EVALUATION OF LAB TEST SPECIMEN

The objective of Task II was to conduct a detailed mechanical property investigation of turbine disk and cooling plate configurations fabricated using the processing parameters defined in Task I. In addition, spin burst testing of four turbine disk shapes was completed and the results were compared to predicted values. A flow chart of the work conducted in Task II appears in Figure 54.

Material for Task II was supplied by both vendors using the techniques developed in Task I. All mechanical testing was performed by General Electric Company or their testing vendor. Spin pit testing was conducted in General Electric's facilities.

Following completion of Task I, disks and cooling plates for Task II were fabricated by both vendors according to parameters in Table 40. All the Task II hardware was heat treated at Vendor A in the same facilities used to treat their Task I material. This decision was made because Vendor B did not have facilities to quench into 1000°F salt. Therefore, in order to maintain the program schedule and to minimize heat treat variations, both vendors agreed to heat treat all Task II material at Vendor A.

MATERIAL PREPARATION

Master powder blends of the -60 mesh powder used for the Task I studies were also employed in Task II. Chemical analyses of the powders are presented in Tables 13 and 14. Scanning electron micrographs of the Task II powders, shown in Figures 9 and 10, indicate that the size, shape, and satellite formation of powders of both vendors are virtually identical. The particle size distributions produced by both powder vendors are illustrated in Figure 55.

Both powder vendors fabricated cooling plates by hot isostatically pressing (HIP) -60 mesh powder into hollow cylindrical billets to the proper dimensions, and by slicing plates of the appropriate thickness from these billets. The turbine disk shapes were prepared using the shape-making technology developed in Task I. In both cases, the powders were encapsulated in mild steel containers and HIP at 2050°F. Final dimensions of the hollow cylinders were approximately 6.5 inches outside diameter and 2.75 inches inside diameter. The compacted cylinders, when cut into 2-inch-thick slices, were prototypes of the cooling plate shapes. The turbine disk shapes were similar to those in Figures 45 and 53.

Heat treatment studies made by powder vendors during Task I has indicated that an approximately 20°F difference in γ' solvus temperatures existed between Vendor A (2135°F) and Vendor B (2115°F) powder. Prior to heat treatment of the Task II hardware, additional studies were conducted by both vendors to confirm that this difference was indeed real and not due to thermocouple or furnace variations. Both vendors heat treated samples of Task I materials at 25°F intervals in their own facilities. Samples were heat treated adjacently and results were obtained by optical metallograph. Photomicrographs of the Vendor A study, which are virtually identical to those of Vendor B study, are presented in Figure 56. The grain sizes produced by each heat treat temperature indicate that the γ' solvus of Vendor A material is just beyond 2125° F, while that of the Vendor B material is between 2100° and 2125°F. These data provided the basis for defining the solution treatment temperatures of Task II material as:

Vendor A T_s -30°F = 2130-30 = 2100°F

Vendor B T_s -30°F = 2115-30 = 2085°F

The turbine disk shapes were solution treated with the mild steel container intact, while the 2-inch-thick cooling plates were unclad on the top and bottom faces. The mild steel container around the inside and outside

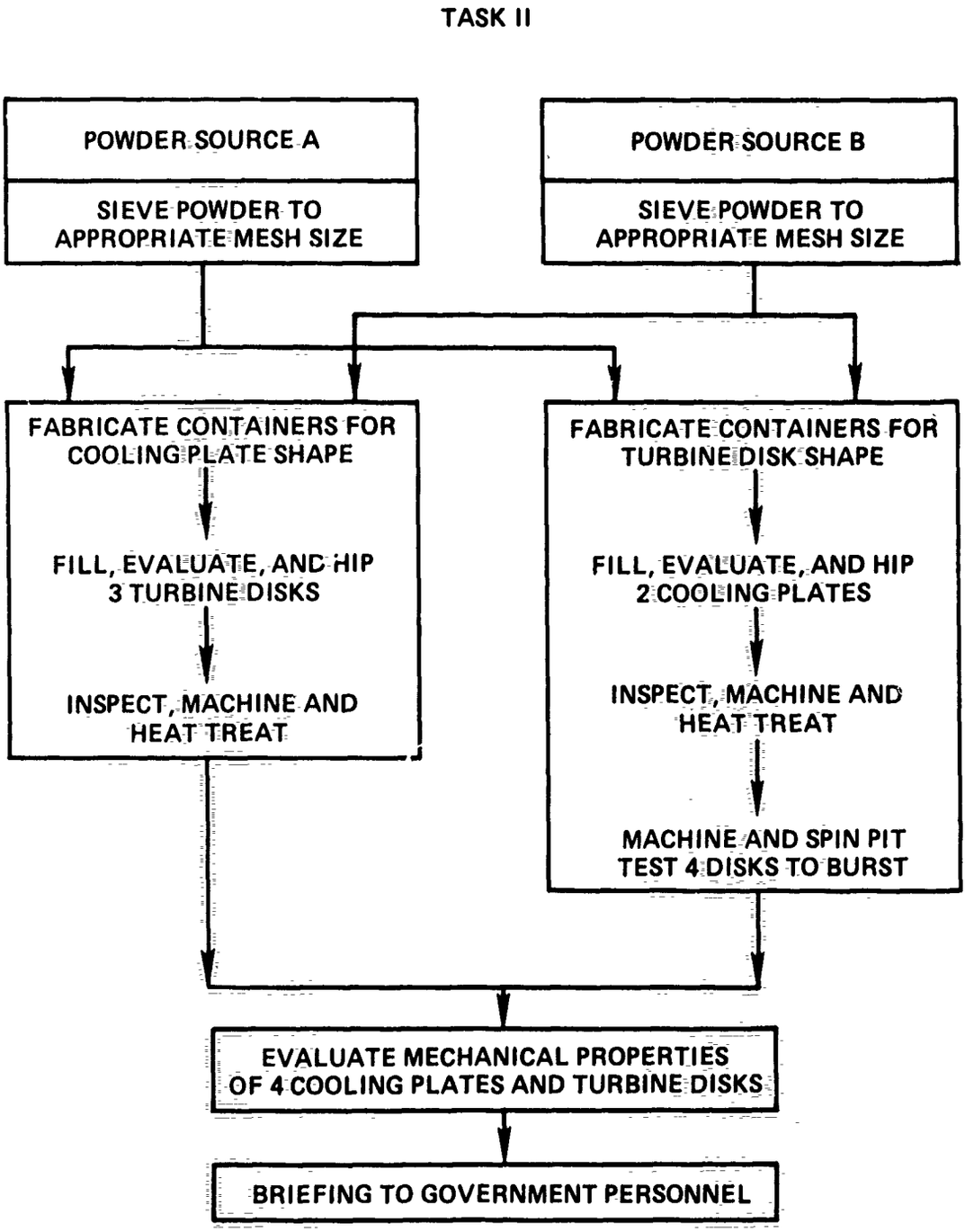


Figure 54. Flow Chart for Task II.

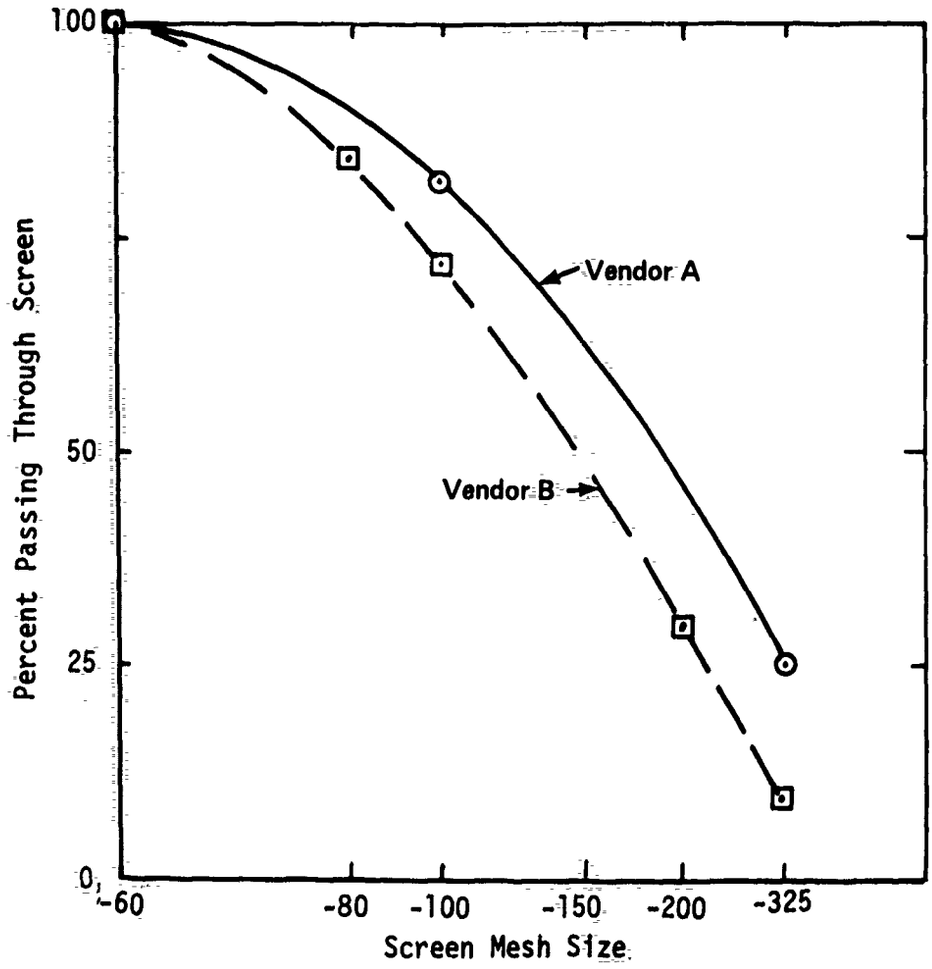


Figure 55. Task II Powder Particle Size Distributions.

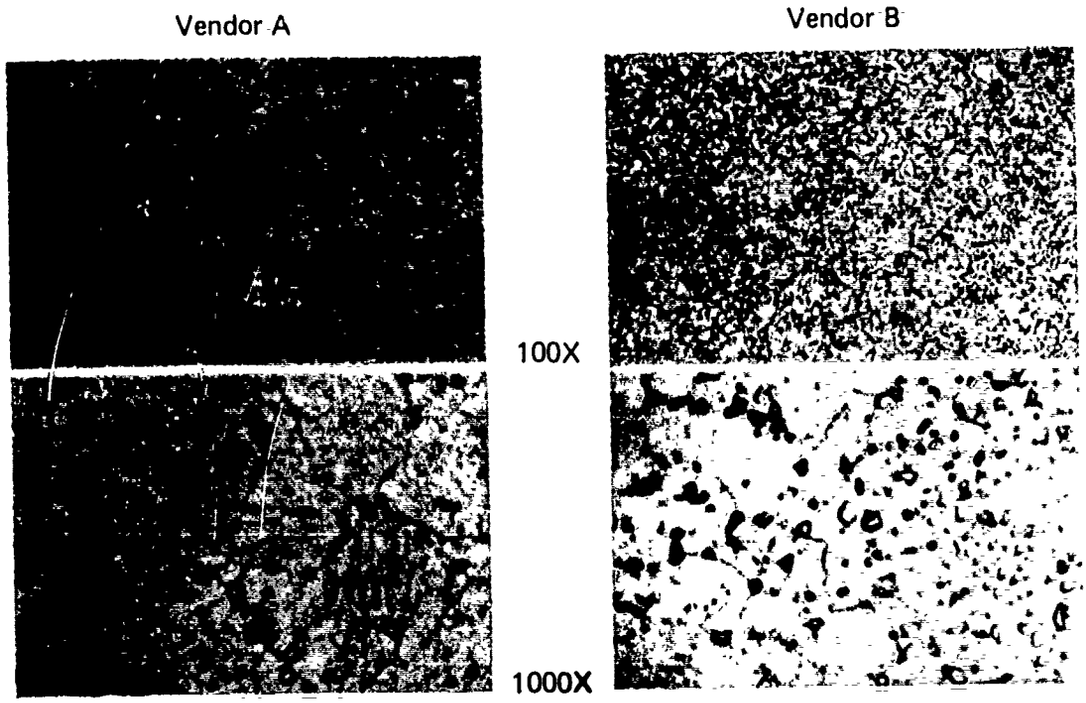
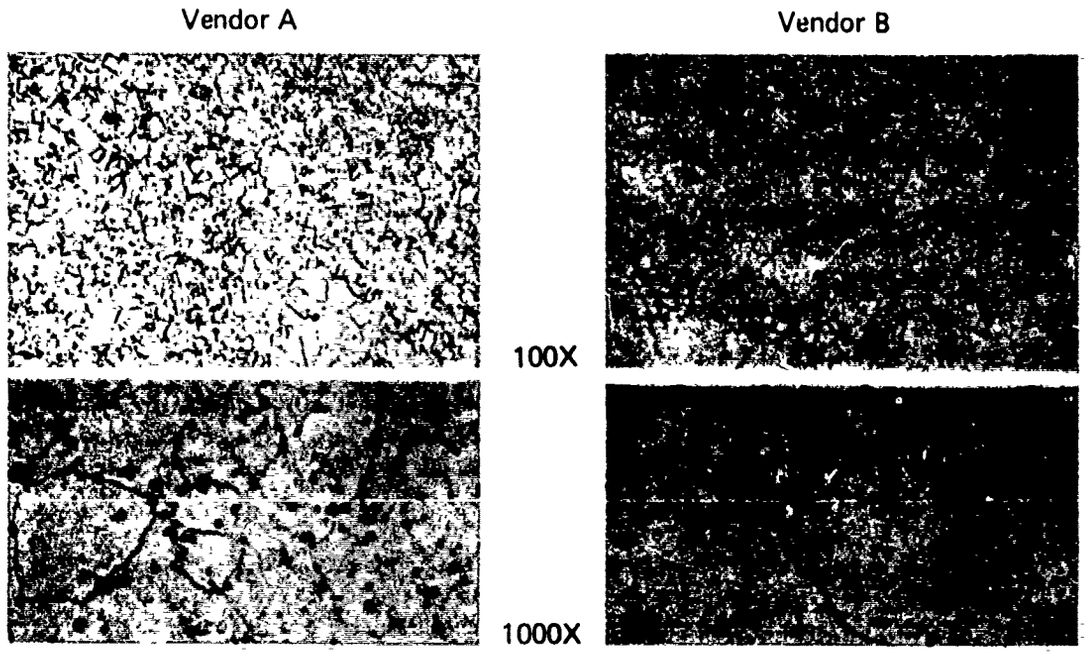


Figure 56. Vendor A γ' Solvus Study on Task I Vendor A and Vendor B Material (Sheet 1).



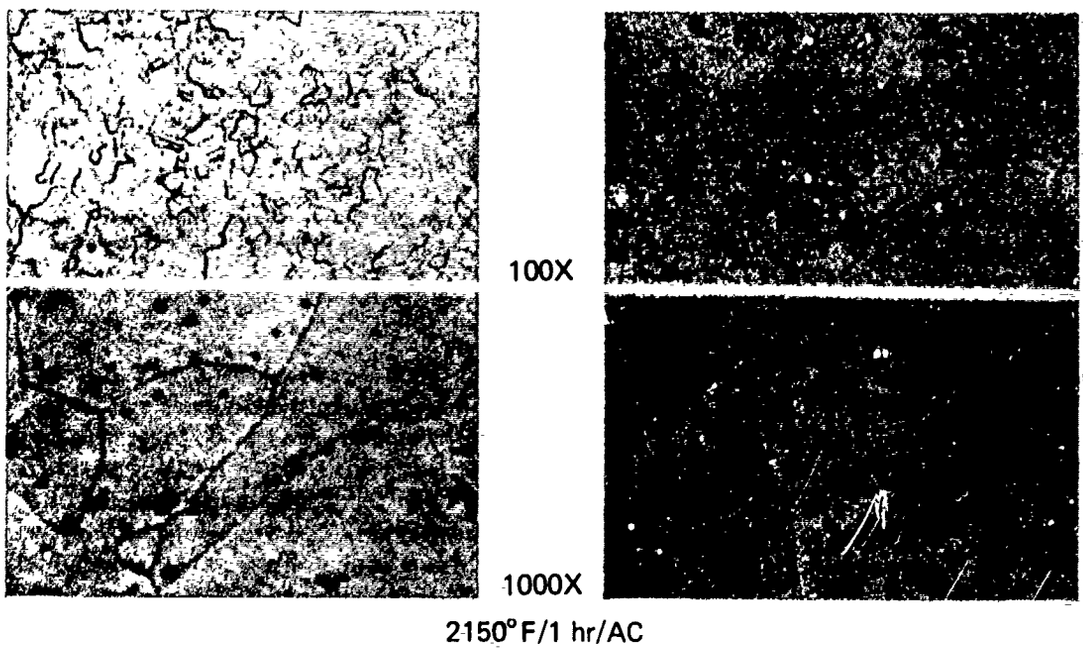


Figure 56. Vendor A γ' Solvus Study on Task I Vendor A and Vendor B Material. (Sheet 2)

diameters of each cooling plate was left intact during heat treatment. All parts were individually solution heat treated and quenched into 1000°F salt bath. Groups of three or four parts were then aged at 1600°F for 1 hour followed by 1200°F for 24 hours. The identification code for all Task II material appears in Table 42.

MATERIAL CHARACTERIZATION

Density and thermally induced porosity (TIP) test results on all Task II material were obtained. Results presented in Table 43 indicate that all the material met the General Electric specification requirement of less than 0.3 percent density change after TIP exposure. The slight disparity in the As-HIP densities between two vendors was produced by minor differences in their powder blend chemistries.

Optical and electron microscopy was also completed on the Task II material used for mechanical property evaluation. The results shown in Figure 57 indicate that the desired grain size (approximately ASTM 8) was achieved in all parts except cooling plate B6 of Vendor B. This part was apparently solution treated at a temperature above its γ' solvus temperature which resulted in grain growth to ASTM 5-7 and uniform precipitation of a large amount of coarse γ'.

The microstructures of the disks from both powder vendors are very similar in both grain size and background (cooling) γ' size. The same comment also applies to all cooling plate structures except B6. However, there is a slight, but distinct, difference in the background γ' sizes of the disks relative to those produced in the cooling plates. This difference, shown in Figures 57a, b, e, and f versus Figures 57c, d, g and h, is primarily a result of the container surrounding the disks. The slower cooling rate obtained when the disks were salt quenched while encapsulated in an oxidized mild steel container allowed the background to coarsen slightly relative to the cooling plates, which had no mild steel container on their top or bottom surfaces. Inspection of the test data generated from this material (to be formally discussed in test results section below) suggests that the slight microstructural difference had no discernable effect on the particular mechanical properties evaluated.

TEST RESULTS

The heat treated Task II material was subjected to detailed mechanical property evaluation, including tensile, stress-rupture, creep, crack propagation, cyclic rupture (SPLCF), and low-cycle fatigue testing. Test specimens used in the evaluation are similar to those in Figures 17, 25, 26, 23, 24 and 58.

Specimen locations for the Task II evaluation are shown in Figures 59 and 60. All specimens were machined from the midplanes of the turbine disk and cooling plate configurations. All disks and cooling plates were used in the mechanical property evaluation except Vendor A disk B231 and Vendor B disk C219, which were machined for spin pit burst testing.

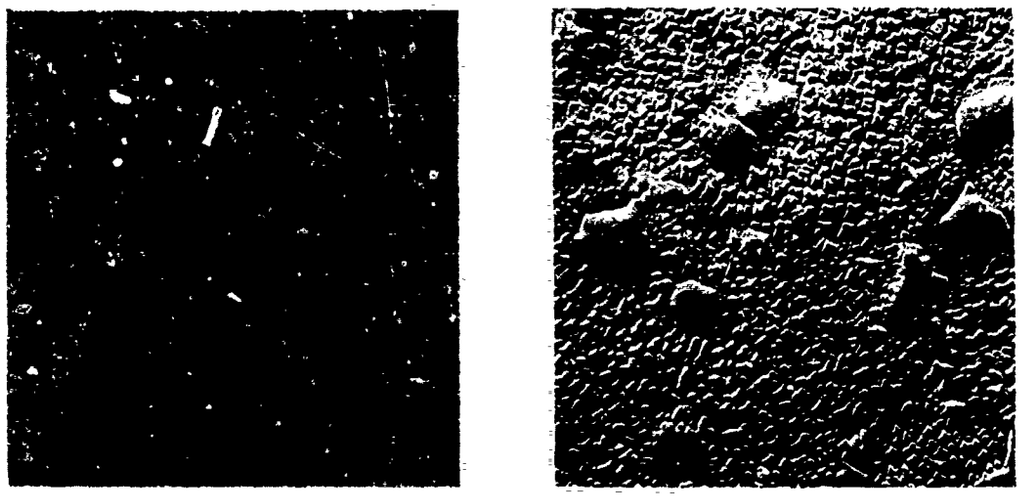
Tensile data shown in Table 44 indicate that the Task II material properties were lower than the Task IA results. The primary areas of deficiency were 0.2 percent yield strengths at all temperatures, and ultimate strengths at 800°F. Tensile ductilities were generally adequate, although somewhat below the level achieved in Task IA. A comparison of the Task II results with PM HIP + forged data from the T700 program is presented in Figures 61 through 63. Although tensile ductilities were approximately equivalent, Task II 0.2 percent yield strengths at all temperatures and ultimate strengths at 1200°F were substantially below the average HIP + forged curves. These unexpectedly low strengths were attributed, at least in the turbine disk shapes, to the reduced quench rate caused by the insulating effect of the oxidized mild steel container. However, no explanation is available for the low results obtained on the 2-inch-thick cooling plate shapes. These shapes were identical to those tested in Task IA and, in the case of Vendor A, heat treated in the same facility using the same procedures as the Task IA material. Since the test source was changed for Task II, several specimens were tested at the Task IA source to determine the effect of test vendor. Results shown in

TABLE 42. IDENTIFICATION OF TASK II DISKS AND COOLING PLATES

	Ident No.	
	Vendor A	Vendor B
Turbine Disks	B227	C219
	B228	C230
	B231	C233
Cooling Plates (2 inches thick)	B195-4	B6
	B195-6	B7

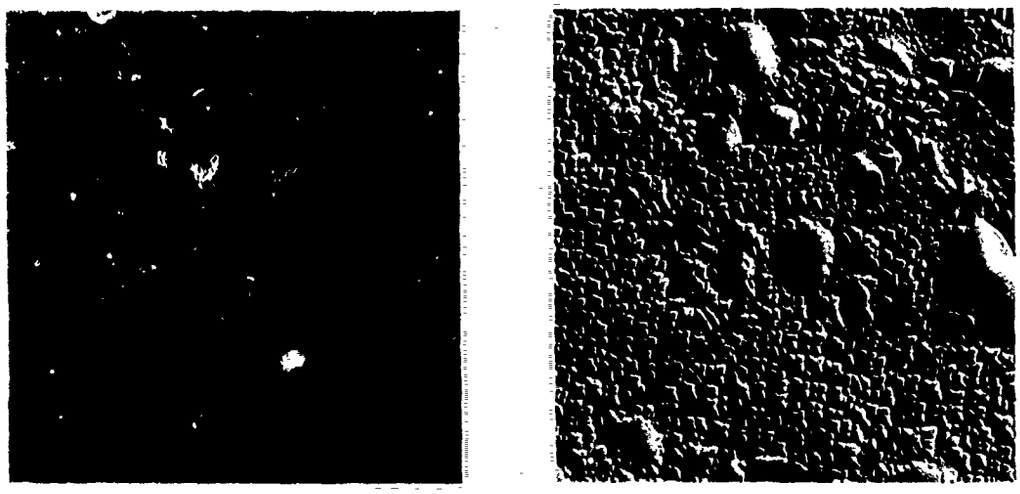
TABLE 43. DENSITY AND TIP TEST RESULTS OF TASK II MATERIAL

Identity	Powder Vendor	Shape	Density ($lb/in.^3$)		
			As-HIP	TIP*	Change (%)
B227	A	Disk	0.2984	0.2978	−0.20
B228	A	Disk	0.2983	0.2977	−0.20
C230	B	Disk	0.2996	0.2990	−0.20
C233	B	Disk	0.2995	0.2991	−0.17
B195-4	A	Cooling Plate	0.2982	0.2976	−0.20
B195-6	A	Cooling Plate	0.2982	0.2976	−0.20
B6	B	Cooling Plate	0.2977	0.2992	−0.17
B7	B	Cooling Plate	0.2995	0.2992	−0.13



100X 5000X

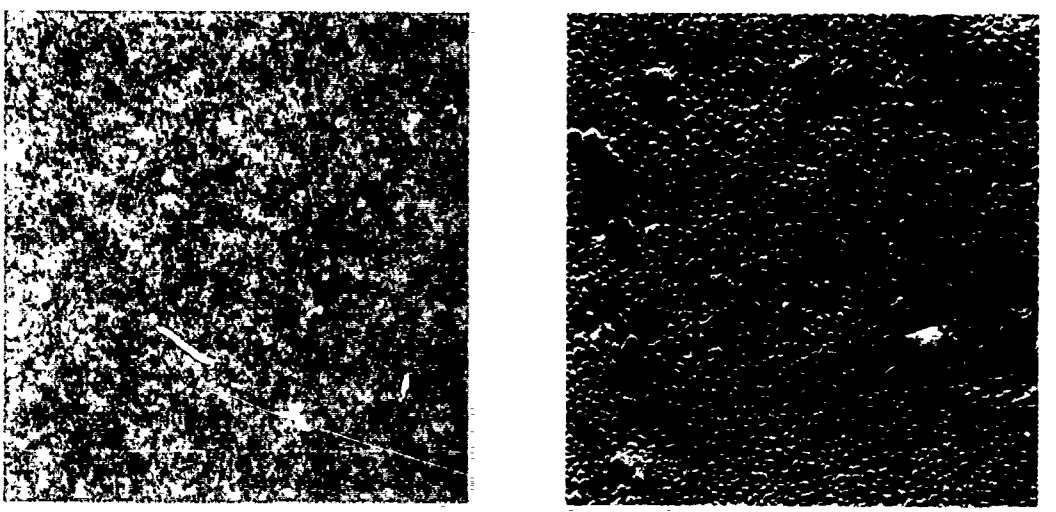
a) Vendor A Disk B227



100X 5000X

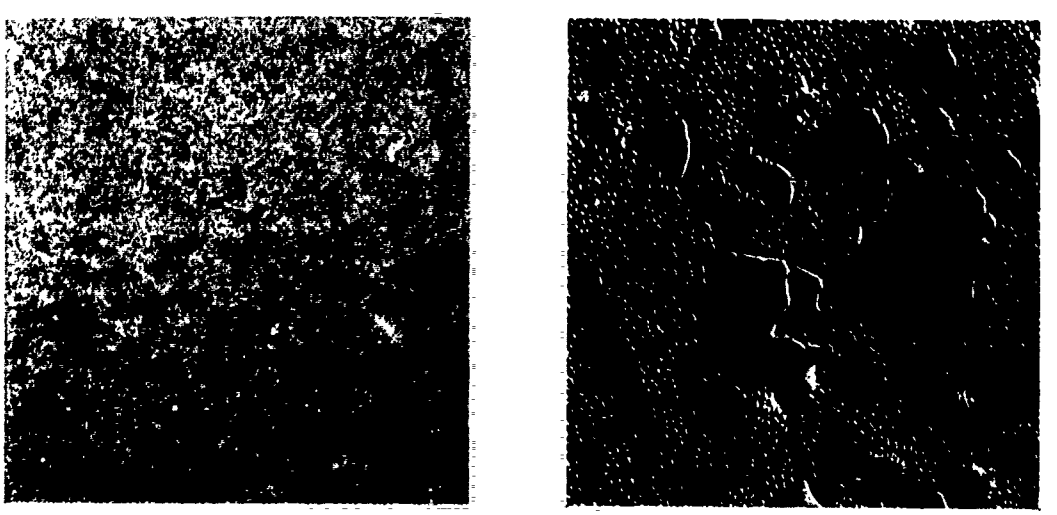
b) Vendor A Disk B228

Figure 57. Microstructure of Task II Material (Sheet 1).



100X 5000X

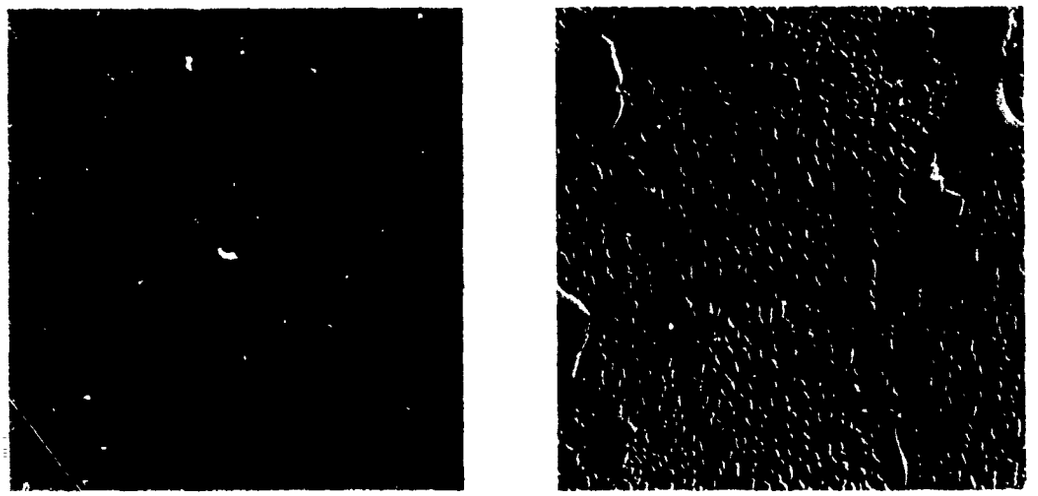
c) Vendor A Cooling Plate B195-4



100X 5000X

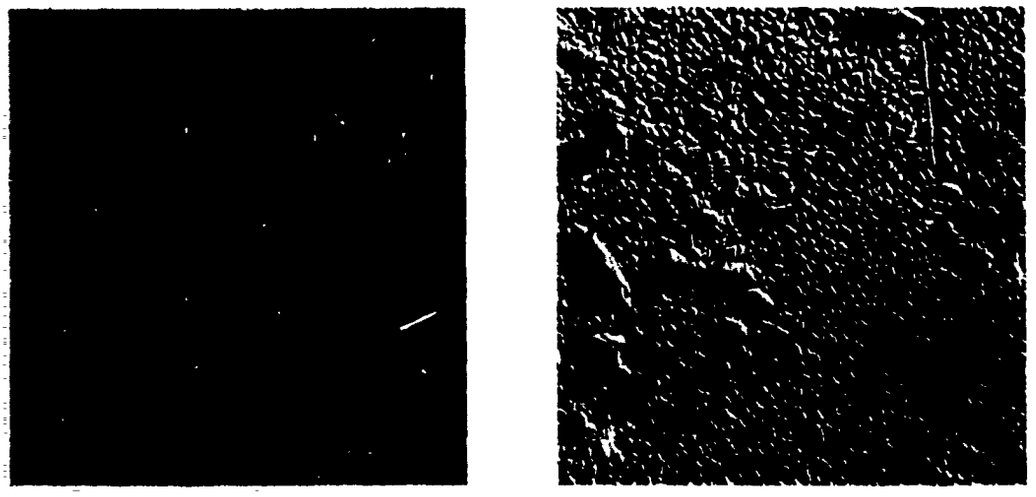
d) Vendor B Cooling Plate B195-6

Figure 57. Microstructure of Task II Material (Sheet 2).



100X 5000X

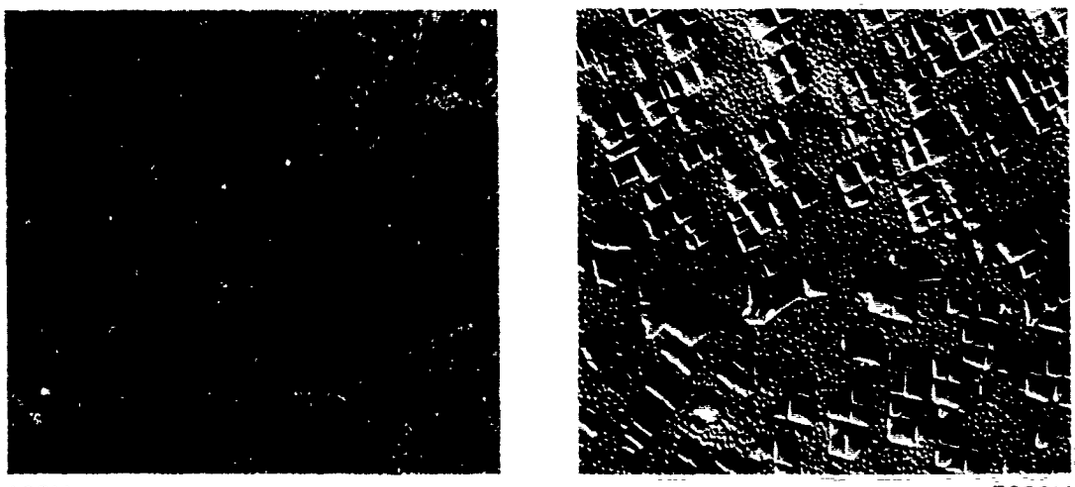
e) Vendor B Disk C230



100X 5000X

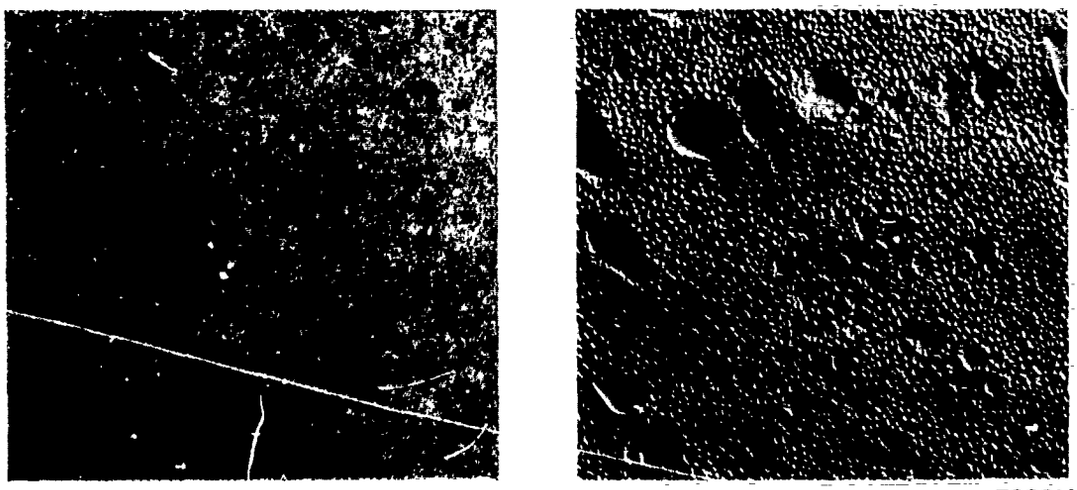
f) Vendor B Disk C233

Figure 57. Microstructure of Task II Material (Sheet 3).



100X 5000X

g) Vendor B Cooling Plate B6



100X 5000X

h) Vendor B Cooling Plate B7

Figure 57. Microstructure of Task II Material. (Sheet 4)

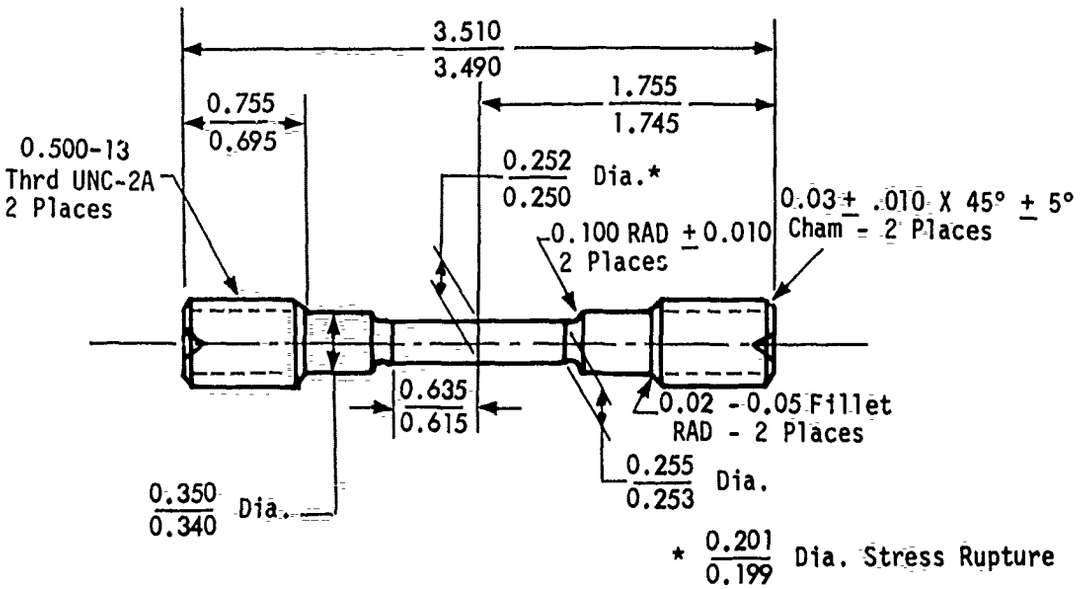


Figure 58. Creep Test Specimen.

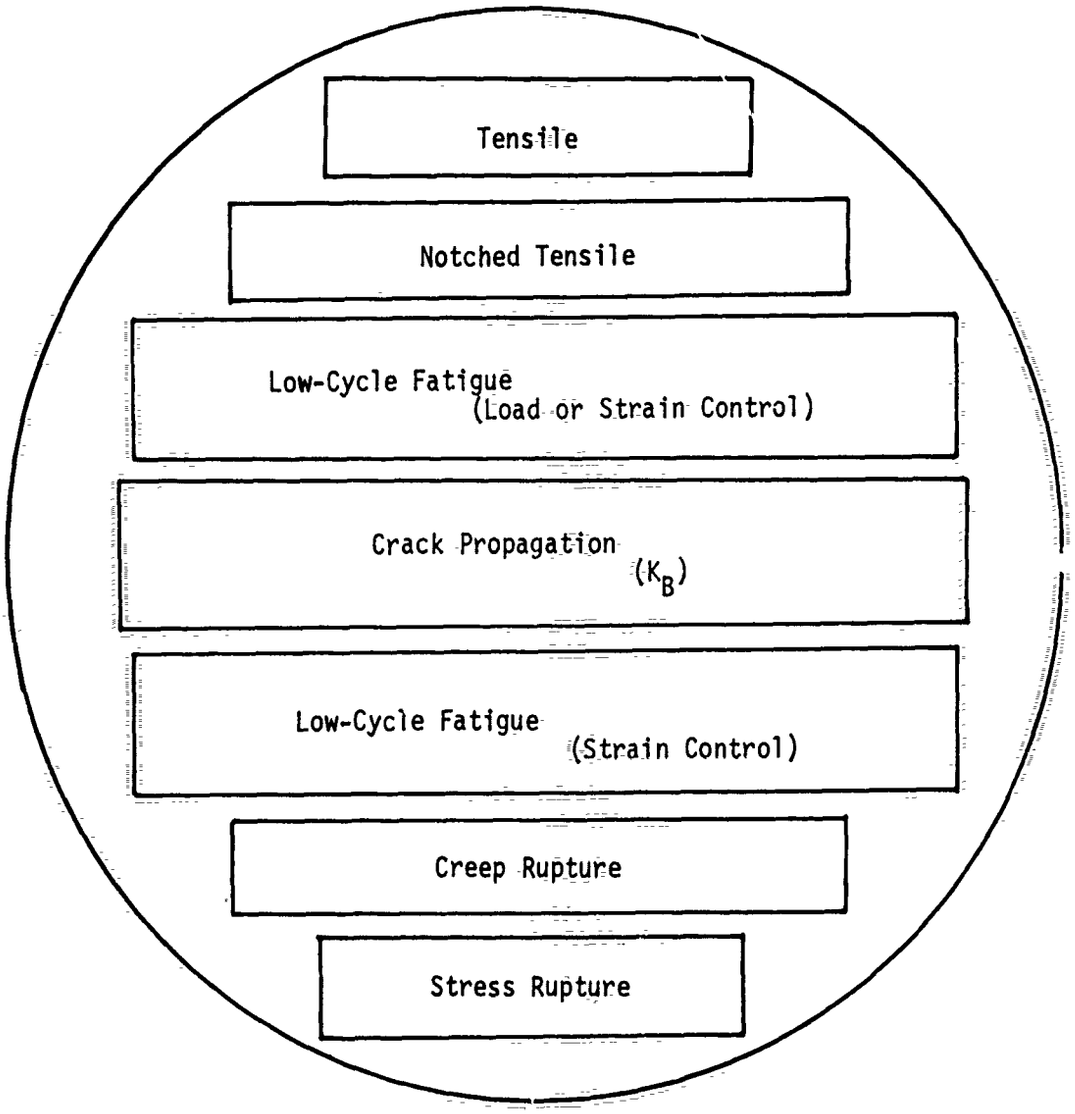


Figure 59. Specimen Location for Task II Turbine Disk Evaluation.

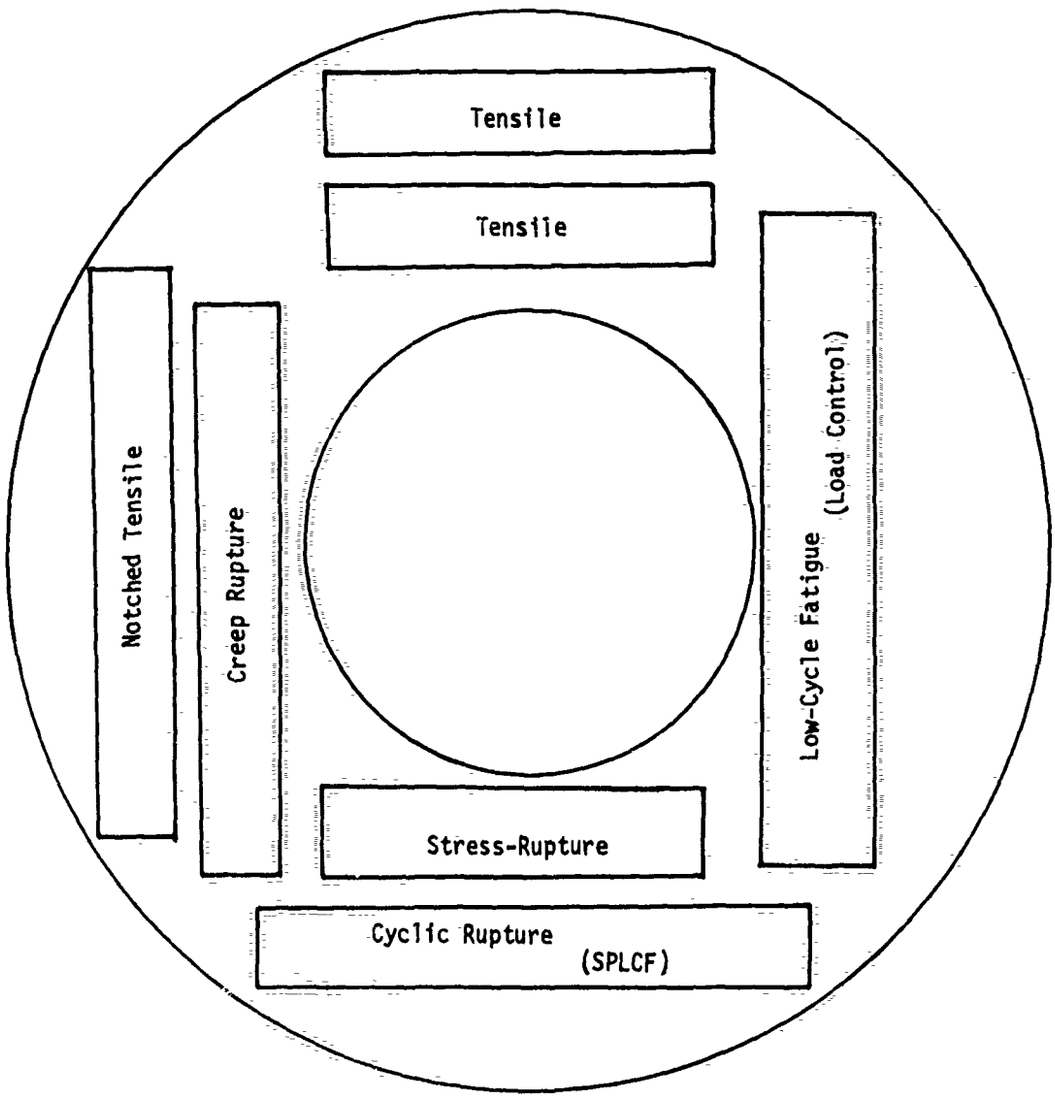


Figure 60. Specimen Location for Task II Cooling Plate Evaluation.

TABLE 44. TASK II TENSILE RESULTS

Identity	Powder Vendor	Shape	Test Temp (°F)[b]	Tensile Properties			
				0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
227	A	Disk	RT	173	233	16.3	17.8
B195-4	A	Cooling Plate	RT	178	232	14.0	14.6
B195-6	A	Cooling Plate	RT	176	233	14.3	15.4
B7	B	Cooling Plate	RT	175	234	17.2	17.2
B7**	B	Cooling Plate	RT	169	226	14.6	16.4
Goal			RT	180	230	10.0	12.0
B228	A	Disk	800	172	207	9.1	12.1
B195-6	A	Cooling Plate	800	167	213	12.3	13.1
B6[a]	B	Cooling Plate	800	164	216	15.8	17.6
B6**[a]	B	Cooling Plate	1000	168	220	14.0	14.3
C233*	B	Disk	1000	171	201	6.7	6.7
B195-4	A	Cooling Plate	1200	162	221	11.1	11.8
C230**	B	Disk	1200	161	218	13.8	16.3
Goal			1200	167	207	8.0	10.0

*Invalid test specimen broke outside gage section.
**Tested at Task I test source.
[a]Over-temperatured during solution heat treatment.
[b]R.T. – Room Temperature.

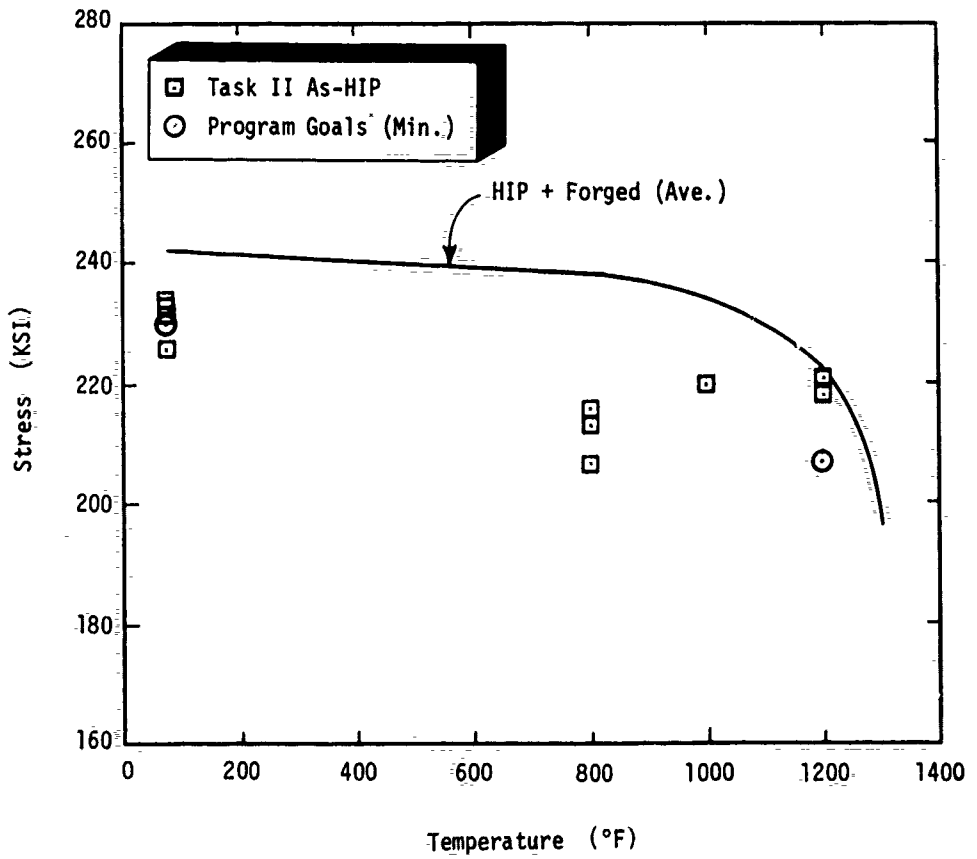


Figure 61. Ultimate Tensile Strength Data for Task II As-HIP Compared to T700 HIP + Forged

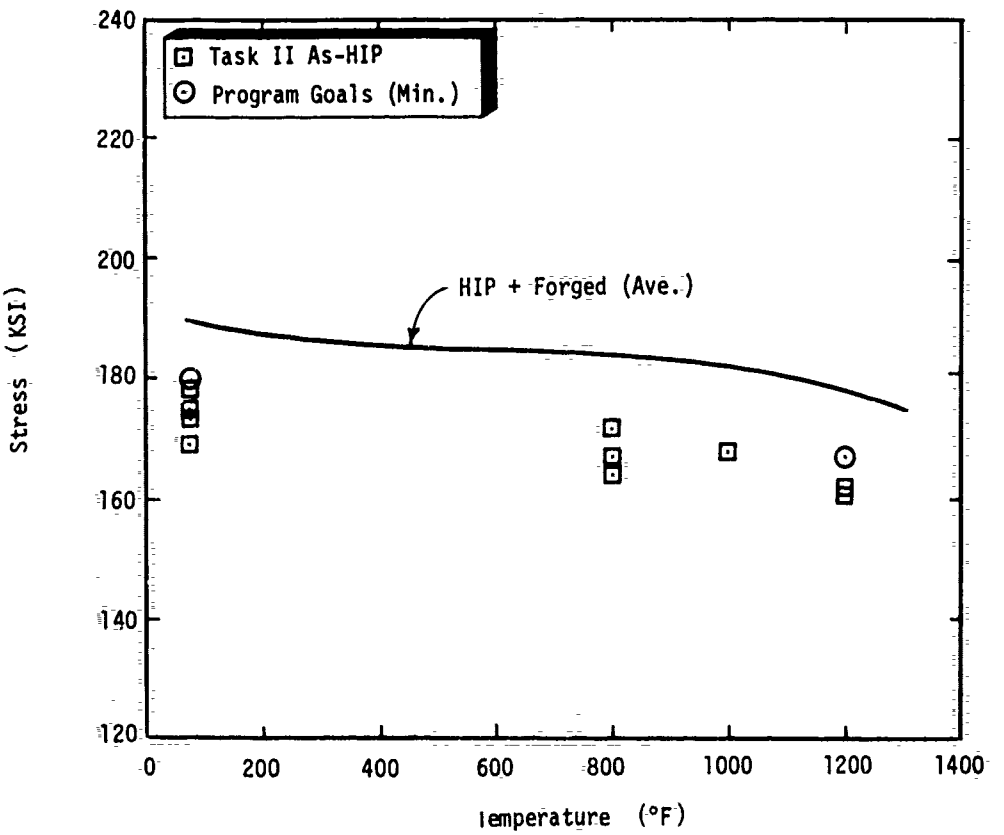


Figure 62. 0.2 Percent Yield Strength Data for Task II As-HIP Compared to T700 HIP + Forged.

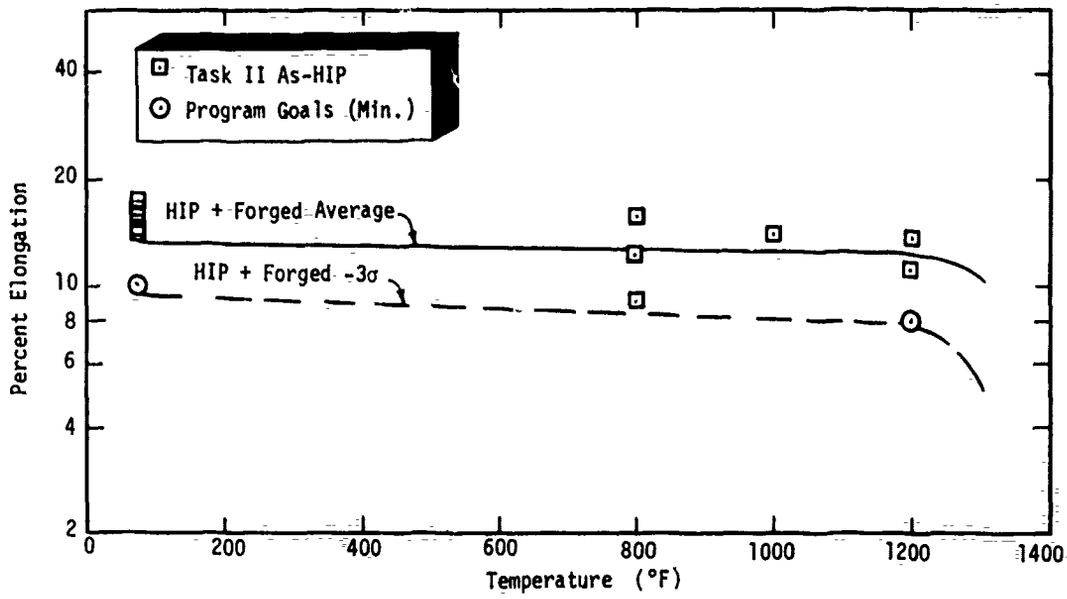


Figure 63A. Percent Elongation Data for Task II As-HIP Compared to T700 HIP + Forged.

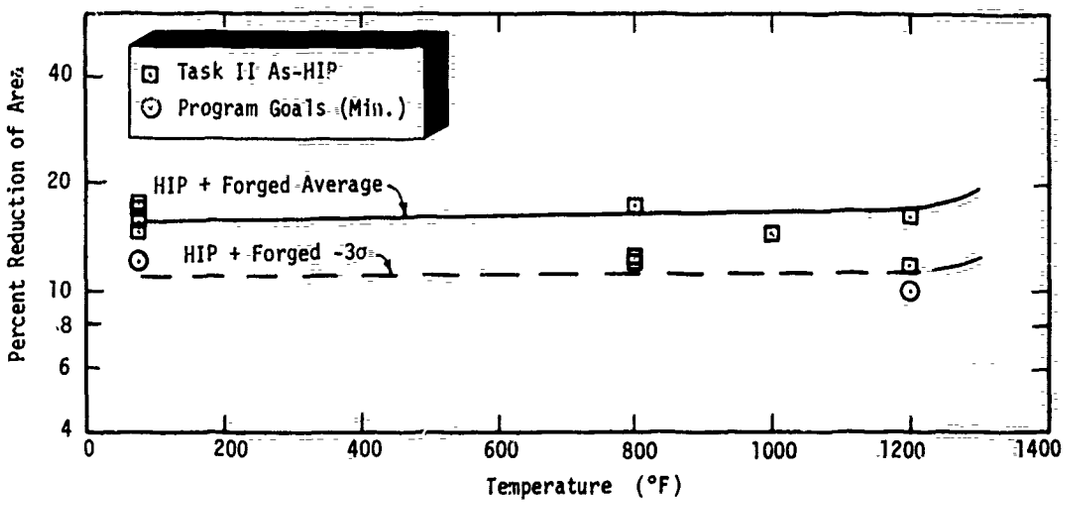


Figure 63B. Percentage Reduction of Area Data for Task II As-HIP Compared to T700 HIP + Forged.

Table 44 indicate that data from the two sources are similar. In fact, room temperature results on cooling plate B7 of Vendor B tested at the Task IA vendor are actually slightly lower than those tested at the Task II vendor.

Notched tensile data shown in Table 45 indicate a notch ratio (notched bar tensile strength/smooth bar tensile strength) of 1.15 at room temperature and a 1.1 ratio at 1000° and 1200°F. These values are slightly below the HIP + forged T700 results of approximately 1.2 at all temperatures.

Stress-rupture data were obtained at temperatures from 1100° to 1300°F and stresses from 100 to 172 ksi. Results are given in Table 46 and compared to a HIP + forged average curve in Figure 64. The Task II material data appears to be comparable to HIP + forged data at 1100° through 1200°F and slightly superior at 1300°F. Stress-rupture ductilities are adequate at all test temperatures.

Creep results were also obtained at test temperatures from 1100° to 1300°F. The data (Figure 65, and Table 47) again show that Task II As-HIP material is equivalent to the T700 HIP + forged parts at lower temperatures and slightly superior at 1300°F.

Sustained peak low-cycle fatigue (SPLCF) testing was conducted at 1000° and 1200°F. Comparison of the Task II data with that of the HIP + forged in Table 48 reveals virtually equivalent properties at both test temperatures.

Crack propagation testing at 1000°F was completed on Task II disk shapes using the KB specimen. Results given in Table 49 indicate the same trend observed during Task IA, i.e., the crack propagation resistance of the As-HIP material is slightly lower than that of HIP + forged (or cast plus wrought) Rene'95.

Low-cycle fatigue (LCF) testing of Task II material was obtained at conditions evaluated in Task IA as well as additional conditions suggested by T700 design engineering. Test temperatures, notch conditions, and stresses were intended to simulate the actual operating environment of Rene' 95 hardware in the T700 engine. Important test parameters are described below:

Temperature	Test Type	Stress Ratio	Notch Severity
750°F	PS/N_f	A = 1	$K_t = 1.0$
900°F	PS/N_f	A = 1	$K_t = 1.0$
1050°F	S/N_f	A = 1	$K_t = 1.2$
1050°F	S/N_f	A = 1	$K_t = 1.85$
1200°F	PS/N_f	A = 1	$K_t = 1.0$
1250°F	S/N_f	A = 1	$K_t = 1.85$

*S - Alternating Stress, PS - Pseudo Stress, N_f - Number of Cycles to Failure.

Task II results are described in Table 50. It is obvious that the data scatter inherent in LCF testing makes evaluation of two data points per condition difficult. For example, at several test conditions the cycles to failure are actually greater at the higher stress condition. This behavior was also observed during evaluation of the HIP + forged T700 engine hardware. Comparison of these meager data with the average HIP + forged curves shown in Figures 66 through 71 reveals an approximate equality at all test conditions. However, completion of the design data program in Task III will be required to confirm this conclusion.

TABLE 45. TASK II NOTCHED TENSILE RESULTS

Identity	Powder Vendor	Shape	Test Temp (°F)	Notch UTS (ksi)
B195-6	A	Cooling Plate	RT	263
B7	B	Cooling Plate	RT	262
C233	B	Disk	RT	269
HIP + Forged (ave)			RT	290
B227	A	Disk	1000	244
C230	B	Disk	1000	237
B6*	B	Cooling Plate	1000	231
HIP + Forged (ave)			1000	276
B228	A	Disk	1200	235
B195-4	A	Cooling Plate	1200	235
HIP + Forged (ave)			1200	261

All tests conducted using $K_t = 4.0$.
*Overtemperatured during solution heat treatment.

TABLE 46. TASK II STRESS-RUPTURE RESULTS

Identity	Powder Vendor	Shape	Test Temp (°F)	Stress (ksi)	Rupture Life (hr)	EL (%)	RA (%)
B195-4	A	Cooling Plate	1100	172	96.5	4.0	5.9
C233	B	Disk	1100	168	186.6	3.7	5.1
B227	A	Disk	1200	155	38.3	6.1	8.7
C230	B	Disk	1200	155	45.5	3.4	5.9
B6*	B	Cooling Plate	1200	140	218.3	8.4	10.2
B228	A	Disk	1300	110	164.2	5.7	5.0
B195-6	A	Cooling Plate	1300	100	177.1	5.9	6.1
B7	B	Cooling Plate	1300	100	332.5	3.7	4.0

*Overtemperatured during solution heat treatment.

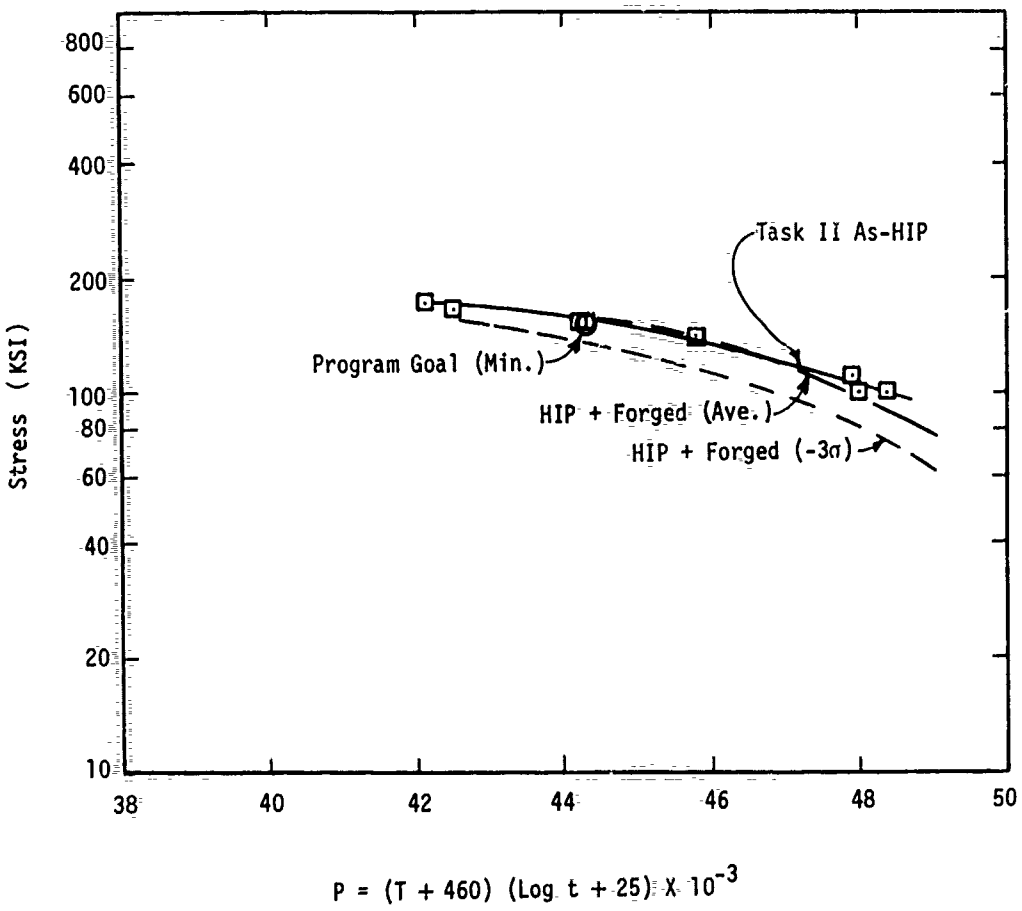


Figure 64. Stress Rupture Data for Task II As-HIP Compared to T700 HIP + Forged.

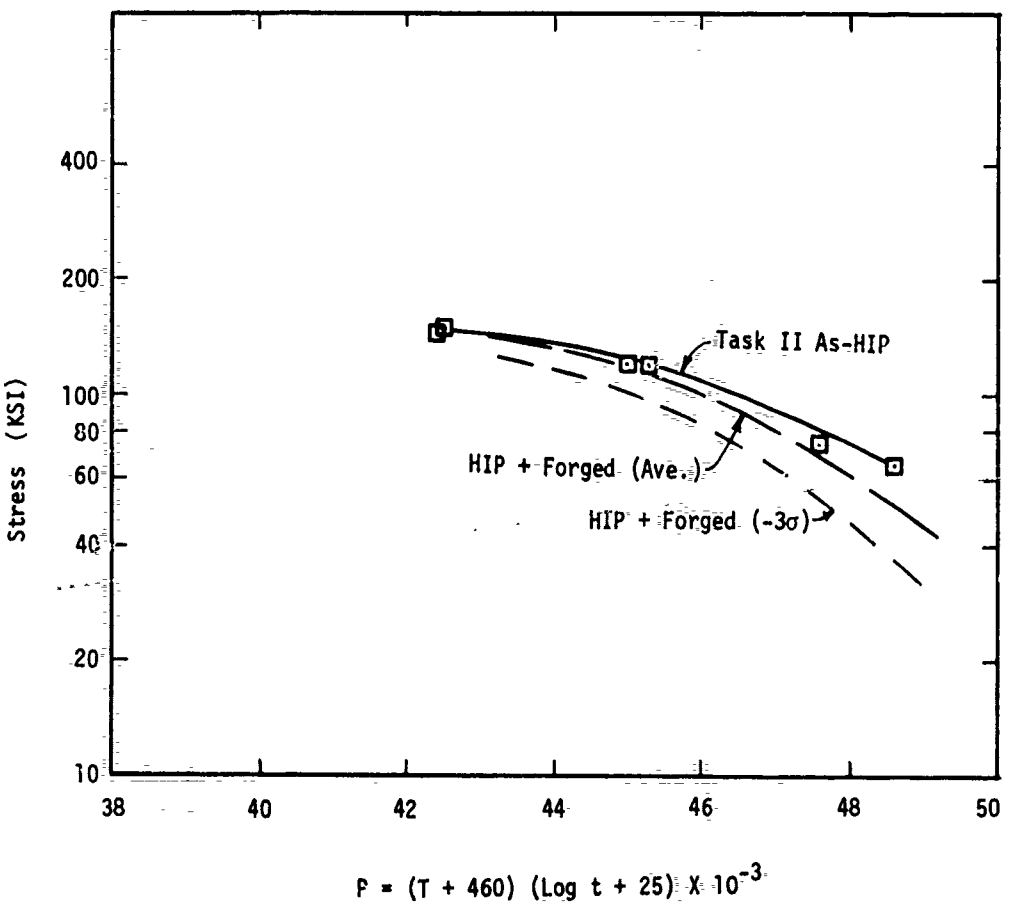


Figure 65. 0.2 Percent Plastic Creep Data for Task II As-HIP Compared to T700 HIP + Forged.

TABLE 47. TASK II CREEP RESULTS

Identity	Powder Vendor	Shape	Test Temp (°F)	Stress (ksi)	Time to 0.2% Creep (hr)
B227	A	Disk	1100	150	168
B195-6	A	Cooling Plate	1100	145	150
B228	A	Disk	1200	120	128
C233	B	Disk	1200	120	190
B6*	B	Cooling Plate	1200	100	793**
C230	B	Disk	1300	75	102
B195-4	A	Cooling Plate	1300	65	395
B7	B	Cooling Plate	1300	65	793**

*Overtemperatured during solution heat treatment.
**Test still in progress.

TABLE 48. TASK II SUSTAINED PEAK LOW-CYCLE FATIGUE RESULTS

Identity	Powder Vendor	Shape	Test Temp (°F)	Max. Stress (ksi)	Cycles to Failure
B195-6	A	Cooling Plate	1000	180	891
HIP + Forged			1000	180	1111
B6*	B	Cooling Plate	1000	160	2463
HIP + Forged			1000	160	2312
B195-4	A	Cooling Plate	1200	145	812
B7	B	Cooling Plate	1200	145	810
HIP + Forged (ave)			1200	145	900

*Overtemperatured during solution heat treatment.

TABLE 49. TASK II CRACK PROPAGATION RESULTS

Identity	Powder Vendor	Shape	Initial Crack Size		Cyclic Life	HIP + Forged Life (Predicted)
			Length (in.)	Depth (in.)		
B227	A	Disk	0.024	0.058	6711	7400
B228	A	Disk	0.020	0.061	7080	8000
C230	B	Disk	0.024	0.060	6742	7300
C233	B	Disk	0.024	0.061	6115	7200

TABLE 50. TASK II LOW-CYCLE FATIGUE RESULTS

Identity	Powder Vendor	Shape	Test Temp (°F)	Notch Severity	Alternating** Stress (ksi)	Cycles to Failure
C233	B	Disk	750	$K_t = 1.0$	169.3	4,094
B227	A	Disk	750	$K_t = 1.0$	130	13,060
B228	A	Disk	900	$K_t = 1.0$	140	7,038
C230	B	Disk	900	$K_t = 1.0$	123.9	8,324
B6*	B	Cooling Plate	1050	$K_t = 1.2$	90	10,563
B195-4	A	Cooling Plate	1050	$K_t = 1.2$	85	7,929
B7	B	Cooling Plate	1050	$K_t = 1.85$	78	2,890
B228	A	Disk	1050	$K_t = 1.85$	74	4,553
C233	B	Disk	1200	$K_t = 1.0$	124	7,296
B227	A	Disk	1200	$K_t = 1.0$	117.1	4,568
B195-4	A	Cooling Plate	1250	$K_t = 1.85$	67	3,885
C230	B	Disk	1250	$K_t = 1.85$	63	15,939

*Overtemperatured during solution heat treatment.
**All tests with $K_t = 1.0$ are strain controlled — stress is calculated alternating pseudo stress.

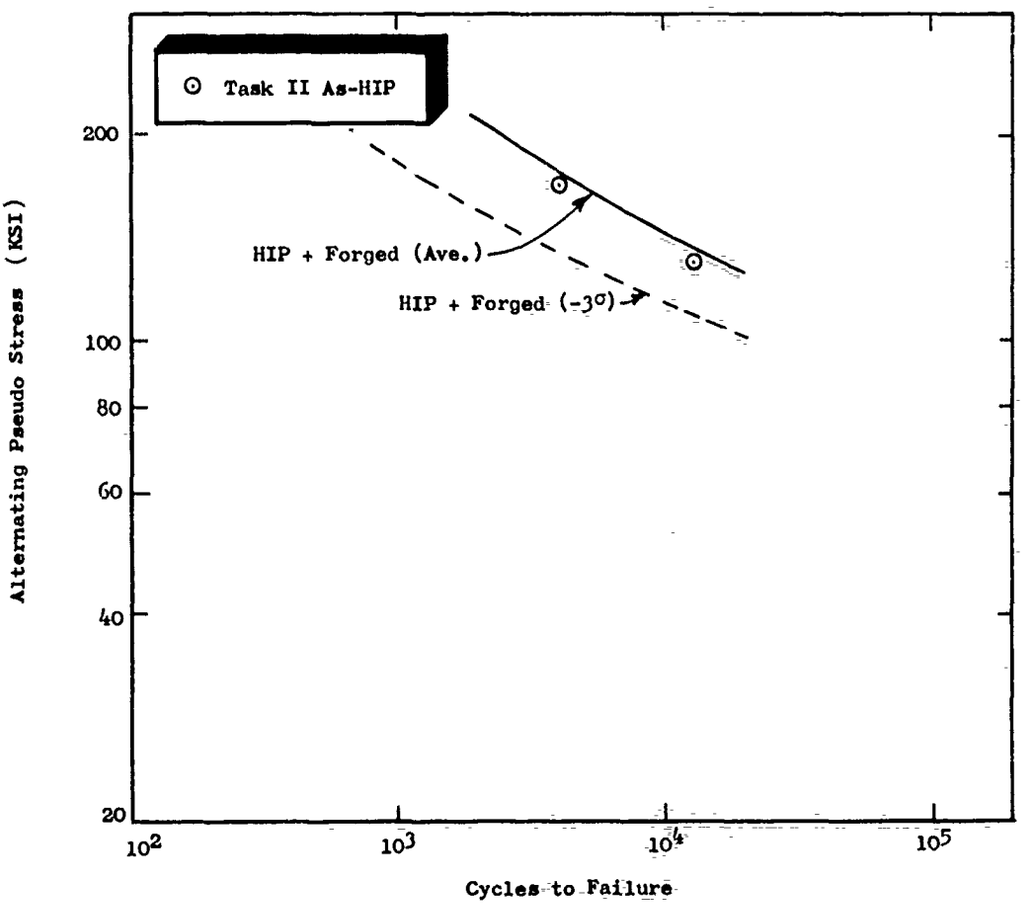


Figure 66. Strain Control 750°F Low-Cycle Fatigue Data at A = 1 for Task II As-HIP Compared to T700 HIP + Forged.

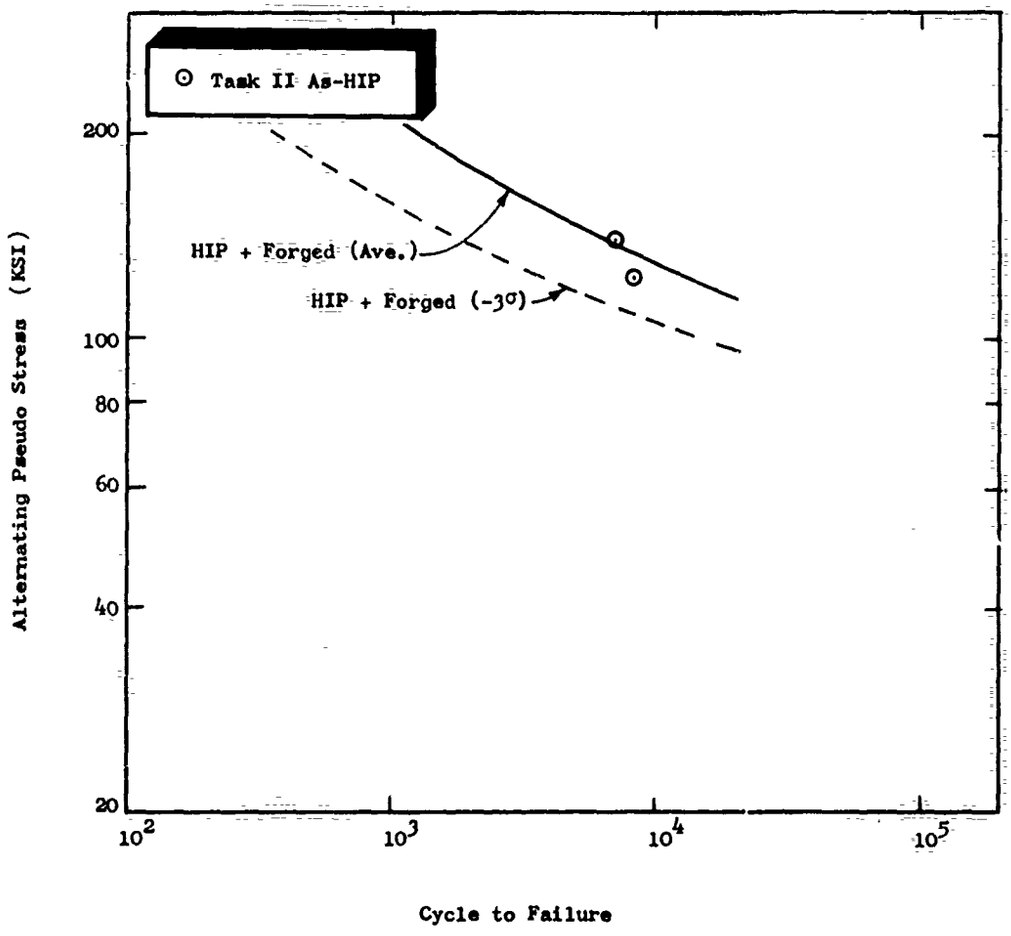


Figure 67. Strain Control 900°F Low-Cycle Fatigue Data at A = 1 for Task II As-HIP Compared to T700 HIP + Forged.

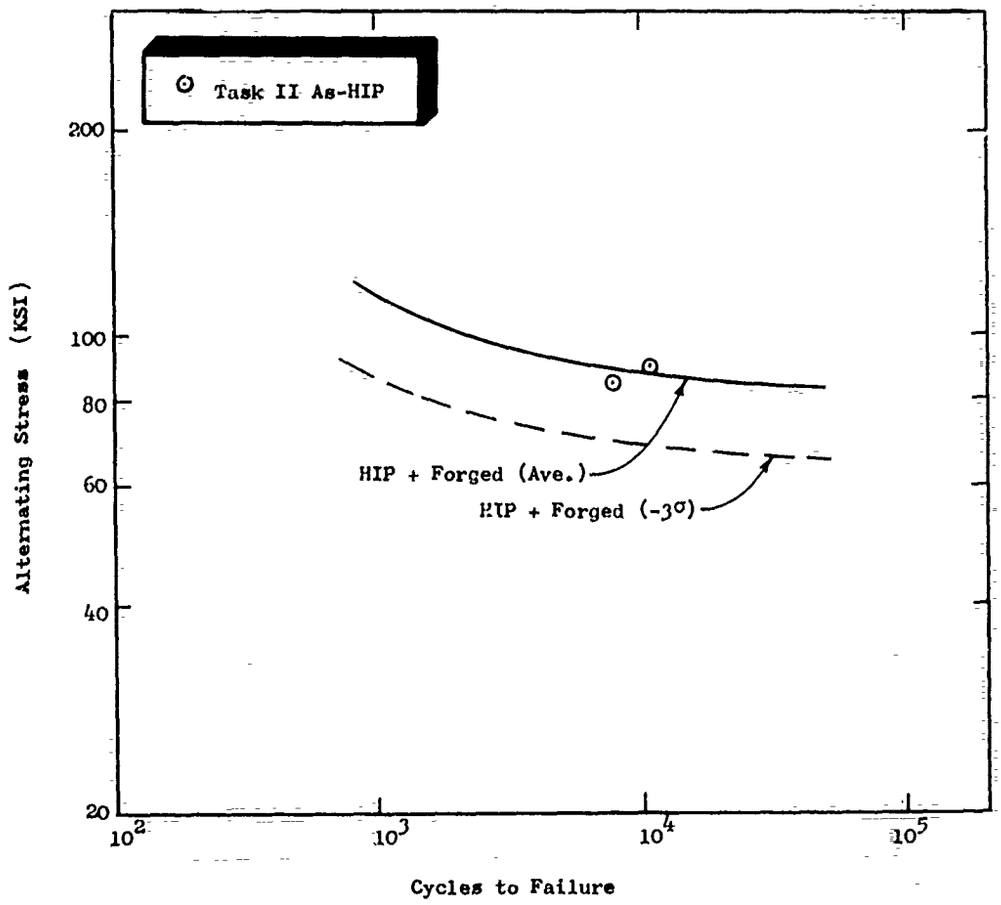


Figure 68. Load Control 1050°F Low-Cycle Fatigue Data at A = 1, K_t = 1.2, for Task II As-HIP Compared to T700 HIP + Forged.

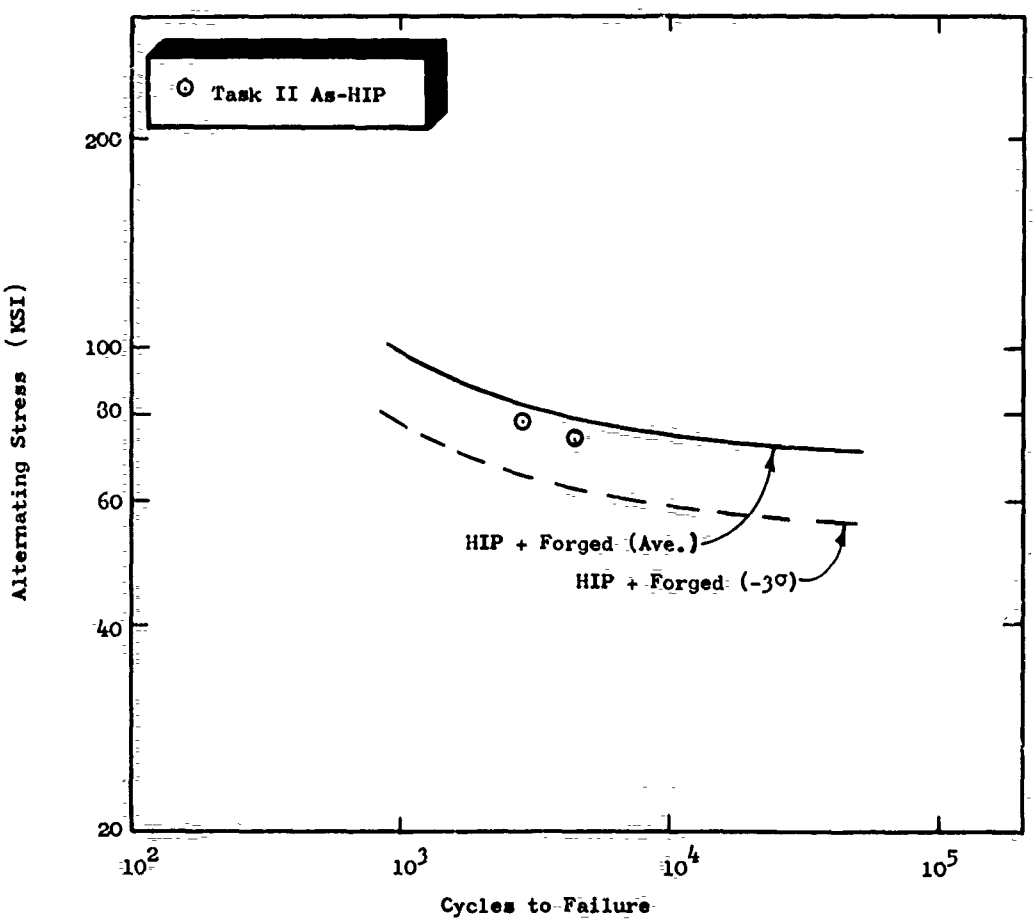


Figure 69. Load Control 1050°F Low-Cycle Fatigue Data at A = 1, K_t = 1.85, for Task II As-HIP Compared to T700 HIP + Forged.

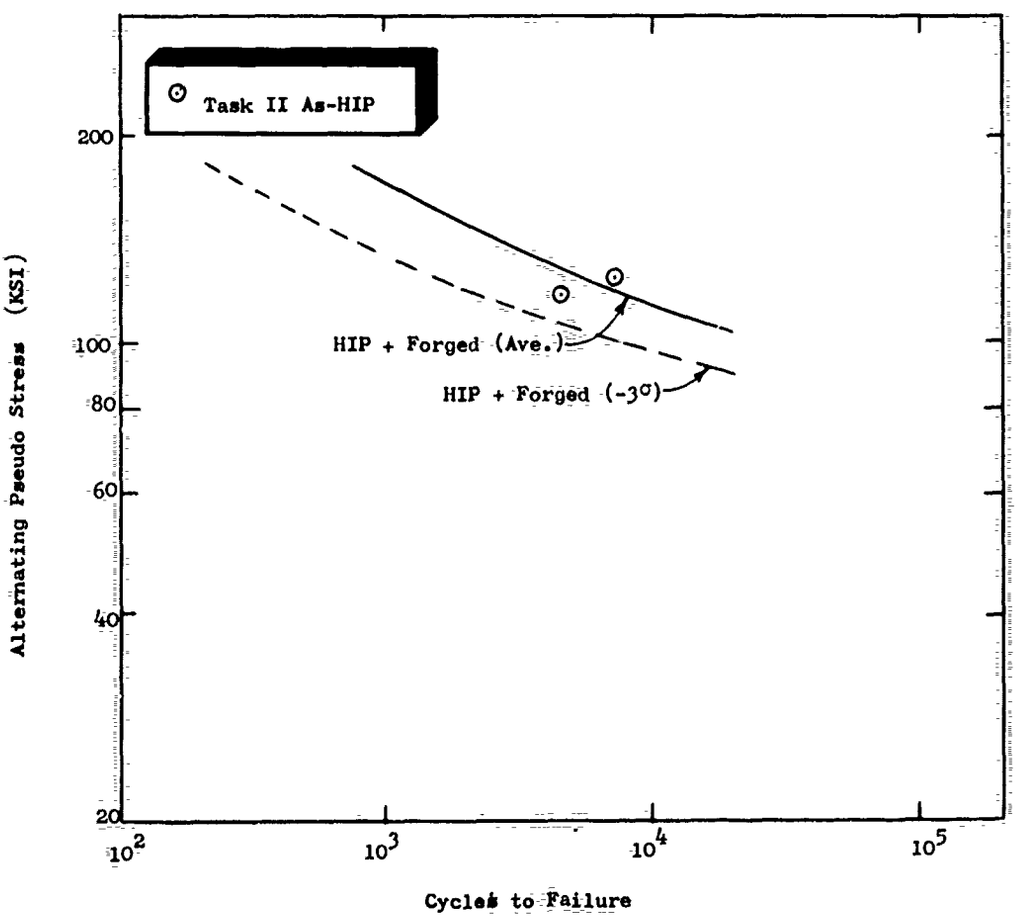


Figure 70. Strain Control 1200°F Low-Cycle Fatigue Data at A = 1 for Task II As-HIP Compared to T700 HIP + Forged.

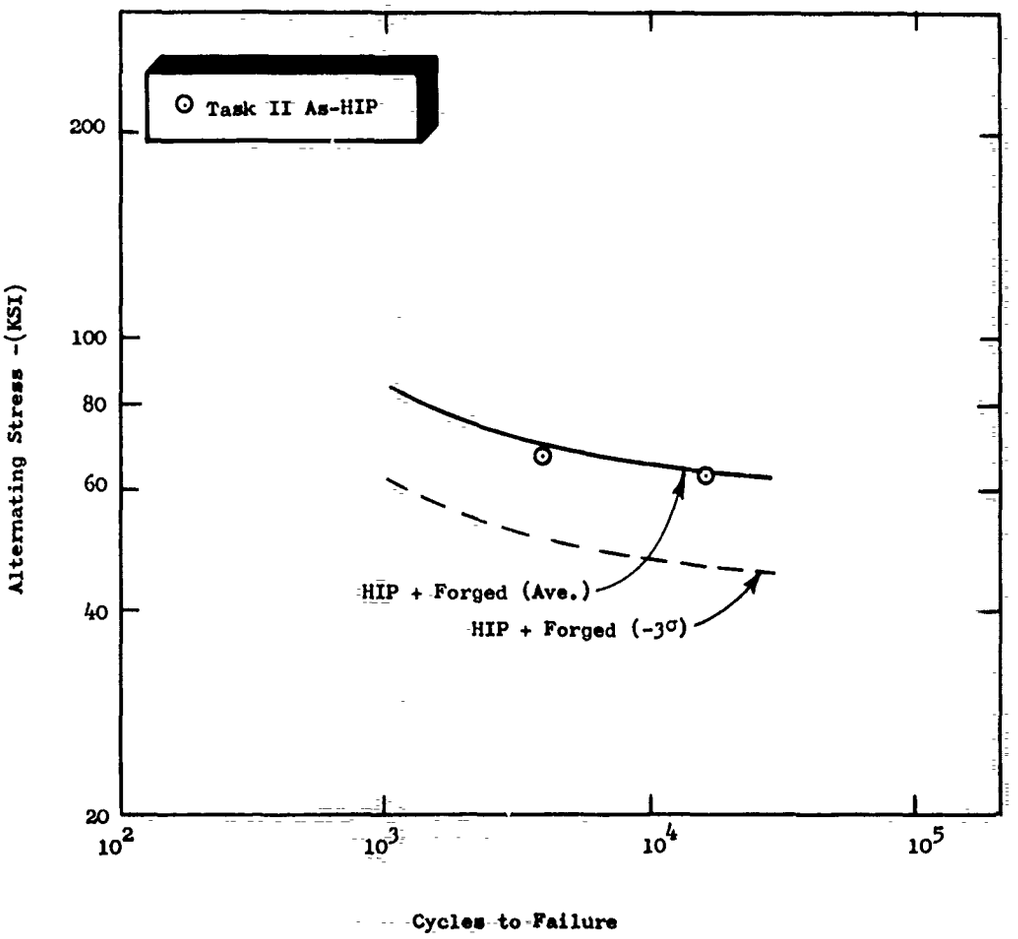


Figure 71. Load Control 1250°F Low-Cycle Fatigue Data at A = 1, K_t = 1.85, for Task II As-HIP Compared to T70υ HIP + Forged.

The problem of low tensile properties in encapsulated turbine disk shapes was alluded to in the initial portion of this section. Consequently, a small study was designed to examine the effect of the mild steel container material on quenching rate and to determine the feasibility of solution treating in a high temperature salt bath rather than an air furnace.

Four turbine disks fabricated from -60 mesh powder (two from each powder vendor) were heat treated. One disk from each powder vendor was solution treated at 2100°F for 1 hour in a gas fired furnace and quenched into 1000°F salt bath. The second disk from each vendor was solutioned in a 2100°F salt bath for 1 hour and then quenched into 1000°F salt. All four disks were aged 1600°F/1 hour/AC + 1200°F/24 hours/AC in the same furnace run.

The solution temperature of 2100°F was used on all four disks to simplify the experiment. The γ' solvus measurements on the Vendor B material indicated that the proper temperature (T_s -30°F) was 2085°F. However, the disks of Vendor B were used primarily to verify the difference in quenching rates produced by solutioning in an air furnace and a salt bath. The Vendor A material was used as a direct comparison with their Task IA hollow cylindrical slices to assess the effect of the complete mild steel encapsulation of the disk on quench rate and mechanical properties.

Transfer times from the gas fired (air) solution furnace to the 1000°F salt was essentially equivalent (approximately 7 seconds) to those achieved during the Task IA and Task II heat treatments at Vendor A. The disks were transferred from the 2100°F salt bath to the 1000°F salt bath in approximately 2 seconds. Three specimens were machined from each disk as shown in Figure 72. The room temperature tensile specimen was taken from the disk bore, while the elevated temperature specimens were machined from the thinner rim in order to obtain data at temperatures approximating those experienced by these locations during service.

As expected, solution treatment in the air furnace produced a substantial oxide scale around each disk. Solutioning in the high temperature salt bath did not oxidize or corrode the mild steel. Tensile and stress-rupture properties of the two Vendor A disks, presented in Table 51, indicate that the oxide layer formed during solution treatment in the air furnace reduced the effective quench rate of the disk relative to that achieved in the Task IA cooling plate blanks. The slower cooling rate resulted in lower mechanical properties, especially yield strengths, compared to the Task IA data. Solutioning in a 2100°F salt bath degraded the quench rate and room temperature mechanical properties to levels somewhat below those of the material solutioned in the air furnace. The material from both vendors exhibited the same trends in spite of the fact that they were solution treated approximately 15°F above the specification temperature.

Electron micrographs of the microstructure in the bore and rim regions of all four disks are presented in Figure 73. Comparison of the microstructures of all four disks clearly indicates a significantly larger background γ' size in the disks solutioned in the 2100°F salt bath. This γ' coarsening, which occurred during the 1000°F salt quench portion of the heat treatment, was responsible for the lower properties of the disk solutioned in 2100°F salt.

The background γ' size of the Task IA Vendor A cooling plate blank, shown in Figure 74, was considerably finer than that produced in any of the four disks heat treated. Therefore, in order to attain Task IA mechanical properties in turbine disk shapes, the quench rate, reflected by the background γ' size, must be increased.

One possible solution to the quench rate problem is to remove the mild steel container prior to the heat treatment. This approach was tried on an early -60 mesh Vendor A Task IA disk (SM 180) fabricated using a ceramic mold. The disk was heat treated without an encapsulating container in the same manner as the Task II disks. Test specimens were machined from the bore and rim, and tensile and stress-rupture properties were determined. The results, presented in Table 52, indicate substantial improvements in yield strengths

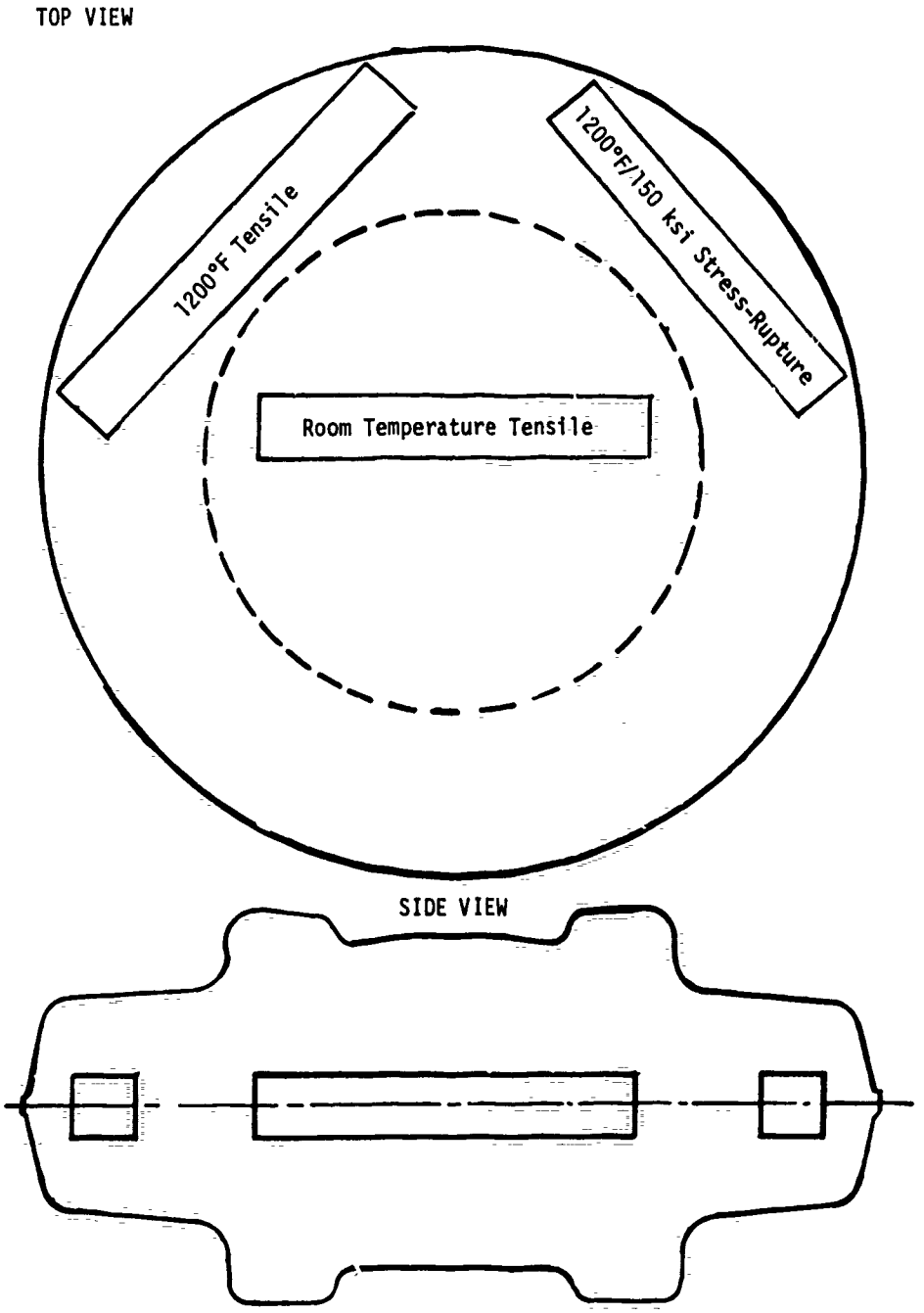


Figure 72. Specimen Locations for Turbine Disks Heat Treated at Production Source.

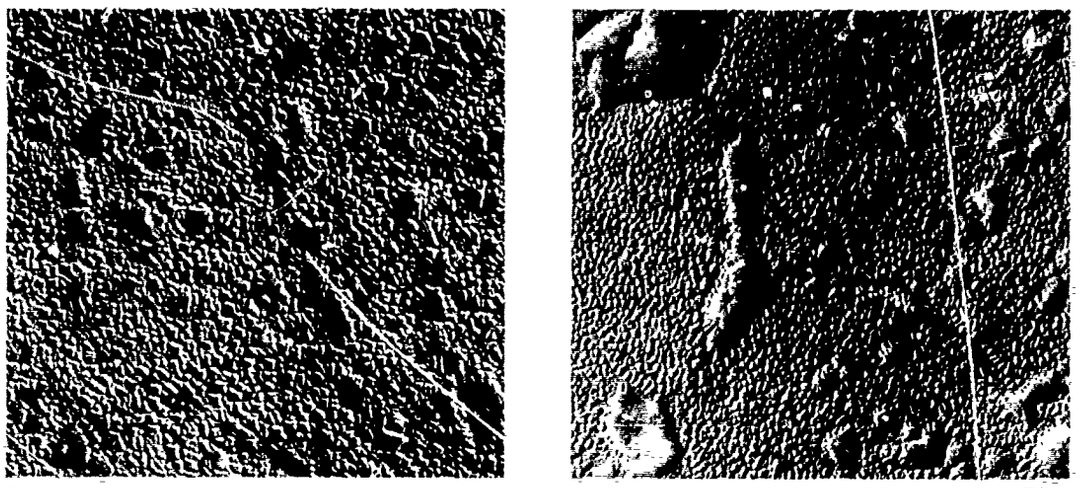
TABLE 51. MECHANICAL PROPERTIES OF TURBINE DISK HEAT TREATED WITHOUT ENCAPSULATING CONTAINER

TENSILE PROPERTIES

Specimen Location	Test Temp (°F)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)
Bore	RT	183	233	11	15
Rim	RT	185	238	12	15
Rim	1200	180	228	10	11

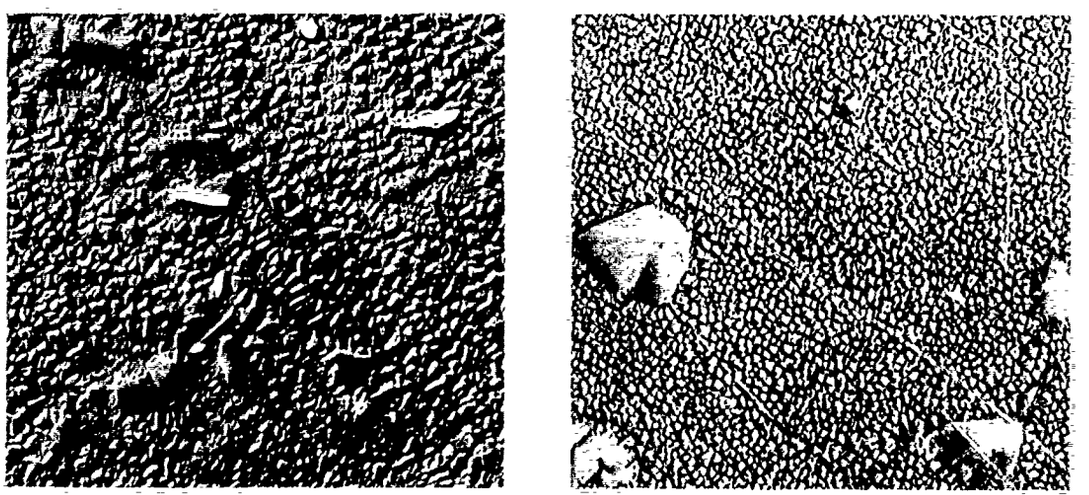
STRESS-RUPTURE PROPERTIES
1200°F/150 ksi

Specimen Location	Life (hr)	EL (%)	RA (%)
Bore	62	9.0	8.6
Rim	59	4.0	5.6
Rim	99	5.0	7.8



Bore Rim

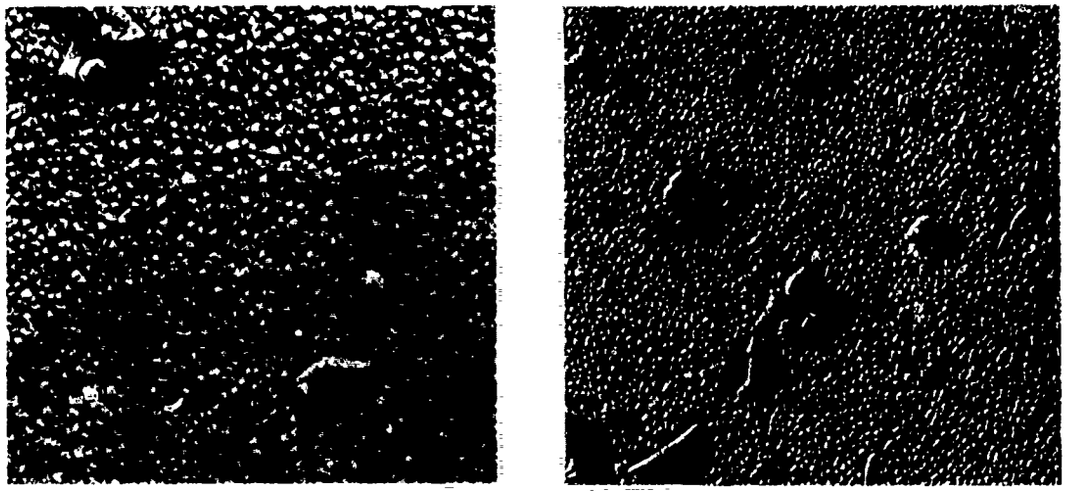
a) Vendor A Disk (Solutioned in 2100°F Air Furnace)



Bore Rim

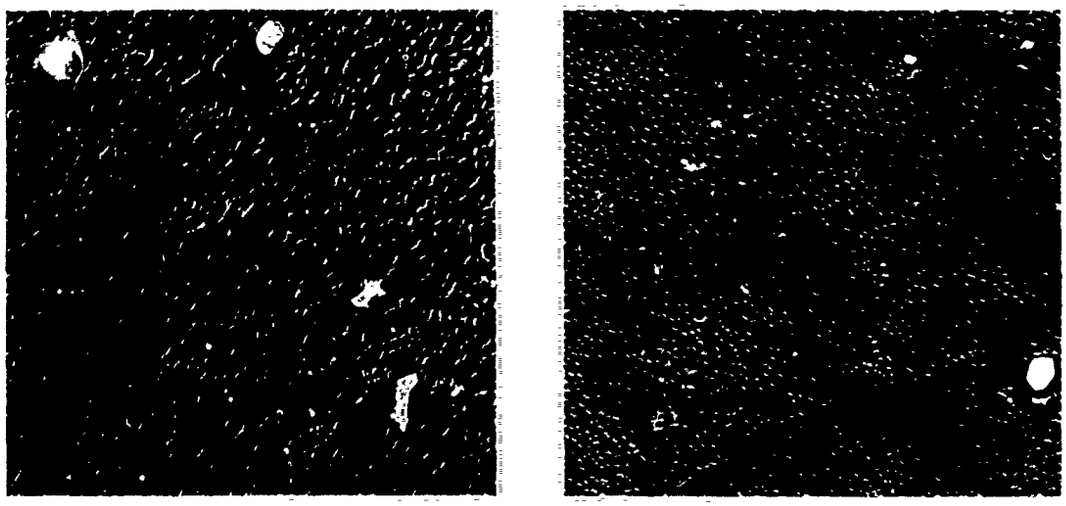
b) Vendor A Disk (Solutioned in 2100°F Salt Bath)

Figure 73. Electron Microscopy of Four Turbine Disks (5000X) (Sheet 1).



Bore Rim

c) Vendor B Disk (Solutioned in 2100°F Air Furnace)



Bore Rim

d) Vendor B Disk (Solutioned in 2100°F Salt Bath)

Figure 73. Electron Microscopy of Four Turbine Disks (5000X) (Sheet 2).

5000X

Figure 74. Electron Microscopy of Task IA Hollow Cylinder.

TABLE 52. MECHANICAL PROPERTIES OF TURBINE DISKS HEAT TREATED AT PRODUCTION SOURCE

Identity	Source	Solution Method	Tensile Properties								Stress-Rupture	
			Room Temperature				1200°F				1200°F/150 ksi	
			0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Life (hr)	EL (%)
Task IA	A	Air*	182	244	15	17	171	225	15	19	130	5.3
	A	Air	175	234	14	12	156	208	17	20	98	4.8
	A	Salt**	166	230	17	18	156	216	16	17	79	5.7
	B	Air	169	230	15	15	155	213	14	16	55	3.2
	B	Salt	163	220	15	15	151	216	14	13	114	3.8

All material heat treated 2100°F/1 hr/1000°F Salt Q + 1600°F/1 hr/AC + 1200°F/24 hr/AC.

*Air = Solution treated in an air furnace.
**Salt = Solution treated in salt bath.

relative to the Task II disks. Tensile ductilities and stress-rupture lives were on the low side but rupture ductilities were excellent. These data substantiate the decision to heat treat Task III turbine disk shapes after removing the mild steel containers. No explanation however remains available for the apparent difference in the properties of Task II cooling plates and Task I specimens similar in configuration.

SPIN PIT BURST TESTING

A primary feature of any engine qualification and certification procedure is a proof investigation known as the overspeed test. The purpose of this test is to impose an excessive speed on either the disks in an engine or on individual disks in a spin pit. The test establishes a margin of safety that ensures that disks will not fail if the operational hardware were suddenly exposed to an excessive overspeed. The mode of failure that is guarded against is known as disk burst, which occurs when the component reaches its ultimate rotational strength.

The overspeed test represents an important design consideration that has to be met in order to validate the engine for service operation. This means that the maximum speed the disk is capable of attaining before bursting must be calculated with a high degree of precision. This must be achieved in order to maintain at least a small margin during the test so that excessive weight penalties are not incurred in meeting a highly improbable condition in actual service.

DISK PREPARATION

Spin pit burst test disks were machined from material of both vendors fabricated during Task II. Two configurations were tested to compare with previous results on T700 PM HIP + forge hardware. A turbine disk (B231) from Vendor A was machined to the configuration shown in Figure 75. The holes in the disk simulate the actual cooling and bolt holes present in an actual T700 turbine disk. A disk (C219) from Vendor B was prepared to the same design except without the 20 holes shown in Figure 75. Both disks were precision balanced prior to testing.

A serious oversight occurred at this point in the program. Due to changes in personnel, communications broke down and the disks were tested without being subjected to nondestructive inspection. In this instance, failure to inspect allowed one defective part to be tested which normally would have been rejected by routine ultrasonic or fluorescent penetrant inspection.

TEST PROCEDURE

The disks were tested at room temperature in a pit illustrated in Figure 76. An air turbine was used to accelerate the parts to very high speeds under vacuum. The burst disks were caught by the wood block/steel ring assembly before striking the cylinder liner. Rotational speeds were monitored by three different instruments. Permanent recordings were made by a tape recorder and a trace recorder. The speed was also displayed on two ATEC digital units and recorded visually by spin pit personnel.

TEST RESULTS

Historically the method of calculating disk burst has depended on the quite simple analytical procedure of equating the speed at burst to the level of the average tangential stress in the disk. Given the fact that previous disk designs were relatively simple and the materials used tended to be tolerant towards this type of failure, the average tangential criterion has provided adequate predictive margins. However, with the advent of the superalloy disk materials coupled with greater demands for engine performance which in turn result in complex geometric designs; the accepted methods of analysis were reexamined to establish their validity, applicability and more important, their dependability.

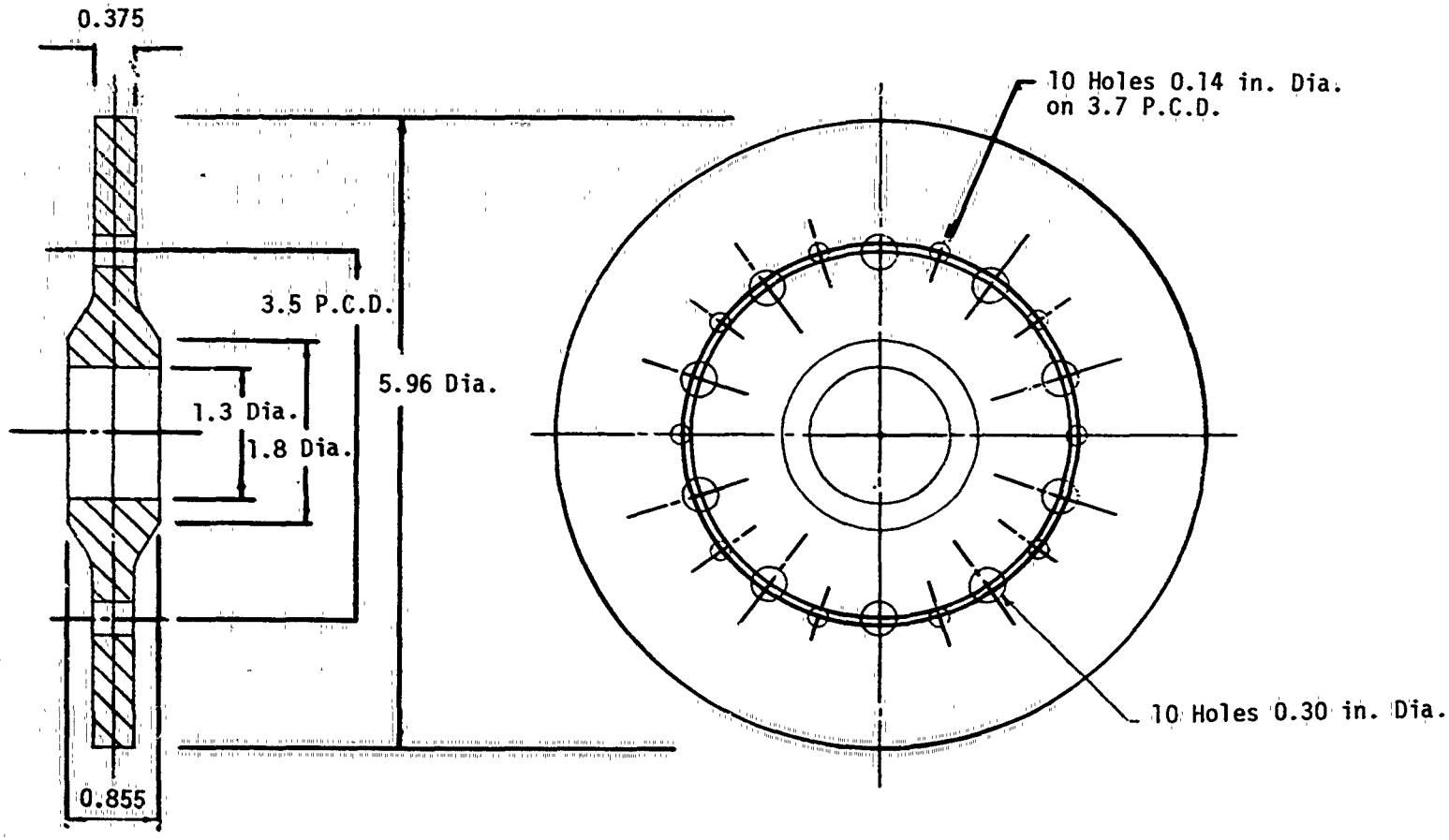


Figure 75. Model T700 Spin Pit Burst Test Disk – Tested With and Without Holes.

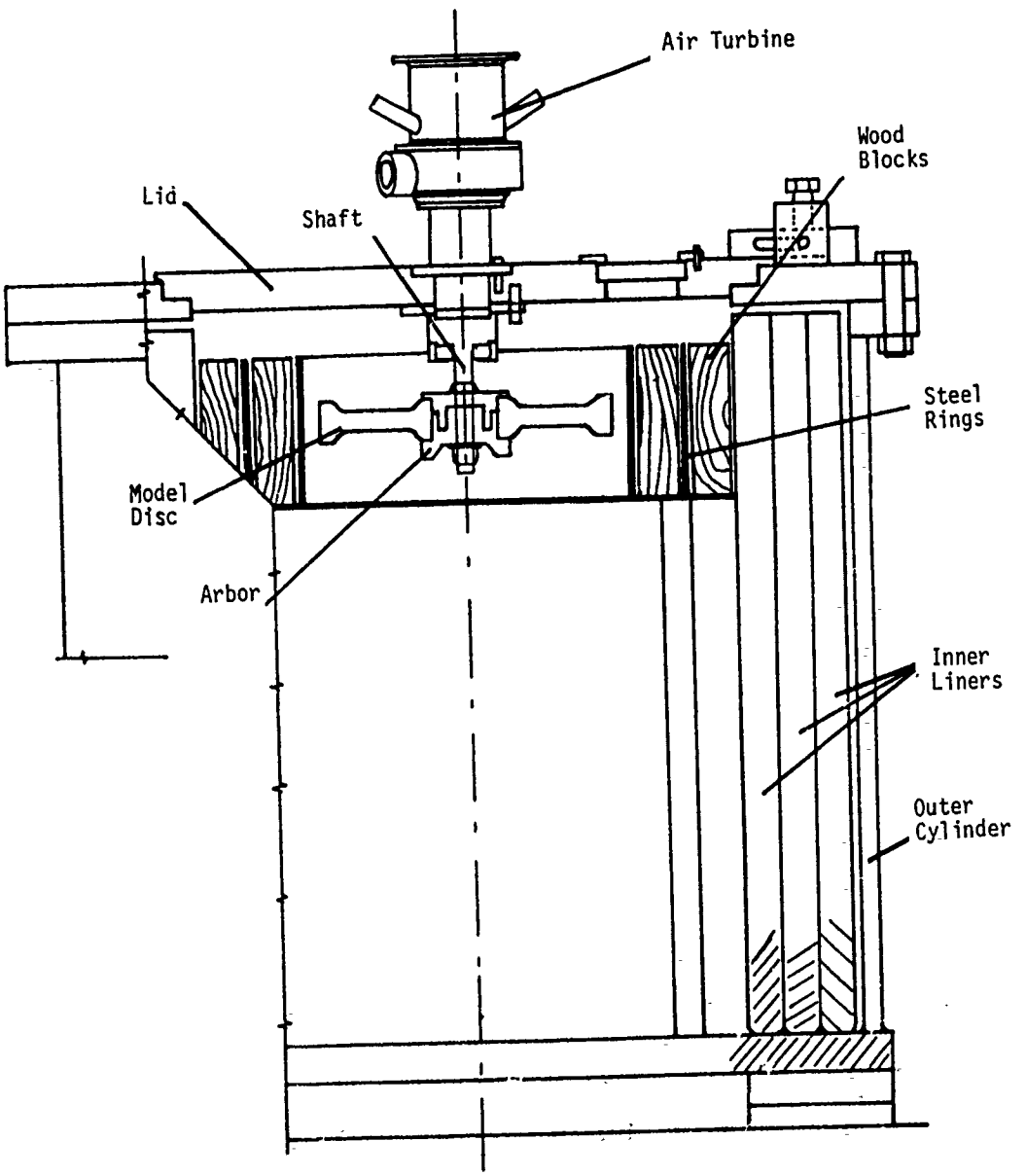


Figure 76. Cross-Sectional View of Spin Pit.

As a result of this reexamination, improved semiempirical equations have been developed at General Electric to predict the disk burst speed. These calculations incorporate material properties such as ultimate tensile strength, ductility, and notch tensile strength at room temperature. An example of the predictive capability of the method is presented in Figure 77. The burst speeds of a substantial number of disks fabricated from materials such as Inco 718, Ti-6-4, and Rene' 95 (PM and cast + wrought) have been predicted with a maximum error of approximately 4.7 percent. This method was used to predict burst speeds for the HIP + forge T700 disks and the Task II As-HIP disks.

The two As-HIP disks were tested to destruction and the fragments were reclaimed from the spin pit catcher. The reassembled disks are compared with the previously tested HIP + forge disks in Figures 78 and 79. The fragmentation patterns are very similar for both processes in each of the model disk configurations.

Actual burst speeds for As-HIP + forged disks are compared to predictions in Table 53. The Vendor A Task II disk, machined to the configuration with holes, burst near the predicted speed and compared favorably with the corresponding HIP + forge test. The Vendor B Task II disk, machined without holes, burst at a speed approximately 15 percent below the predicted value. The fragments of the Vendor B disk were recovered from the spin pit and a fractographic analysis was conducted to determine the cause of the premature failure. Examination of the fracture surfaces revealed that a large radial crack was present at the rim of the disk prior to testing. This crack shown in Figures 80 and 81, extended approximately 0 350 inch into the machined disk. Chevron markings shown in Figure 81 identify this crack as the source of the failure. In a normal failure, the chevron markings would point to a location in the more highly stressed bore region as the source of failure. However, the presence of this preexisting crack shifted the origin of failure to the lower stressed rim region.

Scanning electron micrographs of the fractured surface within and adjacent to the crack, shown in Figure 82, reveal the presence of heavy oxidation within the crack. This fact, along with the absence of any deformation within the crack, suggested that the crack formed during heat treatment of the Task II disk. The most logical theory for the origin of the crack is that a small notch or discontinuity from the Vendor B fill tube/disk rim intersection location propagated during the 1000°F salt quench from 2100°F. Although quench cracks tend to be very tight, which is probably why it was not detected visually after machining, routine ultrasonic, macroetch, and zyglo inspection would have identified this defect prior to testing.

However, once the size and location of the crack were defined, it became possible to predict a burst speed in the presence of the flaw using fracture mechanics and stress distribution calculations. The predicted burst speed for the Vendor B disk containing a 0.350-inch radial rim crack was 69,800 rpm (assuming a room temperature fracture toughness value of 75 ksi-inch $^{1/2}$ for As-HIP Rene' 95). Thus, the actual burst speed of 72,930 is in good agreement with the predicted value when the quench crack is factored into the calculations. Since any premature disk burst failure raises doubts about the intrinsic material and processing integrity, replacement disks were secured from the Task III Lot I pilot production run to confirm the predictable behavior of As-HIP Rene' 95. Two disks, one from Vendor A and one from Vendor B, were consolidated at 2050°F/15 ksi and heat treated at T_s -30°F/1 hour/1000°F salt quench + 1600°F/1 hour/AC/1200°F/24 hours/AC. The processing utilized on these disks differed from the practice employed on the previously described Task II disks in that the mild steel containers were removed by machining (Vendor B) or acid pickling (Vendor A) prior to solution treating. This adjustment was implemented in an effort to improve the yield strengths by increasing the cooling rate from the solution temperature.

Bore slugs from each of the disks were machined into test specimens and tensile tested to determine mechanical properties needed to calculate the theoretical burst speed. Results, presented in Table 54, indicate that the room temperature ultimate strengths and ductilities of both disks were nearly identical, while the yield strength of the Vendor A disk was approximately 5 ksi lower than the disk of Vendor B. Both disks were machined to

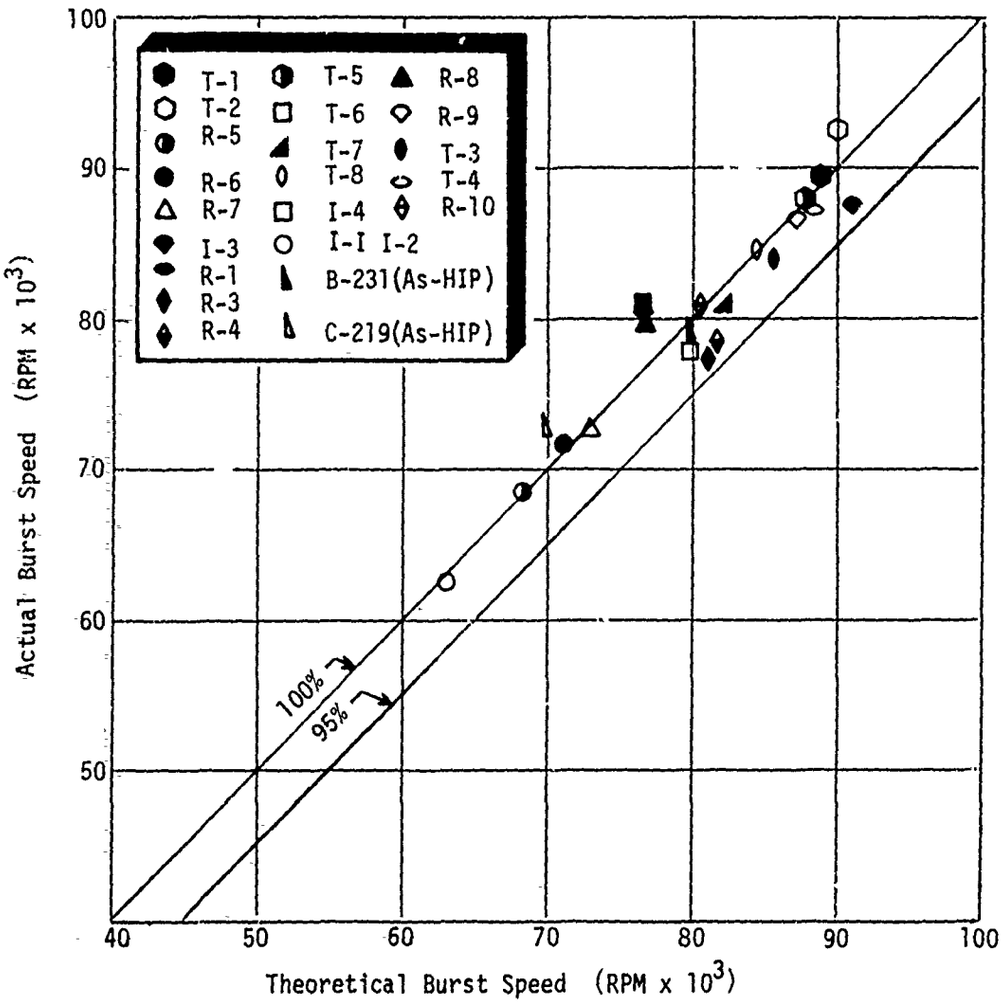
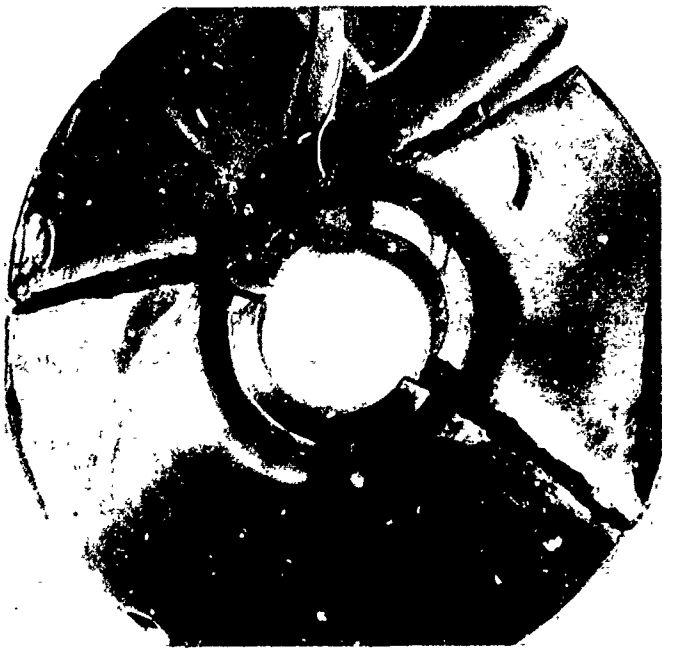


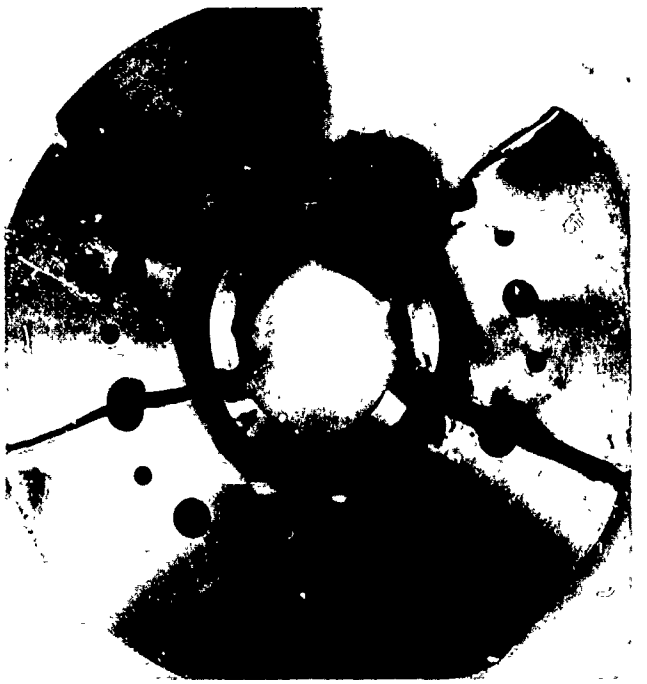
Figure 77. Comparison Between Measured Speed at Burst and Theoretical Speed Using Semiemperical Method.

a) As-HIP Vendor BDisk C219

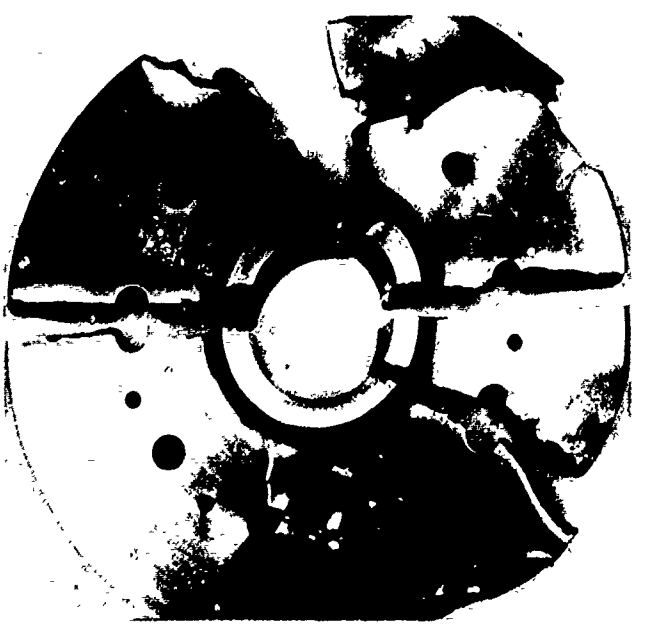


b) HIP + Forge Disk R-9

Figure 78. Spin Bit Burst Fragments of As-HIP and HIP + Forge Disks Machined to T700 Model Disk Configuration without Holes.



a) As-HIP Vendor A Disk B231



b) HIP + Forgé Disk R-3

Figure 79. Spin Pit Burst Fragments of As-HIP and HIP + Forge Disks Machined to T700 Model Disk Configuration with Holes.

TABLE 53. TASK II SPIN PIT BURST TEST RESULTS COMPARED TO T700 HIP + FORGE DATA

Disk No.	Production Process	Disk Configuration	Burst Speed (rpm)	
			Predicted	Actual
B231	As-HIP	With Holes	79,980	78,870
R3	HIP + Forge	With Holes	81,000	77,550
C219	As-HIP	No Holes	86,560*	72,930
R9	HIP + Forge	No Holes	87,000	86,570

*Disk had 0.325-inch quench crack at rim — predicted burst speed in presence of flaw = 69,800 rpm (K_{Ic} = 75 ksi/in.)

TABLE 54. ROOM TEMPERATURE TENSILE PROPERTIES OF BORE SLUGS FROM TASK III SPIN PIT REPLACEMENT DISKS

Disk No.	Powder Vendor	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
B248	A	175	240	16.1	18.6
B248	A	176	233	11.5	13.5
CTD-1	B	180	236	13.1	14.6
CTD-1	B	180	237	13.0	15.3

TABLE 55. SPIN PIT TEST RESULTS ON THE TASK III LOT 1 REPLACEMENT DISKS

Disk No.	Powder Vendor	Production Process	Disk Configuration	Burst Speed (rpm)	
				Predicted	Actual
B248	A	As-HIP	No Holes	86,900	85,920
C374	B	As-HIP	No Holes	86,900	86,250
R9	—	HIP + Forge	No Holes	87,000	86,570

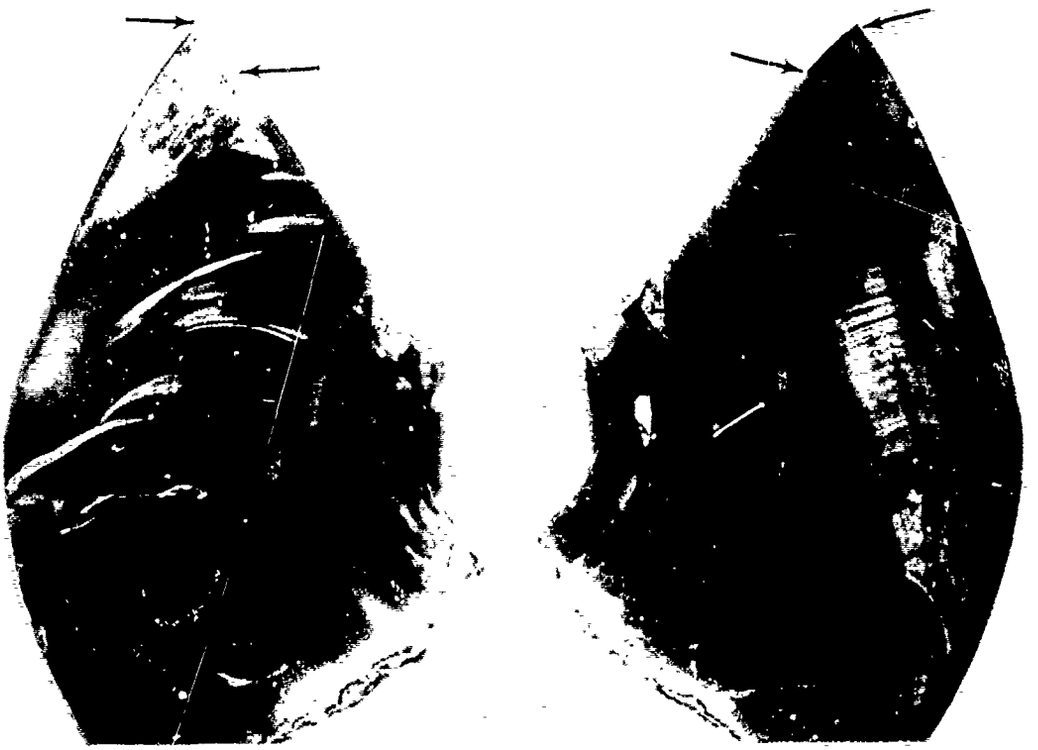
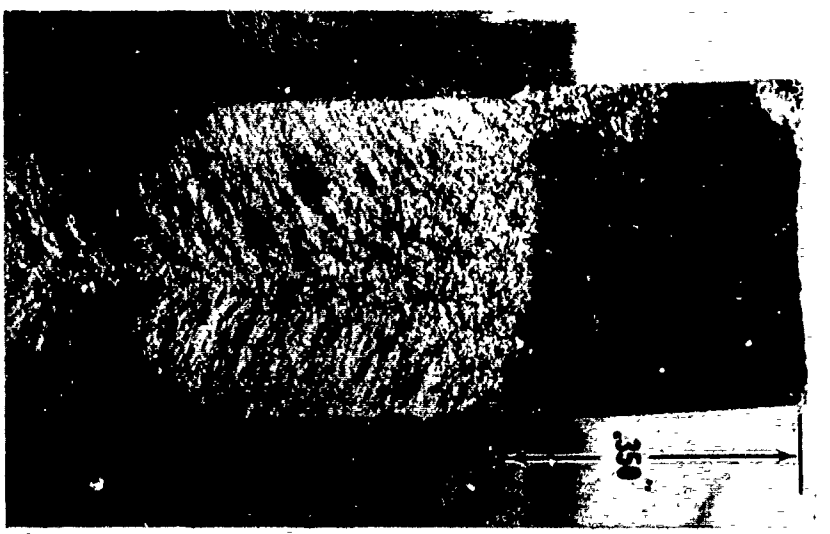


Figure 80. Macro Photographs of Segments of Burst Vendor B Disk, Indicating Location of Preexisting Crack (1.1X)

1.4X

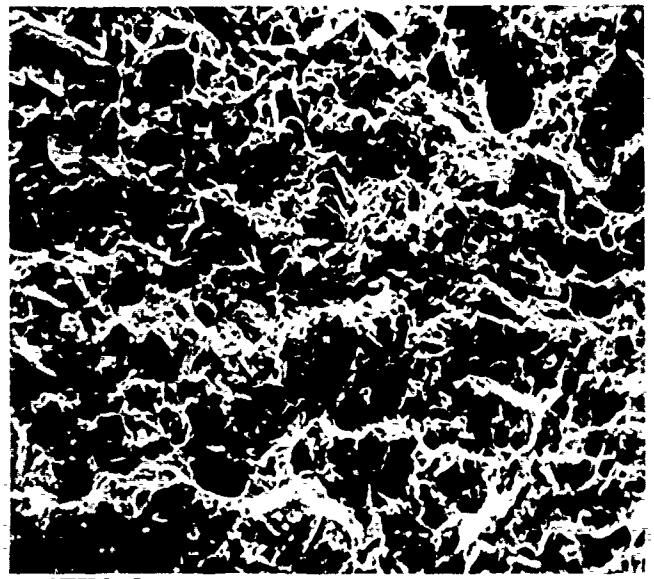
a) Crack Location



4.7X

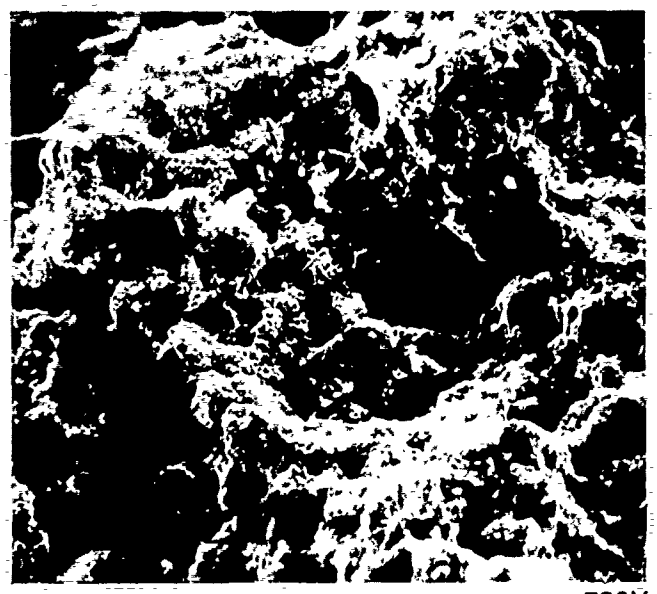
b) Chevron Markings

Figure 81. Fracture Surface of Burst Vendor B Disk, Indicating Chevron Markings and Size of Preexisting Crack.



750X

a) Outside Cracked Region



780X

b) Within Cracked Region

Figure 82. Scanning Electron Micrographs of Fracture Surface of Burst Vendor B Disk (a) Outside and (b) With Preexisting Crack, Indicating Oxidation of Cracked Region.

the "no hole" configuration presented in Figure 75, ultrasonically inspected, zyglo inspected, and balanced prior to testing.

Test results are compared to predictions in Table 55 and Figure 83, and indicate that both disks burst within approximately 1 percent of the calculated speed and compared favorably with the corresponding HIP + forge data shown in Table 53. Fragments of both disks were recovered from the pit and are shown in Figure 84.

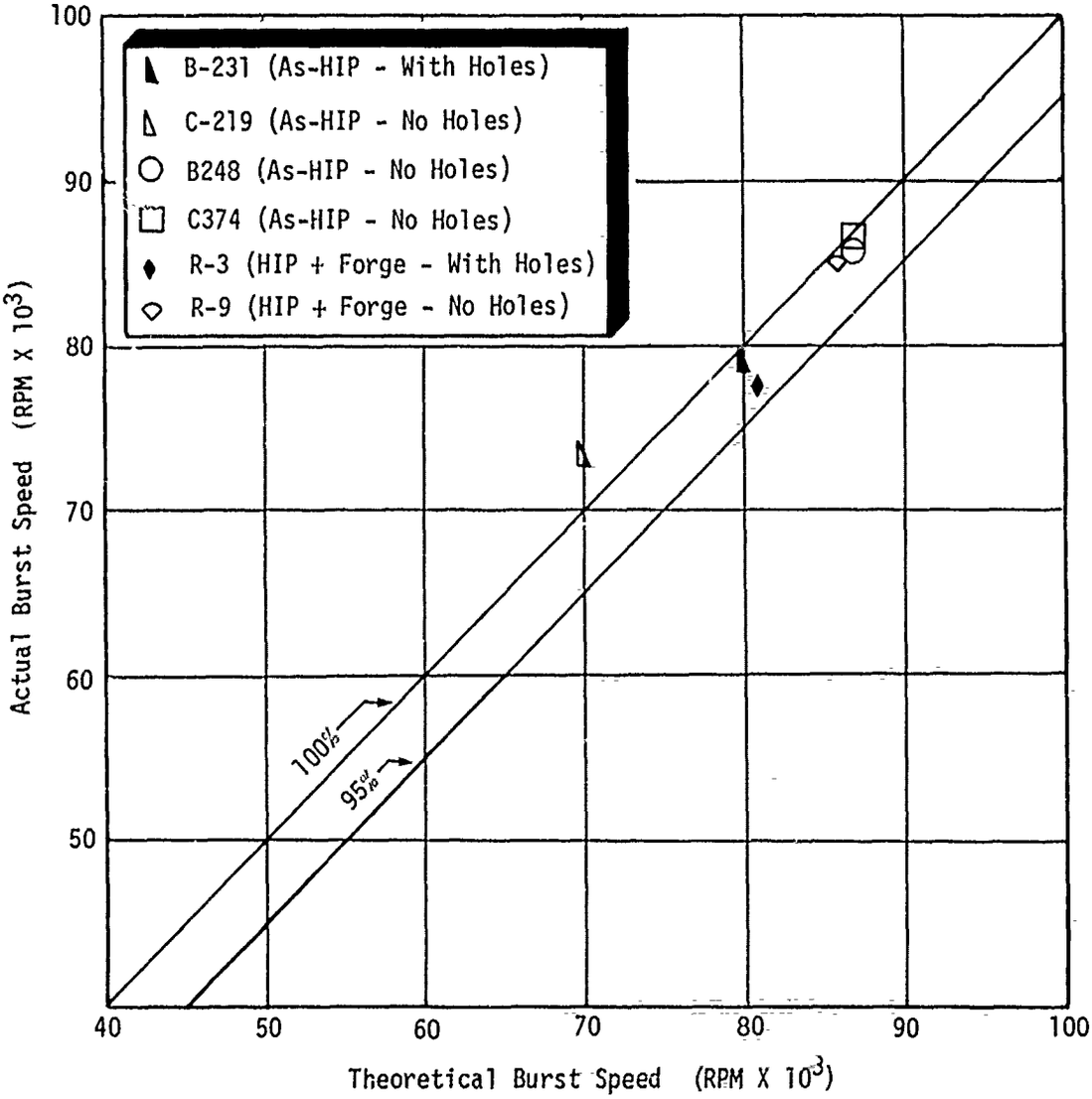
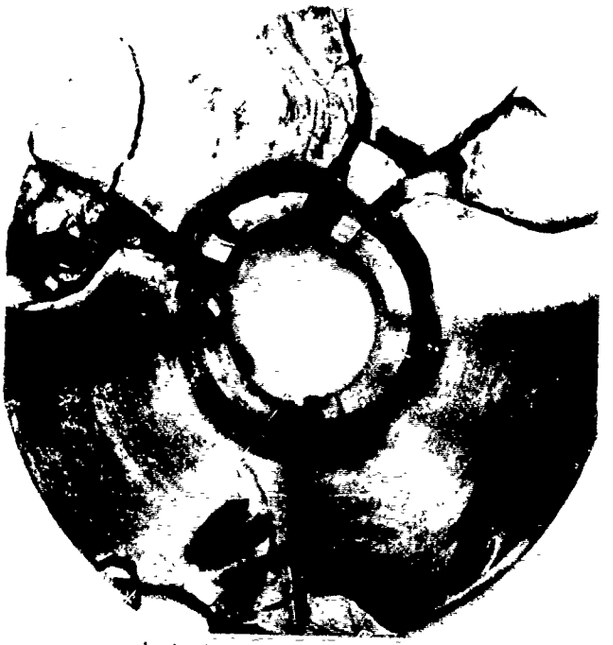
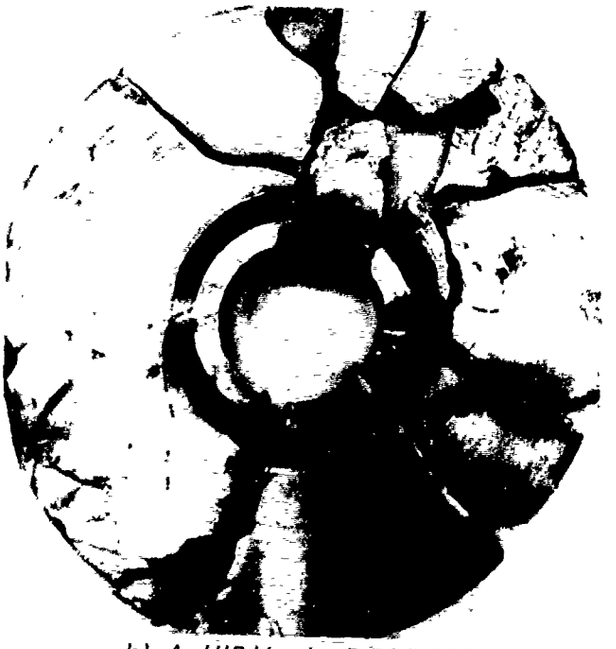


Figure 83. Comparison Between Measured Speed at Burst and Theoretical Speed for As-HIP and HIP + Forge T700 Model Disks Using Semiempirical Method.



a) As-HIP Vendor A Disk B248



b) As-HIP Vendor B Disk C374

Figure 84. Replacement Spin Pit Burst Fragments of As-HIP Disks Machined to T700 Model Disk Configuration Without Holes.

TASK III – FABRICATION OF ENGINE TEST HARDWARE

The objective of Task III, a pilot production program, was to fabricate a series of disks and cooling plates using previously established process specification and quality plan. Additional mechanical testing was to be performed in order to insure conformance of the hardware to material release criteria for a new turbine disk material. A flow chart of the task appears in Figure 85.

A set of two turbine disks and four cooling plates was then to be machined and submitted for engine test.

Powder Production

Rene' 95 powder for Task III was produced by each vendor in several melt heats by vacuum induction melting and Argon atomization. New master powder blends of -60 mesh powder were prepared by both vendors. While Vendor A utilized same atomization parameter and processing techniques as employed in Tasks I and II, Vendor B decided to alter powder production parameters for this blend. This change was permitted with certain restrictions. Since the effect of powder particle size distribution on the properties was an unexpected variable at this time, it was decided to screen and blend the new powder from Vendor B to the same particle size distribution as that of Tasks I and II. The particle size distribution of these blends was therefore identical to Figure 54. However, the scanning electron micrographs of the Vendor B powder (Figure 86) indicate its morphology and satellite formation to be different from those observed in Tasks I and II powder (Figures 9 and 10). The certified chemical analysis and the γ' solvus temperature of all the master powder blends used in Task III are given in Tables 56 and 57 for the respective vendor.

Powder Encapsulation

The steel cans were fabricated to produce turbine disk and cooling plate preforms. The shape-making technology developed in Task IB was utilized in preparation of the turbine disk shapes,and the steel cans were accordingly prepared. The cooling plate preforms were, however, made as a hollow cylindrical compact (6.5-inch OD and 2.75-inch ID) and eventually sliced to different thicknesses. The steel cans were checked for any leaks and undesired foreign inclusions prior to filling with Rene' 95 powder. Vendor B filled the cans under vacuum, while Vendor A used ambient pressure filling followed by an outgassing procedure. The filled cans were finally checked for any posssible leaks and submitted for Hot Isostatic Compaction.

Hot Isostatic Compaction

The autoclaves were employed for hot isostatic pressing of the filled cans to the processing parameters developed in Task IA. A minimum of 20 disks and 20 cooling plate preforms were compacted by each vendor. In order to simulate prototype production, the disk preforms were compacted in more than four HIP lots, while a minimum of two hollow cylinders were compacted to yield the cooling plates. A section of the fill tube of each compact was metallographically examined to check the leakage and/or undesired temperature exposure. A few of the disk compacts were rejected after the inspection and were replaced with additional compacted disks.

Heat Treatment

The difference in the γ' solvus temperature of both vendors was 20°F, same as in Task I and II powder. Same solution temperatures were thus employed. The compacts were heat treated with the procedure developed in Task II. The heat treatment for the cooling plates was, however, modified to achieve desired property goals and is discussed in detail in the section Mechanical Property Evaluation. The HIP and Heat Treatment record of each preform is given in Tables 58 to 61 for both vendors.

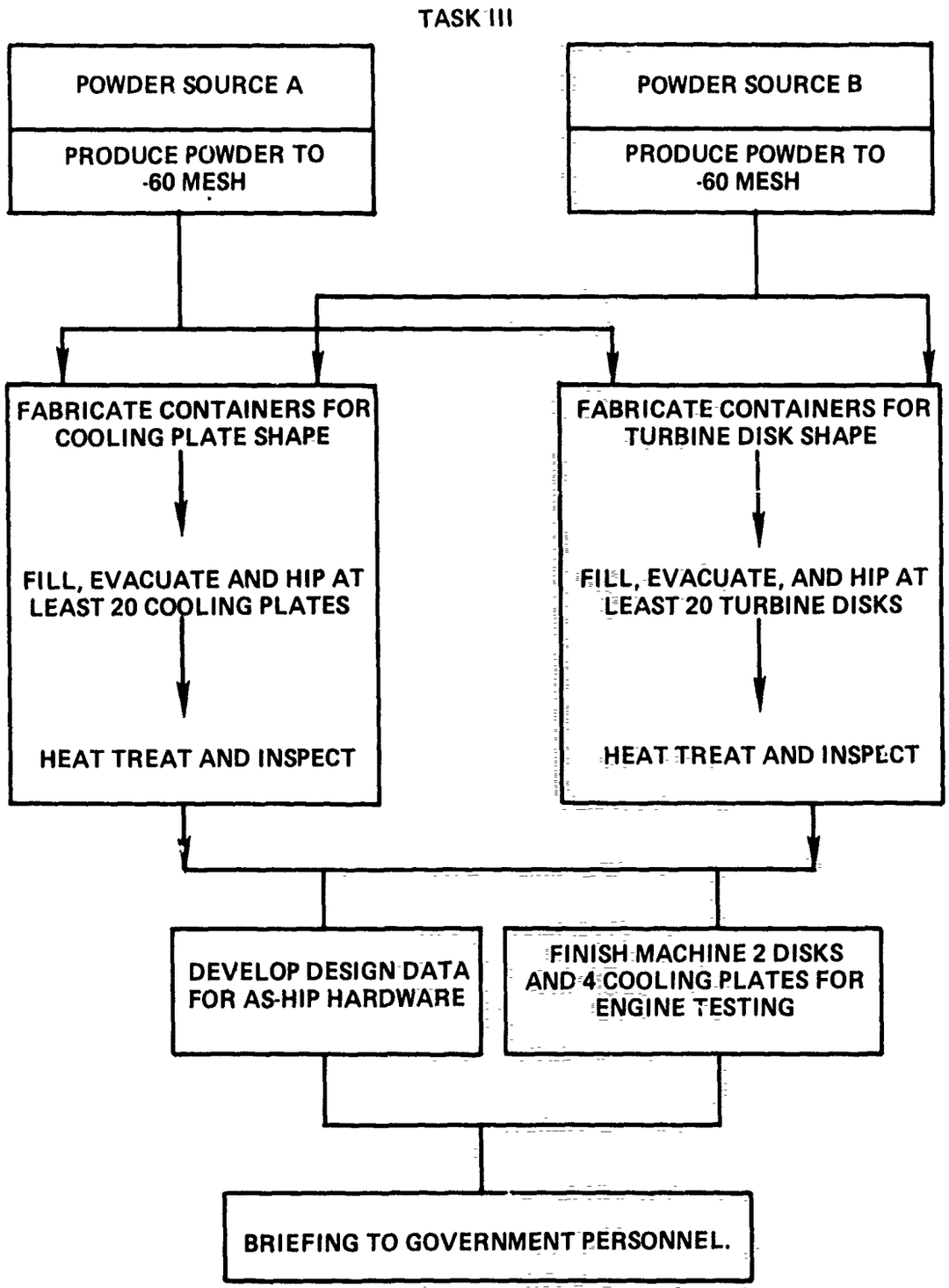
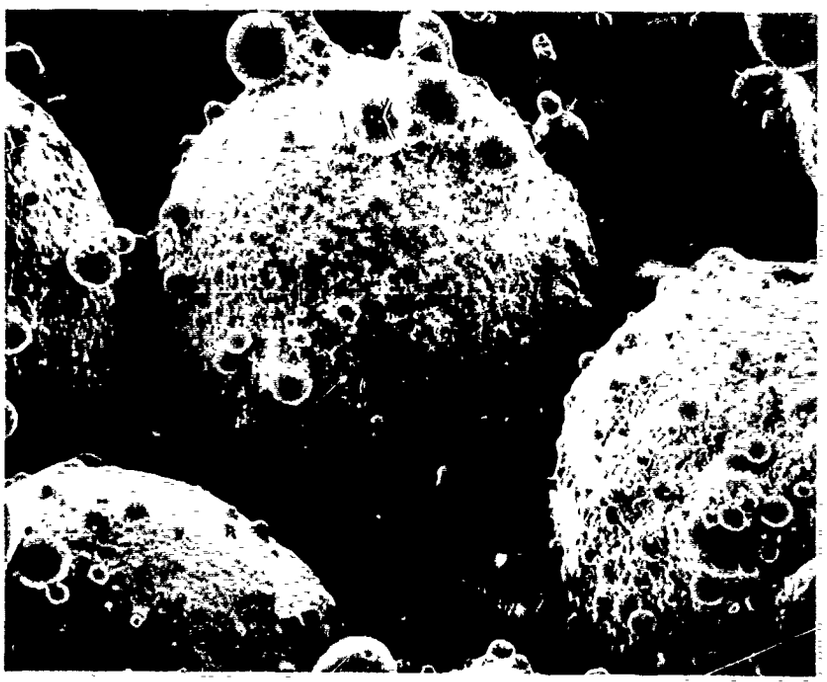


Figure 85. Flow Chart for Task III.



300X

Figure 86. Scanning Electron Micrograph of Vendor B Task III Powder.

TABLE 56. CHEMISTRY OF VENDOR A TASK III RENE' 95 POWDER

Master Blend	Elemental Content (Wt. %)															ppm			
	C		S	Si	Cr	Co	Mo	W	Ti	Al	Cb	B	Zr	Fe	P	O_2	N_2	H_2	Ni
MB016	0.065	<0.01	0.004	0.08	13.05	8.24	3.51	3.36	2.52	3.49	3.53	0.009	0.05	0.17	<0.003	55	29	2.6	Bal
MB018	0.054	<0.01	0.003	0.08	13.09	8.18	3.51	3.33	2.54	3.53	3.54	0.008	0.04	0.12	<0.003	65	35	3.1	Bal
MB022	0.055	<0.01	0.005	0.08	12.79	8.13	3.55	3.41	2.60	3.41	3.53	0.007	0.06	0.16	<0.003	71	23	0.8	Bal
MB023	0.061	<0.01	0.007	0.06	12.88	8.2	3.47	3.33	2.72	3.46	3.57	0.009	0.06	0.13	<0.003	70	26	3.0	Bal
MB024	0.053	<0.01	0.004	0.07	12.91	8.19	3.38	3.32	2.56	3.56	3.51	0.008	0.06	0.11	<0.003	52	22	3.2	Bal
MB029		<0.01		0.08	12.87	8.19	3.48	3.41	2.51	3.43	3.54	0.009	0.04	0.16	<0.003	49	17		Bal

TABLE 57. CHEMISTRY OF VENDOR B TASK III RENE' 95 POWDER

Master Blend	Elemental Content (Wt. %)															ppm			
	C	Mn	S	Si	Cr	Co	Mo	W	Ti	Al	Cb	B	Zr	Fe	P	N_2	H_2	O_2	Ni
33	0.065	<0.01	0.004	0.08	13.05	8.24	3.51	3.36	2.52	3.49	3.53	0.009	0.05	0.17	<0.003	29	2.6	55	Bal
47		<0.01	0.003	0.02	13.09	8.18	3.51	3.33	2.54	3.53	3.54	0.008	0.04	0.12	<0.003	35	3.1	65	Bal
	0.066	<0.01	0.002	0.06	12.76	7.98	3.54	3.43	2.58	3.53	3.55	0.011	0.062	0.15	<0.005	0.002	<0.01	63	Bal
49					12.79	8.13	3.55	3.41	2.60	3.41	3.53	0.007	0.06	0.16		23	0.8	71	Bal
	0.067	<0.01	0.002	0.05	12.55	7.93	3.56	3.40	2.55	3.49	3.51	0.011	0.049	0.15	<0.005	0.003	<0.01	36/38	Bal
31	0.065		0.001	0.04	12.84	8.08			2.62	3.54	3.56	0.012	0.048	0.15	<0.005	0.003	<0.02	50/58	Bal

TABLE 58. VENDOR A TASK III DISKS CHARACTERIZATION

Compact Code	Part Description	S/N	Master Blend No.	HIP Lot No.	Heat Treat Lot No.	Quan. in Heat Treat Lot	Hardness (Rc)	Grain Size (ASTM No.)
B229	Disc	COL 10001	MB016	C1	H1	4	–	–
B230	Disc	COL 10002	MB016	C1	H1	4	–	–
B246	Disc	COL 10003	MB018	C2	H1	4	–	–
B248	Disc	COL 10004	MB018	C2	H1	4	–	–
B290	Disc	COL 10005	MB022	C3	H2	5	44.5	8
B291	Disc	COL 10006	MB022	C3	H2	5	45.0	8
B292	Disc	COL 10007	MB022	C3	H2	5	45.0	8
B293	Disc	COL 10008	MB022	C3	H2	5	45.0	8
B294	Disc	COL 10009	MB022	C3	H2	5	44.5	8
B305	Disc	COL 10010	MB023	C4	H3	1	45.0	8
B306	Disc	COL 10011	MB023	C4	H4	5	46.0	8
B307	Disc	COL 10012	MB023	C4	H4	5	44.0	8
B308	Disc	COL 10013	MB023	C4	H4	5	44.5	8
B309	Disc	COL 10014	MB023	C4	H4	5	44.0	7
B316	Disc	COL 10015	MB024	C5	H5	5	45.5	7
B320	Disc	COL 10016	MB024	C5	H5	5	45.5	6
B327	Disc	COL 10017	MB024	C5	H5	5	45.0	7
B328	Disc	COL 10018	MB024	C5	H5	5	46.0	7
B329	Disc	COL 10019	MB024	C5	H5	5	46.0	7
B344	Disc	COL 10020	MB029	C6	H6	4	44.3	8
B345	Disc	COL 10021	MB029	C6	H6	4	44.6	7
B346	Disc	COL 10022	MB029	C6	H6	4	44.9	8
B347	Disc	COL 10023	MB029	C6	H6	4	44.8	8

TABLE 59. VENDOR A TASK III COOLING PLATES CHARACTERIZATION

Compact Code	Part Description	S/N	HIP Lot No.	Heat[2] Treat Lot No.	Quantity in Heat Treat Lot	Hardness (Rc)	Final Plate Thickness (in.)
B250 1	Cooling Plate	COL 10024	C2	H1[1]	17	–	–
B250 2	Cooling Plate	COL 10025	C2	H1[1]	17		
B250 3	Cooling Plate	COL 10026	C2	H1[1]	17	–	–
B250 4	Cooling Plate	COL 10027	C2	H1[1]	17	–	–
B250 5	Cooling Plate	COL 10028	C2	H1[1]	17	–	–
B250 6	Cooling Plate	COL 10029	C2	H1[1]	17	–	–
B250 7	Cooling Plate	COL 10030	C2	H1[1]	17	–	–
B250 8	Cooling Plate	COL 10031	C2	H1[1]	17		–
B250 9	Cooling Plate	COL 10032	C2	H1[1]	17	–	–
B250 10	Cooling Plate	COL 10033	C2	H1	17	–	–
B250 11	Cooling Plate	COL 10034	C2	H1	17	–	
B250 12	Cooling Plate	COL 10035	C2	H1	17	–	–
B250 13	Cooling Plate	COL 10036	C2	H11[4]	1	–	–
B250 14	Cooling Plate	COL 10037	C2	H12[5]	1	–	–
B312 1	Cooling Plate	COL 10038	C5	H7	5	46.3	1.08
B312 2	Cooling Plate	COL 10039	C5	H8[6]	6	45.1	0.72
B312 3	Cooling Plate	COL 10040	C5	H9	6	45.5	0.72
B312 4	Cooling Plate	COL 10041	C5	H10	6		0.72
B312 5	Cooling Plate	COL 10042	C5	H10	6	45.3	0.72
B312 6	Cooling Plate	COL 10043	C5	H7	5	45.0	0.72
B312 11	Cooling Plate	COL 10044	C5	H7	5	–	1.08
B312 12	Cooling Plate	COL 10045	C5	H7	5	45.0	1.08
B312 13	Cooling Plate	COL 10046	C5	H10	6	45.2	1.08
B312 14	Cooling Plate	COL 10047	C5	H9	6	45.2	1.08
B312 15	Cooling Plate	COL 10048	C5	H8[6]	6	45.0	1.08
B312 16	Cooling Plate	COL 10049	C5	H10	6	45.2	1.08
B312 17	Cooling Plate	COL 10050	C5	H7	5	45.5	1.08
B312 18	Cooling Plate	COL 10051	C5	H8[6]	6	–	1.41
B312 19	Cooling Plate	COL 10052	C5	H9	6	–	1.41
B312 20	Cooling Plate	COL 10053	C5	H9	6	44.7	1.41
B312 21	Cooling Plate	COL 10054	C5	H10	6	45.0	1.41
B312 22	Cooling Plate	COL 10055	C5	H9	6	46.8	1.41
B312 23	Cooling Plate	COL 10056	C5	H8[6]	6	44.6	1.08
B312 24	Cooling Plate	COL 10057	C5	H10	6	45.0	1.08

[2] All cooling plates from B250 were heat treated with a 1000° F salt quench from the solution temperature the first time. Those that were reheat treated and those from B312 were fan air cooled from the solution temperature

[1] Reheat treated twice

[4] Fan air-cool from solution treatment

[5] Solution treated in salt at 2100° F and transferred to 1000°F salt quench

[6] Reheat treated once

TABLE 60. VENDOR B TASK III DISK CHARACTERIZATION

Compact Code	Part Description	Master Blend No.	HIP Lot No.	Qty. in Lot	Ht. Treat Lot No.	Qty. in Lot	Grain Size	Hard.
C483	Disk	47	1139	4	05304	12	9.5-10	48.5
C484	Disk	47	1139	4	05304	12	9.5-10	48.5
C486	Disk	47	1139	4	05304	12	9.5-10	48.5
C487	Disk	49	1137	5	05304	12	9.5-10	47.0
C497	Disk	49	1141	5	05304	12	9.5-10	47.0
C490	Disk	49	1137	5	05304	12	9.5-10	46.5
C499	Disk	49	1141	5	05304	12	9.5-10	47.0
C498	Disk	49	1141	5	05304	12	9.5-10	46.0
C372	Disk	31	876	5	PO11244	5	9.5-10	–
C373	Disk	31	876	5	PO11244	5	9.5-10	47.0
C374	Disk	31	876	5	PO11244	5	9.5-10	48.5
C376	Disk	31	876	5	PO11244	5	9.5-10	–
C377	Disk	31	876	5	PO11244	5	9.5-10	46.0
C431	Disk	33	1020	5	3211	5	9.5-10	–
C432	Disk	33	1020	5	3211	5	9.5-10	–
C433	Disk	33	1020	5	3211	5	9.5-10	–
C435	Disk	33	1020	5	3211	5	9.5-10	–
C436	Disk	33	1020	5	3211	5	9.5-10	–
C496	Disk	49	1141	5	05304	12	9.5-10	46.5
C492	Disk	49	1137	5	05304	12	9.5-10	45.5
C495	Disk	49	1141	5	05304	12	9.5-10	46.0
C493	Disk	49	1137	5	05304	12	9.5-10	47.0

TABLE 61. VENDOR B TASK III COOLING PLATE CHARACTERIZATION

Compact Code	Part Description	Master Blend No.	HIP Lot No.	Qty. in Lot	Ht. Treat Lot No.	Qty. in Log	Grain Size	Hard. Hard.
C344	Cooling Plate	31	853	1 log	038640	12	9.5-10	–
C500-2	Cooling Plate	49	1142	1 log	07290	20	9.5-10	46.5
C500-3	Cooling Plate	49	1142	1 log	07290	20	9.5-10	46.0
C500-4	Cooling Plate	49	1142	1 log	07290	20	9.5-10	46.0
C500-5	Cooling Plate	49	1142	1 log	07290	20	9.5-10	46.5
C500-6	Cooling Plate	49	1142	1 log	07290	20	9.5-10	47.0
C500-7	Cooling Plate	49	1142	1 log	07290	20	9.5-10	46.0
C500-8	Cooling Plate	49	1142	1 log	07290	20	9.5-10	45.5
C500-9	Cooling Plate	49	1142	1 log	07290	20	9.5-10	45.5
C500-10	Cooling Plate	49	1142	1 log	07290	20	9.5-10	45.0
C494-13	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.0
C494-14	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.5
C494-15	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.5
C494-16	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.5
C494-17	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.0
C494-18	Cooling Plate	49	1140	1 log	07290	20	9.5-10	47.0
C494-19	Cooling Plate	49	1140	1 log	07290	20	9.5-10	45.5
C494-21	Cooling Plate	49	1140	1 log	07290	20	9.5-10	45.5
C494-22	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.0
C494-23	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.0
C494-24	Cooling Plate	49	1140	1 log	07290	20	9.5-10	46.5

Density Determination

The mild steel cans of all the compacts were removed by machining. A solid cylinder of 2 inches in diameter was taken out of the center of each disk preform by electrochemical machining. The density of each of these center slugs, as well as the disks, was determined by the buoyancy method. A lever arm type weighing balance with sensitivity of 10 mg in 60 kgs was used. The need for this ultrasensitive balance is discussed in Appendix IV.

A slice from the top and bottom of the cooling plate cylinder was used to check the density of the compact by the buoyancy method. The density of selected cooling plate preforms (heat treated to the final desired treatment) was also determined using the same facilities. The results of all the density measurements are tabulated in Tables 62 to 65. An excellent correlation was observed between the densities of center slugs and the whole disk preforms.

Thermally Induced Porosity

To determine the relative amount of entraped Argon in each compact, thermally induced porosity measurements were completed on all the center slugs from the disk preforms and the top and bottom slices of the cooling plate compact. The determination consisted of density measurements on samples (approximately 100 gm) after exposing for 4 hours at 2200°F and comparing with the original density. In addition, As-HIP samples from each master powder blend were forged to 50 percent reduction and subjected to density determination by buoyancy method. These values were then used for comparison with the densities after 2200°F/4-hour exposure. The TIP response of the disk and cooling plate preforms, well within the requirements of less than 0.3 percent change, is summarized in Tables 66 to 68 for both vendors.

HARDWARE EVALUATION

All the disks and cooling plates fabricated by each vendor were subjected to a rigorous non-destructive evaluation. The hardware was inspected by the vendors and/or their subcontractors and critical inspections were repeated by General Electric.

Vendor Non-Destructive Inspection

The following non-destructive testing was completed by each vendor before the hardware was shipped to General Electric:

Hardness test was conducted at two points 180° apart on the rim and at one point near the bore per ASTM E 10. All the parts were macroscopically etched with HCl and H_2O_2 (9:1) solution to inspect for any gross metallurgical inhomogeneity and to eliminate any possible masking effect on cavities due to machining. All the parts were fluorescent penetrant inspected per General Electric Specification P3TF2CIC to find fine cracks and/or cavities. The method consists of immersing a clean and degreased part in a highly fluorescent liquid penetrant for about 30 minutes. The penetrant is then removed by immersing the part in an emulsifier and rinsing with water. The part is dried and a coating of a developing powder applied to it. The excess powder is removed and the hardware is examined under black light when the fluorescent penetrant lights up the fine cavities. A high sensitivity penetrant hydrophylic remover and non-aquous developer was used to provide a very high sensitivity inspection.

TABLE 62. DENSITY OF VENDOR A DISKS

Serial No.	Whole Part Density (lb/in.^{3})	Center Slug Density (General Electric) (lb/in.^{3})	Center Slug Density (Vendor A) (lb/in.^{3})
COL 1005	0.2984	0.2985	0.2985
COL 1006	0.2984	0.2985	0.2982
COL 1007	0.2985	0.2985	0.2985
COL 1008	0.2984	0.2985	0.2984
COL 1009	0.2984	0.2985	0.2985
COL 1010	–	0.2986	0.2985
COL 1011	0.2985	0.2986	0.2986
COL 1012	0.2984	0.2986	0.2987
CCL 1013	0.2982	0.2986	0.2985
COL 1014	0.2982	0.2986	0.2984
COL 1015	0.2982	0.2984	0.2984
COL 1016	0.2988	0.2983	0.2983
COL 1017	0.2985	0.2983	0.2982
COL 1018	0.2982	0.2983	0.2983
COL 1019	0.2982	0.2983	0.2982
COL 1020	0.2985	–	0.2987
COL 1021	0.2985	–	0.2986
COL 1022	0.2985	–	0.2987
COL 1023	0.2983	–	0.2987

TABLE 63. DENSITY OF VENDOR A COOLING PLATES

Cooling Plate Code	Whole Part Density ($lb/in.^3$)
B312-1 COL 10038	0.2983
B312-2 COL 10039	0.2982
B312-3 COL 10040	0.2983
B312-5 COL 10041	0.2983
B312-6 COL 10042	0.2983
B312-12 COL 10043	0.2983
B312-13 COL 10044	0.2983
B312-14 COL 10045	0.2982
B312-15 COL 10046	0.2982
B312-16 COL 10047	0.2983
B312-17 COL 10048	0.2983
B312-20 COL 10053	0.2983
B312-21 COL 10054	0.2982
B312-22 COL 10055	0.2982
B312-23 COL 10056	0.2981
B312-24 COL 10057	0.2982

TABLE 64. DENSITY OF VENDOR B DISKS

Serial No.	Whole Part Density (lb/in.^{3})	Center Slug Density (General Electric) (lb/in.^{3})	Center Slug Density (Vendor B) (lb/in.^{3})
C483	0.2994	0.2985	0.2985
C484	0.2995	0.2985	0.2982
C487	0.2992	0.2985	0.2985
C497	0.2995	0.2985	0.2984
C490	0.2989	0.2985	0.2985
C499	0.2994	0.2986	0.2985
C498	0.2996	0.2986	0.2986
C496	0.2995	0.2986	0.2987
C492	0.2987	0.2986	0.2985
C495	0.2995	0 2986	0.2984

TABLE 65. DENSITY OF VENDOR B COOLING PLATES

Cooling Plate Code			Whole Part Density ($lb/in.^3$)
C344	B312-1	COL 10038	0.2983
C500-2	B312-2	COL 10039	0.2994
C500-3	B312-3	COL 10040	0.2994
C500-4	B312-5	COL 10041	0.2994
C500-5	B312-6	COL 10042	0.2993
C500-6	B312-12	COL 10043	
C500-7	B312-13	COL 10044	
C500-8	B312-14	COL 10045	0.2993
C500-9	B312-15	COL 10046	0.2993
C500-10	B312-16	COL 10047	0.2993
C494-13	B312-17	COL 10048	0.2993
C494-14	B312-20	COL 10053	0.2992
C494-15	B312-21	COL 10054	0.2993
C496-16	B312-22	COL 10055	0.2992
C494-17	B312-23	COL 10056	0.2993
C494-18	B312-24	COL 10057	0.2992
C494-19			0.2993
C494-21			0.2992
C494-22			0.2993
C494-23			0.2993

TABLE 66. THERMALLY INDUCED POROSITY MEASUREMENT ON VENDOR A DISKS

Serial No.	Master Blend No.	Forge Down Density	Density After H.T. ($lb/in.^3$)	Density After Tip ($lb/in.^3$)	Tip Based On Forge Down (% Δ)	Tip Based On H.T. (% Δ)
COL 1005	MB022	0.2984	0.29852	0.29767	0.24	0.28
1006			0.29824	0.29787	0.18	0.12
1007			0.29851	0.29773	0.22	0.26
1008			0.29843	0.29770	0.23	0.24
1009			0.29852	0.29778	0.21	0.25
1010	MB023	0.29843	0.29853	0.29767	0.25	0.29
1011			0.29856	0.29775	0.23	0.27
1012			0.29868	0.29798	0.15	0.23
1013			0.29853	0.29780	0.21	0.24
1014			0.29836	0.29761	0.27	0.25
1015	MB024	0.29834	0.29843	0.29765	0.23	0.26
1016			0.29833	0.29749	0.28	0.28
1017			0.29816	0.29782	0.17	0.11
1018			0.29830	0.29769	0.22	0.20
1019			0.29815	0.29758	0.25	0.19
1020	MB029	0.29841	0.29873	0.29805	0.10	0.23
1021			0.29860	0.29787	0.16	0.24
1022			0.29865	0.29783	0.17	0.27
1023			0.29866	0.29789	0.15	0.26

TABLE 67. THERMALLY INDUCED POROSITY MEASUREMENT ON VENDOR A COOLING PLATE COMPACT

Compact Code	Master Blend	Forge Down Density (lb/in.^{3})*	HIP Density Top (lb/in.^{3})	Density After Tip Top (lb/in.^{3})	Tip Based On Forge Down Top (%Δ)	Tip Based On HIP Top (%Δ)	HIP Density Bottom (lb/in.^{3})	Density After TIP Bottom (lb/in.^{3})	TIP Based On Forge Down Bottom (%Δ)	TIP Based on HIP Bottom (%Δ)
–	–	–	–	–	–	–	–	–	–	–
B312	MB024	0.29834	0.29838	0.29790	0.15	0.16	0.29838	0.29782	0.17	0.19

*Density after 50% forge down at 2025°F.

TABLE 68. THERMALLY INDUCED POROSITY MEASUREMENT ON VENDOR B COMPACTS

Compact Code	Master Blend	HIP Density (lb/in.^{3})	Density After Tip (lb/in.^{3})	Tip Based On HIP (%Δ)
C494	49	0.29931	0.2988	0.16
C500	49	0.29931	0.29790	0.16

To find any internal defect, inclusion or void, all the parts were ultrasonically inspected per General Electric Specification P3TF1C1A. The inspection called for longitudinal mode (both sides) and shear mode in axial, radial, and circumferential directions for the disks. The cooling plates inspection was similar with the exception of the axial shear mode. A scan plan submitted by each vendor and approved by General Electric was used in performing the inspection.

Vendor Mechanical Property Evaluation

In addition to continuing the mechanical property evaluation at General Electric, each vendor destructively evaluated disks and cooling plates to conform with the Quality Control requirement of evaluating one compact/master powder blend/HIP lot/heat treat lot. The results are discussed in the Design Data Study. The results of test specimen machined from the center slug and evaluated for room temperature mechanical properties are also discussed.

General Electric Nondestructive Inspection

In addition to the above-mentioned vendor nondestructive inspection, the following inspections were repeated at General Electric Company, on all the Task III hardware to provide additional assurance.

Each disk and cooling plate was reinspected by fluorescent penetrant inspection at the General Electric facilities using the same high sensitivity penetrant, remover and developer as those used by the vendors.

An increased sensitivity (12 dB) ultrasonic inspection performed to a more rigorous scan plan which included inspection from within the bore of the disks was carried out on all the incoming hardware. A set of new calibration blocks made from As-HIP Rene' 95 compacts was used instead of conventional IN 718 calibration blocks, and special transducers were utilized for inspection within the bore area. The inspection was most comprehensive given to any T700 turbine hardware.

Acoustical Holography

Under a separate US Army funded program, the Aircraft Engine Group of General Electric Company is currently evaluating some of the emerging nondestructive inspection methods and comparing their sensitivity and resolution using As-HIP Rene' 95 material. Although the program was still far from being complete, one of the inspection techniques showing promise is Acoustical Holography. This process combines the ultrasonic inspection process with holography to yield an imaging portrayal of the object illuminated by ultrasound. A transducer is used to focus ultrasonic energy on the surface of the part. Sound is transmitted through the part and signals are reflected back from defects and surfaces to the transmitting transducer (pulse-echo technique). The transducer traverses the object with the aid of appropriate scanners and bits of intelligence are received and recorded from a series of discrete positions. These bits of intelligence are in the form of a series of super imposed sine waves differing from each other in intensity and phase. These information units when combined with an ultrasound wave (single frequency) result in an electronic interference signal. These signals vary in intensity and phase shift with time. Upon completion of the scanning operation, the bits of intelligence are electronically fed to a TV screen to reconstruct in space the results of ultrasonic impingement. This reconstructed image defines the part and any defects reflecting the ultrasound. Since the object can be manipulated on the TV screen, the exact location and size of the defects can be more readily identified.

Although the development and evaluation of the Acoustical Holographic technique for As-HIP Rene' 95 was not yet complete, the effort to date had resulted in the identification of defects location, if not size, not detectable by conventional ultrasonics. It was decided to use the acoustic holography equipment in the intensity mode (comparable to classical ultrasonics) to reinsure the integrity of a set of turbine hardware destined for

the engine test. A T700 HIP + Forge disk was also included for comparison. The intensity mode inspection has significantly increased sensitivity over the ultrasonic inspection. This is a result of using:

a) Transducers usable over a wide frequency band, thus permitting the exact frequency for the best signal-to-noise ratio.

b) A coherent transmitting mode with increased signal strength into the test material and greater total power in the acoustic beam.

The testing done at Holosonics, Inc. showed As-HIP material to be almost devoid of any background noise, while the HIP + forge disk results were clouded by excessive noise. Any defect indication seemed to be very small (<0.010 inch). To establish the defect size, however, one of the excess cooling plate preforms was destructively evaluated in the areas indicating defects. Thin layers of material were successively removed by electrochemical machining or metallographic polishing. The surface was visually examined after every polish. Although small defects and/or voids of largest dimensions of 0.005 inch were observed, no conclusive observation of sizeable defect was made. Three disks (one extra) and three cooling plates (except the stage 1 rear cooling plate) were then submitted to final machining.

MACHINING OF ENGINE TEST HARDWARE

Using the established procedures for machining the turbine hardware for the T700 engine, the General Electric Company machined the following engine components to the respective T700 MQT configuration:

- Stage 1 Turbine Disk (6034T97)
- Stage 2 Turbine Disk (6034T91)
- Stage 1 Forward Cooling Plate (6034T88)
- Stage 2 Forward Cooling Plate (5036T41)
- Stage 2 Rear Cooling Plate (5036T80)

The numbers in parenthesis are the corresponding engine part-drawing number. These parts,shown in Figure 87, were machined from a set of Vendor A preforms which passed all the nondestructive testing carried out by the vendor as well as the General Electric Company, inciuding Acoustical Holographic Inspection. These parts were then submitted for the test and evaluation in the T700 engine program.

All remaining Task III hardware were included in the Design Data Evaluation.

DESIGN DATA EVALUATION

Following completion of Task II evaluation, it was apparent that the heat treatment procedures utilized were inadequate to produce mechanical properties equivalent to the program goals. The mechanical property degradation was attributed to the presence of a fully encapsulating mild steel container around the parts during heat treatment which reduced the quench (cooling) rate after solution treatment. In order to avoid this problem, it was decided to remove the mild steel container prior to heat treatment to improve cooling rates. Also to minimize heat treat variations on these pilot production quantities, both vendors agreed to heat treat all Task III hardware at the same facility.

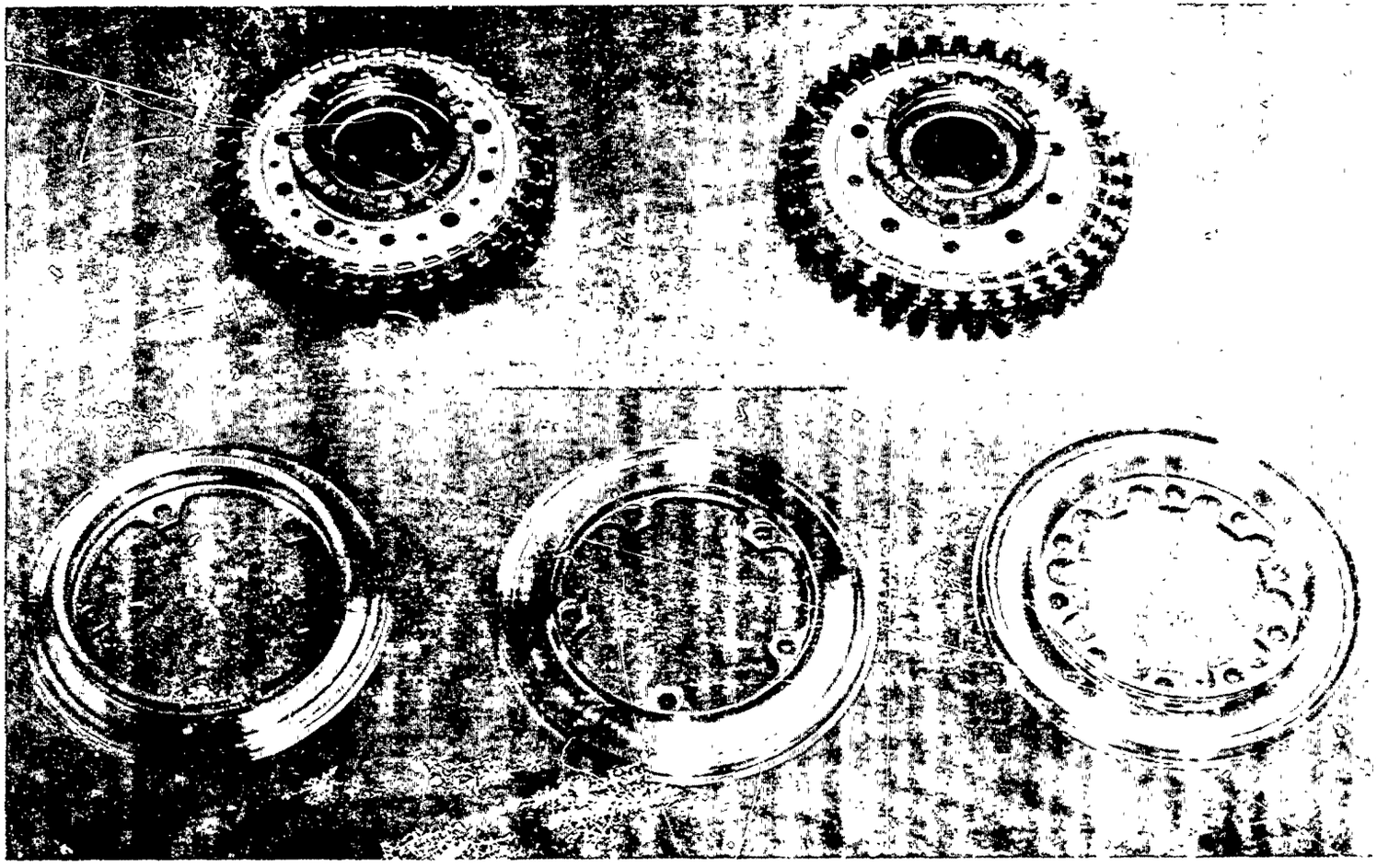


Figure 87. T700 Disks and Cooling Plates Machined from As-HIP Preforms.

Feasibility Studies – Lot I Parts

During the initial portion of Task III each vendor consolidated a hollow cylinder approximately 23 inches long by 8 inches OD and 5 inches ID for fabrication of three sets (total of 12) of cooling plate hardware. Both vendors also prepared five turbine disk shapes although each vendor experienced one or more parts that leaked during compaction and had to be replaced.

The reduced tensile properties observed in Task II hardware led to modification of the heat treatment procedures employed on Task III turbine disks. The effect of removing the mild steel container before heat treatment was assessed by heat treating Lot I from both vendors using this technique. Vendor A removed their mild steel containers by an acid pickling operation, while Vendor B chose to machine their disks. The hollow cylinders were sliced to three sets of different thickness to form all the cooling plates. Thicknesses of the plate blanks in each set prior to heat treatment were 0.75 inch (4 plate), 1.25 inches (2 plates), and 1.5 inches (1 plate).

Following heat treatment of these parts, visual and ultrasonic inspection of the turbine disks indicated that extensive quench cracking occurred in two of the four Vendor B disks, and two of five Vendor A parts. No cracks were detected in any cooling plate blanks. It was concluded that inadequate surface preparation of the disks after container removal was probably responsible for the cracking.

One disk from each powder vendor was evaluated to determine the effect of this new heat treat procedure on mechanical properties. The two parts were sectioned according to the plan shown in Figure 88 and tested.

Tensile results of room temperature and 800°F specimens sectioned from the disk bore and 1200°F specimens machined from the disk rim are shown in Table 69. The strength levels of the Vendor B disk were improved to near Task IA values but the 1200°F ductilities were degraded substantially. The room temperature yield strength of the Vendor A disk was lower than the Task IA data, although the 1200°F yield strength was approximately equivalent to Task IA results. As with the Vendor B disk, the 1200°F ductilities were considerably lower than observed in Task IA.

This data pointed out that the inverse relationship between strength and ductility is much more severe at 1200°F than at room temperature. Adding to the problem is the turbine disk shape. The disk bore cross-section is considerably larger than that of the rim. Therefore, attempts to increase the quench rate in the bore were magnified in the rim. The quench rate required to attain the goal room temperature yield strength in the bore also resulted in higher 1200°F yield strength at the rim accompanied by reduced ductility.

Evidence of the much faster quench rate achieved at the disk rim relative to the bore is shown in Figure 89. The background (cooling) γ' size in both disks was approximately 0.1μm diameter at the rim compared to 0.2-0.3μm diameter at the bore. The significant increase in quench rate of this Task III disk relative to that attained using the Task II heat treatment procedure (solution with mild steel container intact) was obvious when the γ' sizes in Figure 89 were compared to those presented previously in Figure 63.

The loss in 1200°F ductility associated with very rapid quench rates from 2100°F also presented a problem in the Lot I cooling plates. Since the cooling plates were between 0.75 and 1.5 inches thick, they were subjected to a quench rate equal to or exceeding that achieved in the rim area of Lot I disks. This implied that all cooling plates would have very high room temperature yield strengths (approximately 190 ksi), but low 1200°F ductility (approximately 6 percent elongation).

A small study was designed to explore alternate methods of heat treating the cooling plate blanks to yield an acceptable combination of strength and ductility. Vendor A prepared and heat treated two one-inch thick

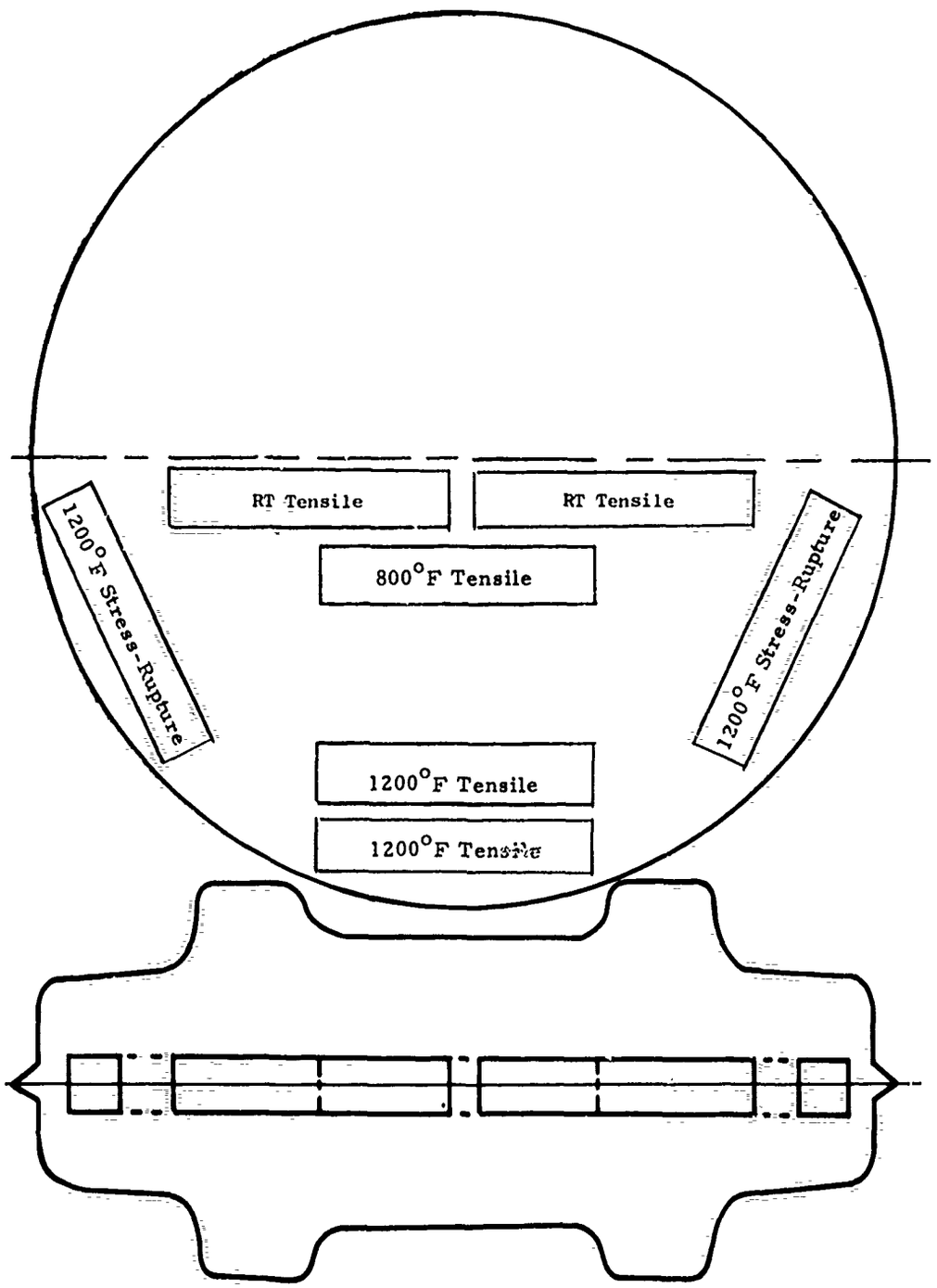
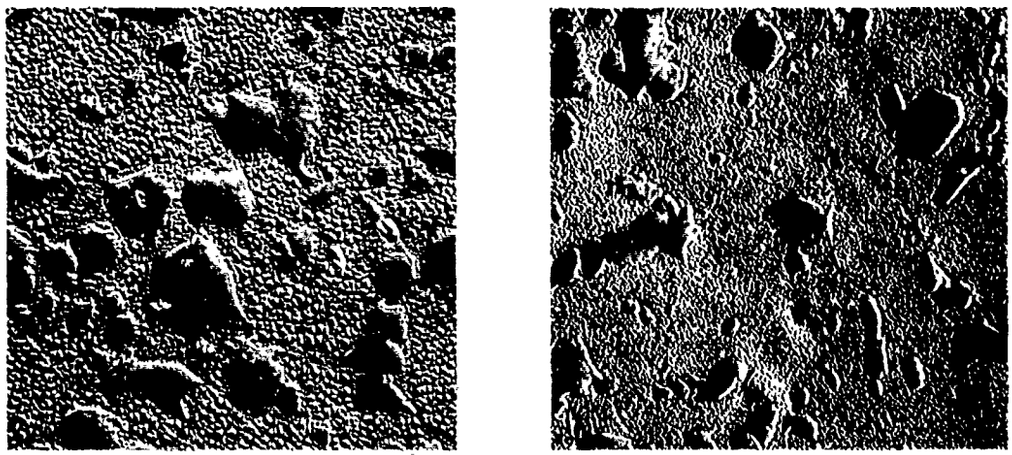
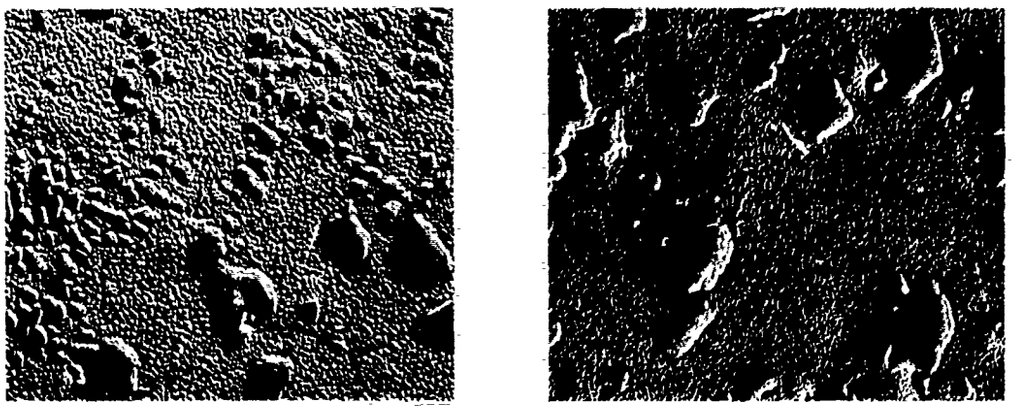


Figure 88. Specimen Location for Task III Lot I Turbine Disk.



Bore Rim

a) Vendor A Disk B246



Bore Rim

b) Vendor B Disk C3

Figure 89. Electron Microscopy of Task III Lot I Turbine Disk (5000X)

cooling plate blanks for evaluation One blank was solution treated in a 2090°F salt bath for 1 hour and quenched in a 1000°F salt bath, while the second was solutioned in a 2100°F air furnace for 1 hour and quenched by fan air cooling. Both blanks were given a 1600°F/1 hour/AC 1200°F/24 hour/AC aging treatment and sectioned for tensile and stress rupture evaluation.

Each 1-inch-thick cooling plate blank was evaluated using room temperature and 1200°F tensile tests and 1200°F/150 ksi stress rupture tests. Results from Vendor A material solutioned in a 2090°F salt bath are presented in Table 70. Tensile strengths and ductilities are excellent, exceeding those obtained on Task II turbine disks. Stress rupture properties were disappointing in view of the superior tensile properties.

As expected, the tensile strengths obtained with a rapid air cool quench (Table 71) were considerably below those achieved with a 1000°F salt quench. Although ultimate strengths were acceptable, 0.2 percent yield strengths were approximately 5 ksi below Task II turbine disk values.

Stress-rupture properties from both cooling plate blanks were obtained with subsize specimens which are prone to thread failures. To obtain a clearer, more accurate estimate of the true stress-rupture properites, larger specimens (0.250 inch diameter and 1 inch long gauge section) were machined from the two plates and tested. Results, shown in Table 72, indicated that both specimens from the rapid air-cooled plate exceeded life and ductility goals,while neither specimen from the T_s -30°F salt bath solutioned plate met the ductility goal.

The difficulties associated with simultaneously achieving program goal strength and ductility levels in the multisection size turbine disk shape and the thin cooling plate blank prompted a review by T700 Design Engineering to ascertain minimum property requirements. A thorough review of engine operating conditions and hardware design resulted in modification of the program tensile strength goals for turbine disks,as shown in Table 73. Addition of one standard deviation (1σ) to the (-3σ) minimum requirements yielded the revised set of (-2σ) program goals. A similar review of cooling plate requirements produced tensile strength goals identical to those presented in Table 73. Since the standard deviations in the As-HIP data were unknown at this time the values for the HIP + Forge data were used for it.

The reduction in strength requirements permitted a greater degree of freedom in the selection of the heat treatment parameters. It was decided, since the goals in Table 73 were achieved in Task II turbine disks, that Lot II disks would be heat treated with mild steel containers intact using the same parameters employed in Task II. The superior stress-rupture properties and adequate tensile strengths attained using a rapid air cool from a T_s -30°F air furnace resulted in selection of that process for all cooling plate blanks.

Preliminary Evaluation -- Lot II, III, IV Parts

Five Lot II turbine disks were prepared by both powder vendors and heat treated according to Task II procedures. To facilitate processing of the remainder of the Task III hardware, Vendor A chose to heat treat Lot III turbine disks with their Lot II parts. Each vendor processed a total of 20 cooling plate blanks (4 sets) in Lot IV and heat treated them along with 7 of their previously heat treated Lot I plates.

Since this Task III hardware represented the first As-HIP parts heat treated at a production source, a preliminary evaluation of mechanical properties was completed before committing a larger number of Task III components to an extensive design data study. Initial test results from Lot II, III, and IV parts were from tensile specimens machined from the bore slugs of Vendor A turbine disks. These subsize axial specimens were to be used primarily as quality control indicators. Room temperature tensile results, shown in

TABLE 69. TENSILE PROPERTIES OF TASK III LOT I TURBINE DISKS

Disk No.	Powder Vendor	Room Temperature				800°F				1200°F			
		0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
C3	B	181	238	13.1	14.9	173	233	16.5	20.1	170	213	6.8	12.6
C3	B	182	242	14.4	14.9					174	211	4.9	7.2
B246	A	175	236	16.6	19.9	166	226	16.5	18.8	170	217	9.7	12.3
B246	A	173	236	15.8	20.9					173	220	7.4	8.4

TABLE 70. MECHANICAL PROPERTIES OF VENDOR A COOLING PLATE BLANK GIVEN SALT BATH SOLUTION PROCESS

Disk No.	Tensile Properties								Stress Rupture 1200°F/150 ksi	
	Room Temperature				1200°F					
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Life (hrs)	EL (%)
B250-21S	184	243	14.7	17.5	168	221	11.8	14.1	47.4	1.4
	183	240	14.1	15.5	166	219	11.7	12.7	Thread Failure	

Heat Treatment: Ts-30°F *1 hr/1000°F Salt Quench + 1600°F/1 hr/AC + 1200°F/24 hrs/AC

*2090°F Salt Bath.

TABLE 71. MECHANICAL PROPERTIES OF VENDOR A AND B COOLING PLATES GIVEN RAPID AIR COOL QUENCH PROCESS

Disk No.	Powder Vendor	Tensile Properties								Stress Rupture	
		Room Temperature				1200°F				1200°F/150 ksi	
		0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Life (hrs)	EL (%)
B250-FAC	A	171	234	15.9	15.5	156	211	15.0	17.5	30.3	3.5
		—	233	17.6	21.6	156	212	16.2	18.5	Thread Failure	
	B	167	233	17.6	19.0	154	212	17.6	17.8	36.2	3.2
		165	233	18.7	19.7	154	210	15.1	16.2	68.8	4.8
		Heat Treatment: Ts-30°F/1 hr/Rapid Air Cool + 1600°F/1 hr/AC + 1200°F/24 hrs/AC									

TABLE 72. STRESS-RUPTURE RETEST RESULTS FOR COOLING PLATE EVALUATION

Spec No.	Solution Process	1200°F/150 ksi Stress Rupture		
		Life (hrs)	EL (%)	RA (%)
21RAC-A7	Rapid Air Cool	58	3.1	5.2
21RAC-A10	Rapid Air Cool	69	4.7	6.7
21S-B7	Ts-30°F Salt Bath Quench	50	1.4	4.6
21S-B10	Ts-30°F Salt Bath Quench	93	2.7	3.9

TABLE 73. T700 TURBINE DISK MECHANICAL PROPERTY REQUIREMENTS

	Tensile Properties							
	Room Temperature				1200°F			
	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
T700 Design Eng. (−3σ) Requirements	160	220	8	10	150	200	6	10
Original Program Goals (−2σ)	180	230	10	12	167	207	8	10
Revised Program* Goals (−2σ)	163	225	10	12	153	203	8	10

*Revised goals equivalent to (−3σ) Design Engineering requirements plus addition of 1σ, where:
σ = 3 ksi for RT yield strength, 1200°F yield strength, and 1200°F UTS
σ = 5 ksi for RT UTS.
These values of σ were determined using current T700 HIP + forge hardware data.

Table 74 indicate that the 0.2 percent yield strengths of the disks were apparently 10 to 15 ksi below the expected value of 170 ksi. Ultimate strengths and ductilities were generally acceptable, although two specimens failed to meet the UTS specification minimum of 225 ksi.

Upon receipt of this data, one disk from each vendor was sectioned according to Figures 90 and 91 to determine yield strength in the tangential orientation using full-size specimens. Results shown in Table 75 indicated that yield strength in the bore was acceptable in both disks. All properties of the Vendor A disk met predicted values except the stress-rupture results.

The Vendor B disk exhibited acceptable yield strengths at RT and 1200°F but failed to meet the specification UTS requirement at RT. Low 1200°F ductilities were also observed along with extremely poor stress-rupture properties.

The first Vendor A cooling plate blanks were also tested after application of the rapid air cool solution treatment. The thickest (1.5-inch) plates were tested first, since they would exhibit the lowest properties of the three cooling plate configurations. The cut-up plan is shown in Figure 92. Results presented in Table 76 are somewhat misleading since both plates received slightly discrepant heat treatments. Plate Number 18 was cooled at a very slow rate initially and had to be reheat treated. A problem in transferring Plate Number 19 from the furnace to the fans delayed the quench by approximately 25 seconds. The effect of either discrepancy on mechanical properties is unknown. Both plates had marginal tensile properties accompanied by low stress-rupture properties.

The unexpectedly low 0.2 percent yield strengths obtained from bore slug specimens and the apparent lack of correlation of this data with results from turbine disk bore specimens initiated a more detailed study of Task III hardware properties. Two additional turbine disks and three cooling plates from each vendor were evaluated according to the test plans illustrated in Figures 93 to 95. In addition, Vendor A machined and tested specimens from two other Task III turbine disks using the cut-up plan shown in Figure 96.

Results from these evaluations are presented in Tables 77 to 80. The turbine disk study was designed to investigate the effects of test vendor specimen size and orientation on tensile properties. Full-size tangential specimens and subsize axial and tangential specimens were tested at two test vendors ("A" and "B") in an effort to resolve the yield strength discrepancies noted in the bore slug test data. Results from the six disks shown in Table 77 suggest that data from both test vendors is essentially equivalent. No significant deviations in yield strength were noted in the 24 tensile tests. Although it is difficult to draw firm conclusions from the data, it appears that yield strength obtained using subsize specimens is slightly lower than results obtained from full-size specimens. The data also suggests that axial yield strengths are slightly lower than tangential properties.

Comparing the turbine disk tensile data presented in Table 77, it was evident that there was a fundamental difference in mechanical property response between the powders of two vendors. Tensile property levels in Vendor A disks were typical of those obtained in Task II, while Vendor B data deviated substantially from the expected results. The 1200°F tensile strengths and ductilities of Vendor B hardware were well below the Task II results and substantiated the initial preliminary test results.

The cooling plate data presented in Table 77 indicated the expected decline in tensile strength with increasing cooling plate thickness. The rapid air cool quench from the solution temperature reduced strengths and increased ductilities in the Vendor A cooling plates relative to the properties produced by the 1000°F salt quench heat treatment. The slower quench rate produced acceptable properties in the 0.75 inch and 1.25 inch thick Vendor A plates but yielded marginal strength levels in the thickest (1.5 inch) cooling plate. A slightly faster quench would be required in the thick plate to raise its strength to the levels achieved by the thinner

TABLE 74. AXIAL BORE SLUG TENSILE RESULTS FROM VENDOR A TASK III LOT 2, 3, 4 DISKS

Disk S/N	Room Temperature			
	0.2% YS (ksi)	UTS (ksi)	ELONG. (%)	RA (%)
B290	161	234	17.0	18.5
B291	168	230	15.5	13.4
B292	156	227	13.9	14.9
B293	154	221	13.0	13.4
B294	158	230	15.7	16.5
B305	160	235	15.8	17.5
B306	157	234	15.5	16.5
B307	165	217	10.1	10.4
B308	153	232	17.0	17.9
B309	156	232	17.2	18.2
B316	156	229	16.5	16.5
B320	151	225	16.6	14.5
B327	159	233	18.0	15.8
B328	156	228	17.0	17.5
B329	158	229	17.4	16.9

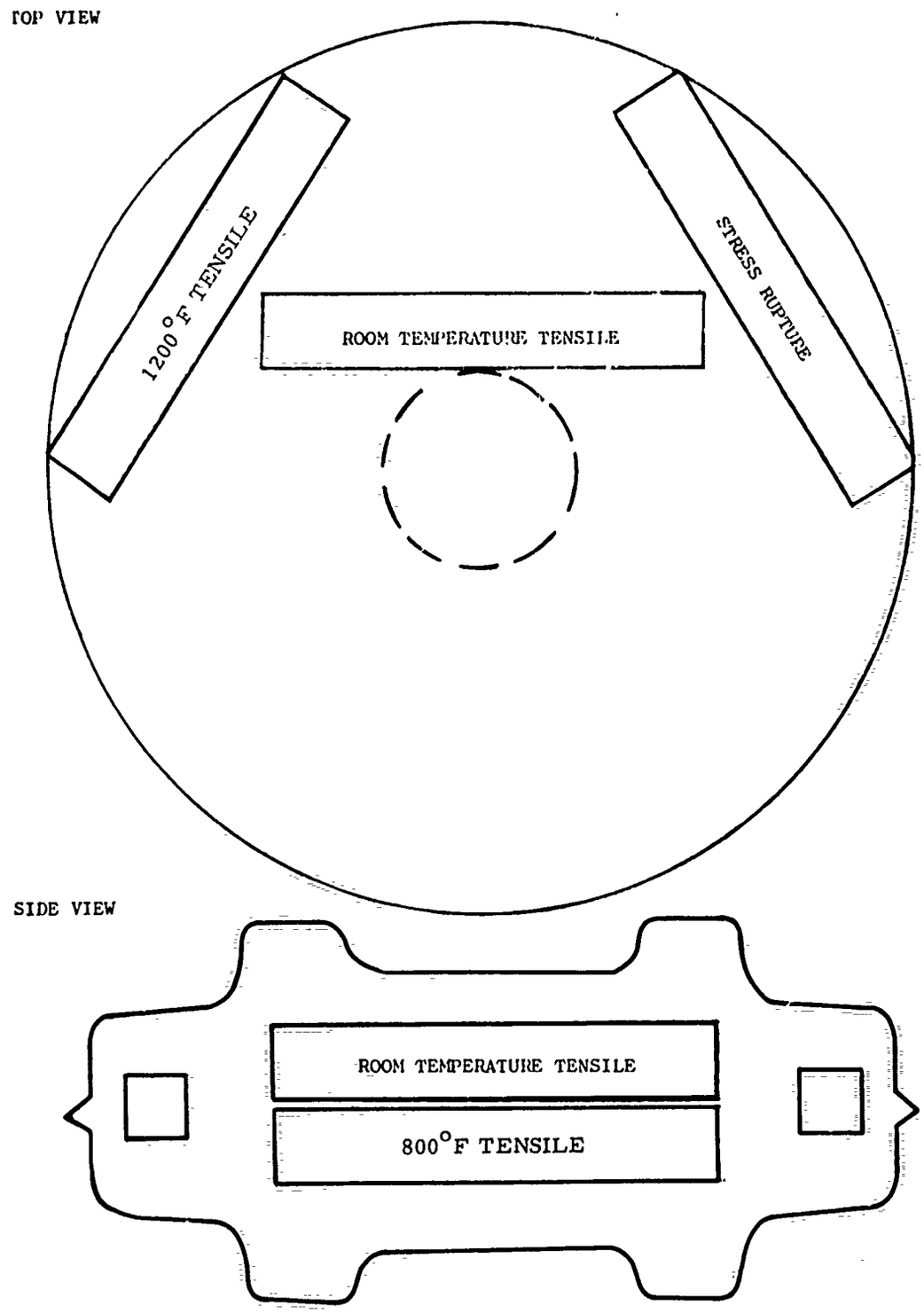


Figure 90. Specimen Location for Vendor A Task III Lot 3 Turbine Disk.

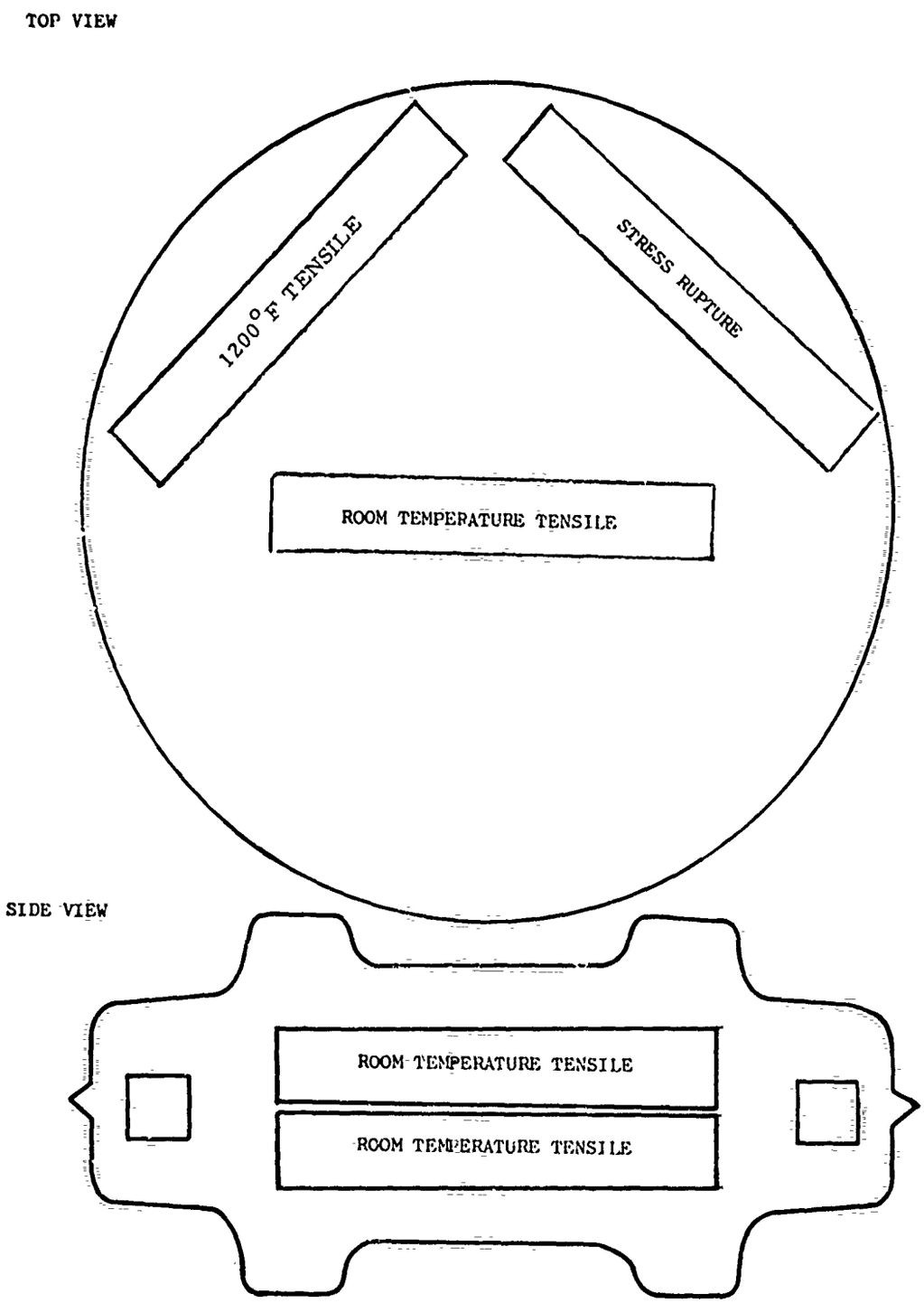


Figure 91. Specimen Location for Vendor B Task III Lot 3 Turbine Disk.

TABLE 75. TEST RESULTS FROM TASK III LOT 2, 3, AND 4 TURBINE DISKS

		Room Temperature				800°F				1200°F				Stress-Rupture 1200°F/150 ksi	
Disk S/N	Powder Vendor	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Life (hr)	EL (%)
B305	A	171	233	14.2	16.9	162	222	16.3	16.5	160	215	15.3	17.8	33.5	2.2
C493	B	169	215	11.2	14.0					160	206	7.9	9.3	12.4	0.6
C493		171	283	13.0	14.4										
C493		169	230	16.5	18.2										
C493		172	216	12.2	15.2										
Specification		163	225	10.0	12.0					153	203	8.0	10.0	50.0	3.0

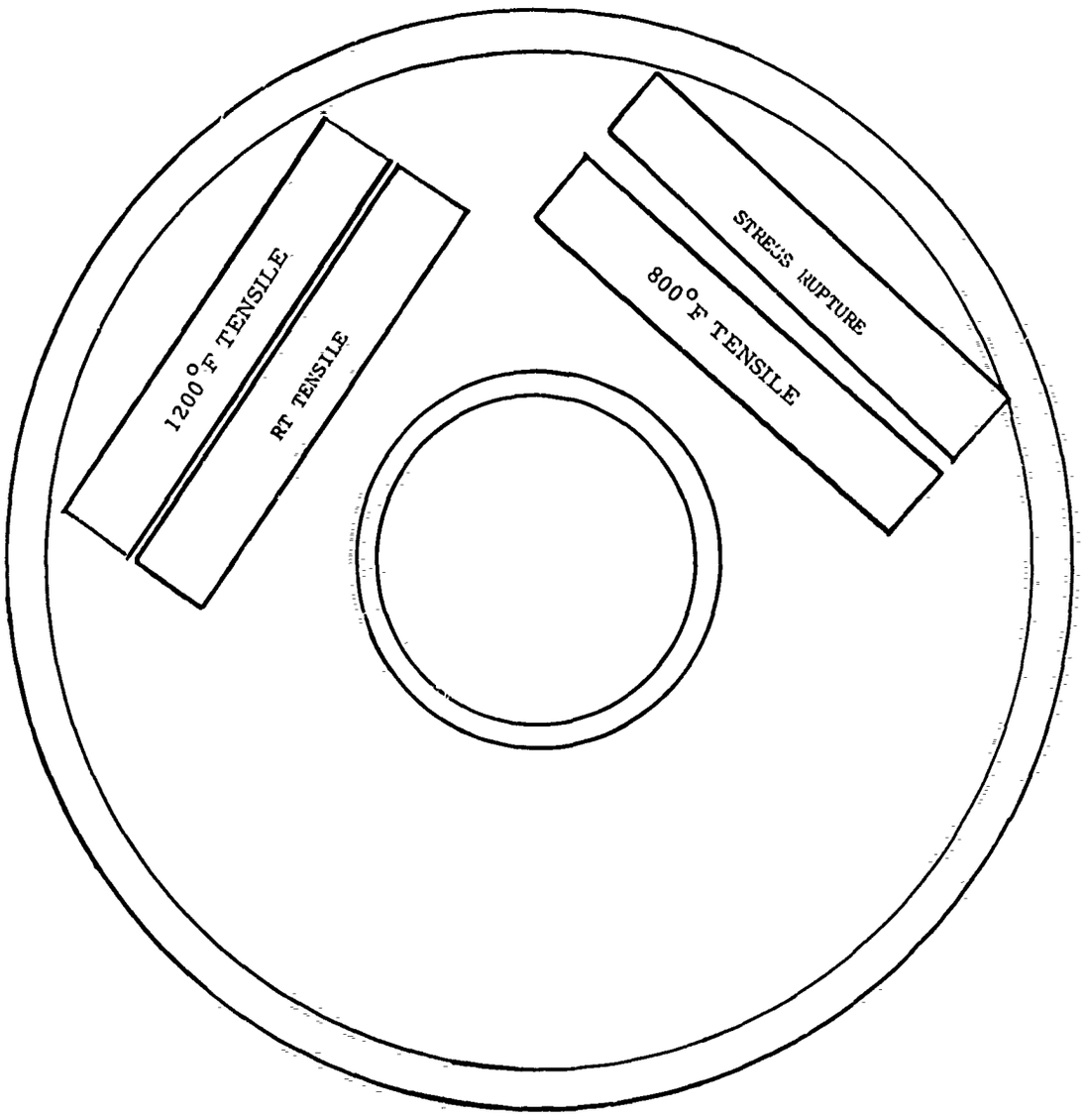


Figure 92. Specimen Locations for Vendor A Task III Lot 4 1.5-Inch-Thick Cooling Plates.

TABLE 76. TEST RESULTS FROM VENDOR A TASK III LOT 2, 3, AND 4 COOLING PLATES

	Room Temperature				800°F				1200°F				1200°F/150 ksi Stress-Rupture	
S/N	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Life (hr)	EL (%)
18	164	226	14.7	16.2	138	212	14.1	17.2	152	205	13.5	17.6	14	5.0
19	167	227	14.5	15.1	161	218	17.3	17.9	155	206	16.0	18.8	44	1.0
Specification	163	225	10	12					153	203	8	10	50	3.0

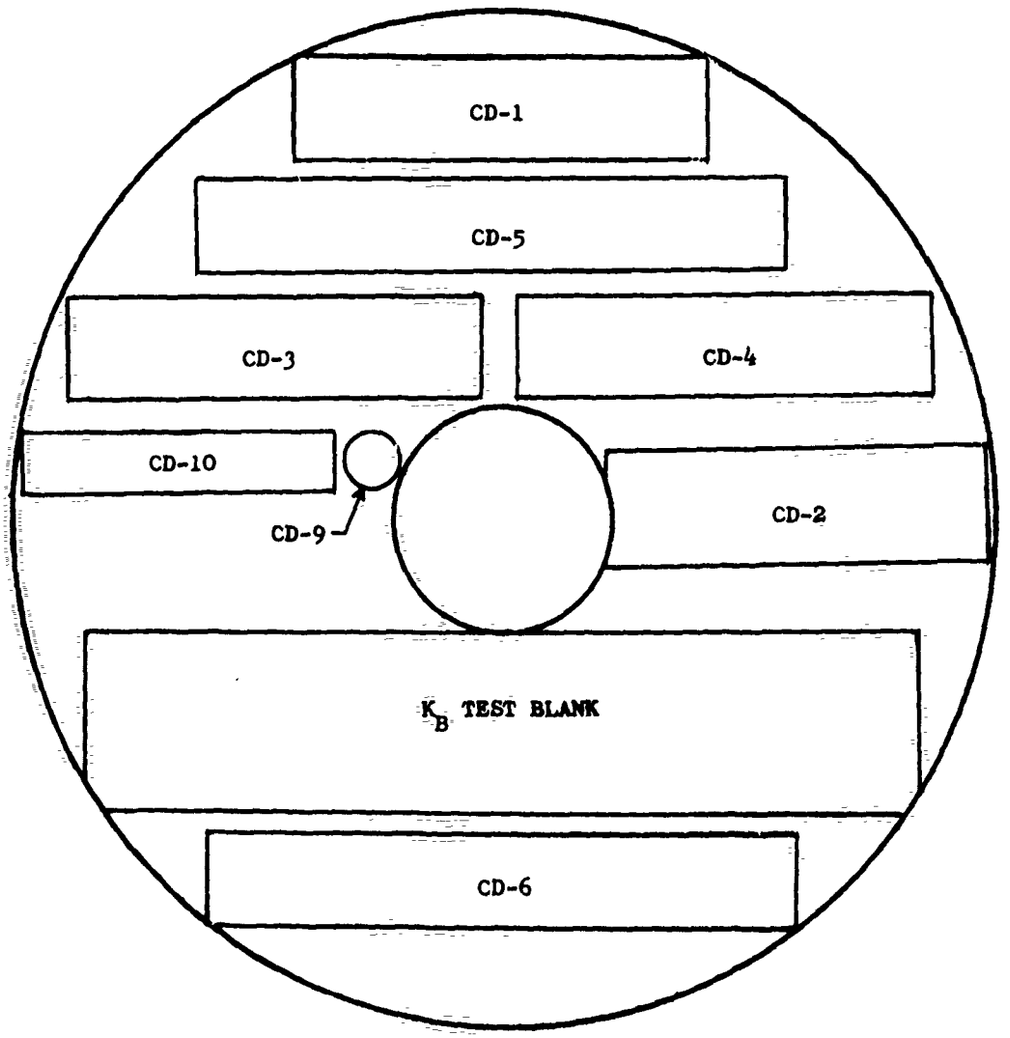


Figure 93. Specimen Location for Detailed Mechanical Property Study of Task III Vendor A Turbine Disks.

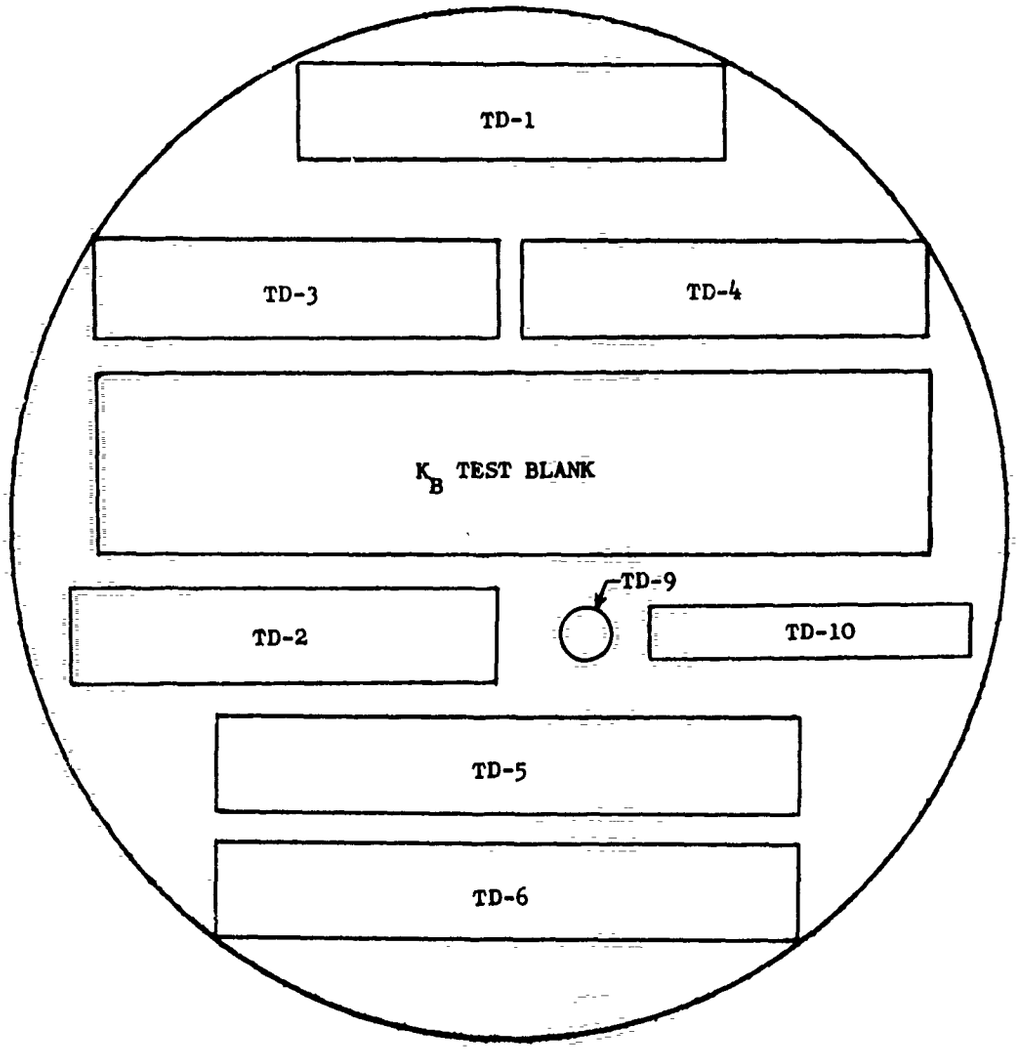


Figure 94. Speciman Location for Detailed Mechanical Property Study of Task III Vendor B Turbine Disks.

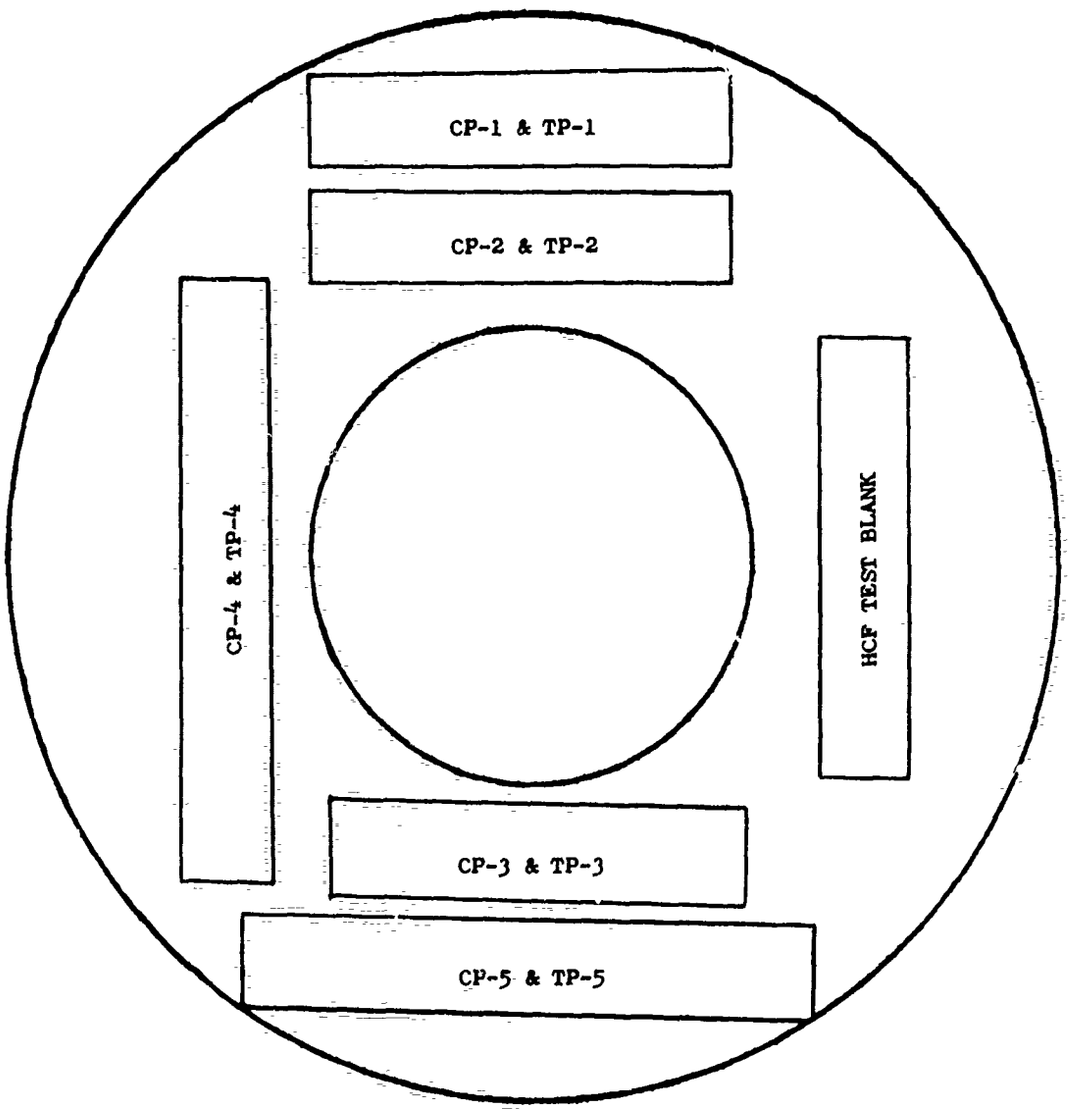


Figure 95. Specimen Location for Detailed Mechanical Property Study of Task III Cooling Plates.

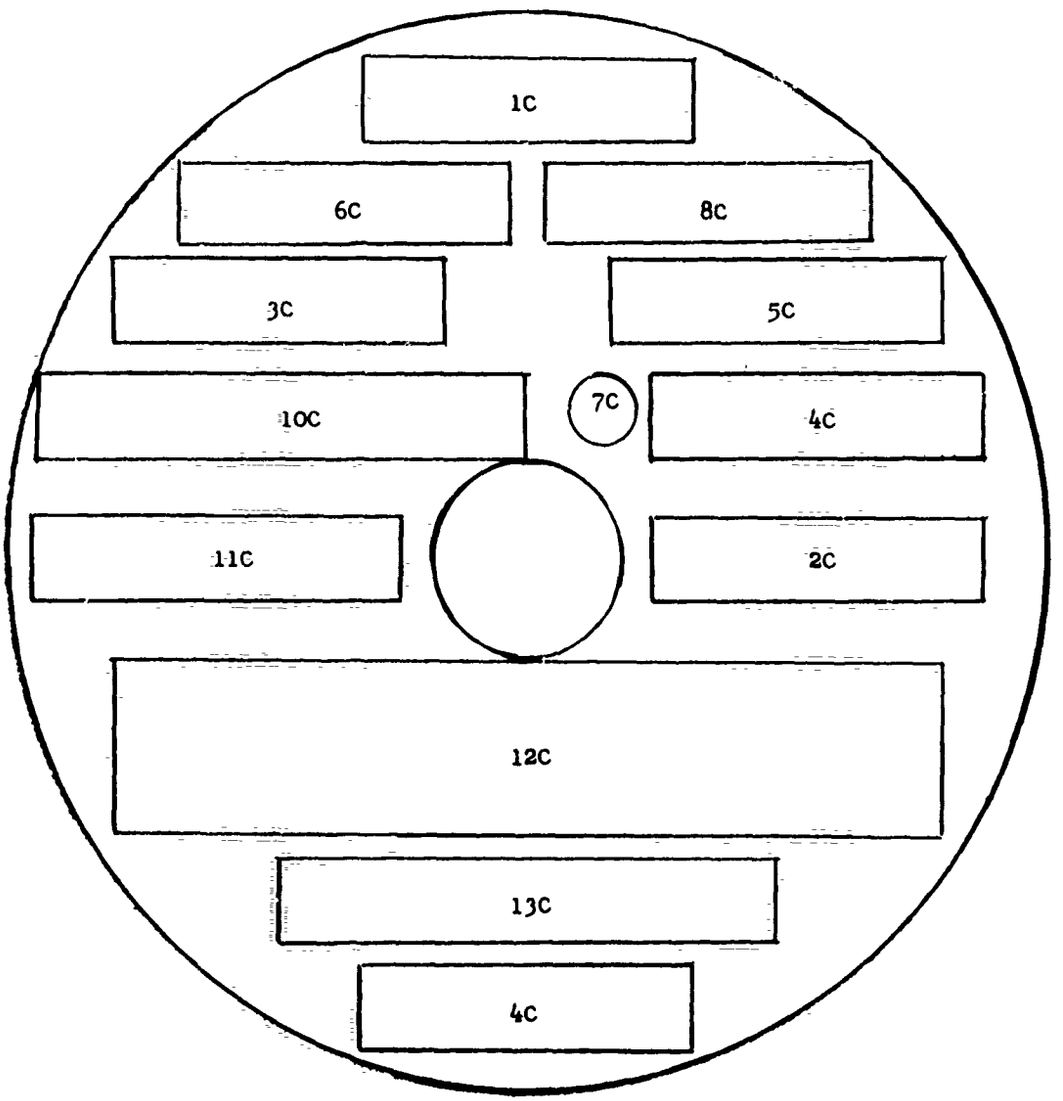


Figure 96. Specimen Location for Vendor A Evaluation of Task III Disks.

TABLE 77. TENSILE PROPERTIES OF TASK III TURBINE HARDWARE

Powder Vendor	Part	S/N	Thickness (in.)	Specimen Location	Specimen (1) Size	Specimen Orient	Test Vend	0.2%YS (ksi)	UTS (ksi)	EL (%)	RA (%)
Room Temperature											
A	Disk	8290	-	CD 3	Std	Tang	B	169	233	17.6	16.7
				CD 9	Sub	Axial	B	165	232	17.0	22.9
A	Disk	8293		CD 10	Sub	Radial	B	164	231	16.9	17.3
				CD 9	Sub	Axial	A	162	233	17.4	18.8
A	Disk	8305	-	CD 3.4"	Std	Tang	B	131	233	14.2	16.9
				CD 10	Sub	Tang	B	168	231	14.9	19.9
				CD 9	Sub	Axial	B	166	230	14.5	18.2
B	Disk	C483	-	TD 10	Sub	Tang	A	170	227	19.0	22.5
				TD 9	Sub	Axial	B	167	224	12.4	13.1
B	Disk	C495	-	TD 2	Std	Tang	B	170	236	19.0	21.8
				TD 9	Sub	Axial	A	164	237	20.6	28.3
B	Disk	C493	-	TD 3.4"	Std	Tang	B	169	215	11.2	14.0
				TD 3.4"	Std	Tang	B	171	223	13.0	14.4
A	CP	8312-4	0.75	CP 2	Std	Tang	A	174	235	15.7	15.6
A	CP	8312 11	1.25	CP 2	Std	Tang	B	171	236	17.7	20.8
A	CP	8312 19	1.5	CP 2	Std	Tang	B	167	227	14.5	15.1
B	CP	C500-7	0.75	TP 2	Std	Tang	B	178	241	18.9	27.4
B	CP	C500-6	1.25	TP 2	Std	Tang	B	178	237	14.5	14.1
B	CP	C494 18	1.5	TP 2	Std	Tang	A	174	238	18.4	16.7
Specification Minimum								163	225	10.0	12.0
800 F											
				CD 10	Sub	Radial	A	163	226	16.9	18.3
				CD 4	Std	Tang	B	163	212	15.1	15.6
				CD 3.4"	Std	Tang	B	62	222	16.3	14.5
				TD 2	Std	Tang	A	167	216	12.2	13.1
				TD 10	Sub	Tang	B	156	222	19.7	24.7
					-				-		
					-						
					-		-				
				CP 5	Std	Tang	B	161	218	17.3	17.4
				-					-		
				TP 1	Std	Tang	B	168	221	14.8	13.7
				TP 1	Std	Tang	B	164	228	20.3	22.4
1200 F											
				CD 1	Std	Tang	B	149	229	14.6	15
				CD 2	Std	Radial	B	156	214	15.1	15
				CD 1	Std	Tang	B	160	215	15.3	17
				TD 4	Std	Tang	B	159	204	9.6	11
				TD 1	Std	Tang	A	[illegible]	203	11.1	10
				TD 1	Std	Tang	B	160	206	12	9
				CP 5	Std	Tang	B	155	211	13.3	14
				CP 1	Std	Tang	A	156	207	16.2	17
				CP 1	Std	Tang	B	155	206	14.0	14
				TP 1	Std	Tang	A	164	194	7.6	8
				TP 3	Std	Tang	B	167	204	11.8	12

*Two specimens located between specimens (3) and (4) oriented around disk circumference.
(1) Standard size specimen - 0.250 inch wide x 1.25 inch long gage section
Subsize specimen - 0.160 inch wide x 0.65 inch long gage section

TABLE 78. STRESS-RUPTURE, CREEP, AND SPLCF PROPERTIES OF TASK III TURBINE HARDWARE

				Stress-Rupture					Creep				SPLCF			
				Specimen			1200°F/ 150 ksi		Specimen			1100°F/ 150 ksi	Specimen			1200°F/ 145 ksi
Powder Vendor	Part	S/N	Thickness (in)	Location	Orient.	Test Vend.	Life	EL (%)	Location	Orient.	Test Vend.	Elong. after 100 hr (%)	Location	Orient.	Test Vend.	Cycles to Failure
A	Disk	B290	–	CD-2	Radial	B	151.3	7.9	–	–	–	–	CD-6	Tang.	B	2775
				CD-4	Tang.	A	55.7	7.6								
A	Disk	B293	–	CD-1	Tang.	A	45.9	3.3	CD-5	Tang.	A	0.17	CD-6	Tang.	D	1568
				CD-3	Tang.	A	38.5	4.5								
A	Disk	B305	–	CD-1	Tang.	B	33.5	2.2	–	–	–	–	CD-6	Tang.	B	<4000
				CD-1	Tang.	B	70.0	2.5								
B	Disk	C483	–	TD-3	Tang.	B	18.9	2.4	–	–	–	–	TD-6	Tang.	A	900
				TD-1	Tang.	A	15.0	2.2								
B	Disk	C495	–	TD-3	Tang.	A	21.1	4.5	TD-5	Tang.	A	0.20**	TD-6	Tang.	D	840
				TD-4	Tang.	A	18.1	4.0								
B	Disk	C493	–	TD-4	Tang.	B	12.4	0.6	–	–	–	–	TD-6	Tang.	B	2215
				TD-1	Tang.	A	13.2	2.6								
A	C.P.	B312-4	0.75	CP-3	Tang.	A	49.4	3.3	–	–	–	–	CP-5	Tang.	A	1325
A	C.P.	B312-11	1.25	CP-3	Tang.	A	48.2	5.2	CP-4	Tang.	A	0.23**	CP-5	Tang.	D	1834
A	C.P.	B312-19	1.5	CP-3	Tang.	B	14.0	5.8	–	–	–	–	CP-5	Tang.	A	2137
B	C.P.	C500-7	0.75	TP-3	Tang.	A	32.9	2.9	TP-4	Tang.	A	0.09**	TP-5	Tang.	A	459
B	C.P.	C500-6	1.25	TP-3	Tang.	A	22.0	2.4	–	–	–	–	TP-5	Tang.	A	664
B	C.P.	C494-18	1.5	TP-3	Tang.	A	12.5	1.8*	–	–	–	–	TP-5	Tang.	D	1407
Specification Minimum							50.0	3.0				<0.2%				300

*Failed outside gage section
**Elongation after 115 hours

TABLE 79. VENDOR A TASK III DISK TENSILE PROPERTIES

Room Temperature							1200°F					
Disk S/N	Specimen[1] Location	Orient.	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)	Specimen[1] Location	Orient.	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)
B307	1C	Tang.	173	236	16.0	17.9	4C	Tang.	158[2]	222[2]	8.0[2]	14.4[2]
	2C	Radial	169	234	16.0	18.5	5C	Tang.	155	211	26.0	24.0
	3C	Tang.	167	234	18.0	18.9	6C	Tang.	155	214	24.0	23.4
							7C	Axial	154[2]	210[2]	12.0[2]	15.0[2]
B316	1C	Tang.	167	232	16.0	18.9	4C	Tang.	153	212	18.0	17.9
	2C	Radial	164	229	18.0	20.7	5C	Tang.	151	210	20.0	18.5
	3C	Tang.	163	223	14.0	13.5	6C	Tang.	150	210	20.0	22.0
							7C	Axial	150	207	20.0	21.4

[1] Subsize Specimen – 0.160 inch wide x 0.640 inch long gage section
[2] Failed in extensometer mark

TABLE 80. VENDOR A TASK III DISK STRESS-RUPTURE, CREEP, AND SPLCF DATA

Stress-Rupture					Creep			SPLCF			Crack Propagation		
			1200°F/ 150 ksi				1100°F/ 150 ksi			1200°F/ 145 ksi			1000°F/ 100 ksi
Disk S/N	Specimen[1] Location	Orient.	Life (hr)	EL (%)	Specimen Location	Orient.	Elong. in 50 hr (%)	Specimen Location	Orient.	Life Cycles	Specimen Location	Orient.	Life Cycles
B307	8C	Tang.	67.1	4.5	11C	Radial	0.05	13C	Tang.	2176	12C	Tang.	8030
	9C	Tang.	82.1	9.1	10C	Tang.	0.08						
B316	8C	Tang.	98.1	3.0	11C	Radial	0.02	13C	Tang.	903	12C	Tang.	6806
	9C	Tang.	53.2	6.0	10C	Tang.	0.13[2]						
Specification			50	3.0			≤0.2			300			5000

[1] Subsize specimen – 0.160 inch wide x 0.64 inch long gage section
[2] Specimen indicated 0.23% plastic deformation on loading

plates. Although room temperature and 800°F tensile properties of the Vendor B cooling plates were excellent, the 1200°F strength and ductility deficiencies noted in the turbine disks are again evident in their cooling plates.

Stress rupture results presented in Table 78 indicated that properties in Vendor A disks fluctuate around the 50-hour and 3.0 percent specification values. Vendor B disk results revealed very low rupture lives and ductilities, perhaps reflecting the 1200°F tensile ductility deficiency noted in Table 77. Stress rupture properties of the thin and medium thickness Vendor A cooling plates were near the specification levels, while the lower strength thick plate had a much lower rupture life. The Vendor B cooling plates all indicate low rupture lives and ductilities.

To further investigate the 1200°F capability of Task III hardware, a sustained peak low-cycle fatigue (SPLCF) test was conducted on each part. This test is considered to be more indicative of actual engine operating conditions, and therefore is probably a better indicator of the true acceptability of turbine components than the stress rupture test. Results from Vendor A disks, shown in Table 78, indicate superior SPLCF capability. The cycles to failure of all three parts were far beyond the 300 cycle m mum life typical of HIP - Forge and cast-wrought Rene' 95.

The Vendor B disk data were more erratic, with one test falling below the specification value. Vendor A cooling plate results were also vastly superior to the specification minimum, while Vendor B data were somewhat more erratic but also exceeded the specification minimum.

The Vendor A's evaluation of two additional Task III disks at test vendor "C" yielded supplemental tensile, stress rupture, and SPLCF data. Specimen locations are shown in Figure 96. Tensile results, presented in Table 78, indicate that disk B307 is essentially equivalent to the three Vendor A disks included in the detailed property study. No explanation was available for the unexpectedly high 1200°F ductilities observed in two specimens. Data from disk B316 was similar to B307 with the exception of 1200°F yield strength, which is 4-5 ksi low. Stress rupture properties, shown in Table 80, all exceeded specification minimums. SPLCF results on both disks were excellent, with the superior life of B307 being typical of the Vendor A disks reported in Table 78. Crack propagation testing was also conducted on these two disks using the KB specimen employed in Task II. Residual cyclic lives of both disks exceeded the specification minimum of 5000 cycles and were essentially equivalent to results reported on Task II hardware.

In order to determine the acceptability of Task III hardware, all preliminary results were summarized and compared to goal properties in Tables 81 to 84. The turbine disk results of Vendor A, summarized in Table 81, included data from all disks except B316. The heat-treat log (H5) in which B316 was included contained one disk that was over-temperatured during solution treatment. Because of the uncertain quality of lot H5, all five disks in the lot were withheld from further participation in the program. Therefore, properties of disks B290, B293, B305 and B307 represented hardware currently being considered for engine testing and detailed Design Data generation. Data in Table 81 indicate that all tensile stress-rupture and SPLCF average properties exceed the goals. Only one tensile datum fell below the goal and that test was from a subsize axial test specimen. The minimum stress-rupture life and ductility both failed to meet goals, but minimum SPLCF life easily exceeded the goal.

The summary of Vendor B disk data, given in Table 83, indicated that all averages except stress-rupture life and ductility exceeded the goals. However, minimum properties indicated that, in addition to the stress-rupture properties, room temperature tensile strength, 1200°F tensile ductility and SPLCF life were below goals.

TABLE 81. SUMMARY OF TASK III VENDOR A TURBINE DISK TEST RESULTS*

Property	No. of Spec.	Ave.	Max.	Min.	Goal
RTYS (ksi)	10	167	173	162 ≠	163
RTUTS (ksi)	10	233	236	230	225
RT EL (%)	10	16.3	18.0	14.2	10.0
1200°F YS (ksi)	7	157	160	154 ≠	153
1200°F UTS (ksi)	7	216	228	210	203
1200°F EL (%)	7	16.1	26.0	8.0 +	8.0
Stress Rupture (1200°F/150 ksi)					
Life (hr)	8	68	151	33.5	50
EL (%)	8	5.2	9.1	2.2	3.0
SPLCF (1200°F/145 ksi)					
Cycles to Failure	3	—	>4,000	1,568	300

*Deleting Heat Treat Lot H5
+Knife-Edge Failure
≠Subsize Axial Specimen

TABLE 82. SUMMARY OF TASK III VENDOR A COOLING PLATE TEST RESULTS

Property	Thin (0.75 in.)	Med. (1.25 in.)	Thick (1.5 in.)	Goal
RTYS (ksi)	174	171	167	163
RTUTS (ksi)	235	236	227	225
RT EL (%)	15.7	17.7	14.5	10.0
1200 YS (ksi)	155	156	155	153
1200 UTS (ksi)	211	207	206	203
1200 EL (%)	13.9	16.2	16.0	8.0
Stress Rupture (1200°F/150 ksi)				
Life (hr)	49	48	14	50
EL (%)	3.3	5.2	5.8	3.0
SPLCF (1200°F/145 ksi)				
Cycles to Failure	1,325	1,834	2,137	300

TABLE 83. SUMMARY OF TASK III VENDOR B TURBINE DISK TEST RESULTS

Property	No. Spec.	Ave.	Max.	Min.	Goal
RTYS (ksi)	6	169	171	164	163
RTUTS (ksi)	6	229	239	215	225
RT E1 (%)	6	15.9	20.6	11.2	10.0
1200°F YS (ksi)	3	159	160	158	153
1200°F UTS (ksi)	3	204	206	203	203
1200°F EL (%)	3	8.9	11.1	7.6	8.0
Stress Rupture (1200°F/150 ksi)					
Life (hr)	6	16.5	21.1	12.4	50
EL (%)	6	2.7	4.5	0.6	3.0
SPLCF (1200°F/165 ksi)					
Cycles to Failure	3	1,092	2,215	220	300

TABLE 84. SUMMARY OF TASK III VENDOR B COOLING PLATE TEST RESULTS

Property	Thin (0.75 in.)	Med. (1.25 in.)	Thick (1.5 in.)	Goal
RTYS (ksi)	178	178	174	163
RTUTS (ksi)	241	237	238	225
RT EL (%)	18.9	14.5	18.4	10.0
1200 YS (ksi)	164	–	157	153
1200 UTS (ksi)	199	–	204	203
1200 EL (%)	7.6	–	11.8	8.0
Stress Rupture (1200°F/150 ksi)				
Life (hr)	33	22	12.5	50
EL (%)	2.9	2.4	1.8	3.0
SPLCF (1200°F/145 ksi)				
Cycles of Failure	459	664	1,407	300

The cooling plate results of Vendor A,summarized in Table 82, indicated that tensile and SPLCF properties of the thin and medium thickness plates met the goals while stress rupture lives were slightly below the 50-hour goal. Tensile properties of the thick plate were slightly above goals, SPLCF life was excellent, but stress rupture life fell far short.

The cooling plate data of Vendor B,shown in Table 84, indicated that 1200°F tensile strength and ductility of the thin plate did not meet the goals while stress rupture lives and ductilities were substantially below the goals for all three plates. All SPLCF data exceeded the goal. This coupled with Vendor B disk result suggest that the Task III hardware properties are less than desirable and lower than those obtained in Task II hardware. A probable cause for it could be the different powder morphology as mentioned in the discussion of powder production. The changed morphology are satellite formation on Vendor B Task III powder (Figure 92) as compared to that of Task I and II powder (Figure 9 and 10) is very apparent.

Analysis of all Task III preliminary data with T700 Design, Materials Engineering, and Army personnel resulted in the following conclusions:

a. The Vendor A turbine disks and thin and medium thickness cooling plates were acceptable for engine testing.

b. The Vendor A thick cooling plates should not be engine tested pending modification of Quench.

c. The Vendor B disks and cooling plates were not acceptable for engine testing.

d. Two turbine disks and three cooling plates of Vendor A should be finished machined into engine hardware.

e. The Task III design data study should proceed using Vendor A hardware only and should be modified slightly to reflect the reduced quantity of hardware available, since all Vendor B material would be excluded.

f. A study should be initiated under Army funding to investigate cooling rates and their effect on properties, with hopes of developing a more optimum quench technique for this As-HIP geometry.

Design Data Study — Vendor A Lot II, III, IV Parts

The detailed design data study was modified somewhat to permit generation of required data with the reduced quantity of test material. Complete identification of all Task III Vendor A turbine disks and cooling plates are summarized in Tables 58 and 59. Test bar configurations were identical to those used in Task II except for the tensile (Figure 97) and high-cycle fatigue (Figure 98) specimens. The total test plan, shown in Table 85, indicates the extensive Low-Cycle Fatigue (LCF) testing. Additional tensile, stress rupture, and creep data, and crack propagation results were obtained, as well as data on two turbine disks subjected to a 1200°F/1000-hour thermal exposure. The specimen distribution within available hardware is presented in Table 85. Test locations are described in the cut-up plans shown in Figures 99 through 103.

Tensile results from the design data study are presented in Table 86. These results, when compared to previous HIP + forge T700 data, indicated that 0.2% yield strengths were substantially lower in the As-HIP material. Ultimate tensile strengths of the As-HIP parts were slightly below HIP + forge results while tensile ductilities of the two materials were essentially equivalent. The tensile properties of As-HIP material change very little with temperature in the intermediate temperature range of 600°-1000°F.

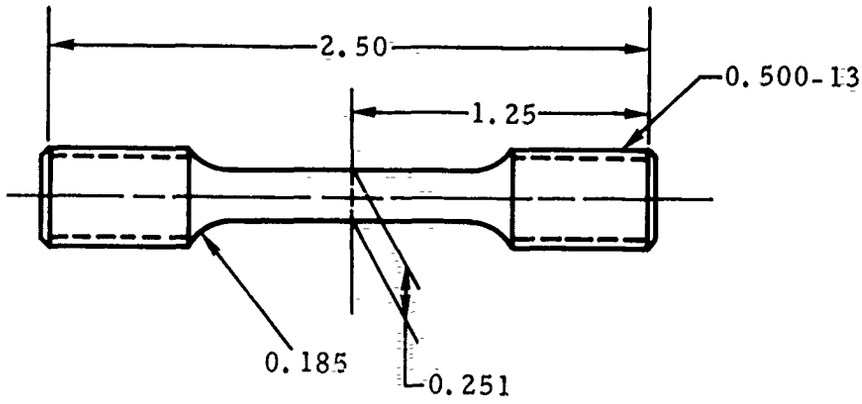


Figure 97. Smooth Bar Tensile Test Specimen.

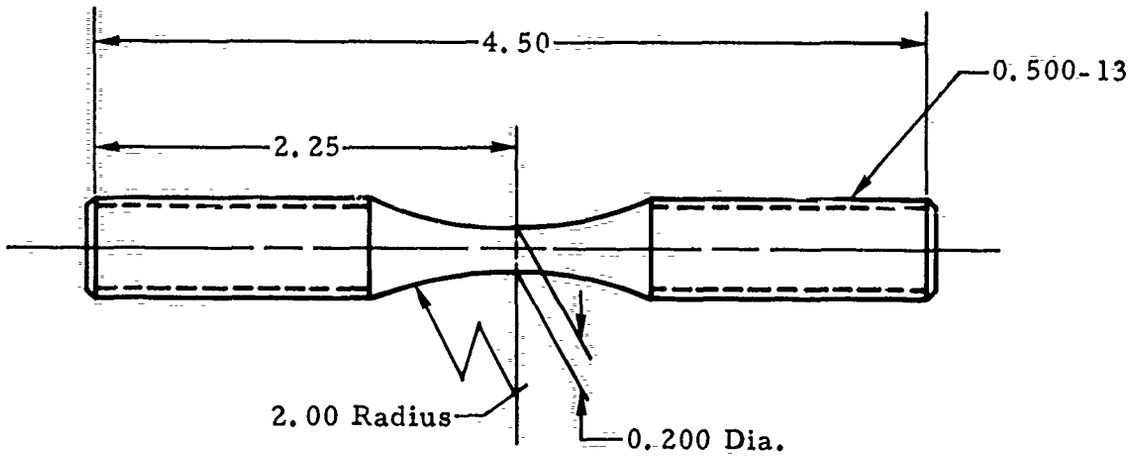


Figure 98. Smooth Bar High-Cycle Fatigue Test Specimen.

TABLE 85. SPECIMEN DISTRIBUTION FOR DESIGN DATA STUDY OF VENDOR A TASK III HARDWARE

Part	S/N	Thickness (in.)	Master Powder Blend No.	Heat Treat Lot No.	Specimens To Be Machined
Disk	COL 10011	–	MB 023	H 4	10 LCF
Disk	COL 10022	–	MB 029	H 6	10 LCF
Disk	COL 10023	–	MB 029	H 6	10 LCF
Disk	COL 10014	–	MB 023	H 4	2 Stress-Rupture
					1 Creep
					2 Crack Propagation
					1 SPLCF
Disk	COL 10020	–	MB 029	H 6	Same as COL 10014
Disk	COL 10021*	–	MB 029	H 6	3 Crack Propagation
					2 Tensile
					1 Stress-Rupture
Disk	COL 10013*	–	MB 029	H 4	1 Crack Propagation
					1 Stress-Rupture
					2 Tensile
Cooling Plate	COL 10038	1.25	MB 024	H 7	3 Tensile
					2 Creep
					1 SPLCF
					1 High Cycle Fatigue
					1 Stress-Rupture
Cooling Plate	COL 10042	0.75	MB 024	H 10	Same as COL 10038
Cooling Plate	COL 10050	1.25	MB 024	H 7	Same as COL 10038
Cooling Plate	COL 10057	1.25	MB 024	H 10	Same as COL 10038

*Thermal exposure of 1200°F/1000 hr.

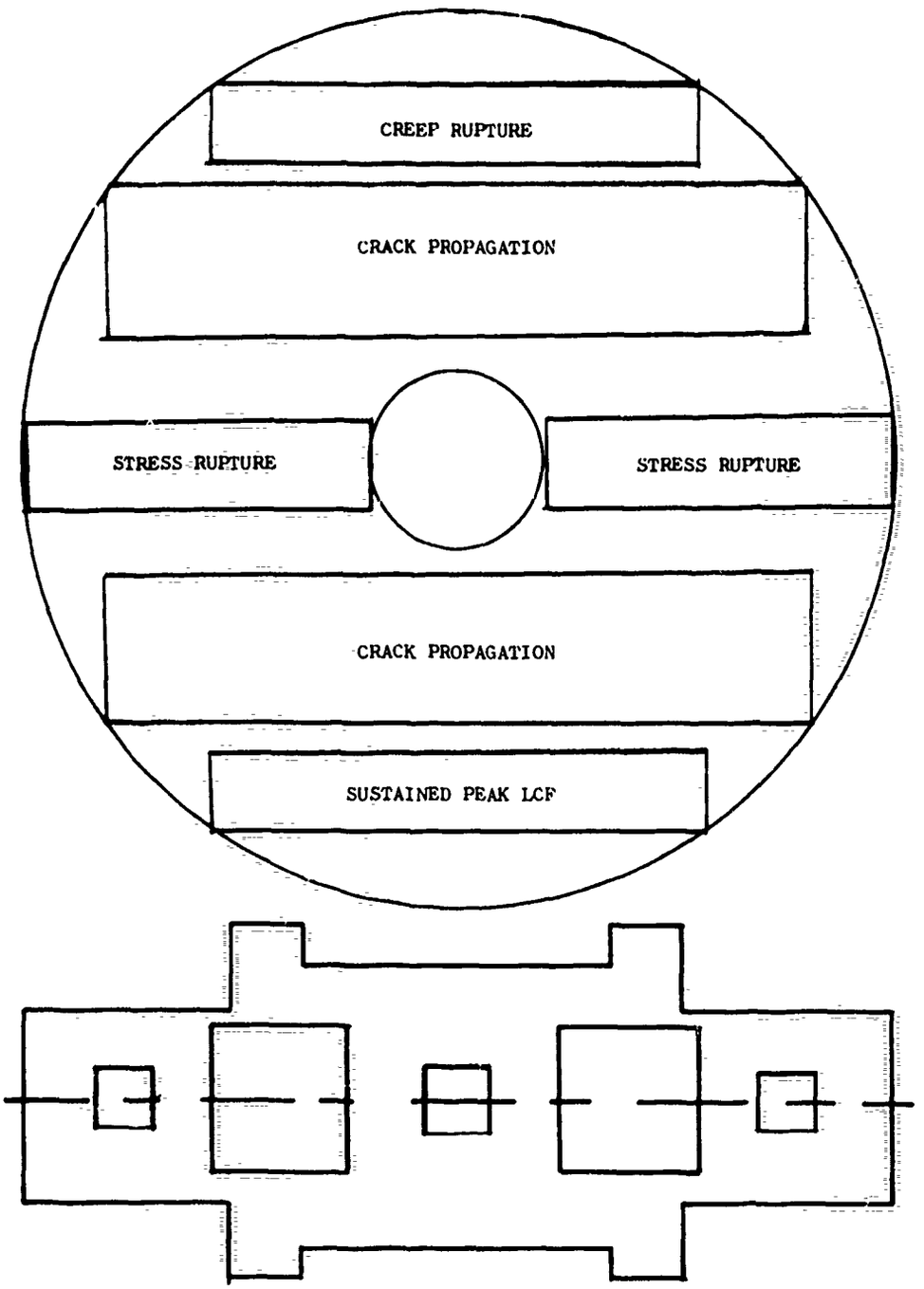


Figure 99. Specimen Location for Design Data Evaluation of Vendor A Task III Disks (S/N COL 10014 and COL 10020).

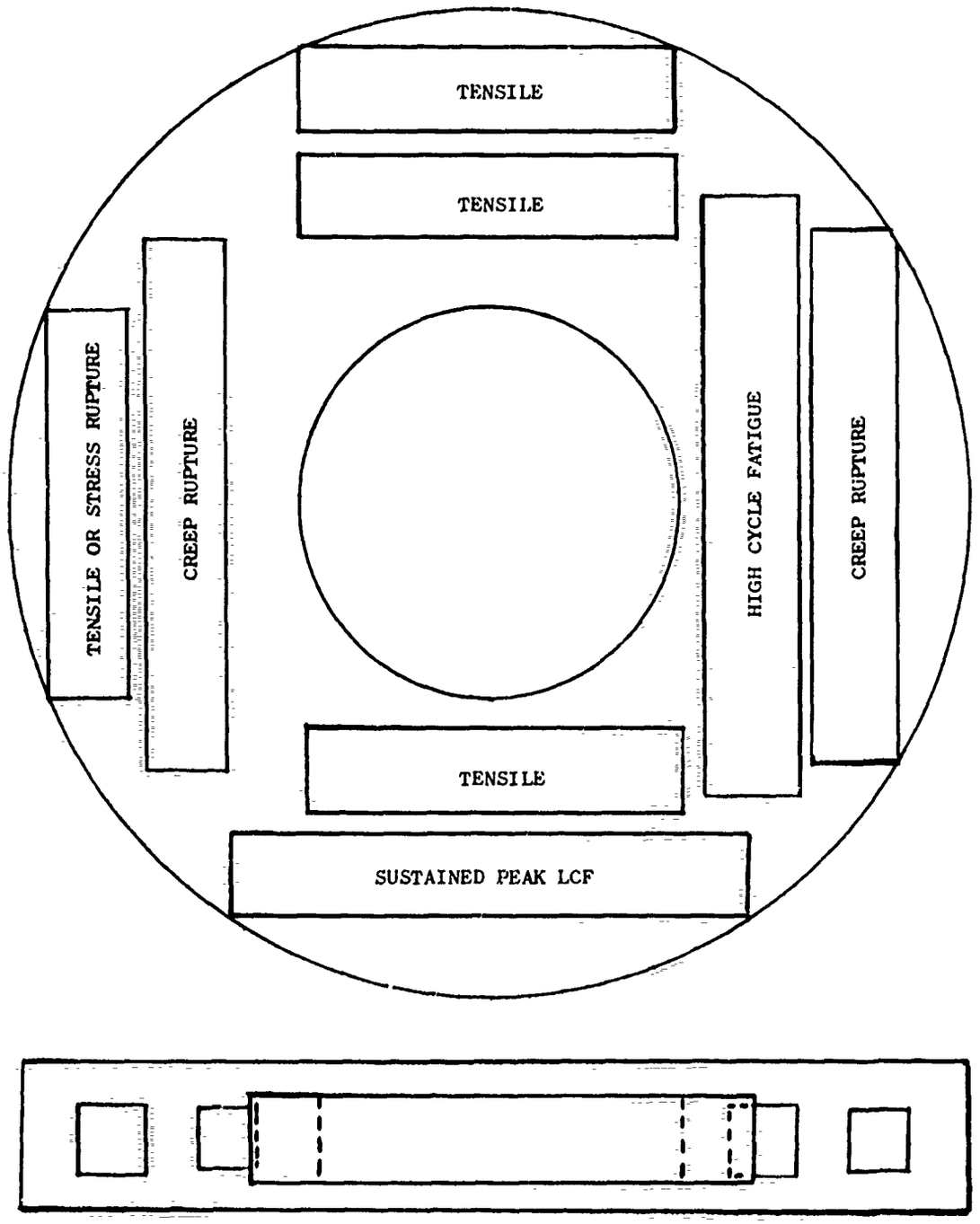


Figure 100. Specimen Location for Design Data Evaluation of Vendor A Task III Cooling Plates (S/N COL 10038, COL 10042, COL 10050 and COL 10057).

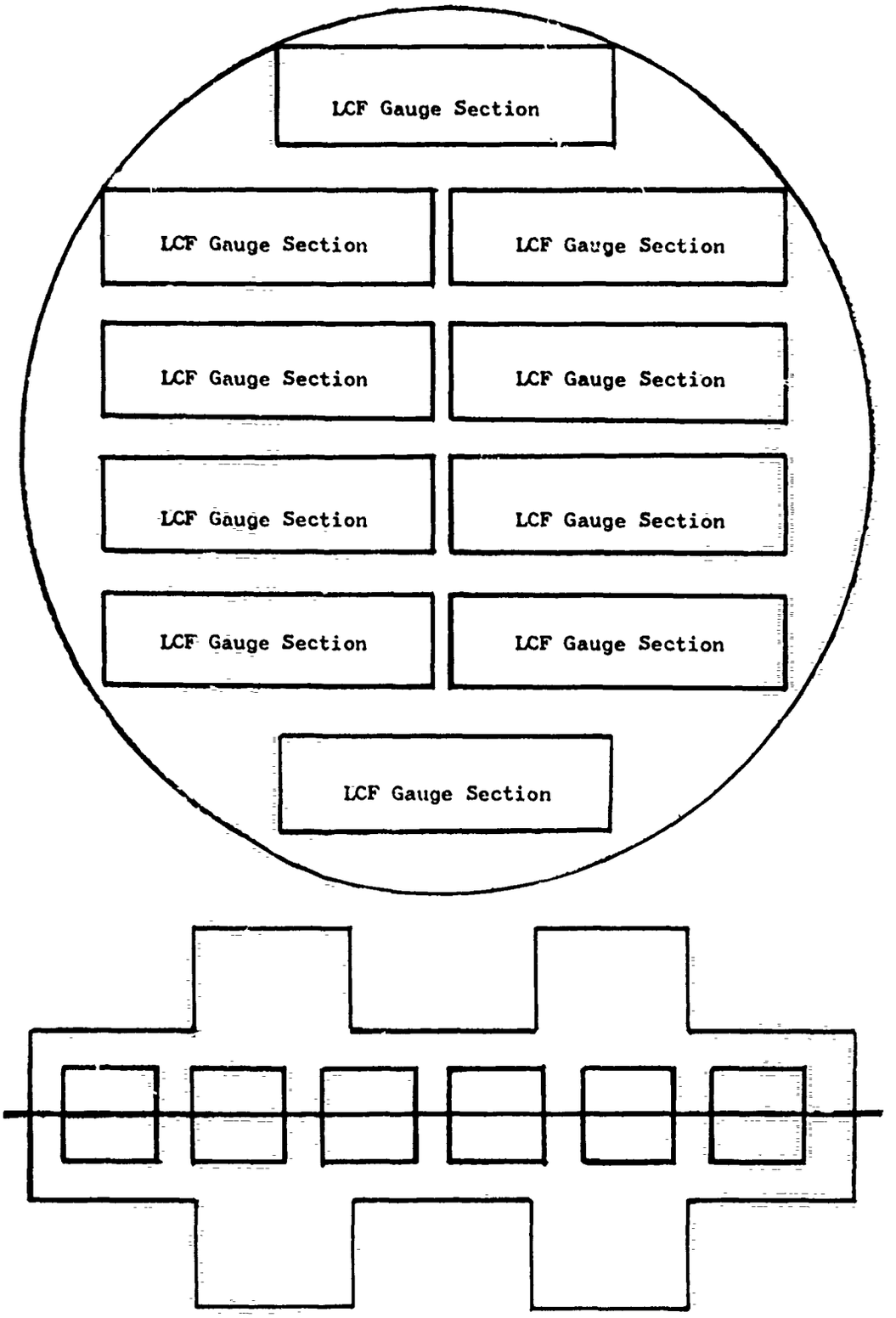


Figure 101. Task III Turbine Disk LCF Specimen Locations (6 Disks).

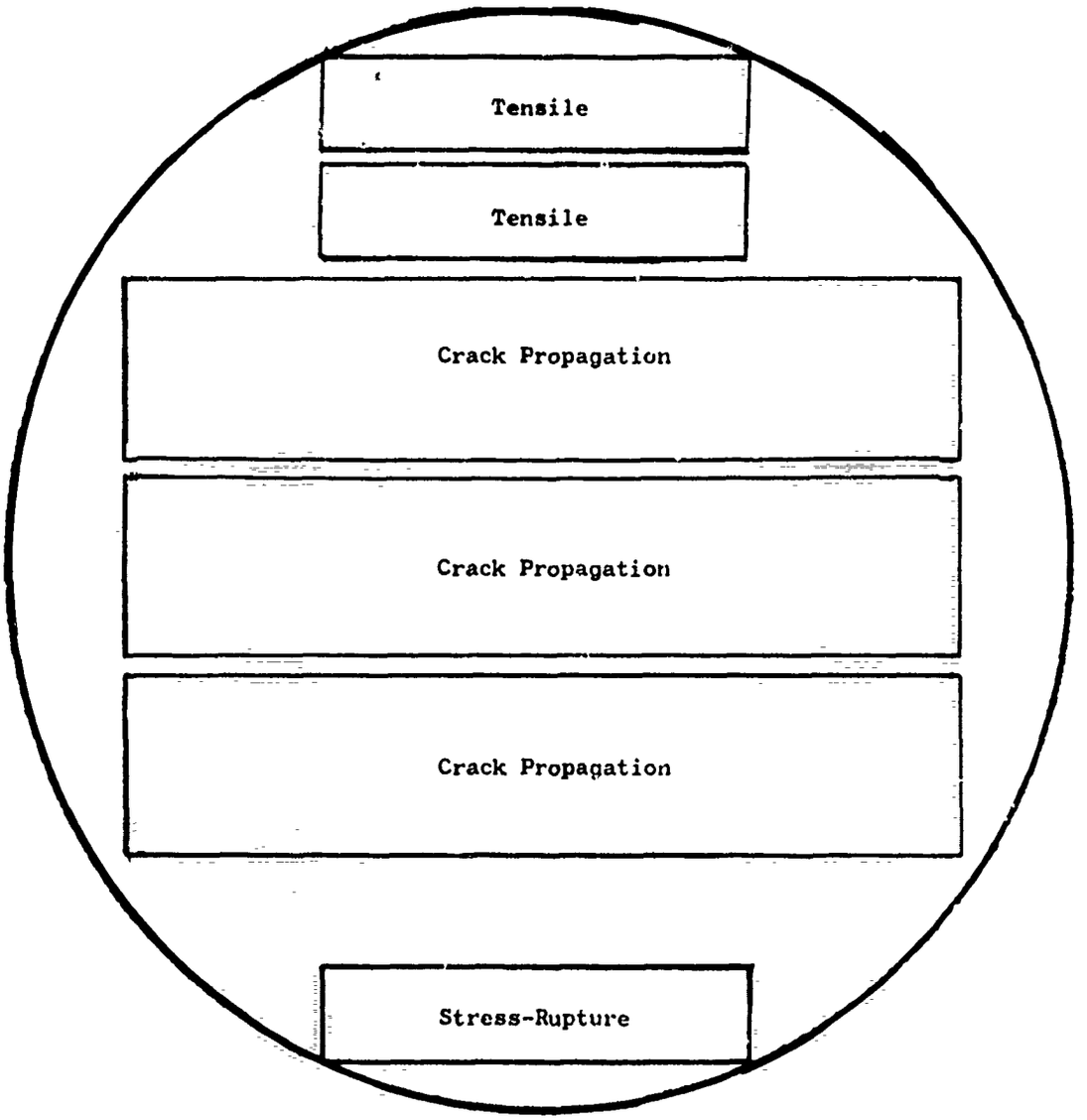


Figure 102. Task III Thermal Exposure (1200°F/1000 hr) Turbine Disk Specimen Location (1 Disk).

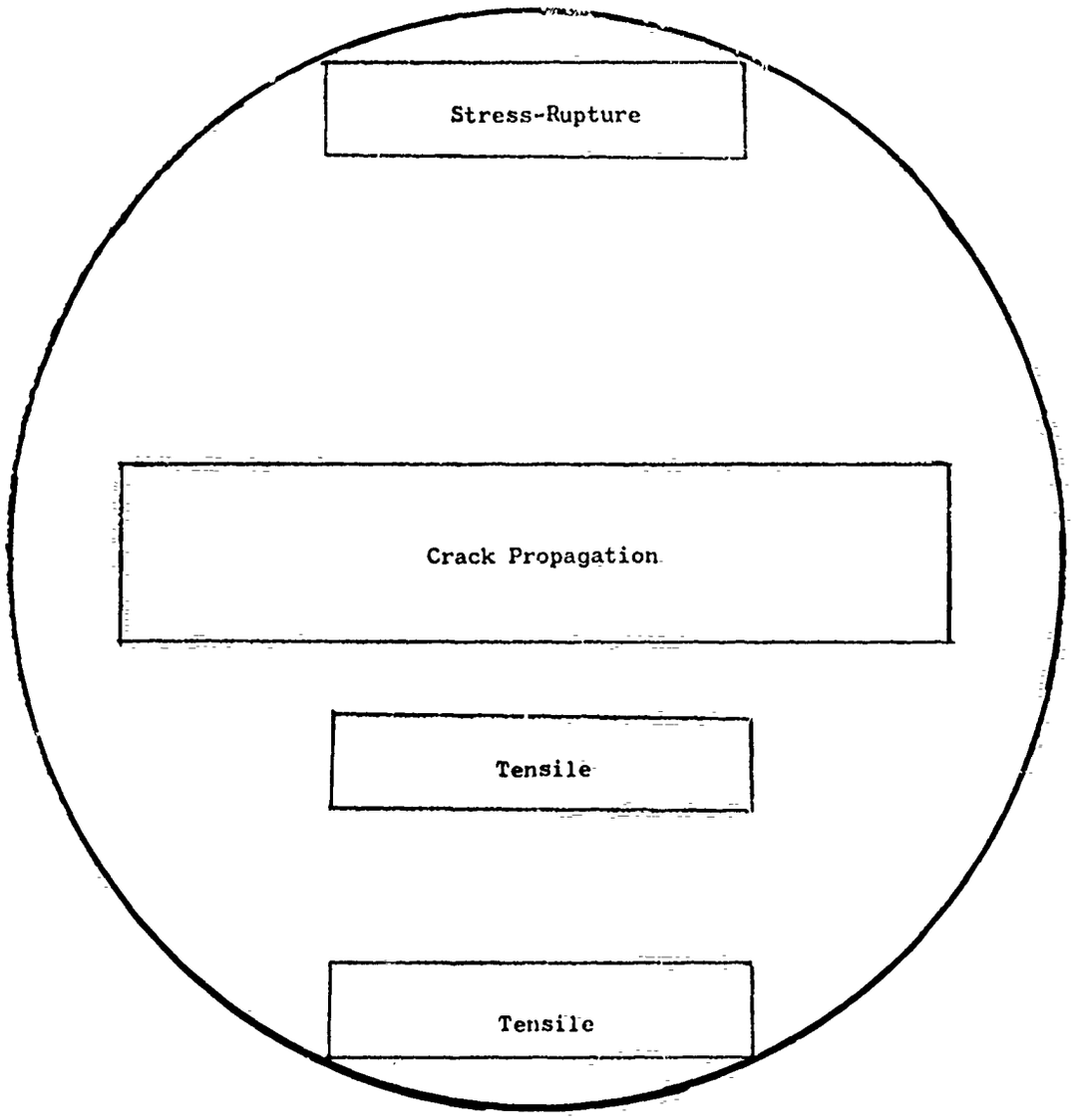


Figure 103. Task III Thermal Exposure (1200°F/1000 hr) Turbine Disk Specimen Location (1 Disk).

Sustained Peak Low-Cycle Fatigue (SPLCF) results were compared to HIP + forge data at the same test conditions in Table 87. Data from the cooling plate specimens appeared to be somewhat lower than expected, probably due to the slow air cool their parts received during the heat treatment. However, the small number of test results and the substantial amount of data scatter generally associated with the SPLCF test made any conclusions tenuous at best.

High-cycle fatigue data from cooling plate components, presented in Table 88, were slightly below the results from HIP + forge turbine disk hardware at relatively low cyclic lives. Comparative data was not obtained at lives of more than 10^6 cycles.

As-HIP crack propagation test data at 1000°F on turbine disk hardware compared favorably with HIP + forge results as shown in Table 89. Residual lives at maximum test stresses above and below 100 ksi also indicated consistent, predictable behavior. Testing was also completed on two As-HIP disks subjected to a 1200°F/1000-hour thermal exposure. Results, also presented in Table 89, indicated no degradation of residual cyclic life due to the thermal exposure.

The Low-Cycle Fatigue data from the disks is presented in Tables 90 and 91 and Figures 104 through 107. It suggests that the low-cycle fatigue properties of As-HIP material to be essentially equivalent to those of HIP + Forge hardware. These results confirm the similar conclusions drawn from the meager Task II data.

The stress-rupture results presented in Figure 108 and Table 92 indicate the same trends noted in Task II. Rupture lives at test stresses above approximately 130 ksi are approximately 0.5 parameters below average HIP + forge data. This effect is probably associated with the lower 0.2 percent yield strength of As-HIP material relative to the HIP + Forge product. However, at stresses below 130 ksi, As-HIP rupture lives are at least equivalent to HIP + Forge values. Rupture ductilities were somewhat erratic but acceptable over the total temperature range.

Creep results, presented in Figure 109 and Table 93, suggest properties of As-HIP material are at least equivalent to those of HIP + forge parts at all stress levels and temperatures tested. The Task III results also confirm preliminary trends noted in Task II.

Design Curves

Statistically analyzed design curves were prepared from the Crucible Task III disk and cooling plate data and appear in Figures 110 through 119.

Tensile

All tensile properties were analyzed using heat separation and fit to a power series equation. Heats were defined as master powder blends and, due to the limited amount of data available, no attempt was made to define the effect of material section size on properties. After analysis, the curve shapes were compared to a second set of As-HIP curves which incorporate a much larger body of data. The 0.2% yield strength (Figure 110), elongation (Figure 111), and reduction of area (Figure 112), curves closely resembled the master curves, but a minor adjustment in the ultimate tensile strength curve (Figure 113) was made (the 1000°F UTS was decreased by ~5 KSI) to make its shape similar to that defined by previous testing of a wide variety of As-HIP components. Since the effect of section size was not analyzed, the standard deviation associated with all properties is somewhat larger than would be expected when a section size correction factor is incorporated.

Both the 0.2% yield and ultimate strength curves indicate the lower strength and higher ductility of Task III components relative to HIP + forge material. Modification of the heat treat procedure should reduce the strength differences between the materials significantly.

TABLE 86. TENSILE RESULTS FROM TASK III DESIGN DATA VENDOR A HARDWARE

Component	S/N	Thickness (in.)	Test Temp (°F)	0.2 YS (ksi)	UTS (ksi)	EL (%)	RA (%)
Cooling Plate	COL 10042	0.75	400	167	223	10.1	13.4
Cooling Plate	COL 10057	1.25	400	164	225	13.8	14.5
Cooling Plate	COL 10038	1.25	800	166	222	15.0	14.0
Cooling Plate	COL 10042	0.75	800	167	226	15.6	16.2
Cooling Plate	COL 10050	1.25	800	163	220	13.9	15.8
Cooling Plate	COL 10057	1.25	800	166	224	17.3	17.8
Cooling Plate	COL 10042	0.75	1000	163	229	15.8	15.0
Cooling Plate	COL 10057	1.25	1000	161	225	14.6	16.0
Cooling Plate	COL 10038	1.25	1300	153	190	12.7	17.1
Cooling Plate	COL 10050	1.25	1300	153	184	11.1	17.1

TABLE 87. SPLCF RESULTS FROM VENDOR A TASK III DESIGN DATA HARDWARE

Fabrication Process	Component	S/N	Thickness (in.)	Test Temp (°F)	Max. Stress (ksi)*	Cycles to Failure (N_f)
As-HIP	Cooling Plate	COL 10038	1.25	1000	200	497
HIP + Forge	Disk	121	–	1000	200	696
As-HIP	Disk	COL 10014	–	1000	180	901
HIP + Forge	Disk	121	–	1000	180	1111
As-HIP	Cooling Plate	COL 10050	1.25	1000	160	804
HIP + Forge	Disk		–	1000	160	2312
As-HIP	Disk	COL 10020	–	1200	155	317
As-HIP	Cooling Plate	COL 10057	1.25	1200	140	428
As-HIP	Cooling Plate	COL 10042	0.75	1200	135	612

*All specimens tested with K_t = 2.0 and A = 0.95.

TABLE 88. 1000°F HIGH-CYCLE FATIGUE RESULTS FROM TASK III VENDOR A HARDWARE

Component	Process	S/N	Thickness (in.)	Alternating Stress (ksi)	Life Cycles X 10^3
Cooling Plate	As-HIP	COL 10038	1.75	75	102
Turbine Disk	HIP + Forge	22A	–	75	216
Cooling Plate	As-HIP	COL 10042	1.25	65	281
Turbine Disk	HIP + Forge	121	–	65	373
Cooling Plate	As-HIP	COL 10050	1.75	60	449
Cooling Plate	As-HIP	COL 10057	1.75	55	920

Load controlled axial-axial testing A = 0.95

K_t = 1.0 frequency = 3600 cpm

TABLE 89. 1000°F CRACK PROPAGATION RESULTS FROM TASK III VENDOR A HARDWARE

Component	Process	S/N	Nominal Initial Fatigue Crack		Max. Stress (ksi)	Residual Life (Cycles)
			Length (in.)	Depth (in.)		
Disk	As-HIP	COL 10014	0.060	0.020	80	17,337
Disk	As-HIP	COL 10021*	0.059	0.021	80	18,323
Disk	As-HIP	COL 10014	0.061	0.023	100	7,034
Disk	As-HIP	COL 10020	0.059	0.021	100	7,745
Disk	As-HIP	COL 10013*	0.065	0.023	100	8,253
Disk	As-HIP	COL 10021*	0.060	0.022	100	8,584
Disk	HIP + Forge	4 Tests	0.060	0.020	100	7,200–10,900
Disk	As-HIP	COL 10020	0.063	0.023	118.5	4,718
Disk	As-HIP	COL 10013*	0.061	0.022	118.5	4,953

A ratio = 0.95

Frequency = 20 cpm

All specimens precracked at room temperature

*Subjected to 1200°F/1000 hr thermal exposure

TABLE 90. STRAIN CONTROL LOW-CYCLE FATIGUE DATA FROM VENDOR A TASK III DISKS

Disk Number	Test Temperature (°F)	Strain Range	Alternate Pseudo Stress (ksi)	Cycle to Failure
1011-4	900	1.4	192.8	2,035
1022-4	900	1.15	158.4	5,142
10022-3	900	1.0	137.7	9,016
10023-4	900	0.92	126.7	12,024
10023-5	900	0.85	117.0	14,112
10011-5	900	0.85	117.0	10,312
10022-5	900	0.8	110.2	58,796
10023-3	900	0.8	110.2	60,756
10011-1	1200	1.1	143.2	2,170
10022-1	1200	1.0	130.1	2,976
10022-2	1200	1.0	130.1	2,846
10023-1	1200	0.9	117.1	7,228
10011-2	1200	0.8	104.1	32,945
10011-3	1200	0.75	97.6	228,512

TABLE 91. LOAD CONTROL LOW-CYCLE FATIGUE DATA FROM VENDOR A TASK III DISKS

Disk Number	Test Temperature (°F)	Notch Severity	Maximum Stress (ksi)	Cycle to Failure
10023-7	1050	1.2	244.4	253
10011-6	1050	1.2	200	2,110
10011-7	1050	1.2	190	6,205
10023-6	1050	1.2	180	7,090
10022-7	1050	1.2	175	61,585
10023-8	1050	1.2	170	162,494
10022-9	1250	1.85	170	1,667
10011-8	1250	1.85	160	4,625
10023-9	1250	1.85	160	2,598
10022-8	1250	1.85	150	2,829
10011-10	1250	1.85	150	2,319
10023-10	1250	1.85	140	6,191
10011-9	1250	1.85	130	10,884
10022-10	1250	1.85	125	65,088

TABLE 92. STRESS RUPTURE PROPERTIES OF VENDOR A TASK III HARDWARE

Idenity	Shape	Test Temperature (°F)	Stress (ksi)	Time to 0.1% Creep (hr)	Time to 0.2% Creep (hr)	Rupture Life (hr)	El %	RA %
10042	Cooling Plate**	1100	165	2.5	9	254.1	4.8	4.1
10014	Disk	1100	170	-	-	236.4	9.4	13.5
10038	Cooling Plate	1200	125	120.0	180	1280.7	3.8	6.7
10020	Disk	1200	140	3.0	9	179.3	5.8	10.1
10021	Disk*	1200	150	-	-	72.2	9.1	11.9
10013	Disk*	1200	150	-	-	53.6	7.2	12.7
10050	Cooling Plate	1200	155	-	-	27.3	5.8	9.1
10057	Cooling Plate	1300	85	23.0	50	688.0	3.3	3.7
10038	Cooling Plate	1300	100	6.5	14	202.3	5.8	5.1
10014	Disk	1300	115	-	-	112.3	9.3	12.4
10050	Cooling Plate	1400	65	6	15	101.6	2.7	1.7
10020	Disk	1400	80	-	-	43.6	4.5	5.6

*Thermally Exposed (1200°F/1000 hr)

**Thin Cooling Plate (3/4 inch)

TABLE 93. CREEP PROPERTIES OF VENDOR A TASK III HARDWARE

Idenity	Shape	Test Temperature (°F)	Stress (ksi)	Time to 0.1% Creep (hr)	Time to 0.2% Creep (hr)
10014	Disk	1100	150	245	915
10042	Cooling Plate*	1100	140	600	1420
10050	Cooling Plate	1200	95	770	1280
10038	Cooling Plate	1200	100	440	720
10020	Disk	1200	110	160	310
10050	Cooling Plate	1300	55	400	910
10042	Cooling Plate*	1300	60	90	320
10057	Cooling Plate	1300	65	90	280
10057	Cooling Plate	1400	40	34	74
10038	Cooling Plate	1400	50	18	48

*Thin cooling plate (3/4 in)

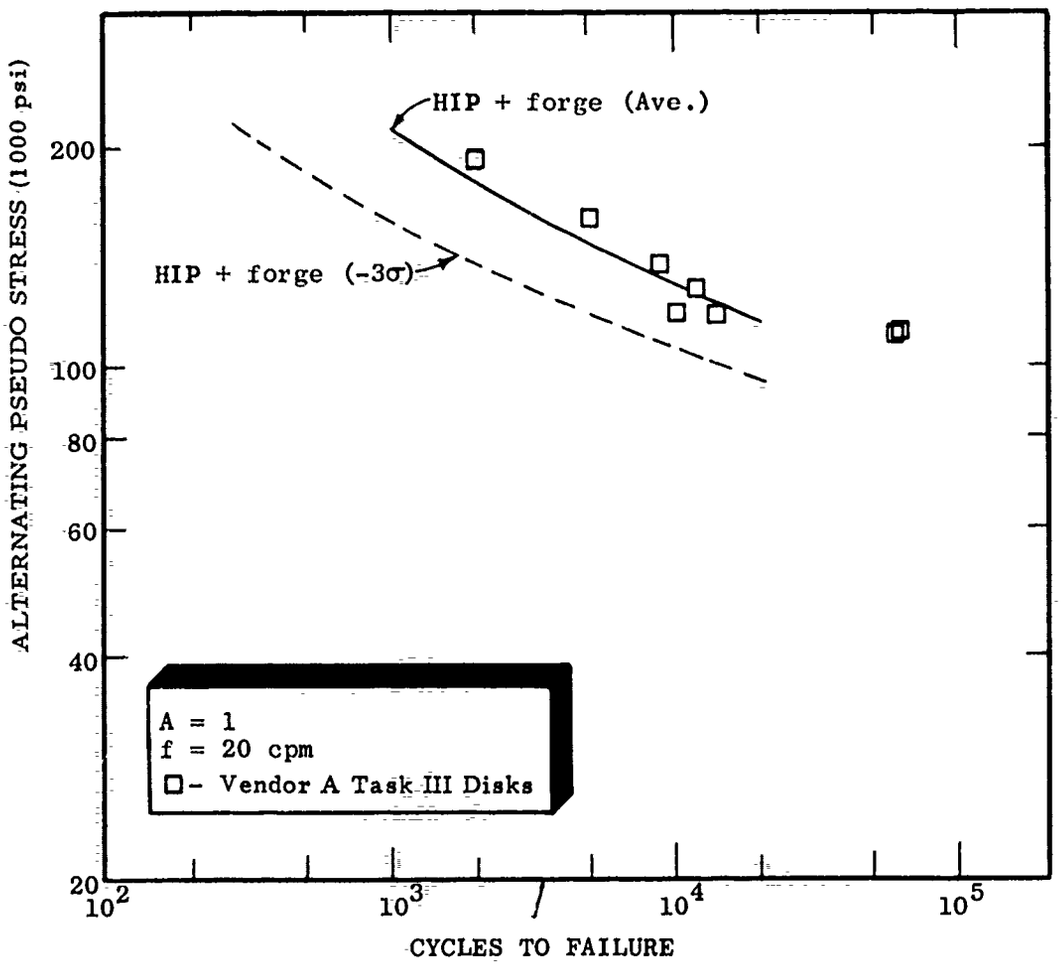


Figure 104. 900°F Strain Control Low-Cycle Fatigue Data From Vendor A Task III Disks Compared to T-700 HIP + Forge Results.

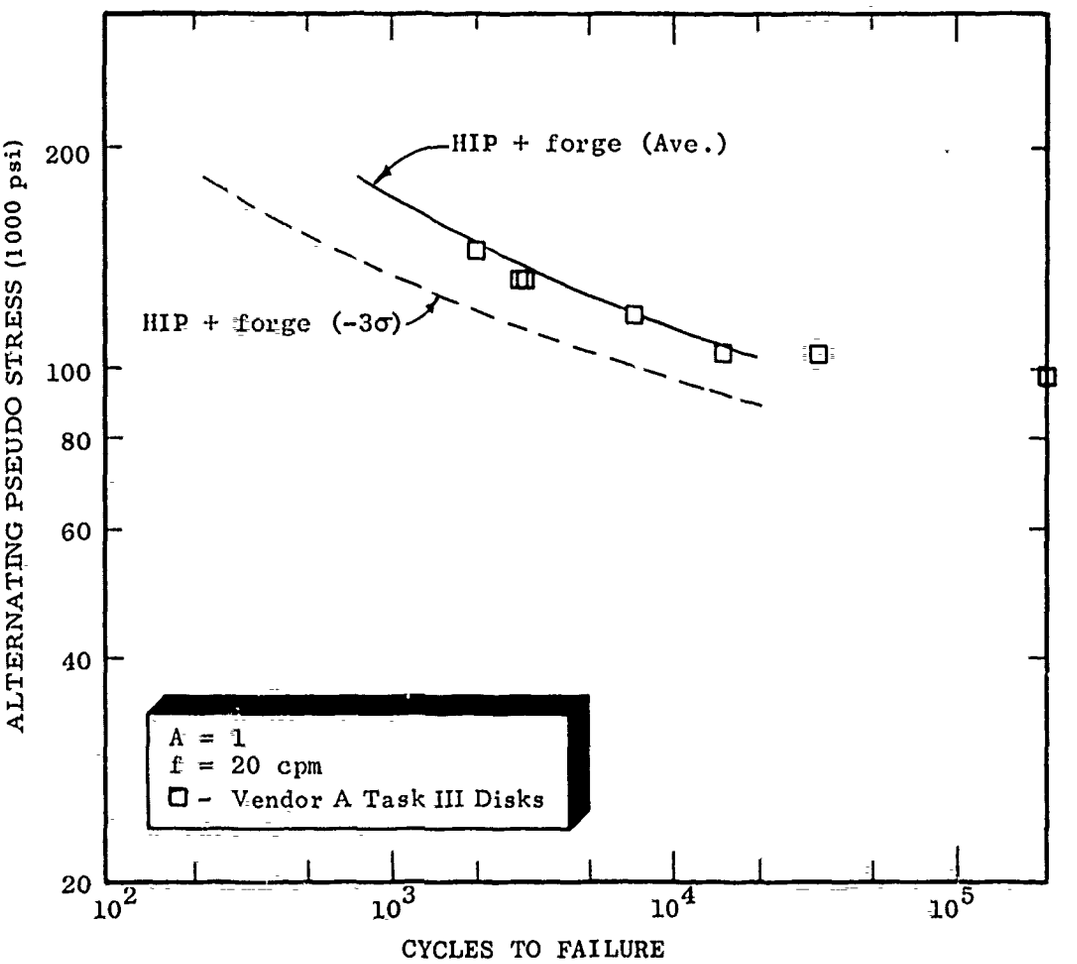


Figure 105. 1200°F Strain Control Low-Cycle Fatigue Data From Vendor A Task III Disks Compared to T-700 HIP + Forge Results.

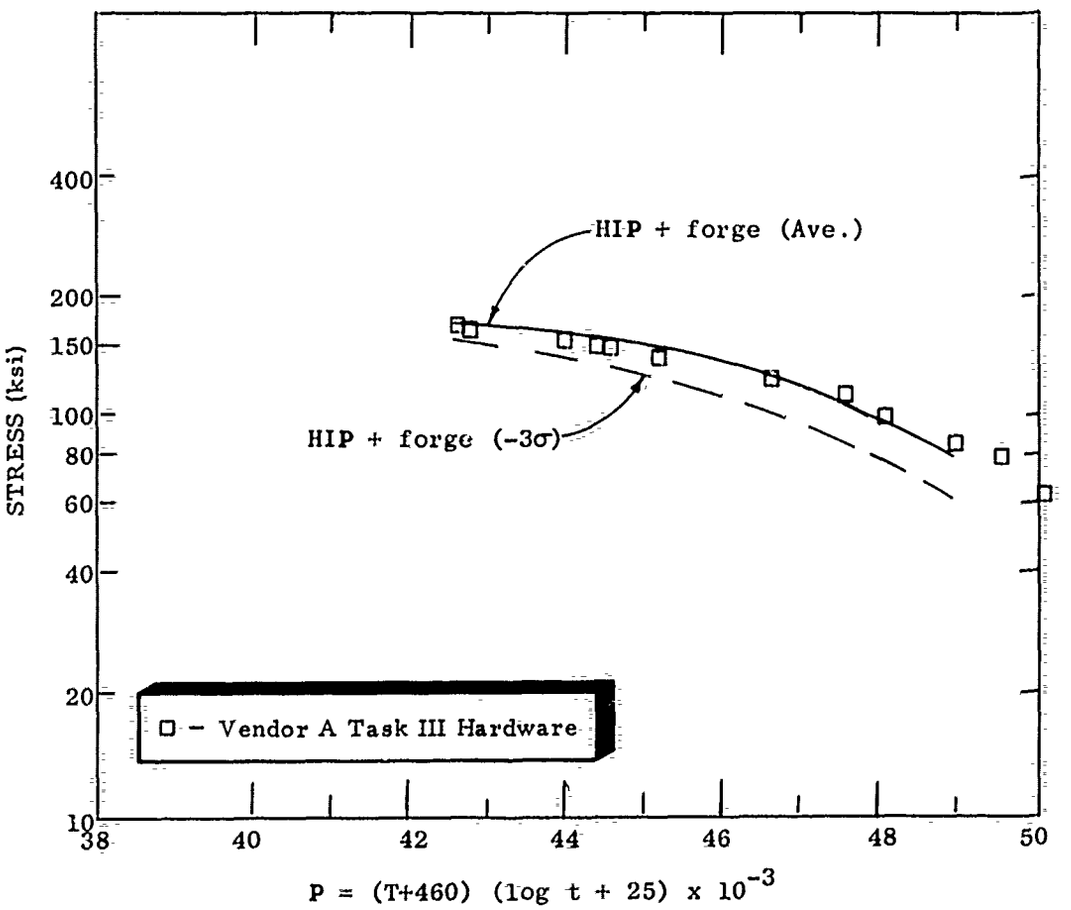


Figure 106. Stress Rupture Data From Vendor A Task III Hardware Compared to T-700 HIP + Forge Results.

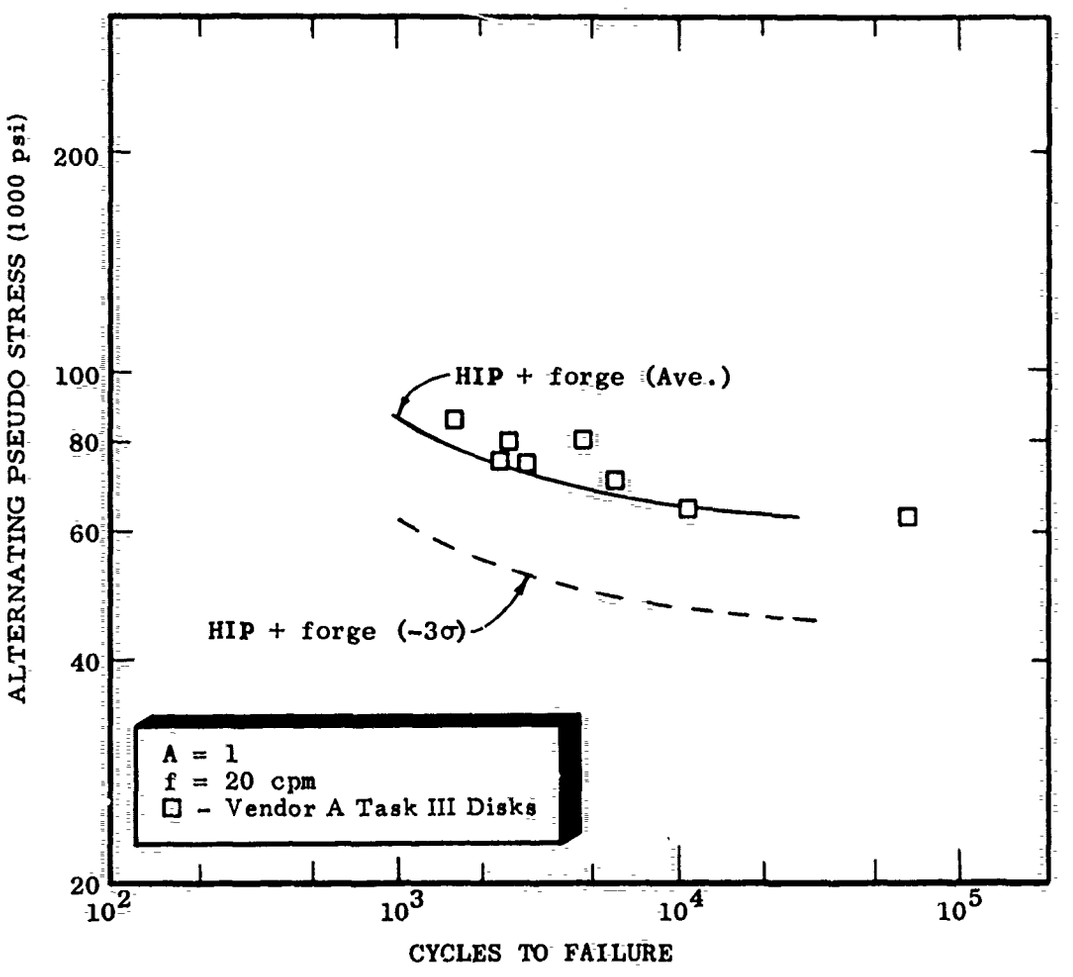


Figure 107. 1250°F Load Control (K_t = 1.85) Low-Cycle Fatigue Data From Vendor A Task III Disks Compared to T-700 HIP + Forge Results.

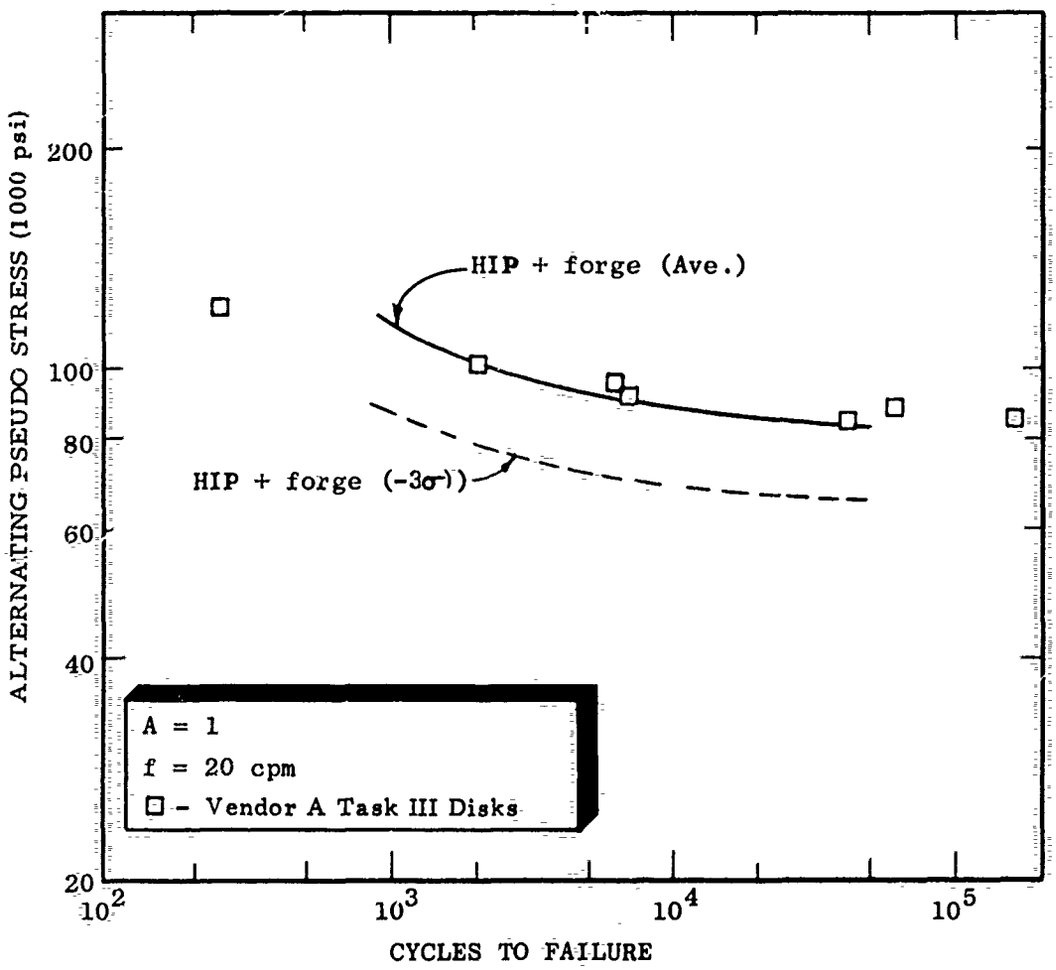


Figure 108. 1050°F Load Control (K_t = 1.2) Low-Cycle Fatigue Data From Vendor A Task III Disks Compared to T-700 HIP + Forge Results.

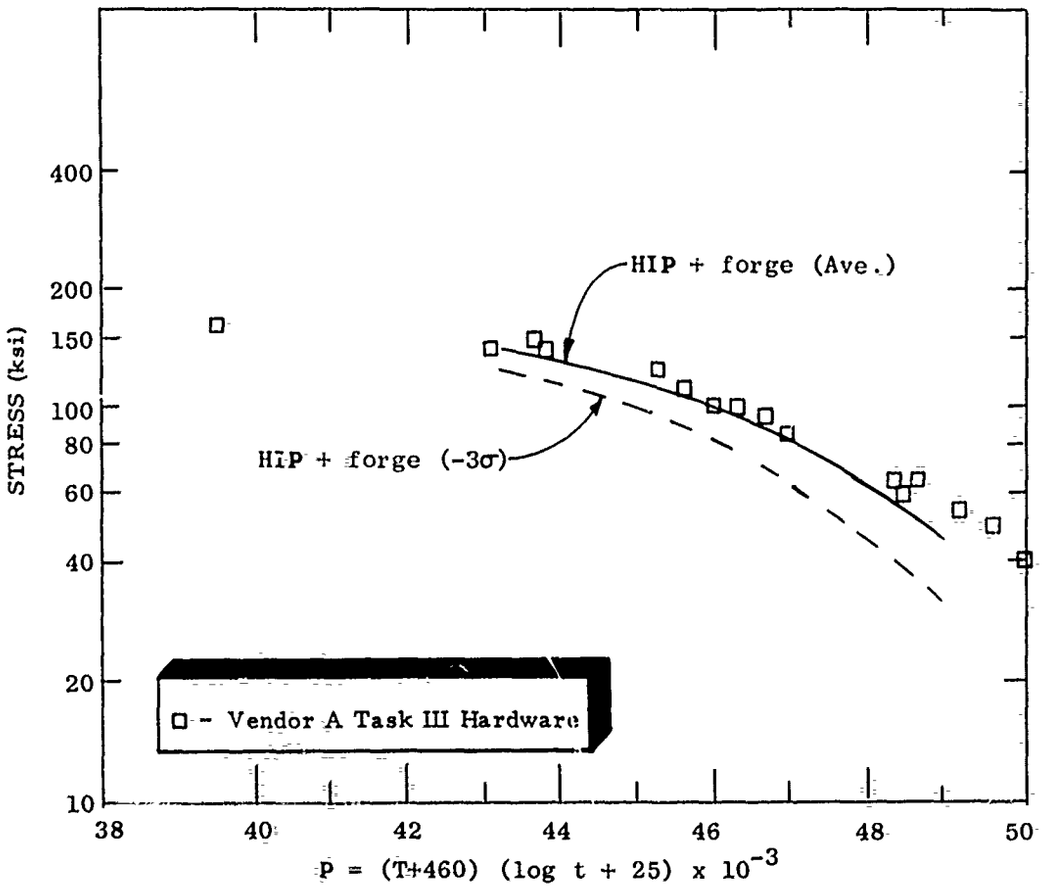


Figure 109. 0.2% Creep Data From Vendor A Task III Hardware Compared to T-700 HIP + Forge Results.

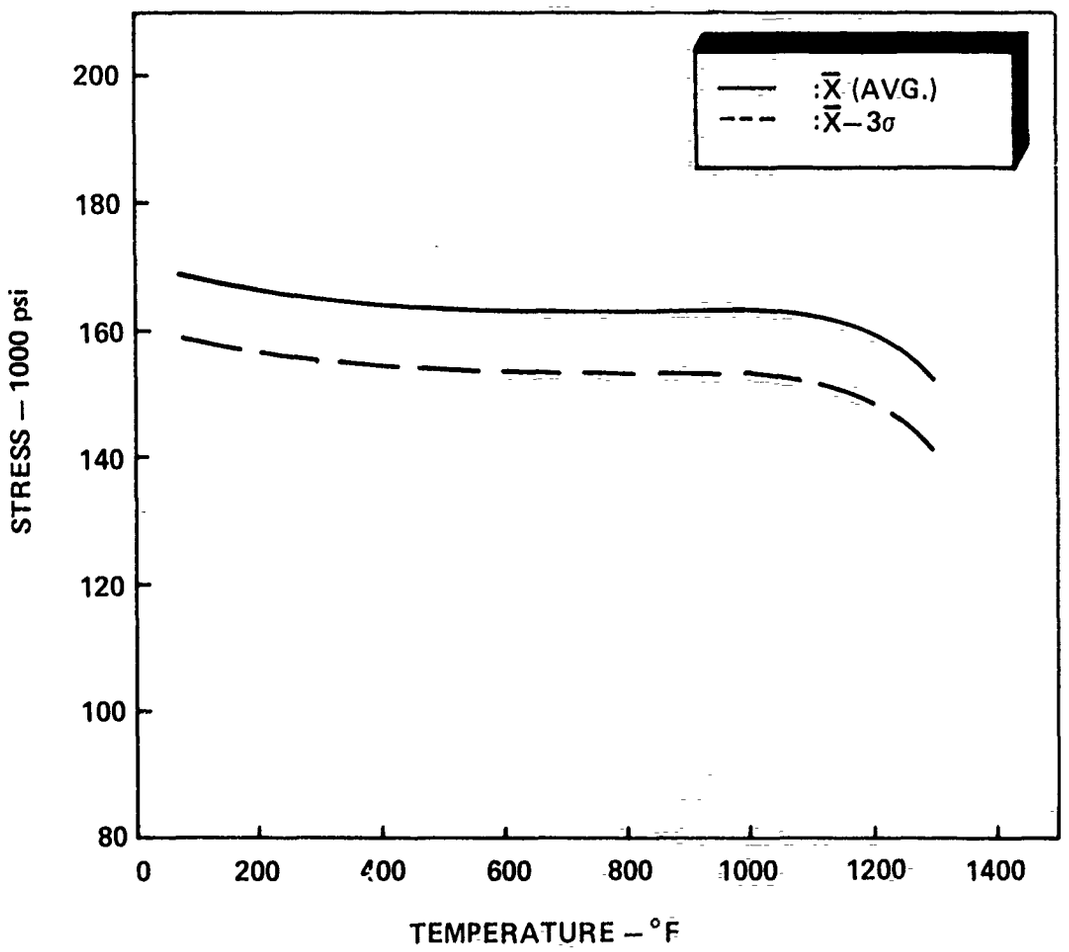


Figure 110. Design Curve for 0.2 Percent Yield Strength Data

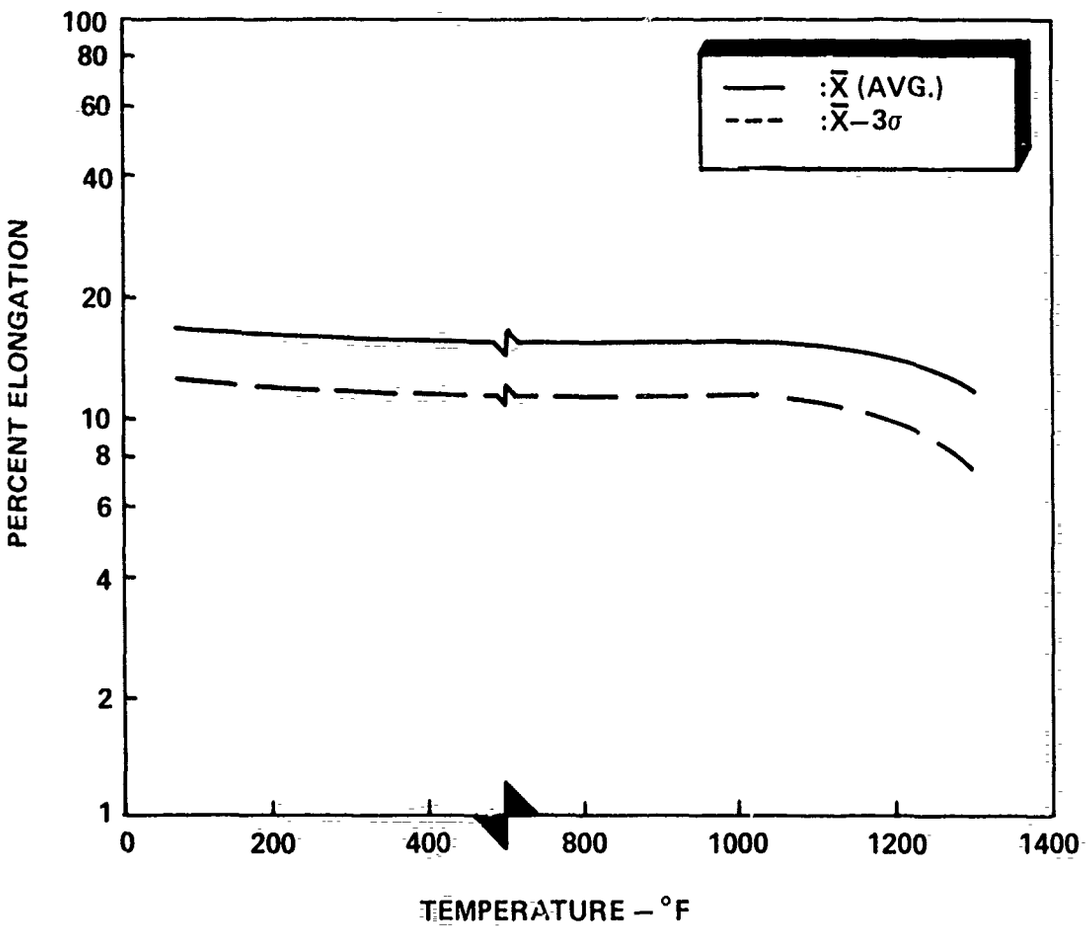


Figure 111. Design Curve for Percent Elongation Data

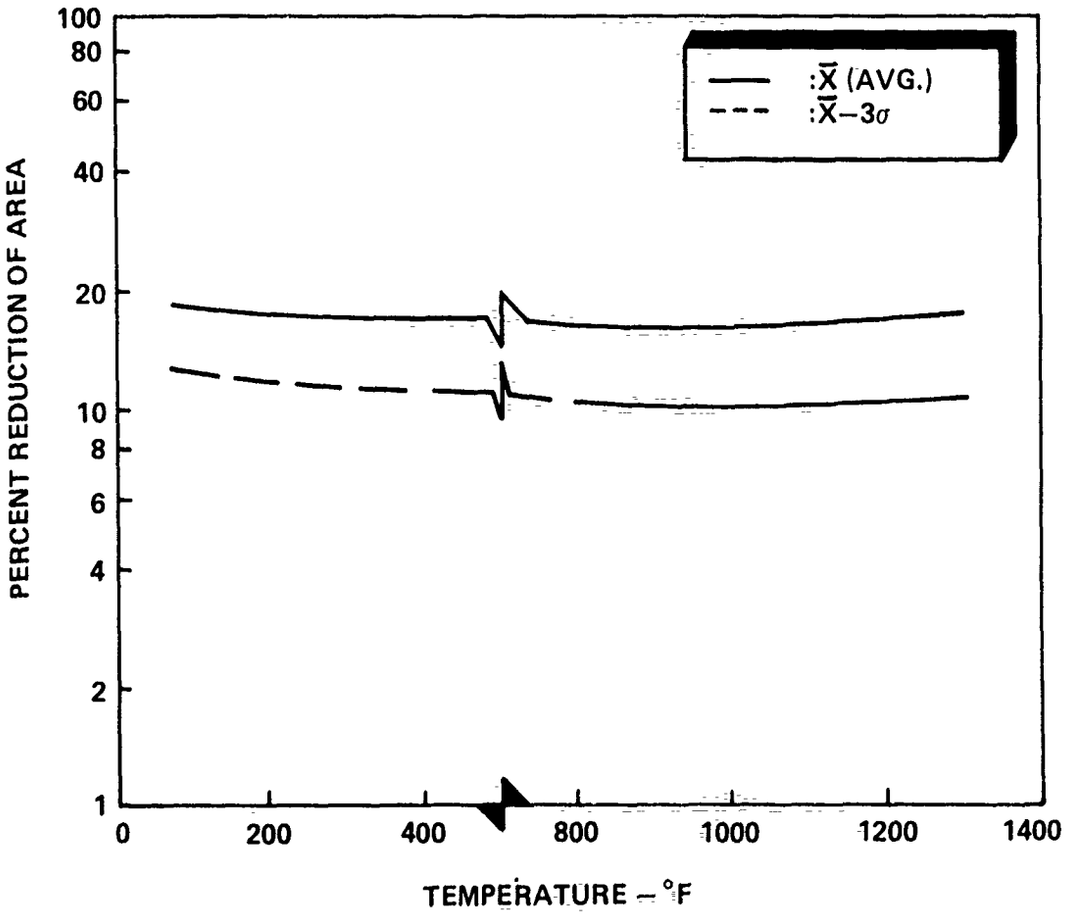


Figure 112. Design Curve for Reduction in Area Data

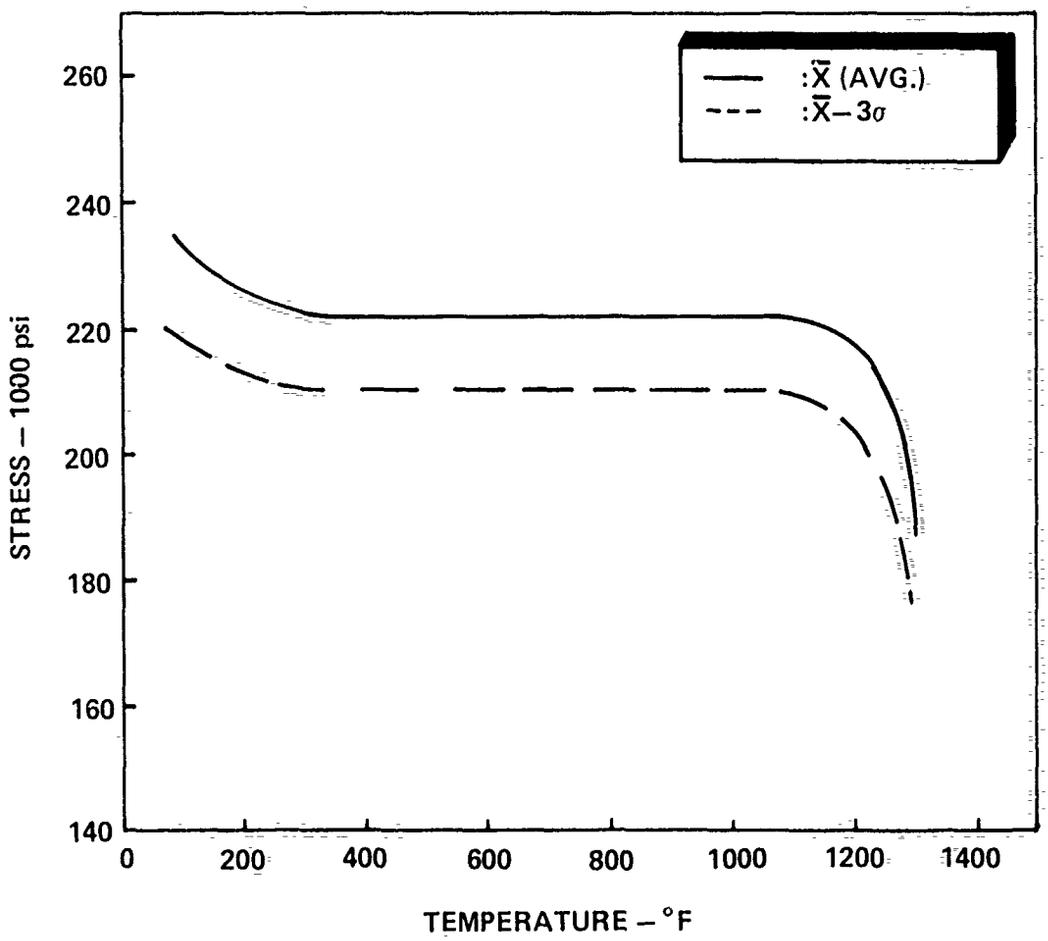


Figure 113. Design Curve for Ultimate Tensile Strength Data

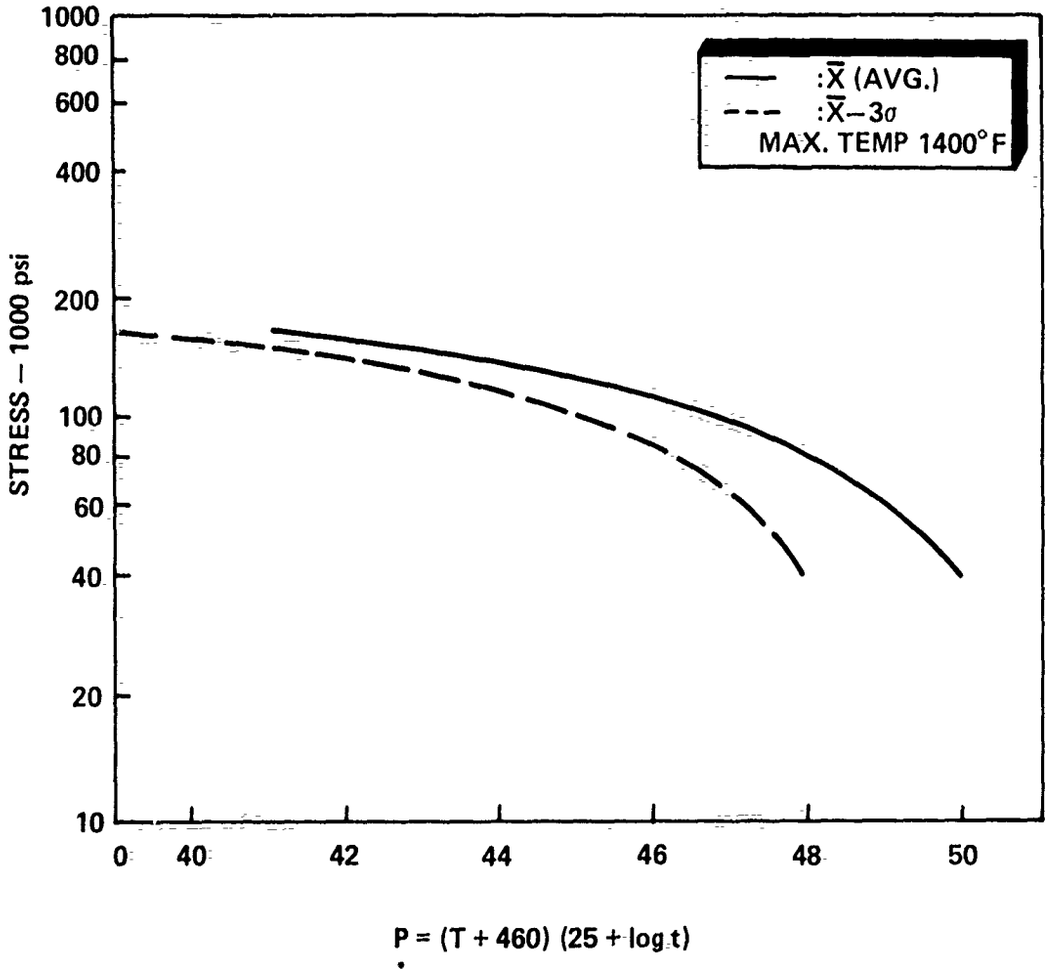


Figure 114. Design Curve for 0.2 Percent Plastic Creep Data

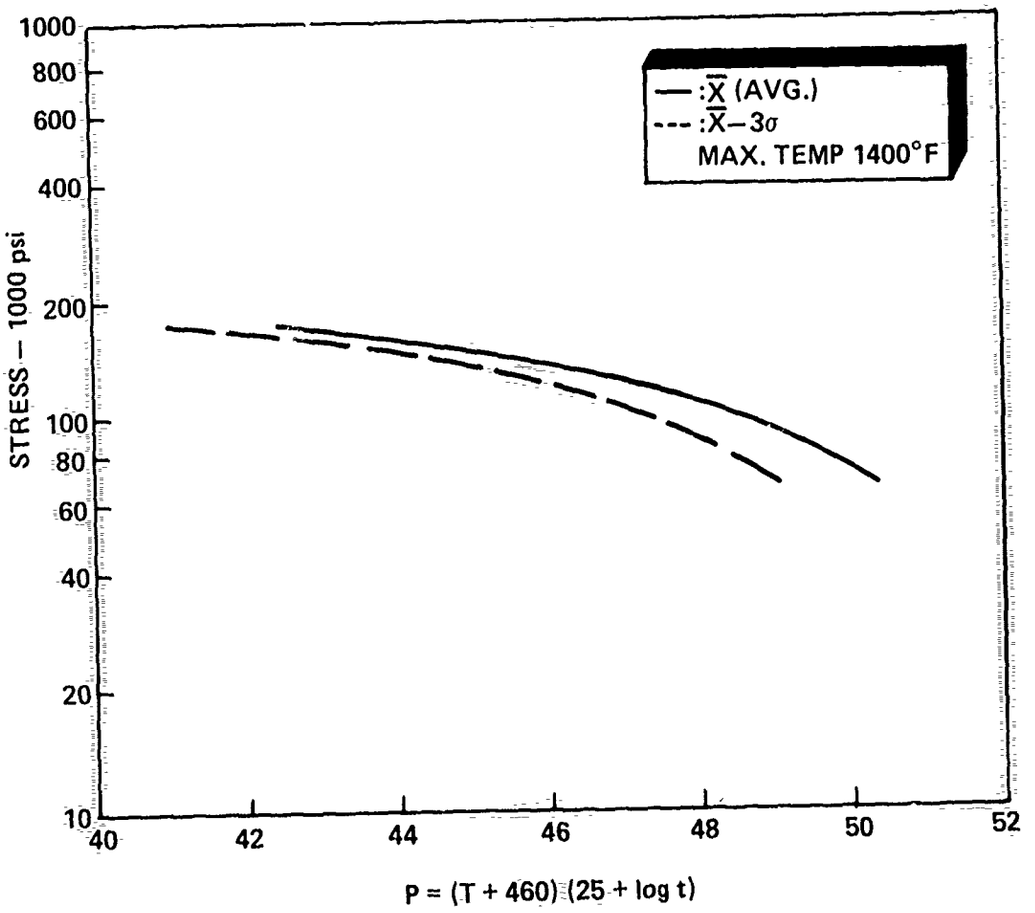


Figure 115. Design Curve for Stress Rupture Data

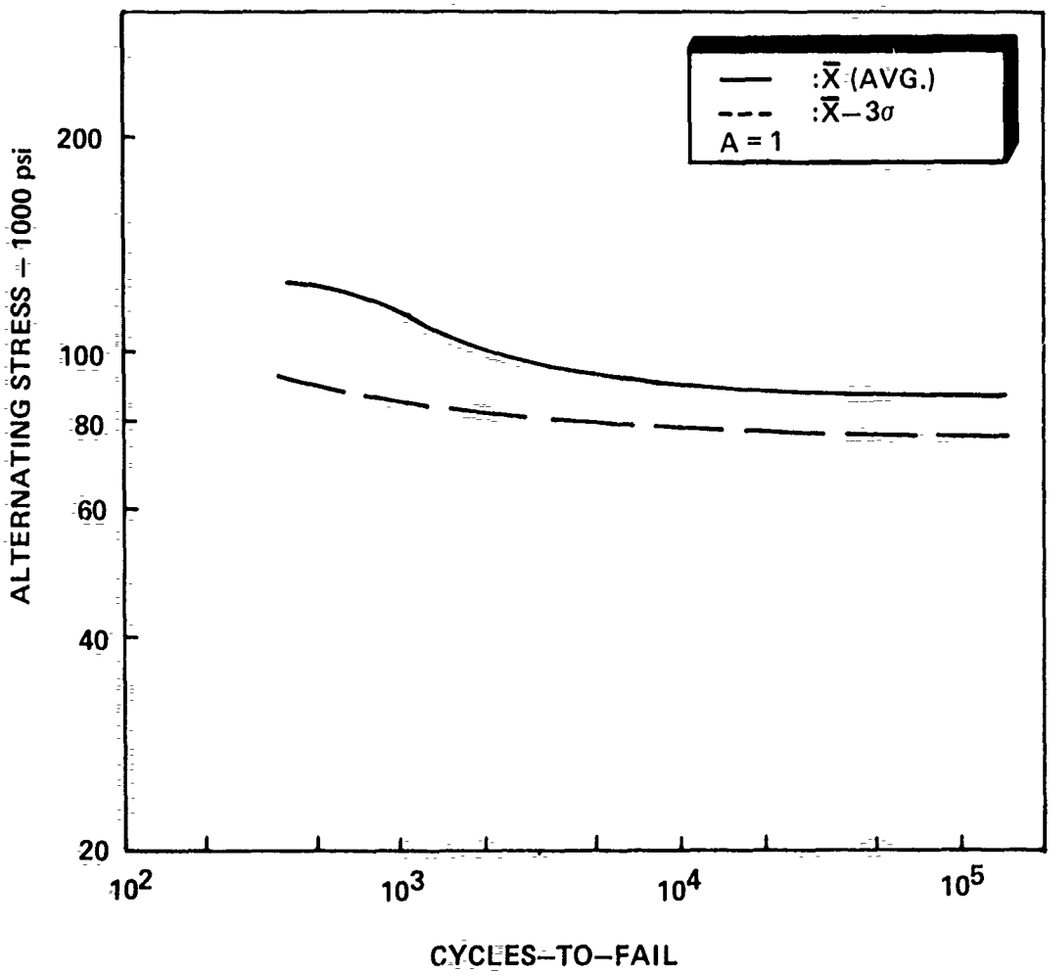


Figure 116. Design Curve for 1050°F Load Control (K_t = 1.2) Low-Cycle Fatigue Data

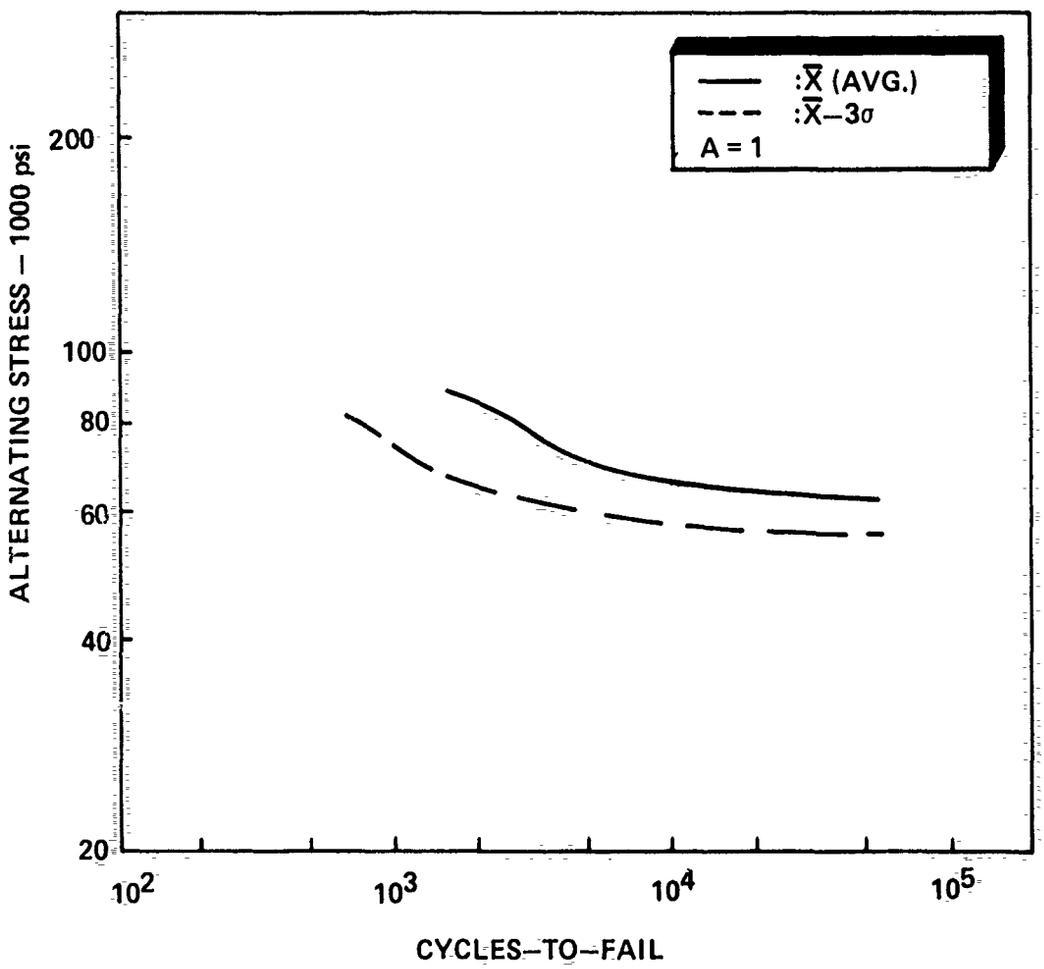


Figure 117. Design Curve for 1250°F Load Control (K_t = 1.85) Low-Cycle Fatigue Data

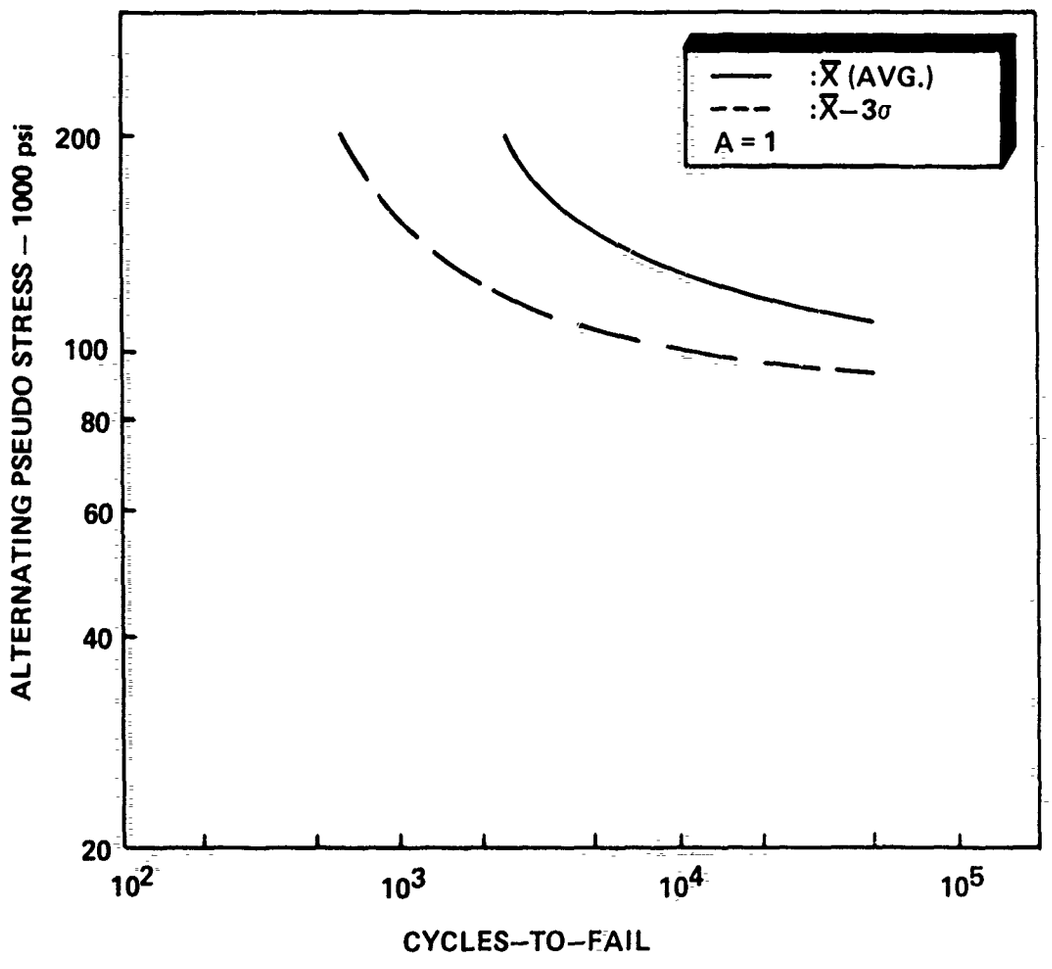


Figure 118. Design Curve for 900°F Strain Control Low-Cycle Fatigue Data

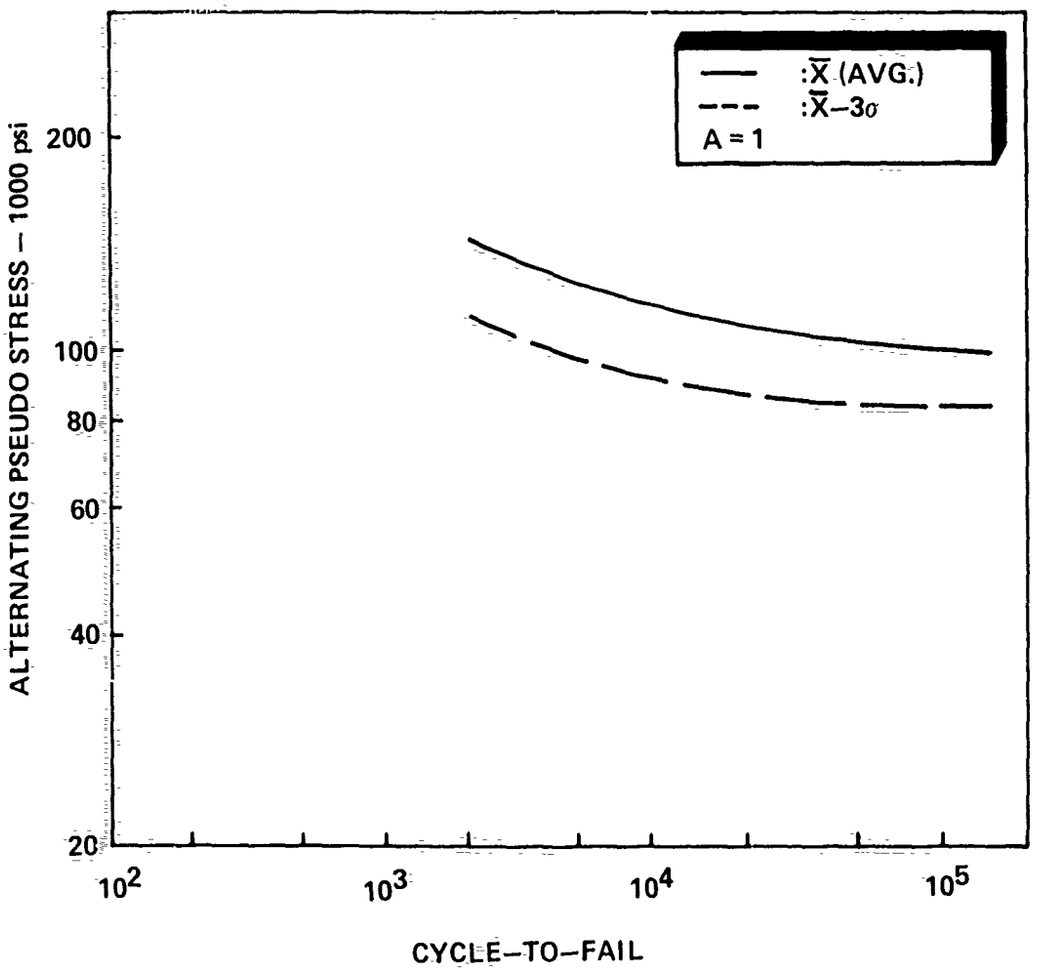


Figure 119. Design Curve for 1200°F Strain Control Low-Cycle Fatigue Data

Creep and Rupture

All data were computer fit on an isothermal basis and a best fit Larson-Miller constant was calculated. The constants in both creep and rupture were very close to 25, the value used for conventional and HIP + forge Rene' 95 analyses. Again, no section size correction was attempted but the effect on standard deviation is not as pronounced as observed in the ultimate tensile strength curve. Both curves (Figures 114 and 115) are identical to those derived from previous As-HIP data. When compared to the HIP + forge results, the Task III rupture data are slightly inferior at high stress levels (> 140 KSI) but somewhat superior at lower stresses. The Task III creep results are superior to HIP + forge data, especially at lower test stresses (or higher test temperatures).

Low-Cycle Fatigue

Load control (notched) fatigue data were fit to either a cubic or quadratic function of stress and a maximum stress boundary condition of UTS/2 was forced on the model to define curve shapes. Although the curve shape is slightly different than the corresponding HIP + forge results, the notched LCF capability of Task III material (Figures 116 and 117) is equivalent or slightly superior at both test temperatures and notch severities evaluated.

Strain controlled data were analyzed using a slightly different model than that employed on the load control results. The resulting curves at both 900 and 1200°F (Figures 118 and 119) indicate virtually identical capability to previously evaluated HIP + forge T-700 hardware.

Quality Control

In addition to supervising a strict conformance to the Process Control Plans (Appendix II) and Product Acceptance Plans (Appendix III), the Quality Control of General Electric Company was extended to establish procedures and organization, to develop techniques for better assurances, and to aid in vendor conformance to total quality plan.

In conformance with General Electric Specification P1TF35, both vendors were assisted in developing a quality control organization for their Powder Metallurgy operations. These QC organizations have developed a detailed process definition which has been approved and thus confined to the rigorous change control procedure of General Electric. Any change or diversion from the prescribed process definition must meet with General Electric Company's approval.

All the significant operations by each vendor and their subcontractors were witnessed by qualified GE personnel to check conformance to the process definition. This, of course, was preceded by the signing of a mutual nondisclosure agreement between the General Electric Company and the two vendors. The calibration of all the testing equipment and standardization and conformance to ASTM specification of specimen machining source was insured by GE's Quality Control.

Several improvements in vendor facilities were suggested and incorporated to insure adequate processing and thus the integrity of hardware. A few significant changes are listed below.

- Both vendors constructed enclosures around powder atomizer unloading area.
- A clean room was constructed by both vendors to perform screening and blending of powder.
- A separate clean room was constructed to fabricate metallic cans.

Improved and frequent inspection procedures were also adopted by the vendors as well as the General Electric Company to enhance the quality assurance. Following are the highlights:

- A magnetic separator has been incorporated in the powder handling to effectively remove any undesirable magnetic particles.
- A visual examination of sample powder from each heat has been added.
- Each part is required to be macro etched and subjected to ultrasensitive Fluorescent Penetrant Inspection with hydrophylic emulsifier to detect any surface cracks or defects.
- An additional ultrasonic inspection with increased sensitivity (12 dB) was added for extra assurance.

It is noteworthy that the above-mentioned inspection is neither required nor performed on the current T700 turbine hardware made from forgings using powdered Rene′95 preforms.

As a direct result of the knowledge gained in this program, General Electric Company has now prepared specifications for PM Rene′95 HIP hardware in production quantities. The two specifications "Manufacture of Premium Rene′95 Powder" and "Hot Isostatic Pressing of Rene′95 Alloy Powder" are included in Appendix I. A Quality Control plan for the acceptance of T700 HIP Rene′95 production hardware now exists at the General Electric Quality Control and is the basic requirement for the source substantiation and eventual procurement of production hardware.

For future procurement of the disks and cooling plates from powder metallurgy vendors, the corresponding General Electric approved drawings (17A116-554 and 17A116-555) were prepared and are available to supplement future production requirements.

TASK IV – TEST AND EVALUATION

In order to introduce new materials or processes to the production of a rotating engine component, a critical milestone of the overall testing program is the engine test for the new hardware simulating flight conditions. The three disks and two cooling plates were thus assembled in a test engine scheduled for Maturity Hardware Assurance Test. The test comprised of engine operation simulating various flight conditions. It was conducted in the start-stop cycles of 6 hours each. The engine test consisted of 25 cycles, i.e., a total of 150 "endurance hours". The engine was then disassembled and all the five parts were subjected to dimensional check, visual inspection, ultrasensitivity Fluorescent Penetrant Inspection and high sensitivity Ultrasonic Inspection (in the bore). These nondestructive tests confirmed the parts to be flawless after accumulating 150 hours of the 'engine time'. A comparison with the corresponding standard part with similar endurance history revealed these to be very similar. The engine test was thus successfully completed by the hot isostatically pressed Rene' 95 turbine parts.

TASK V – TECHNICAL DATA PACKAGE

A technical data package was compiled which included the following:

1. Process Drawings 17A116-354, 17A116-355.

2. General Electric Specifications:
   C50TF64 (Premium Quality Powder Metallurgy As-HIP Rene' 95 Alloy Parts.
   P1TF47 (Manufacture of Rene' 95 Alloy Powder)
   P7TF5 (Containerization and Hot Isostatic Pressing (HIP) of Rene' 95 Alloy Powder)

This package shall be used for future procurement of T700 As-HIP Turbine Parts

SUMMARY AND CONCLUSIONS

The primary objective of this program was to develop a reliable, low-cost, reproducible powder metallurgy production process for manufacturing premium quality hot isostatically pressed (As-HIP) Rene' 95 engine hardware. The program was carried out by two powder vendors, Vendor A and B, and was divided into five tasks, designed to:

1. Define processing and shape-making parameters required to meet mechanical property goals.

2. Evaluate the selected process with lab test specimens.

3. Fabricate engine test hardware and generate detailed design data.

4. Complete engine testing of at least one set of As-HIP T700 parts.

5. Compile a technical data package including process drawings and engineering specifications for the production of As-HIP Rene' 95 hardware.

Processing parameter studies in Task I indicated that the desired mechanical properties and turbine disk shape could be achieved in As-HIP Rene' 95 through application of a specific combination of hot isostatic pressing (HIP) temperature, pressure, and post-compaction heat treatment. The processing sequence consisted of hot isostatic pressing of -60 mesh powders in metallic or ceramic containers at 2050°F and 15,000 psi pressure for a minimum of 2 hours. Heat treatment procedure included solution treatment at T_s -30°F for 1 hour followed by a quench into 1000°F salt bath. A double age cycle of 1600°F/1 hour/AC + 1200°F/24 hours/AC produced the required properties in 2-inch-thick test blanks. Shape-making studies in Task I indicated that a uniform, reproducible material envelope around the target ultrasonic shape could be fabricated using either mild steel or ceramic containers.

A more detailed study of mechanical properties using actual turbine disk hardware in Task II indicated that not all desired properties were attained. Tensile properties were below program goals, although stress-rupture, creep, and low-cycle fatigue data were essentially equivalent to previously tested T700 HIP + forge Rene' 95 components.

Several attempts were made to modify the Task II processing sequence to improve tensile properties, but no completely satisfactory method was identified. Reassessment of the T700 property requirements by T700 Design Engineering resulted in a reduced set of tensile goals which could be attained using Task II production practices. Application of these parameters to Vendor A components in Task III yielded acceptable engine hardware. However, a change in powder production methods was apparently responsible for the unsatisfactory properties in Vendor B Task III hardware. Design data studies on Vendor A components indicated that mechanical property goals were met in all but one component. Therefore, a partial set of As-HIP hardware consisting of two turbine disks and three (instead of four) cooling plates were finish-machined for engine testing.

In summary:

- The hot isostatic pressing process is capable of producing low-cost, reproducible premium quality T700 turbine hardware.

- Mechanical properties essentially equivalent to the powder metallurgy HIP + forge product can be attained in As-HIP Rene' 95.

- Accurate, reproducible T700 turbine disk shapes can be produced using either mild steel or ceramic containers.

- T700 model disk burst speed characteristics of As-HIP Rene'95 are equivalent to those of the HIP + forge product.

- All mechanical properties of the pilot production As-HIP Rene'95 turbine disk and cooling plate hardware met the modified T700 design requirements with the exception of stress-rupture properties in the thickest (1.5 inch) cooling plate.

- Changes in powder production methods can have a significant effect on mechanical properties of As-HIP material.

- Heat treatment is the most critical processing step in the As-HIP process. The heat treatment procedures must be carefully monitored to avoid substantial deviations in resultant mechanical properties, even when identical solutioning and aging temperatures and times are applied.

SUGGESTIONS FOR FUTURE WORK

The successful completion of the first 4 tasks of this program has established a manufacturing process for the production of As-HIP Rene' 95 turbine hardware. The technically and economically crucial areas of the process however should further be investigated to "productionize" the process and make it further cost effective. Some of these areas are as follows:

Heat Treatment

The development of desired mechanical properties is extremely sensitive to various parameters of heat treatment; i.e., solution temperature and its range, quench media, time to transfer, full or partial canning of the parts, etc. These parameters are part of a heat treat study already initiated as the Task VI of this program. The results will be reported separately.

Powder Characteristics

It was observed that powder size, size distribution and morphology affect the mechanical property of the As-HIP compacts. Further investigation to establish the effect of various parameters would be very desirable.

Density

The whole part density determination is an expensive proposition. A sampling technique using a part from a larger lot or an integral small piece must be developed. Moreover the reference standard of HIP + forge should be evaluated and compared with other possible and accurate reference standards.

Quality Plan

The present quality plan calls for an extensive destructive evaluation and should be carefully reviewed to reduce the number and the frequency of testing.

Cleanliness

As opposed to a metal ingot, powder is exposed to possible contamination during handling. At present there is no standard method of determining the cleanliness of either the powder or the powder product. Such a method will be of extreme value. Moreover, stricter methods of controlling powder handling and physical devices to "clean" the powder of impurities will be of immense help and should be investigated. Can preparation is presently expensive. The production methods of making sheet metal cans should be incorporated.

APPENDIX I
GENERAL ELECTRIC, AIRCRAFT ENGINE GROUP, SPECIFICATIONS
CODE IDENT NO. 07482

PREMIUM QUALITY POWDER METALLURGY AS-HIP RENE' 95 ALLOY PARTS (C50TF64-S1)

1. SCOPE

1.1 Scope. This specification presents requirements for premium quality powder metallurgy As-HIP Rene' 95 alloy parts.

1.1.1 Classification. This specification contains the following classes:

CLASS A:	230,000 psi (1586 MPa) Ultimate Tensile Strength
CLASS B:	220,000 psi (1517 MPa) Ultimate Tensile Strength
CLASS C:	208,000 psi (1434 MPa) Ultimate Tensile Strength

The requirements specified herein apply to all classes unless otherwise specified.

1.2 Definitions. For purposes of this specification, the following definitions shall apply.

As-HIP – Hot isostatically pressed and heat treated.

HIP – Hot isostatically pressed.

Master Powder Blend – A blend of two or more powder heats.

Part Lot – Parts produced in the same autoclave cycle.

Powder Heat – The blend of powders produced from one or more powder lots of a single original vacuum induction melted heat of the alloy.

Powder Lot – Powder produced during a single cycle of the powder production equipment and screened to the specified size.

Purchaser – The procuring activity of the Aircraft Engine Group (AEG) of the General Electric Company that issued the procurement document invoking this specification.

2. APPLICABLE DOCUMENTS

2.1 The following documents shall form a part of this specification to the extent specified herein. Unless a specific issue is specified, the latest revision shall apply.

GENERAL ELECTRIC SPECIFICATIONS

P3TF1	Ultrasonic Inspection
P3TF2	Fluorescent Penetrant Inspection

P21TF7	Hot Isostatic Pressing (HIP) of Castings
P29TF19	Acceptability Limits for Trace Elements in Nickel and Cobalt Base Superalloys

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM B214	Sieve Analysis of Granular Metal Powders
ASTM B215	Sampling Finished Lots of Metal Powders
ASTM E8	Tension Testing of Metallic Materials
ASTM E10	Brinell Hardness of Metallic Materials
ASTM E18	Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials
ASTM E21	Elevated Temperature Tension Tests of Metallic Materials
ASTM E45	Determining the Inclusion Content of Steel
ASTM E112	Estimating the Average Grain Size of Metals
ASTM E139	Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials

AEROSPACE MATERIAL SPECIFICATIONS

AMS 2269	Chemical Check Analysis Limits—Wrought Nickel and Nickel Base Alloys

3. REQUIREMENTS

3.1 Raw Material

3.1.1 Parts shall be produced from powder of a nickel base alloy known as Rene' 95.

3.1.2 Chemical Composition, Percent

Carbon	0.04 – 0.09	Columbium	3.30 – 3.70
Manganese	0.15 Max.	Zirconium	0.03 – 0.07
Silicon	0.20 Max.	Titanium	2.30 – 2.70
Sulfur	0.015 Max.	Aluminum	3.30 – 3.70
Phosphorus	0.015 Max.	Boron	0.006 – 0.015
Chromium	12.00 – 14.00	Tungsten	3.30 – 3.70
Cobalt	7.00 – 9.00	Oxygen	0.010 Max.
Molybdenum	3.30 – 3.70	Nitrogen	0.005 Max.
Iron	0.50 Max.	Hydrogen	0.001 Max.
Tantalum	0.20 Max.	Nickel	Remainder

3.1.2.1 Powder from each powder lot shall meet the carbon, hydrogen, oxygen, and nitrogen limits before blending to form a powder heat. If the powder heat is to be made up by blending several powder lots, procedures for blending and sampling for chemical analysis shall be as agreed upon by Purchaser and powder suppliers.

3.1.2.2 Two or more powder heats may be blended to form a master powder blend. A chemical analysis shall be performed on each powder heat and it shall conform to the requirements of 3.1.2. A powder heat which does not meet the requirements of 3.1.2 shall not be used in a master powder blend or in any other way except as remelt stock. In addition, trace element content of consolidated samples of each powder heat shall be determined for all elements required per P29TF19, CLASS A. Results of tests for trace elements shall be reported to the Purchaser per 3.9.1, but unless otherwise specified on the drawing, shall not be cause for rejection.

3.1.2.3 All analyses made by the manufacturer to determine the percentages of elements required by this specification shall conform to the requirements of 3.1.2 and 3.1.2.1 and shall be reported in the certificate of test herein specified.

3.1.2.4 An analysis may be made on powder metallurgy parts by the Purchaser and the chemical analysis thus determined shall conform to the requirements of 3.1.2.

3.1.3 Manufacture of Metal Powders

3.1.3.1 The base alloy shall be produced by vacuum induction melting. The base alloy shall be converted to powder by one of the following processes:

a) Inert gas atomization
b) Rotating electrode process in inert atmosphere
c) Hydrogen/vacuum atomization

3.1.4 Sieve Analysis

3.1.4.1 All powder shall pass through an ASTM No. 60 (250 μm) sieve. Once the weight percents retained on ASTM No. 100 (150 μm) and No. 325 (45 μm) sieves have been established and approved by the Purchaser, each master blend of powder shall conform to the approved analysis within plus or minus five percentage points.

3.2 Process Requirements

3.2.1 Vendors shall inform the Purchaser of all manufacturing processes and procedures used to produce parts to this specification. Once these practices are approved, they shall not be changed without approval of the Purchaser.

3.2.2 Powder shall be obtained only from sources approved by the Purchaser.

3.2.3 Hot isostatic pressing shall be conducted per P21TF7, CLASS A. HIP conditions shall be 2050° ±25°F (1121° ± 14°C) and 14,000 psi (97 MPa) minimum pressure for 2 hours minimum.

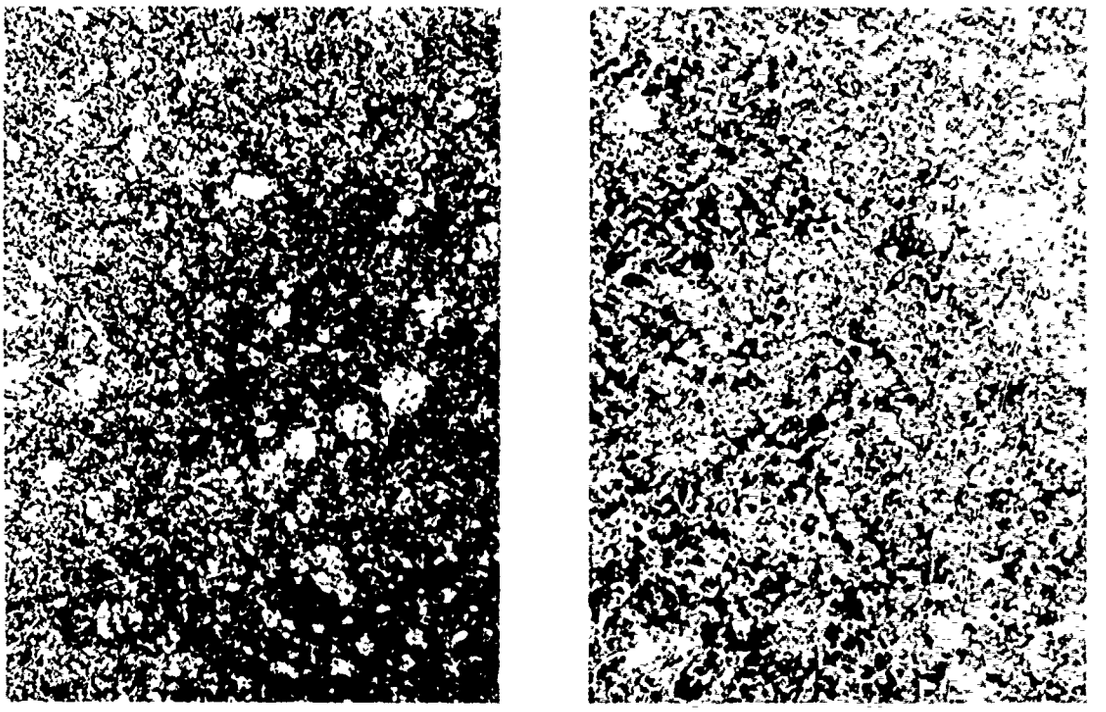
3.2.3.1 Powder containers shall be fabricated from materials approved by the Purchaser and leak checked by an approved method.

3.2.3.2 Powder shall be loaded into the container and the loaded container outgassed and sealed by a method approved by the Purchaser.

3.2.3.3 The autoclave heat-up/pressurization and cooling cycles shall be approved by the Purchaser.

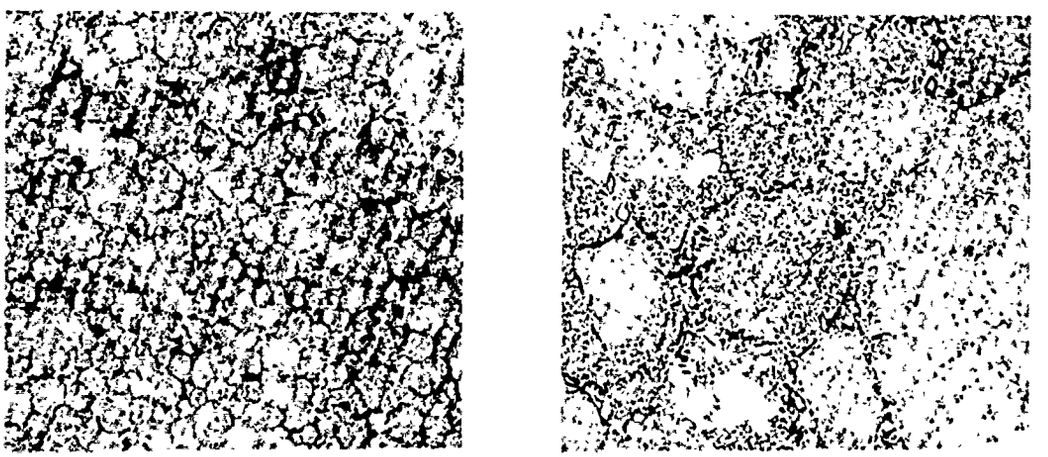
3.2.4 HIP parts shall have a density greater than 99.9 percent of a HIP plus forged test sample fabricated from the same powder heat or master powder blend. The powder pressing and forging processes used on the test sample shall be by methods agreed upon by the Purchaser and the vendor.

3.2.5 HIP parts shall have a uniform average grain size of ASTM No. 8 or finer with no appreciable outlining of prior particle boundaries. A typical acceptable HIP microstructure is shown in Figure 120. Unacceptable HIP microstructures are shown in Figure 121.



100X 500X

Figure 120. Acceptable Microstructure for As-Compacted Rene' 95 (2050°F/15 ksi – Waterless Kallings).



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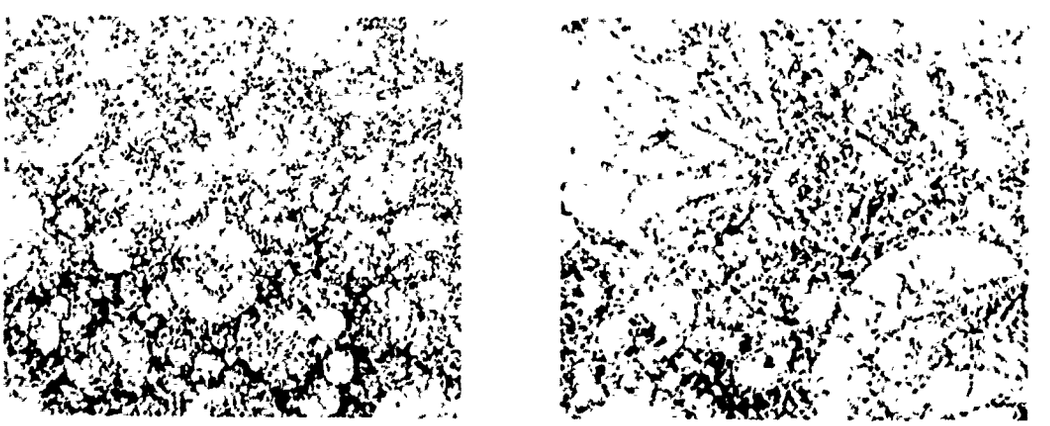
(a) Over Temperature (>2050°F) During HIP Cycle



100X 500X

(b) Under Temperature (<2050°F) During HIP Cycle

Figure 121. Unacceptable As-Compacted Microstructures Caused by Deviation from 2050°F HIP Temperature – Waterless Kallings.

3.2.6 The γ' solvus temperature shall be determined on a HIP part from each master powder blend.

3.2.7 Rough machined parts shall be etched and all surfaces inspected. The etching method shall be approved by the Purchaser. Parts containing large grains visible at 1X magnification shall be cause for rejection.

3.2.8 Heat Treatment

3.2.8.1 All solution heat treat temperatures refer to metal temperature ±15°F (±8°C). All aging temperatures refer to metal temperature ±25°F (±14°C). All times refer to time at temperature for the heaviest section.

3.2.8.2 Parts shall be supplied in the solution heat treated and aged condition as specified below:

Solution heat treat at 30°F (17°C) below the γ' solvus temperature (see 3.2.6) for 1 hour and salt quench with maximum bath temperature of 1000°F (583°C). Rapid cooling from the solution temperature through 1200°F (649°C) is essential to obtain optimum mechanical properties. Age at 1600°F (871°C) for 1 hour, air cool to room temperature, plus 1200°F (649°C) for 24 hours and air cool.

3.3 Mechanical Properties

3.3.1 Tensile

3.3.1.1 Parts, heat treated per 3.2.8.2, shall meet the applicable minimum tensile requirements shown below:

	Room Temperature		
	CLASS A	CLASS B	CLASS C
Tensile Strength, psi	230,000	220,000	208,000
Yield Strength, (0.2 percent offset), psi	180,000	170,000	166,000
Elongation, percent in 2 inches or 4D	10	10	10
Reduction of Area, percent	12	12	12

	1200°F		
	CLASS A	CLASS B	CLASS C
Tensile Strength, psi	207,000	197,000	186,000
Yield Strength (0.2 percent offset), psi	167,000	161,000	153,000
Elongation, percent in 2 inches or 4D	8	8	8
Reduction of Area, percent	10	10	10

SI UNITS

	Room Temperature		
	CLASS A	CLASS B	CLASS C
Tensile Strength, MPa	1,586	1,517	1,434
Yield Strength (0.2 percent offset), MPa	1,241	1,172	1,145
Elongation, percent in 50.8 mm or 4D	10	10	10
Reduction of Area, percent	12	12	12

	649°C		
	CLASS A	CLASS B	CLASS C
Tensile Strength, MPa	1,427	1,358	1,282
Yield Strength (0.2 percent offset), MPa	1,151	1,110	1,055
Elongation, percent in 50.8 mm or 4D	8	8	8
Reduction of Area, percent	10	10	10

3.3.1.2 The location and CLASS of the required tensile specimens shall be as specified on the drawing.

3.3.2 Stress Rupture

3.3.2.1 Test specimens shall be tested at 1200°F (648.9°C) and 150,000 psi (1034 MPa) and shall meet the applicable minimum life requirement specified below. Tests shall be continued to rupture, and elongation after rupture, measured at room temperature, shall be not less than three percent in 4D.

	Minimum Life, Hours
CLASSES A and B:	50
CLASS C:	35

3.3.2.2 Stress rupture testing may be conducted at stress levels higher than that specified provided all other test conditions are maintained. The specified life measurements and elongation requirements shall apply and the stress shall remain constant while the test is in progress. Specific stresses used shall be reported in the powder vendor's certificate of test.

3.3.3 Plastic Creep

3.3.3.1 Creep specimens shall be tested at 1100°F (593.3°C) and 150,000 psi (1034 MPa). Total plastic deformation shall not exceed 0.2 percent after completion of the time period specified below.

CLASS A:	100 hours
CLASS B:	50 hours
CLASS C:	25 hours

3.3.4 Residual Cyclic Life

3.3.4.1 Residual cyclic life tests shall be conducted and the number of cycles to failure shall be reported to the Purchaser in the certificate of test. Tests shall be conducted at 1000°F (537.8°C) at a stress ratio (alternating/mean stress) of 0.95 ± 0.05 with a maximum stress level (mean stress plus alternating stress) of 100,000 psi (689 MPa), at a cycle rate of 10-30 cycles per minute. When specifically required by the drawing, the residual cyclic life shall be a minimum of 5000 cycles.

3.3.5 Cyclic Rupture Test

3.3.5.1 Cyclic rupture testing shall be conducted at 1200°F (648.9°C) and the time to failure and the number of cycles shall be reported to the Purchaser in the certificate of test. The periodic intervals shall consist of holding at a peak stress of 145,000 psi (1000 MPa) for 90 ± 10 seconds. The minimum stress shall range from 0 to 4800 psi (0 to 33 MPa), and the time to load or unload shall range from 5 to 15 seconds. When specifically required by the drawing, the cyclic rupture life shall be a minimum of 300 cycles.

3.4 Hardness

3.4.1 Parts shall have a minimum hardness of Brinell 415 or equivalent.

3.5 Grain Size

3.5.1 Parts shall have a uniform average grain size of ASTM No. 8 or finer with no appreciable prior particle boundary outlining. Figure 122 shows an example of an acceptable As-HIP microstructure. Unacceptable As-HIP microstructures are shown in Figure 123. Glossy prints are available from the Purchaser on request.

3.6 Density

3.6.1 After solution heat treatment and aging, the As-HIP part density measured by weighing the entire part, shall meet or exceed the density of the HIP part. The density of a representative sample shall not decrease more than 0.3 percent after a 4 hour exposure at 2200° ± 15°F (1200° ± 8°C) in air.

3.7 Incipient Melting

3.7.1 Parts shall exhibit no evidence of incipient melting.

3.8 Cleanliness

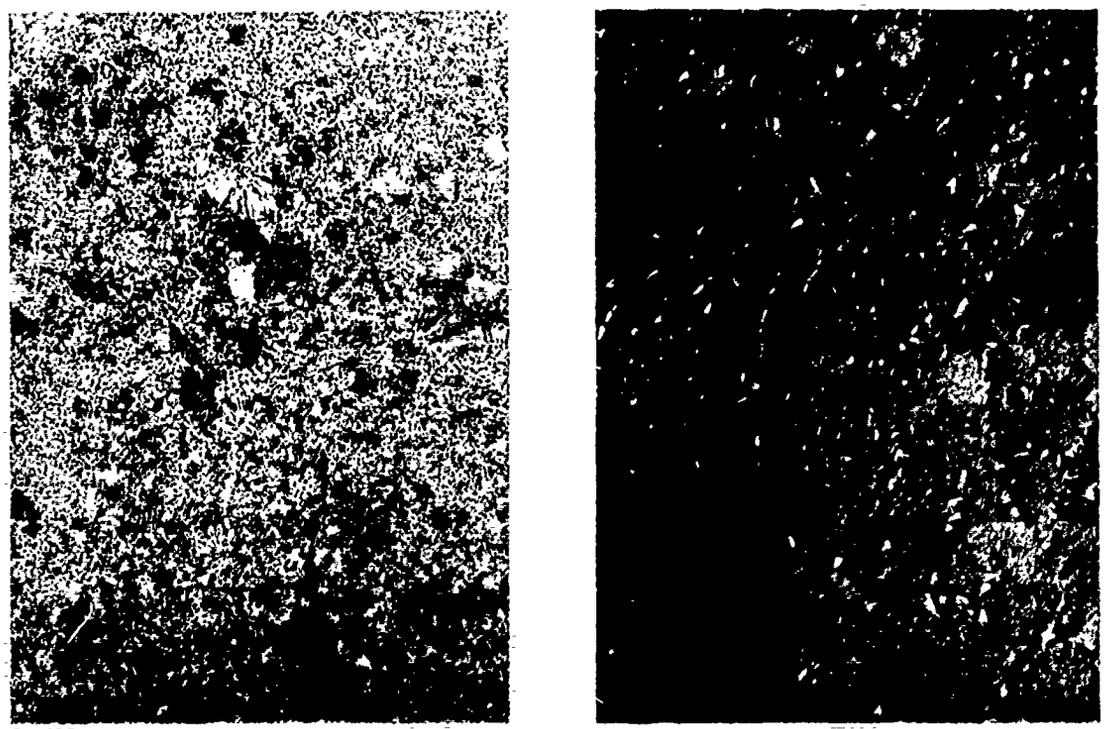
3.8.1 Parts shall be checked by quantitative metallography in any two representative areas for foreign particles. Foreign particles are defined as any non-metallic inclusions (silicates, aluminates, etc.) and metallic particles other than Rene'95. The worst area of non-metallic inclusions in each inspection sample shall not exceed the inclusion rating limits shown below. The number of foreign particles (particles which do not respond to a Rene'95 etch as does Rene'95) in each inspection sample shall be reported. If four or more particles are reported in any inspection area, or if the sum of the long dimensions of the observed particles exceeds 0.010 inch (0.254 mm), Purchaser approval shall be required for acceptance.

	Inclusion Rating
Inclusion Type	Worst Field
B – Thin	1.5
B – Heavy	1.0
D – Heavy	1.0

3.9 Part Vendor's Certificate of Test

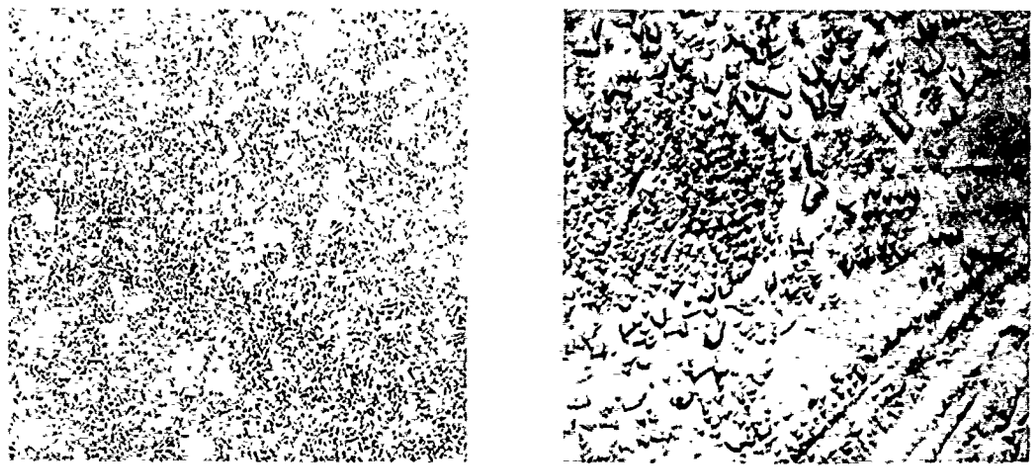
3.9.1 The part vendor shall certify all chemical and mechanical tests herein specified. A certificate of test, in triplicate, on each lot of parts supplied to this specification shall be mailed by the vendor to the machining vendor with or preceding the shipment of parts. This certificate shall give the numerical results of all required tests and inspections and shall show that the results are in accordance with the requirements of this specification. If a heat appears in more than one lot of parts, the numerical results of the tests shall be recorded in the certificate of test for each of the lots of parts in which it appears. In addition, the certificate shall contain the following information:

a) Purchase order number
b) Vacuum induction melt heat number, powder heat number, and master powder blend number

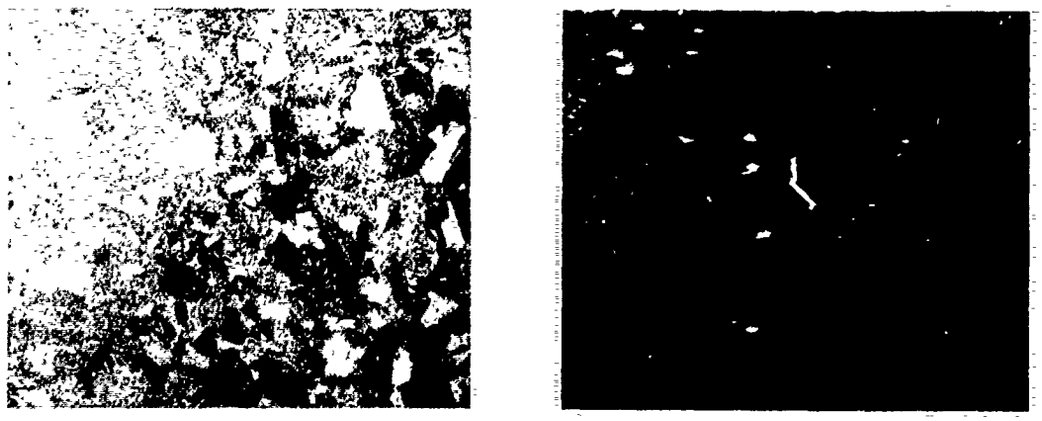


100X 1000X

Figure 122. Acceptable Microstructure of As-HIP + Heat Treated Part — Waterless Kallings.



100X (a) 1000X



100X (b) 1000X

Figure 123. Examples of Unacceptable Microstructures Resulting from (a) Under or (b) Over Temperature During Solution Treatment – Waterless Kallings.

c) Powder lot number and HIP lot number
d) Chemical analysis and γ' solvus temperature of each master powder blend
e) Sieve analysis for each master powder blend
f) Heat treat lot number for each part
g) Part lot number for each part
h) Specific heat treatment used
i) Specific stress rupture stress used
j) Testing source for tensile, stress rupture, and creep specimens
k) Density measurement values for 3.2.4 and 3.6.1 and method used
l) Quantity
m) Specification number, CLASS, and revision number

3.10 Material Identification Record

3.10.1 A material identification record shall be submitted by the machining vendor to the Purchaser and shall include the following information:

a) Powder vendor's certificate of test
b) Heat treat vendor
c) Machining vendor's laboratory release report number
d) Specification number, CLASS, and revision number

3.11 Marking

3.11.1 The type of marking and location shall be as specified on the part drawing.

4. QUALITY ASSURANCE PROVISIONS

4.1 The certificate of test for each lot or lots within a shipment shall report the data required by this specification for the number of sample items or test specimens as required by this specification, or as additionally directed by the Purchaser.

4.2 Chemical Analysis

4.2.1 Chemical analyses shall be conducted in accordance with standard ASTM methods, or by methods agreed upon by Purchaser and vendor. Sampling procedures for powder lot analyses shall be conducted per ASTM B215.

4.2.2 Chemical check analysis limits shall be in accordance with AMS 2269.

4.3 Mechanical Properties

4.3.1 Testing vendors and test specimen machining sources shall be subject to approval by the Purchaser.

4.3.2 All testing shall be conducted in accordance with ASTM methods unless otherwise agreed upon by the vendor and the Purchaser. All parts received are subject to cut-up upon receipt by the Purchaser and shall have the required properties throughout the parts.

4.3.3 Unless otherwise specified, parts which do not have integral test rings shall be evaluated by testing a minimum of one part per heat, per heat treated lot.

4.3.4 Tensile and stress rupture specimens shall be machined from integral test rings or parts representing 1) each heat or master blend of material not previously tested, 2) each part lot not previously tested, and 3) each solution heat treat lot of parts or as otherwise specified.

4.3.4.1 Parts with integral test rings shall be cut up periodically and tested to the requirements of this specification. The frequency of testing and the number and types of tests shall be as designated by the applicable Quality Control organization of the Purchaser in the Quality Plan. The location of test specimens shall be as indicated on the specific part number drawings as available from the Purchaser, or as otherwise specified. Results of tests with all pertinent identification shall be reported to the Purchaser in a certificate of test. In the event significant changes to the metal-working process are planned, which may affect the abilit of the resultant part to meet the properties of this specification, a representative part shall be sectioned and tested for conformance to requirements.

4.3.5 Tensile

4.3.5.1 Tensile specimens, taken per 4.3.4 and tested in accordance with the applicable requirements of ASTM E8 and E21, shall meet the tensile requirements of 3.3.1.

4.3.5.2 For referee tensile tests, a strain rate of 0.005 inch per inch (0.005 mm per mm) per minute through the 0.2 percent yield strength shall be used.

4.3.6 Stress Rupture

4.3.6.1 Stress rupture specimens, taken per 4.3.4 and tested in accordance with the applicable requirements of ASTM E139, shall meet the stress rupture requirements of 3.3.2.

4.3.6.2 Stress Rupture Specimens for Referee Tests. For referee tests, smooth specimens shall conform to the dimensions and proportions of a standard 0.250 inch (6.35 mm) diameter test bar per ASTM E139 except that a gage diameter as small as 0.200 inch (5.08 mm), with other dimensions proportional, may be used in order to maintain a thread diameter to gage diameter ratio of 2.5 minimum.

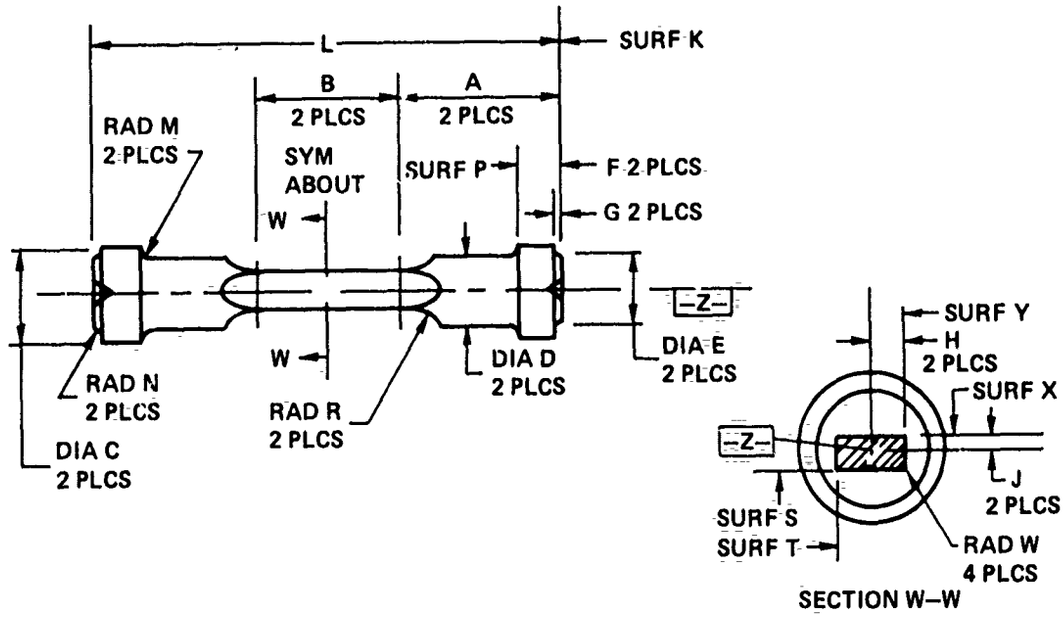
4.3.7 Plastic Creep

4.3.7.1 Creep test specimens, taken per 4.3.4.1 and tested in accordance with the applicable requirements of ASTM E139, shall meet the plastic creep requirements of 3.3.3. Strain measuring techniques shall be approved by the Purchaser.

4.3.7.2 Unless otherwise agreed upon by the Purchaser and the vendor, creep specimens shall be of standard proportions with a 0.250 inch (6.35 mm) diameter at the reduced parallel section and shall have a 2.000 ± 0.005 inch (50.80 ± 0.13 mm) gage length.

4.3.8 Residual Cyclic Life

4.3.8.1 Residual cyclic life test specimens, taken per 4.3.3 or 4.3.4.1, shall be machined to the configuration and dimensions shown in Figure 124. The reduced section of the specimen shall be machined using low stress grinding techniques to prevent the formation of high residual stresses in the surfaces. Pre-cracking of the specimens shall be conducted at room temperature (high cycle mode axial or bending is acceptable) using a stress not exceeding 90,000 psi (621 MPa) until the crack length is 0.060 ± 0.005 inch (1.52 ± 0.13 mm).



A	B	C	D	E	F	G	H	J	L	M	N	R	W
1.65	1.40	0.998	0.7495	0.745	0.490	0.055	0.299	0.124	4.97	0.03	0.005	0.49	0.015
1.85	1.60	1.002	0.7505	0.755	0.510	0.065	0.301	0.126	5.03	0.05	0.015	0.51	0.025
SI UNITS													
41.9	35.6	25.35	19.037	18.92	12.45	1.40	7.59	3.15	126.2	0.76	0.13	12.45	0.38
47.0	40.6	25.45	19.063	19.18	12.95	1.65	7.65	3.20	127.8	1.27	0.38	12.95	0.64

NOTES:
1. All dimensions are in inches, with SI units in millimeters.
2. Unless otherwise specified, all surfaces are 32.
3. Remove burrs and sharp edges with 0.015 inch (0.381 mm) max. radius or chamfer.
4. Diameters "C" and "E" to be concentric about "Z" within 0.001 inch (0.025 mm); diameter "D" to be concentric about "Z" within 0.0005 inch (0.013 mm).
5. Surfaces "K" and "P" to be perpendicular to "Z" within 0.001 inch (0.025 mm).
6. Surfaces "X" and "S" to be parallel within 0.001 inch (0.025 mm); surfaces "Y" and "T" to be parallel within 0.001 inch (0.025 mm).
7. Radius "R" and gage section to blend smoothly with no undercuts.
8. EDM surface notch at mid length or centerline of surface "S".
   Notch dimensions to be Length = 0.040±0.001 inch (1.02±0.025 mm); L to "Z"
   Width = 0.002±0.001 inch (0.051±0.025 mm)
   Depth = 0.010±0.0005 inch (0.250±0.013 mm)
9. Lathe centers permitted, 0.20 inch (5.08 mm) max. depth.

Figure 124. Rectangular Gage Section Residual Cyclic Life Test Specimen.

4.3.9 Cyclic Rupture

4.3.9.1 Cyclic rupture test specimens, taken per 4.33 or 4.3.4.1 shall be tested in accordance with all requirements of ASTM E139. Tests shall be conducted on conventional rupture machines that have been adapted to automatically load and unload the specimen load assembly periodically. Specimens shall be machined to the configuration and dimensions shown in Figure 125 with a $K_t = 2.0$ stress concentration in the gage section. The notch shall be machined using low stress grinding techniques to prevent the formation of high residual stresses in the surfaces.

4.4 Hardness

4.4.1 Hardness tests shall be conducted in accordance with ASTM E10 or E18 as applicable.

4.4.1.1 Hardness of wheels shall be tested at two points 180° apart on the rim and at one point near the center of the web. Torque rings shall be tested at three points 120° apart. Turbine shafts shall be tested at two points 180° apart at the ends of the shaft. Seals shall be tested at three points 120° apart. Location for hardness checks on other parts shall be as shown on the part drawing.

4.5 Grain Size

4.5.1 Grain size shall be determined by comparison of a polished and etched specimen with the chart in ASTM E112. Representative parts from each heat, each part lot, and each solution heat treat lot shall be examined for grain size determination. In case of disagreement on grain size by the comparison procedure, the intercept (Heyn) procedure shall be used.

4.6 Density

4.6.1 Density measurements shall be made in accordance with a method agreed upon by the Purchaser and the vendor.

4.7 Incipient Melting

4.7.1 Determinations for evidence of incipient melting shall be performed by metallographic examination of polished specimens at 100X and 500X magnifications.

4.8 γ' Solvus Temperature

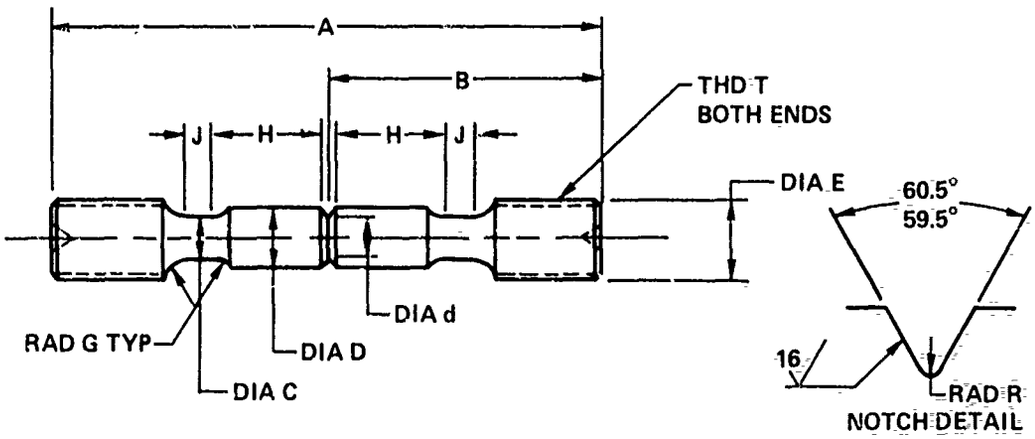
4.8.1 The γ' solvus temperature shall be determined metallographically as approved by the Purchaser.

4.9 Cleanliness

4.9.1 The non-metallic inclusion content shall be determined per ASTM E45, Plate III, Method D. Metallic foreign particle contamination shall be determined by metallographic examination of the same sample at 100X magnification.

4.10 Ultrasonic Inspection

4.10.1 Parts shall be ultrasonic inspected per P3TF1, CLASS A, in accordance with limits specified on the drawing.



Part No.	A	B	D	D	d	E	G	H	J	R	T
1	3.55 3.45	1.78 1.72	0.271 0.269	0.355 0.353	0.251 0.249	0.498 0.495	0.14 0.10	0.72 0.68	0.21 0.17	0.0368 0.0358	0.500- 13UNC-2A

SI UNITS

1	90.2 87.6	45.2 43.7	6.883 6.833	9.017 8.966	6.375 6.325	12.649 12.573	3.6 2.5	18.3 17.3	5.3 4.3	0.935 0.909

NOTES:
1. Remove burrs and sharp edges. 0.015 inch (0.381 mm) max. radius or chamfer.
2. All diameters to be concentric within 0.002 inch (0.51 mm) FIR.
3. Lathe centers permitted, 0.20 inch (5.08 mm)max. depth
4. Radius and gage sections to blend smoothly without undercut.
5. All dimensions are in inches: with metric conversion in millimeters.
6. Surface roughness shall be 32 or better unless indicated otherwise.

Figure 125. Cyclic Rupture Test Specimen.

4.10.2 If no limits are specified on the drawing, allowable limits for all indications shall conform to the requirements of P3TF1, CLASS A.

4.11 Fluorescent Penetrant Inspection

4.11.1 After completion of all processing operations, all parts shall be fluorescent penetrant inspected per P3TF2, CLASS D, in accordance with limits specified on the drawing.

4.11.2 Fluorescent penetrant indications may be reworked providing the reworked area is macroetched prior to fluorescent penetrant inspection per the applicable drawing requirements. Etching procedures shall be approved by the Purchaser.

4.11.3 Rework of fluorescent penetrant indications shall fall within the blend limits of the applicable drawings. All blends shall be smooth in contour with no sharp breaks or scratches within them.

4.11.4 No rework of fluorescent penetrant indications is permitted on the pressure faces or root radii of dovetail serrations.

4.11.5 When specified on the drawing, finished machined parts shall be etched on all surface areas, prior to fluorescent penetrant inspection, by procedures approved by the Purchaser.

5. PREPARATION FOR DELIVERY

5.1 Packing

5.1.1 All parts shall be suitably packed to prevent damage or loss in shipment.

5.2 Marking

5.2.1 Each shipment shall be legibly marked with the purchase order number, manufacturer's name, part name, and drawing number.

6. NOTES

6.1 Classification of Characteristics

CRITICAL:	3.4.1, 4.10.2
MINOR:	All other paragraphs

6.2 Intended Usage

6.2.1 Various tensile strength levels have been designated by the usage of CLASS letters to reflect property variations due to section size and processing.

6.3 The Data for Ordering Sheet shown below is listed for information.

DFO-C50TF64 Premium Quality Powder Metallurgy As-HIP Rene' 95 Alloy Parts

MANUFACTURE OF RENE' 95 ALLOY POWDER
(PITF47-S1)

1. SCOPE

1.1 Scope. This specification presents requirements for the manufacture of Rene' 95 alloy powder.

1.1.1 Classification. This specification contains the following class:

CLASS A

1.2 Definitions. For purposes of this specification, the following definitions shall apply:

Master Powder Blend – A blend of one or more powder heats or powder lots.

Powder Heat – The blend of powders produced from one or more powder lots of a single original vacuum induction melted heat of the alloy.

Powder Lot – Powder produced during a single cycle of the powder production equipment and screened to the specified size.

Purchaser – The procuring activity of the Aircraft Engine Group (AEG) of the General Electric Company that issued the procurement document invoking this specification.

2. APPLICABLE DOCUMENTS

2.1 The following documents shall form a part of this specification to the extent specified herein. Unless a specific issue is specified the latest revision shall apply.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM B212	Apparent Density of Metal Powders
ASTM B214	Sieve Analysis of Granular Metal Powders
ASTM B215	Sampling Finished Lots of Metal Powders

GENERAL ELECTRIC SPECIFICATIONS

E50TF126	Determination of the Density of Engine Parts
P7TF5	Containerization and Hot Isostatic Pressing (HIP) of Rene' 95 Alloy Powder
P29TF19	Acceptability Limits for Trace Elements in Nickel and Cobalt Base Superalloys

3. REQUIREMENTS

3.1 Process Sheets. The powder vendor shall have documented instructions defining the processing methods and the routing in the manufacturing cycle, for the processing and evaluation of Rene' 95 alloy powder as described in this specification.

3.2 Accountability. The powder vendor shall forward to the Purchaser a record of the disposition of each powder lot, powder heat, or master powder blend, which is used on AEG parts.

3.3 Raw Material. Powder shall be produced from vacuum induction melted ingot, virgin melt stock, or revert material.

3.3.1 The alloy powder vendor shall establish specifications for the procurement of raw material, which shall include certification and testing. Traceability shall be assured for all raw material, including the type and percentage of revert, that is used to make a powder lot.

3.3.2 The surface of the vacuum induction melted ingot shall be ground in accordance with a procedure approved by the Purchaser to remove surface contamination resulting from the ingot casting operation. After grinding, the ingot shall be cleaned to remove residue from the grinding operation using a procedure approved by the Purchaser.

3.3.3 The ingot source shall employ a cropping procedure approved by the Purchaser.

3.4 Melting Control. Sources for vacuum induction melted ingot shall maintain controls to supply material suited to the atomization processes employed from the standpoint of segregation and inclusions. Inert gas atomizing sources shall maintain similar controls for the vacuum induction melting process for consistently producing an alloy powder that will yield compacts which meet all cleanliness requirements of this specification.

3.4.1 The melting procedure shall be documented to include specific provisions for melting abnormalities and the conditions under which a melt will be aborted. The power input, holding temperature and time, and vacuum pressure shall be measured and recorded at frequent intervals throughout the melting cycle.

3.5 Powder Atomization. The base alloy shall be converted to powder by one of the following processes:

a) Inert gas atomization
b) Rotating electrode process in inert atmosphere

3.5.1 Unless otherwise approved by the Purchaser, when an atomization unit previously used for a different alloy is used to produce Rene' 95 powder, trace element content shall be determined on each powder lot until conformance to P29TF19, CLASS A, is obtained. Determinations shall then be made on each powder lot, powder heat, or each master powder blend as specified in 3.7.1. Non-conforming powder lots shall not be mixed with other material to produce powder heats or master powder blends.

3.5.2 The alloy powder manufacturer shall, as part of the atomizing procedure, define the equipment and parameters to include gas pressure, number of gas nozzles and their position, orifice size and shape, and distance and orientation with respect to the molten stream. The tundish size and shape shall be established and maintained as a constant, along with the height of the molten metal in the tundish during the pour.

3.6 Sieve Analysis. A minimum of 99.9 percent of each powder lot shall pass through an ASTM No. 60 (250 μm) sieve. Once the weight percents on ASTM No. 100 (150 μm) and No. 325 (45 μm) sieves have been established and approved by the Purchaser, each powder lot, powder heat, or master powder blend shall conform to the approved analysis within the limits agreed upon by the vendor and the Purchaser.

3.6.1 The powder producer shall establish a procedure for screen inspection, maintenance and replacement. This procedure shall be approved by the Purchaser.

3.7 Chemical Composition. Powder from each powder lot shall meet the carbon, hydrogen, oxygen and nitrogen limits before blending to form a powder heat. If the powder heat is to be made up by blending

several powder lots, procedures for blending and sampling for chemical analysis shall be as agreed upon by Purchaser and powder suppliers.

3.7.1 A chemical analysis shall be performed on each powder lot or heat and it shall conform to the requirements of the procurement part specification. A powder lot or heat which does not meet the requirements of the procurement specification shall not be used except as remelt stock. Trace element content of consolidated samples of each powder lot or heat shall be determined for all elements required per P29TF19, CLASS A. When lots or heats are blended to form a master powder blend, trace element analyses may be conducted on the master powder blend rather than on each separate powder lot or heat. Results of tests for trace elements shall be reported to the Purchaser per 3.16, but unless otherwise specified, shall not be cause for rejection.

3.8 Apparent Density. The apparent density of powder lots, powder heats, or master powder blends shall be determined and reported per 3.16.

3.9 Outgassing. Removal of inert gasses associated with the atomizing process shall be accomplished using a procedure approved by the Purchaser. The outgassing procedure shall be documented and capable of being monitored in a manner which measures the consistency of the process.

3.10 Blending. The powder blending procedure including powder input weight, equipment description, environment, time and revolutions per minute shall be documented.

3.11 Contamination Control. All processing procedures shall be carefully controlled to minimize contamination during all manufacturing cycles.

3.11.1 No alloys containing intentional additions of the elements controlled by P29TF19, CLASS A, shall be produced in the equipment used to make Rene' 95 without written approval of the Purchaser.

3.11.2 Each powder lot, powder heat, or master powder blend shall be evaluated for contaminants by examination of a HIP sample from each powder lot, powder heat, or master powder blend. This sample shall be HIP according to conditions outlined in P7TF5, CLASS A. A minimum of 400 square inches (0.258 m^2) of the electrochemical machined HIP sample surface area shall be examined for protrusions and pits. Allowable limits for protrusions and pits shall be as agreed upon by the Purchaser and the vendor.

3.11.3 The alloy powder producer's specifications for melt crucibles and other ceramic type components and materials used throughout the process shall be approved by the Purchaser. New crucibles, and crucibles which have been used for other alloys shall be conditioned by a method agreed upon by the vendor and the Purchaser. When not in use, crucibles shall be stored in polyethylene or other material approved by the Purchaser.

3.11.4 Special instructions shall exist for cleaning all equipment surfaces which may come into contact with either the raw material, molten alloy or powder. This includes melting and atomizing chambers, powder collection and transfer facilities, sieves, blenders and storage containers. The Purchaser shall approve all cleaning procedures.

3.11.5 Unless otherwise approved by the Purchaser, the powder producer shall employ a containerized process throughout the powder manufacturing and handling cycle, including preparation for shipment.

3.11.6 Storage procedures for raw material and alloy powder shall be approved by the Purchaser. Containers shall be constructed of an approved material. They shall be free of burrs throughout the interior and free from sharp corners that can entrap particles.

3.12 Density Standard. Density determinations shall be made on a representative specimen taken from the sample produced in 3.11.2. The density of the specimen shall be determined in the as-compacted condition and the specimen then re-HIP per P7TF5, CLASS A, and the density again determined. The density of the double HIP specimen shall be used as the theoretical density standard for the particular powder lot, powder heat, or master powder blend.

3.13 γ' Solvus Procedure. The γ' solvus shall be determined for each powder lot, powder heat, or master powder blend to within ±5°F (±3°C) utilizing specimens taken from the sample made in 3.11.2. One specimen shall be annealed [±5°F (±3°C) temperature control] for 30 minutes minimum at each temperature in the temperature range of 2090°F (1143°C) to above the γ' solvus at 10°F (6°C) increments. The specimens shall then be polished and etched to delineate γ' solvus at grain boundaries and the γ' solvus shall be considered the lowest temperature at which the γ' is completely solutioned or significant (Figure 126) grain growth occurs. Alternate methods may be used for γ' solvus determination with prior approval.

3.14 Maintenance and Calibration. The powder producer shall have a set of procedures for the operation maintenance, calibration and care of equipment and instrumentation. Instrumentation used to monitor and control the powder process shall be calibrated periodically. Detailed records shall be maintained on the calibration of all instruments, and on the maintenance of standards used for calibration.

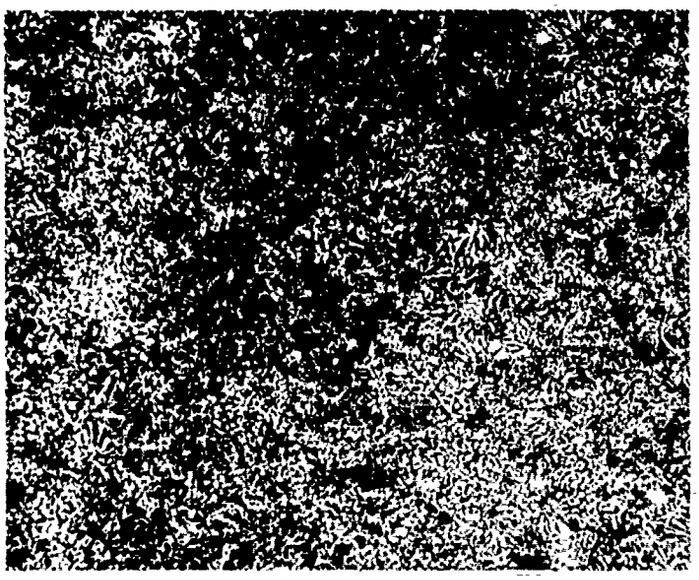
3.15 Inspection and Tests. All inspections and tests required by this specification shall be performed per a Quality Control Plan approved by the Purchaser. The results of these inspections or tests shall meet the requirements of this specification and the applicable portions of the procurement specification.

3.16 Records. The following information and test results for powder lots, powder heats, and master powder blends shall be supplied to the Purchaser:

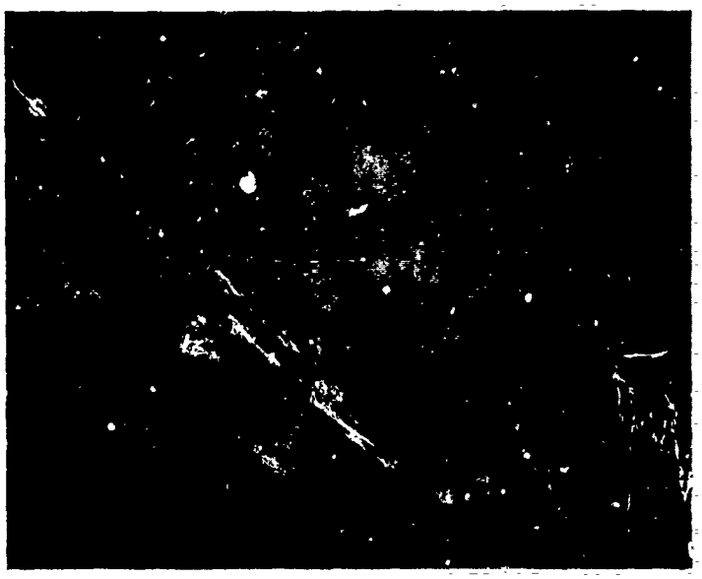
a) Vacuum induction melt heat number, powder heat number, and master powder blend number
b) Chemical analyses results
c) Sieve analyses results
d) Contamination control results
e) Disposition of each powder lot, powder heat, or master powder blend
f) Disposition of residual oversize powder from each powder lot
g) Apparent density
h) γ' solvus temperature
i) Density standard

3.16.1 In addition, the powder vendor shall maintain the following information for Purchaser surveillance:

a) Melting parameters
b) Atomization parameters
c) Outgassing procedures
d) Blending procedures
e) Process description and control procedures for any contaminant removal step not called out by this specification
f) A sequential list of all alloys processed through the equipment used to make the powder lot, powder heat, or master powder blend
g) A list of consumable materials used in the manufacture of each powder lot, powder heat, or master powder blend
h) Source control practice for all consumable materials used in the manufacture and handling of the powder.



NO SIGNIFICANT GRAIN GROWTH AFTER ANNEALING BELOW γ' SOLVUS



SIGNIFICANT GRAIN GROWTH AFTER ANNEALING ABOVE γ' SOLVUS

Figure 126. The Difference in Microstructure by Annealing Below and Above γ' Solvus.

4. QUALITY ASSURANCE PROVISIONS

4.1 General

4.1.1 A vendor shall obtain prior approval of all processing, control and inspection procedures used in the manufacture of Rene' 95 powder which include, but are not restricted to, items covered in this specification. The vendor shall further demonstrate capability in implementing all of the approved procedures used in the manufacture and control of powder quality.

4.1.2 New Producer Qualification and Corrective Action Assurance

4.1.2.1 For new producer qualification and requalification of producers, the alloy powder vendor shall successfully complete the processing and evaluation of three consecutive powder lots in strict compliance with all the requirements of this specification. Each powder lot shall be evaluated per 4.1.2.2 through 4.1.2.3 and the results shall be submitted to the Purchaser for approval.

4.1.2.2 Quantitative metallography shall be conducted on a loose powder sample to determine the presence of foreign particles. Allowable limits for foreign particles shall be as agreed upon by the Purchaser and the vendor. The sample size and the specific procedure used shall be approved by the Purchaser.

4.1.2.3 A contamination check shall also be performed on each powder lot by preparing a sample in accordance with 4.5. A minimum of 400 square inches (0.258 m^2) shall be examined for each powder lot and the minimum total surface area required for certification shall be 2000 square inches (1.29 m^2). Allowable limits for protrusions and pits based on 2000 square inches (1.29 m^2) shall be as agreed upon by the Purchaser and the vendor.

4.1.2.4 Requalification in accordance with 4.1.2.1 through 4.1.2.3 shall be mandatory if contamination of the powder exceeds the limits set forth in 3.11 on two consecutive or more than one in ten powder lots. Requalification shall also be required whenever a process approved per 4.1.1 is changed, except as authorized in writing by the Purchaser.

4.2 Sampling. Sampling procedures for powder analyses shall be conducted per ASTM B215 or by a method approved by the Purchaser.

4.3 Sieve Analysis. Sieve analyses shall be conducted in accordance with ASTM B214.

4.4 Apparent Density. Apparent density determinations shall be conducted per ASTM B212.

4.5 Contamination Control. A sample shall be taken from each master powder blend and the sample shall be hot isostatic pressed (HIP) per P7TF5, CLASS A. Unless otherwise agreed upon by the vendor and the Purchaser, the HIP sample shall be 5.0 to 5.5 inches (127.0 to 138.7 mm) in diameter and 1.0 to 1.5 inches (25.4 to 38.1 mm) in thickness, with parallel faces, and made using the same powder manufacturing containerization and HIP procedures as are used to make parts from the evaluated master powder blend. The surface shall be electrochemical machined and remachined, if necessary, to provide a minimum total surface area of 400 square inches (0.258 m^2) for examination by a method agreed upon by the vendor and the Purchaser. Electrochemical machining shall be by a method agreed upon by the vendor and the Purchaser.

4.6 Density Standard

4.6.1 All density determinations shall be made in accordance with E50TF126, CLASS A.

4.7 Sample Retention. A 1 pound sample of screened powder from the powder lot, powder heat, or the master powder blend shall be stored in a sealed container and retained by the powder producer for a minimum of 3 years.

4.8 Incoming Raw Material. The powder producer shall establish a method for approval and release of incoming raw material.

5. PREPARATION FOR DELIVERY

5.1 Packing. Powder shall be packaged under controlled conditions in sealed, moisture-proof containers to protect it from damage or contamination during shipment and under normal storage conditions.

5.2 Marking. Each container shall be suitably marked with the following information:

a) Purchase order number
b) Net weight
c) Powder lot, powder heat, or master powder blend number
d) Manufacturer's name
e) This GE specification number, CLASS and revision number

CONTAINERIZATION AND HOT ISOSTATIC PRESSING (HIP) OF RENE' 95 ALLOY POWDER
(P7TF5-S1)

1. SCOPE

1.1 Scope. This specification presents requirements for containerization and hot isostatic pressing of Rene' 95 alloy powder forging preforms and HIP parts.

1.1.1 Classification. This specification contains the following classes:

CLASS A: HIP Parts
CLASS B: Forging Preforms

The requirements specified herein apply to all classes unless otherwise specified.

1.2 Definitions. For purposes of this specification, the following definitions shall apply:

Capability – The words "shall be capable of" or "capability test" indicate characteristics or properties required in the product for which testing of each lot is not required. However, if such testing is performed by the Purchaser, material not conforming to the requirements shall be subject to rejection.

Container – The total vessel separating the powder from the pressurizing gas.

Part Lot – Parts produced in a single autoclave run.

Purchaser – The procurement activity of the Aircraft Engine Group (AEG) of the General Electric Company that issued the procurement document invoking this specification.

Working Zone – The volume of the uniformly heated region of a preheat furnace or an autoclave which may be occupied by parts or material to be hot isostatically pressed.

2. APPLICABLE DOCUMENTS

2.1 The following documents shall form a part of this specification to the extent specified herein. Unless a specific issue is specified, the latest revision shall apply.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM E230 Temperature-Electromotive Force (EMF) Tables for Thermocouples

GENERAL ELECTRIC SPECIFICATIONS

P1TF47 Manufacture of Rene' 95 Alloy Powder

3. EQUIPMENT

3.1 Autoclave

3.1.1 CLASS A: Autoclaves shall be of the inert gas pressurization type, internally heated, cold wall pressure vessel.

CLASS B: Autoclaves shall be of the inert gas pressurization type.

3.2 Fixtures

3.2.1 Suitable jigs, trays, baskets, hangers, racks or other fixtures shall be provided as necessary for proper handling and positioning of parts or materials to be hot isostatic pressed. All fixtures shall be made of suitable material which is compatible with the parts or materials to be treated or adequately isolated to assure that undesirable reactions or mechanical distortion do not occur.

3.3 Containers

3.3.1 Powder containers shall be made from materials approved by the Purchaser.

3.4 Temperature Measurement and Control Devices

3.4.1 Temperature Measurement

3.4.1.1 Temperature measuring and recording devices shall be provided for the autoclave. The devices shall be of the potentiometric type, shall use thermocouple sensors, and shall provide permanent records of the temperature during the entire treatment.

3.4.2 Temperature Control

3.4.2.1 A sufficient number of suitable temperature control devices shall be provided and properly arranged on the autoclave to assure the required temperature control in the working zone. The devices shall be of the potentiometric type and shall use thermocouple sensors.

3.5 Pressure Measurement Devices

3.5.1 Pressure measurement devices shall be accurate to within plus or minus two percent at the maximum operating pressure. The device shall be capable of continuously monitoring and recording the pressure throughout the process.

4. PROCEDURE

4.1 General

4.1.1 All processing equipment and significant processing parameters, as agreed upon by the vendor and the Purchaser, shall be approved by the Purchaser. Once a technique for producing a specific part or preform has been established and approved, no changes shall be made prior to obtaining approval of the Purchaser.

4.1.2 All hot isostatic pressing facilities shall be qualified in accordance with section 5 of this specification.

4.2 Container Fabrication and Cleaning

4.2.1 Fabrication. All materials and processes used in the fabrication of containers shall be approved by the Purchaser.

4.2.2 Cleaning. All containers shall be cleaned to remove all loose particles and all surface contaminants which may be detrimental to the Rene' 95 alloy being treated. Cleaning and subsequent storage and handling shall be done in such a manner as to ensure that the surfaces remain clean prior to container filling. Cleaning and inspection procedures shall be approved by the Purchaser.

4.3 Container Filling

4.3.1 Leak Check. Empty containers shall be evacuated to an ultimate vacuum of less than 25 X 10^{-3} Torr (25 microns) (3.33 Pa) and the closed system leak up rate shall not exceed 20 X 10^{-3} Torr (20 microns) (2.67 Pa) per minute. Alternate leak check methods may be used with prior approval of the Purchaser.

4.3.2 Weighing. Metal containers shall be weighed before and after filling to ensure that they are adequately filled based on pre-determined individual container volume measurements. Powder fill determinations shall be made on ceramic type containers by a method approved by the Purchaser.

4.3.3 Filling and Sealing. Powder shall be loaded into the container through an ASTM No. 40 sieve in such a manner as to minimize particle size segregation in the filled container. The quantity of material retained on the sieve shall be recorded and available for Purchaser review, and the material not used pending that review. The loaded container shall be outgassed and sealed by a method approved by the Purchaser. Containers shall be outgassed to a maximum level of 25 X 10^{-3} Torr (25 microns) (3.33 Pa) and the leak up rate shall not exceed 20 X 10^{-3} Torr (20 microns) (2.67 Pa) per minute. Hot outgassing of the filled container is not permitted without written approval of the Purchaser. The time between sealing the container and loading into the autoclave shall be recorded.

4.4 Loading of Preheat Furnace and Autoclave

4.4.1 All material to be treated shall be located within the working zone. Positioning in the autoclave shall also facilitate pressurization of the chamber and cooling of the material.

4.5 Instrumentation of the Preheat Furnace and Autoclave

4.5.1 A minimum of three thermocouples shall accompany the material during treatment. One each shall be located in the hottest and coldest temperature regions of the working zone which is in use as determined by the temperature uniformity qualification test. The third thermocouple shall be located as close as possible to the center of the load. The thermocouples shall be in close proximity to the containers. An alternate instrumentation plan may be used with prior approval of the Purchaser.

4.6 Time, Temperature and Pressure

4.6.1 The heat-up, pressurization, and cooling cycles shall be approved by the Purchaser.

4.7 Pressure and Thermal Environment

4.7.1 Equipment. All pressure and temperature indicating equipment shall be adjusted in accordance with the instrument manufacturer's instructions.

4.7.2 HIP Cycle. CLASS A: The cycle shall be 2050° ± 25°F (1121° ± 14°C) for 2 hours minimum under a pressure of 14,000 psi (97 MPa) minimum.

CLASS B: The cycle shall be conducted at a designated temperature in the range of 2050° through 2225°F (1121° to 1218°C). The selected temperature and pressure cycles are subject to Purchaser approval. The temperature shall be controlled within ±25°F (±14°C).

4.7.2.1 The temperatures and pressures shall be continuously measured and recorded with respect to time during the entire HIP cycle. The use of multi-point recorders with a periodic print out of five minutes maximum per thermocouple and pressure gauge is permitted.

4.8 Density

4.8.1 CLASS A: HIP parts shall have a density greater than 99.9 percent of the density of the HIP test sample fabricated from the same powder lot, powder heat, or master powder blend as specified in P1TF47 CLASS A.

CLASS B: As-compacted preforms shall have a density greater than 99.7 percent of the density of the test sample fabricated from the same powder lot, powder heat, or master powder blend as specified in P1TF47, CLASS A.

4.9 Grain Size

4.9.1 CLASS A: HIP parts shall have a uniform average grain size of ASTM No. 8 or finer with no outlining of prior particle boundaries. A typical acceptable HIP microstructure is shown in Figure 120. Unacceptable HIP microstructures are shown in Figure 121. Glossy prints are available from the Purchased upon request.

CLASS B: As-compacted preforms shall have a uniform average grain size of ASTM No. 3 or finer.

4.10 Decanning

4.10.1 HIP containers and associated diffusion zones shall be completely removed by a method approved by the Purchaser.

4.11 Re-HIP

4.11.1 Re-HIP procedures, when permitted, shall be as defined in a Quality Control Plan approved by the Purchaser.

4.12 Inspections and Tests

4.12.1 All inspections or tests required by the drawing or applicable specifications shall be performed. The results of these inspections or tests shall meet the requirements of the drawing or applicable specifications.

4.12.2 Sample parts or representative material shall be evaluated with respect to microstructure and density to the requirements of the drawing or applicable specification.

4.13 Records

4.13.1 All records and test results for each hot isostatic pressing treatment shall be maintained for Purchaser surveillance. These records shall include at least the following information:

a) Purchaser identification of parts or material treated
b) Part or material alloy designation
c) Autoclave identification
d) Container fabrication and cleaning procedures
e) Loading procedures including fixture materials and part placement
f) Instrumentation procedures including thermocouple type and placement
g) Pressure records
h) Temperature records
i) Time between sealing container and loading into autoclave
j) Powder container material and container removal procedures
k) Pressure media
l) Metallographic evaluation results
m) Visual inspection results
n) Vacuum induction melt number, powder lot number, powder heat number, and master powder blend number
o) Quantity of material retained on ASTM No. 40 sieve (see 4.3.3)

4.13.2 Records shall be maintained to provide traceability for each serialized part. Each part shall be traceable to a particular hot isostatic pressure treatment, date, time, autoclave, and location within the autoclave.

5. QUALITY ASSURANCE PROVISIONS

5.1 General

5.1.1 All qualifications shall be the responsibility of the prime hardware vendor. Prime vendors may request approvals through the Purchaser. The vendor shall be responsible for all testing and shall sign all necessary forms which certify that qualification in accordance with this specification has been attained.

5.1.2 Procedures for equipment qualifications, if other than those required by this specification, are subject to approval by the Purchaser.

5.1.3 The Purchaser reserves the right to observe any of the qualification tests required by this specification to determine conformance to this specification.

5.2 Preheat Furnace and Autoclave Qualification

5.2.1 Temperature Uniformity. All preheat furnaces and autoclaves shall be qualified for working zone temperature uniformity prior to use for production hot isostatic pressing. All preheat furnaces and autoclaves shall be requalified after any alterations to the equipment which may affect temperature uniformity. Requalification may be on a working load.

5.2.1.1 When approaching thermal equilibrium, per 5.2.2, none of the load temperature readings shall exceed the selected control temperature by more than 25°F (14°C). After thermal equilibrium is reached, the maximum temperature variation of any load test thermocouple shall not deviate from the selected control temperature by more than ±25°F (±14°C).

5.2.2 Qualification Procedure. Temperature uniformity tests shall be conducted with the preheat furnace or autoclave containing a representative production load of parts or material and a typical production pressure. The test shall be made using calibrated test thermocouples and a potentiometer type measuring instrument with a minimum sensitivity of 0.02 millivolt. The readouts of the test thermocouples shall be properly corrected as determined by the thermocouple calibrations. A minimum of three test thermocouples or one per each 5 cubic feet (1.4 m^3) of working zone, whichever is greater, shall be used for determining the temperature uniformity. When more than three thermocouples are required, the additional thermocouple locations shall be symmetrically distributed within the working zone. The initial qualification shall be performed over a temperature range considered for the product as agreed upon by Purchaser and vendor for the preheat furnace or autoclave. Requalifications shall be performed at a convenient temperature within the operating range. The temperature of all test and control thermocouples shall be recorded at 5 minute intervals starting immediately after charging the test load to the preheat furnace or autoclave. Temperature measurements shall be continued for at least 1/2 hour after the control thermocouple indicates that thermal equilibrium has been reached so that the recurrent temperature pattern of the preheat furnace or autoclave can be determined. In addition, HIP quality control samples of powder from a single powder lot, powder heat, or master powder blend, conforming to a configuration agreed upon by vendor and Purchaser, shall be positioned at the center and extremities of the working zone during the qualification run. The samples shall contain powder conforming to PIFTF47, CLASS A, and shall be fabricated per the procedures outlined in 4.2 and 4.3. Metallographic and density examinations shall be conducted on these compacts to ensure uniformity of operating conditions.

5.3 Temperature Measurement and Control Qualification

5.3.1 Instruments. All instruments used for temperature measurement shall have an indicated temperature accuracy of ±0.25 percent of the maximum operating temperature over the entire operating temperature range. All instruments used for temperature control shall have an indicated temperature accuracy of ±0.5 percent of the maximum operating temperature over the entire operating temperature range. The indicated temperature accuracy of each instrument shall be determined in accordance with the equipment manufacturer's recommendations and using a known emf input of suitable accuracy. After the initial qualification, all instruments shall be requalified at least every 30 days, unless otherwise agreed upon by the vendor and the Purchaser.

5.3.2 Thermocouples. Prior to each use, all thermocouples shall be capable of meeting the temperature-electromotive force requirements of ASTM E230 for special grade wire as determined by suitable test methods and requalification intervals.

5.4 Pressure Indicating Instrument Qualification

5.4.1 All pressure indicating instruments shall be checked in accordance with the equipment manufacturer's recommendations. The equipment's performance shall be within the limits supplied by the equipment manufacturer. After the initial qualification, each instrument shall be requalified at least every 6 months.

5.5 Process Qualification

5.5.1 Prior to production processing, detailed process procedures and results of test samples shall be submitted to the Purchaser for approval.

5.5.2 Process procedures shall include the same information required by 4.13.1.

5.6 Records

5.6.1 All records and test results shall be maintained for Purchaser surveillance. A special process certification form(s) shall be posted near the autoclave and other necessary components after qualification indicate compliance with this specification. The form(s) shall contain the following minimum information:

a) Type of equipment
b) Equipment manufacturer where applicable
c) Equipment model and serial number where applicable
d) Equipment location
e) Statement indicating compliance with this specification
f) Signature of vendor's qualifying agent

APPENDIX II
PROCESS CONTROL PLAN

	VENDOR A	VENDOR B
I. POWDER PRODUCTION		
A. Input Material	PITF47	PITF47
a. Purity	C50TF64, PITF47	C50TF64, PITF47
B. Crucibles Refractories	Vendor Internal Spec.	Vendor Internal Spec.
a. Type		
b. Material		
c. Replacement Rate		
C. Melting Parameters	P1TF26	P1TF26
D. Atomization Parameters	Vendor Internal Spec.	Vendor Internal Spec.
a. Nozzle Design		
b. Pour Temperature		
c. Gas Pressure		
E. Powder Characteristics	Vendor Internal Spec.	Vendor Internal Spec.
a. Reproducibility of Mesh Size	Vendor Internal Spec.	Vendor Internal Spec.
b. Flow Rates	Vendor Internal Spec.	Vendor Internal Spec.
c. Tap Density	Vendor Internal Spec.	Vendor Internal Spec.
d. Particle Size Distribution	C50TF64	C50TF64
F. Chemical Analysis		
a. Procedures for Major Elements	C50TF64, PITF47	C50TF64
b. Oxygen, Nitrogen	C50TF64, PITF47	C50TF64
c. Trace Elements	P29TF19	P29TF19
II. POWDER HANDLING		
A. Source of Contamination During:	Vendor Internal Spec.	Vendor Internal Spec.
a. Removal from Atomization Unit		
b. Transfer to Screening Room		
c. Screening		
d. Deorganization		
e. Container Filling		
f. Blending		
g. Sampling		

	VENDOR A	VENDOR B
B. Screening Procedure	Vendor Internal Spec.	Vendor Internal Spec.
a. Sizes Used		
b. Cleaning Procedures for Screens and Vibrators		
c. Lot Size		
d. Time and Degree of Agitation		
e. Screen Inspection and Calibration		
C. Deargonization Procedure	Vendor Internal Spec.	Vendor Internal Spec.
a. Vacuum Level		
b. Time		
c. Temperature		
d. Handling Procedures		
D. Container Filling Procedure	Vendor Internal Spec.	Vendor Internal Spec.
a. Facilities		
b. Vacuum Level		
c. Container Cleaning Procedures		
d. Vibration Parameters		
e. Sealing Technique		
f. Container Volume Measurement		
g. Reproducible Filling Technique		
h. Leak Check Procedure		
E. Storage Procedure (Powder and Filled Container)	Vendor Internal Spec.	Vendor Internal Spec.
a. Transient Procedures		
b. Container Cleanliness		
c. Shelf Life, Storage Environment		
III. HOT ISOSTATIC PRESSING	P7TF5	P7TF5
A. Parameters	Vendor Internal Spec.	Vendor Internal Spec.
a. Time-Temperature-Pressure Profile	Vendor Internal Spec.	Vendor Internal Spec.
b. Pressurizing Gas	Vendor Internal Spec.	Vendor Internal Spec.
c. Post-HIP Cooling Rate	Vendor Internal Spec.	Vendor Internal Spec.
d. Special Container – Secondary Pressing Media, Pump Down Procedure	Vendor Internal Spec.	Vendor Internal Spec.

	VENDOR A	VENDOR B
e. Thermocouple Location – Temperature, Measurement	P21TF7	P21TF7
IV. HEAT TREATMENT	C50TF64, P10TF1	C50TF64, P10TF1

APPENDIX III
PRODUCT ACCEPTANCE PLAN

CHARACTERISTIC	REQUIREMENT	METHOD
A. Chemical Composition	C50TF64, Par. 3.1.2	Standard ASTM Methods
B. Cleanliness	C50TF64, Par. 3.8.1	ASTM E45
C. Microstructure		
1. Uniformity of Grain Size	C50TF64, Par. 3.5.1	ASTM E112
2. Prior Particle Boundary Outline	C50TF64, Par. 3.5.1	ASTME112
D. Density (Forged Sample of HIP'ed Master Powder Blend = 100% Theoretical Density)		
1. As-HIP'ed		
a. QC Center Slug-Disks	C50TF64 Par. 3.6.1 (min. 99.9% of Theoretical Density)	Buoyancy Method per ASTM B311 Modified ASTM B311
b. Parts		
2. TIP Response	C50TF64, Par. 3.6.1 (Density must not decrease by more than 0.3%)	Same as D.1.(a)
3. Procedures	Correlation of D.1.(a) and D.1.(b) will be made	Statistical Analysis
E. NDT		
1. Ultrasonic		
a. Surface Condition	Per Drawings 17A116-354 and -355. P3TF1 with 40% Rejection Amplitude per Drawings.	Standard Methods P3TF1 Class A
b. Requirements		Standard Methods P3TF1 Class A

CHARACTERISTIC	REQUIREMENT	METHOD
2. Fluorescent Penetrant Inspection	C50TF64, Par. 4.11	P3TF2 Class D
F. Mechanical Properties	C50TF64	C50TF64
1. Tensile	Par. 3.3.1	Par. 4.3.5
2. Stress-Rupture	Par. 3.3.2	Par. 4.3.6
3. Plastic Creep	Par. 3.3.3	Par. 4.3.7
4. Low-Cycle Fatigue	Par. 3.3.4	Par. 4.3.8
5. Cyclic Rupture	Par. 3.3.5	Par. 4.3.9
6. Hardness	Par. 3.4.1	Par. 4.4 – ASTM No. 10
G. Dimensional Inspection	Must Conform to Drawing	Standard Methods
H. Records and Documentation	C50TF64, Par. 3.9.1 and 3.10.1 + HIP Cycle and Disk Location in Autoclave by S/N	Standard Identification

APPENDIX IV
MEASUREMENT SENSITIVITY FOR DENSITY DETERMINATION

The density measured by the buoyancy method is given by:

$$\rho_s = \frac{\rho f \, W_A}{W_A W_f} \tag{1}$$

where

ρ_s = Density of solid

ρf = Density of immersion fluid

W_A = Weight of specimen in air

W_f = Weight of specimen in water

Differentiating:

$$d\rho_s = \frac{\partial \rho_s}{\partial \rho f} d\rho f + \frac{\partial \rho_s}{\partial W_A} dW_A + \frac{\partial \rho_s}{\partial W_f} dWf \tag{2}$$

From 1 and 2:

$$\Delta\rho_s = \frac{W_A}{W_A - W_f} \Delta\rho f + \frac{\rho f \, W_A}{(W_A - W_f)^2} \Delta Wf + \frac{\rho f \, W_f}{(W_A - W_f)^2} \Delta W_A \tag{3}$$

Combining 1 and 3:

$$\frac{\Delta\rho_s}{\rho_s} = \frac{\Delta\rho_f}{\rho f} + \frac{\rho_s - \rho_f}{\rho_f} \frac{\Delta W_f}{W_f} + \frac{\rho_s - \rho_f}{\rho_f} \frac{\Delta W_A}{W_A} \tag{4}$$

Equation (4) describes the change in the density of specimen due to change in the density of fluid $\Delta\rho_f$, error in weighing in fluid ΔW_f, and the error in weighing in air ΔW_A.

In order to comply with the specification requirement of a 99.9 percent density:

$$\frac{\Delta\rho_s}{\rho_s} = 10^{-3}$$

However, since $\Delta\rho_s$ is also dependent on the other variables* besides the errors in weighing in air and water, the actual allowable change should not be more than 10 percent of 10^{-3}, i.e., 10^{-4}.

Using water measured to an accuracy of 1°C:

$$\frac{\Delta\rho_f}{\rho_f} = 3 \times 10^{-5}$$

and since

$\rho_s - \rho_f/\rho_f$ for Rene' 95 and water is 7.3.

Equation (4) is:

$$10^{-4} = 3 \times 10^{-5} + 7.3 \times \frac{\Delta W_f}{W_f} + 7.3 \frac{\Delta W_A}{W_A}$$

Assuming:

$$\frac{\Delta W_f}{W_f} = 10 \frac{\Delta W_A}{W_A}$$

$$\frac{\Delta W_A}{W_A} = 10^{-6}$$

Thus, a balance sensitive enough to detect 5 mg variation in a 50 kg load is required.

*Some of the other factors affecting the density determination are:

- Bubble attachment to specimen
- Capillary force in wire
- Viscosity of liquid
- Specimen temperature
- Buoyancy of wire