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HOT ISOSTATIC PRESSURE HEALING OF NAVY  
GUN METAL CASTINGS

D. A. Seifert, et al

Battelle Columbus Laboratories

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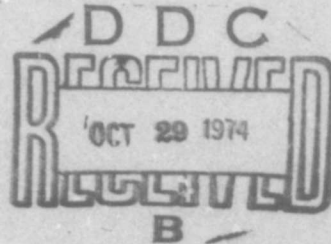
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D. A. Seifert and H. D. Hanes

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20. (Continued)

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## FOREWORD

This report documents the work performed on Contract No. N00024-73-C-5375 by Battelle's Columbus Laboratories for U.S. Naval Ship Engineering Center, Hyattsville, Maryland, from 7 March 1973 to 30 August 1974. The work was conducted under the administrative supervision of Messrs. Harrison Sayre and Frank Rosenthal of the Naval Ship Engineering Center. The assistance and cooperation of Messrs. John Carosiello and Michael Simon of the Philadelphia Naval Shipyard who provided the cast bronze material and performed the final analysis of the HIP-processed full-sized bronze castings are gratefully acknowledged.

## ABSTRACT

This report summarizes the investigation of the use of Hot Isostatic Pressure (HIP) processing to heal defects in Navy Gun Metal castings. The effects of HIP processing temperature at 15,000-psi pressure on the mechanical properties, microstructure, and cast-in porosity in G-metal were investigated. HIP at temperatures between 1250 and 1500 F were found to practically eliminate porosity. Gas permeable porosity was eliminated in every case. Increases in yield strength of 14 percent, ultimate tensile strength of 37 percent, and elongation of 100 percent were obtained compared to as-cast properties. Dendritic segregation was reduced and second phase material redissolved as a result of HIP processing. The HIP conditions developed were applied to the processing of cast 4-in. flex connector bodies with generally similar results. On the basis of these findings it was concluded that the quality of G-metal castings and the cost-effectiveness of their production could be significantly benefited by the incorporation of HIP processing as a routine step in the manufacturing process.

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# HOT ISOSTATIC PRESSURE HEALING OF NAVY GUN METAL CASTINGS

by

D. A. Seifert and H. D. Hanes

## INTRODUCTION

The increased sophistication of Naval ship systems has brought about a need for increased durability and integrity in the system components and, concomitantly, demands for greater cost effectiveness. Consequently, the continued utility of castings for ship systems is, to a large extent, dependent on the ability of the producers to make structurally sound castings consistently and economically. Bronze and other copper-base alloy castings, which are among those most widely used by the Navy for fluid and heat transfer systems associated with ship propulsion, are inherently prone to the formation of gas and shrinkage porosity during solidification. The difficulties associated with consistently producing sound bronze castings increase as the casting size and, therefore, the amount of cast-in internal porosity increases. While bronze castings are relatively inexpensive to produce and rejected castings can be easily recycled, the cost of rejection is usually significant because interconnected cast-in porosity cannot usually be detected until after final machining. Fluid leakage through porous material exposed by removal of the dense as-cast skin during the machining of attachment and bearing surfaces and bolt holes is, then, the major cause for rejection of bronze castings.

Experimental work performed at Battelle on other porous cast materials has indicated that pores and cavities in cast structures can be collapsed to the point of nondetection and welded closed by the simultaneous application of heat and isostatic pressure. The application of this process, known as Hot Isostatic Pressure (HIP) Processing, to an alloy of significant interest to the Navy was the subject of this research investigation. Navy Gun Metal, copper alloy No. 903, was chosen as the subject material because of its wide utility in the fabrication of cast components for pressurized fluid systems and the relative inability to repair casting defects and porosity in it by standard welding

techniques. A two-phased approach was employed to: (1) investigate the feasibility of and develop the processing conditions for healing defects in G-metal castings by HIP and (2) to demonstrate that the process could be applied to improving the properties of cast G-metal components while reducing production losses due to rejection of porous parts.

It was found as a result of the work described herein that HIP-processing is a viable technique for healing microshrinkage and gas induced porosity in G-metal castings and that bulk mechanical property improvements can be expected as an added benefit. The process could be applied as a step in the production process and has the potential to practically eliminate porosity-induced leakage during final hydrostatic inspection of cast parts. Further development effort may be required, however, in cases where large or extensive near-surface porosity might result in significant alteration of surface contours or might fail to consolidate as a result of strain-induced leaking during HIP processing. In general, however, it was concluded that the potential benefits to be derived from HIP processing are sufficient to warrant further investigation of the process as it might be applied as a routine step in the production of components cast from bronze and other alloys of interest to the Navy.

#### EXPERIMENTAL APPROACH AND PROCEDURES

A two-phased approach was used to investigate the applicability of hot isostatic pressure (HIP) processing to the healing of casting defects in copper alloy 903 (G-metal). The first, and major, phase of the program was directed toward investigating the effects of various HIP processing conditions on porosity and mechanical properties of G-metal castings. It was, then, the purpose of the second phase of the program to apply the findings of the preceding experimental work to the HIP processing of cast parts of interest to the Navy.

Specimen materials for the HIP processing study under Phase I of the program were obtained from the Philadelphia Naval Shipyard in the form of scrap castings (primarily flanges and flex connector bodies) which leaked during hydrostatic proof testing. The castings which could physically accommodate

3/4-in.-diameter by 4 or 5-in.-long tensile specimen blanks were heated in vacuum to about 400 F to drive off any water which might be trapped in the pores as a result of the Navy's hydrostatic tests. Each casting was then retested by pressurizing with helium and submersion in methanol. The locations of all surface-connected porosity from the interior of the castings to either bolt holes or external machined surfaces were then marked so that specimens for HIP and control mechanical property determination could be located and the castings sectioned. Approximately 35 specimen blanks, each measuring 5 in. long by 3/4-in. diameter were cut from the bronze castings provided by the Navy. Each of these specimens was checked for surface-connected porosity by helium penetration. A total of 15 grossly porous specimens and 6 specimens showing no surface-connected porosity were selected for HIP treatment at 3 temperatures between 1200 and 1500 F. The remaining specimen blanks were finish machined into tensile bars for control testing. These were again helium pressure tested to verify the presence or absence of surface-connected porosity in the gage section prior to mechanical testing. One group of four porous control specimens was heat treated at 1300 F under argon at reduced pressure to simulate the thermal portion of a HIP cycle.

The 21 specimens selected for HIP treatment were encapsulated in carbon steel cans and given an alternating vacuum/hydrogen heat treatment at 600 F. The capsules were then hermetically sealed under a vacuum of  $2 \times 10^{-6}$  Torr. Three HIP cycles, each containing five porous and two nonporous specimens were carried out at 15,000-psi pressure for 3 hours. The three temperatures used during these HIP cycles were approximately 1500 F, 1400 F, and 1250 F. After HIP processing, the mild steel envelopes were removed and the specimen blanks were machined into tensile bars. Each finished bar was helium pressure checked for the presence of surface-connected porosity in the gage section.

All specimens were tested in uniaxial tension using an Instron testing machine equipped to record load and strain. Values of elongation at rupture were measured manually. These data along with modulus values and tensile yield and ultimate strengths were then compared by statistical means to evaluate the effects of HIP temperature on mechanical properties.

Microstructural effects of HIP processing were evaluated using cross sections cut from the grip ends of one of each of the various groups of specimens. Changes in microstructure caused by HIP processing were noted. The ability of HIP to close porosity in cast G-metal was measured by quantitative metallographic techniques and the data statistically analyzed.

Specimens for the second, or process demonstration phase of the program were also supplied by the Philadelphia Naval Shipyard. An entire heat of six 4-inch flex connector bodies was especially cast for this program. Gas heat was used instead of the usual electric arc melting because a higher percentage of defects could be expected to result from use of this method. Each casting, including the Webbert test piece, was X-ray inspected in the as-cast condition. All risers were left in place but gates were cut off about 1 inch from the cast bodies prior to shipment to BCL for HIP treatment. This was done to maintain, as nearly as possible, the dense skin around the castings which would permit HIP processing without the use of auxiliary encapsulation or intermediate pressure transfer media.

Upon arrival at BCL, the castings were visually inspected for surface flaws. The cut surfaces of the gates were sealed by fusing with a TIG arc. The fillet at the juncture of the riser and the body of the Webbert casting was also fusion sealed, because a considerable amount of surface-connected shrinkage cracking was noted in this area. The entire lot of castings was then HIP processed without further preparation. After HIP processing, the castings were again visually inspected for surface evidence of large pore collapse. They were then returned to the Philadelphia Naval Shipyard for finish machining, X-ray, hydrostatic inspection, and testing according to normal manufacturing procedure.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Phase I Investigation

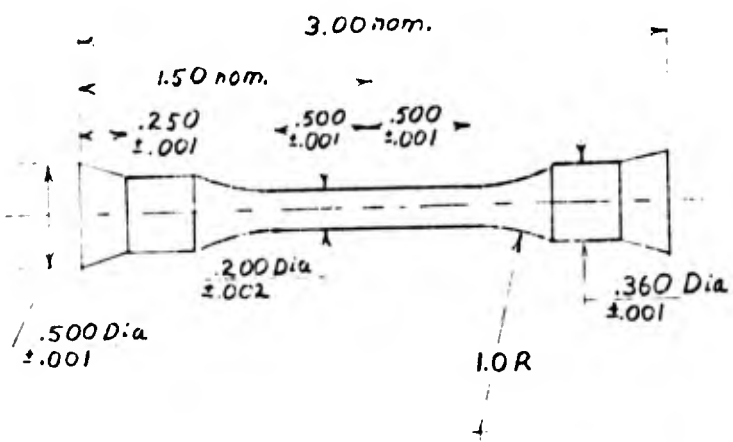
It was the purpose of the first and major phase of the program to investigate the ability of HIP processing at three different temperatures to reduce or eliminate the porosity inherent to the cast bronze material being used by the Navy for high-pressure plumbing applications. The effects of this treatment on the mechanical properties of the cast material were also investigated. Material for this work was supplied by the Philadelphia Naval Shipyard in the form of scrap castings which did not pass the Navy's hydrostatic pressure tests.

Preliminary experiments were carried out to characterize the G-metal castings with respect to the nature and locations of leaks and porosity, mechanical properties, and microstructure. Helium pressurization of the interior (core) surfaces of the cast parts to 40 to 50 psi followed by immersion in alcohol was used to locate the areas from which suitable test specimens, both porous and

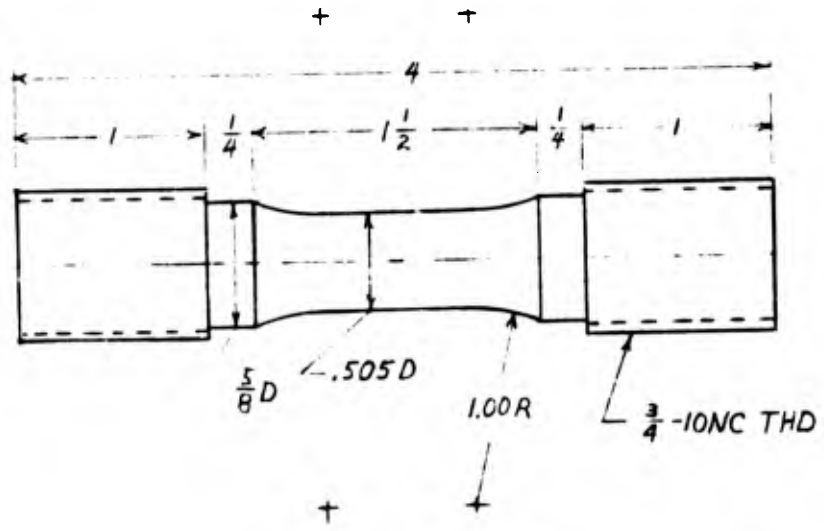
nonporous, might be removed. During the course of this work, it was found that a low-temperature (400 F) vacuum heat treatment of the cast parts to remove residual water from the Navy's pressure tests greatly facilitated the location of gas passages through the material. The number of leakage sites was also found to be greater than had been indicated by the Navy tests.

Preliminary mechanical property tests were conducted on the as-received bronze castings using the two different sized specimens shown in Figure 1 to determine the effects of both specimens size and detectable porosity on tensile properties. The results of these tests, presented in Table 1, indicate that the presence of porosity of the type permitting gas passage through the material causes a significant decrease in both fracture strength and ductility (strain to failure). Yield strength was not significantly affected. The reasons for the differences in elastic modulus values are not clearly understood but are probably related to the large grain size of the material as shown in Figure 2, and to possible differences in orientation of the smaller specimens with respect to the dendrite structure of the castings.

Quantitative metallographic examination of the flange cross section shown in Figure 2 revealed an extremely large dendrite structure averaging about 8 grains to the inch with some of the central grains being as large as 1/4 inch in diameter. Porosity measurements using the "Quantimet" technique on 50 different areas selected at random indicated that porosity in the as-received castings ranged from about 3 volume percent near the original cast surfaces to about 16 volume percent near the center of the section. The overall average porosity was found to be 7.6 volume percent. Because of the large grain size of the cast material, the nonuniform distribution of the porosity, and the nonuniformity of plastic deformation observed in the tensile specimens, it was decided that the larger test specimens should be used throughout the remainder of the program to minimize the influence of grain size and orientation on mechanical properties. This severely limited the amount of material provided by the Navy which could be used for this investigation. It was determined, however, that a sufficient number of 3/4-inch-diameter by 5-inch-long tensile specimen blanks could be obtained from the available material to carry out a meaningful study. As noted in Table 1, it was also determined at this time that the presence or lack of surface-connected porosity would have to be verified for each individual specimen at each step during its preparation.



a. Miniature Tensile Specimen



b. ASTM(E8) Cast Material Tensile Specimen

FIGURE 1. MECHANICAL TEST SPECIMEN DESIGNS



8G987

10 percent  $(\text{NH}_4)_2\text{S}_2\text{O}_8$   
(dark field)

4X

FIGURE 2. MACROSTRUCTURE OF AS-RECEIVED COPPER ALLOY NO.  
903 CASTING

TABLE 1. PRELIMINARY MECHANICAL PROPERTY STUDY OF  
CAST COPPER ALLOY 903

Specimen No.	Specimen Condition	Gage Diam, in.	Modulus, $10^6$ psi	0.2 Percent Offset Yield Strength, $10^3$ psi	Ultimate Tensile Strength, $10^3$ psi	Elongation, percent
1	porous <sup>(a)</sup>	.2004	15.6	16.08	29.12	13.25
2	nonporous <sup>(a)</sup>	.2002	10.9	16.81	30.15	16.50
3	nonporous	.480	10.22	17.13	45 <sup>(b)</sup>	36.5 <sup>(b)</sup>
4	porous	.500	12.48	17.06	29.8	15.5
5	porous	.1998	10.4	15.98	24.93	9.5
6	nonporous	.1999	10.52	17.67	38.55	40.1

- (a) Presence or lack of communicative porosity not verified by He permeation test after specimen removed from casting.
- (b) Specimen not ruptured due to mechanical difficulty with testing machine.

A total of about 35 cylindrical tensile specimen blanks measuring 3/4 inch in diameter by either 4 or 5 inches long were machined from the available cast bronze material, checked for the presence of communicative porosity by a helium permeation check, and separated, on this basis, into two groups, porous and non-porous. Five porous blanks and two blanks exhibiting no surface-connected porosity were then selected for HIP processing at each of three temperatures in the range of 1200 to 1500 F. The remaining 14 cylinders were finish machined to tensile specimens of the type shown in Figure 1b and checked for the presence of surface-connected porosity in the gage section by helium permeation. Eight porous specimens and four specimens showing no communicative porosity were obtained for mechanical testing in the as-cast condition. The remaining two specimens were not useable because the surface of the casting from which they were machined intersected the gage section of the finished tensile specimens.

The 21 specimens selected for HIP processing were encapsulated in close-fitting welded carbon steel cans equipped with evacuation tubes. They were given an alternating vacuum/hydrogen treatment at 600 F to remove as much oxygen and other contamination as possible from the pore surfaces. The specimens were then hermetically sealed under a vacuum of  $2 \times 10^{-6}$  Torr by forge-welding the evacuation stems. It should, perhaps, be pointed out that the singular purpose of encapsulating the bronze specimens for HIP was to provide a pressure transfer medium impervious to the autoclave environment. If the helium atmosphere of the autoclave had been permitted to enter the surface-connected porosity of the bronze specimens, there would have been no pressure differential to act as a driving force to promote closure and healing of the porosity by HIP. The vacuum/hydrogen treatment designed to minimize internal contamination of the bronze material which may have been introduced during hydrostatic testing by the Navy, presumably would not be necessary when HIP-processing freshly cast material.

Three HIP cycles, each containing five porous and two nonporous specimens were carried out at 15,000-psi pressure for 3 hours. Heat and pressure were applied simultaneously and depressurization after the hold period was carried out while the specimens cooled. Temperatures during the respective HIP cycles were maintained at 1470-1505 F, 1390-1400 F, and 1239-1250 F. The steel envelopes were removed after HIP processing by machining, and the specimen blanks again were checked for surface-connected porosity by helium permeation. None could be detected either in the as-HIP condition or after final machining to tensile specimens. One of the initially

porous specimens processed during each of the above HIP cycles was lost due either to deformation-induced rupture of the steel can or, as described above, intersection of the gage section with the original casting surface during final machining.

Four as-cast tensile specimens showing surface-connected porosity were heat-treated at 1300 F for 3 hours in a reduced pressure atmosphere of argon to simulate the thermal effects of HIP processing. Helium permeation tests showed no evidence of porosity closure as a result of this treatment.

All of the specimens discussed above were tensile tested at room temperature in an Instron testing machine equipped with an extensometer for direct measurement of strain. The specimen treatment conditions for which tensile data were obtained and the number of specimens tested for each condition are summarized in Table 2. The mechanical property data obtained for the individual specimens are listed in Appendix Table A-1.

Dramatic improvements in the mechanical properties of cast G-metal were achieved by HIP processing as is apparent in Figures 3 and 4. Yield and tensile strengths were improved by 14 and 37 percent, respectively, with a corresponding increase in ductility (elongation at rupture) of the order of 100 percent. The data were analyzed statistically, assuming normal distributions, to obtain the mean values and 95 percent confidence bands shown in the figures. Student's "t" comparisons of the mean property data obtained for each treatment listed in Table 2 indicated that no significant differences exist between specimens which originally exhibited communicative porosity and those which did not. The statistical analysis of the data is summarized in Appendix Tables A-2 and A-3. According to the data presented in Figures 3 and 4, it would appear that ultimate tensile strength and ductility increase with increasing HIP temperature while yield strength exhibited its greatest improvement at the lowest HIP temperature. The statistical evaluation, however, indicated that while the improvement in mechanical properties as a result of HIP processing is real and dramatic, there is no evidence to indicate that HIP processing temperature within the range investigated had a significant effect on any of the resulting mechanical properties. To determine whether the thermal treatment during HIP could alone account for the enhancement of properties, control specimens were heat treated in a partial vacuum and tested. These showed no enhancement of properties but rather some degree of degradation. The reasons for the decrease in mechanical properties are not fully understood and were not fully investigated but may be associated with volatilization of one or more of the

TABLE 2. SUMMARY OF SPECIMEN CONDITIONS AND TREATMENTS  
USED FOR MECHANICAL PROPERTY STUDIES

Specimen Group Identification	Original Condition (1)	No. of Specimens	Experimental Treatment Prior to Tensile Testing
OP	porous	4	None - as cast
OP-H	porous	4	Heat-treated 1300 F, 3 hr, partial vacuum
OS	nonporous	4	None - as cast
1P	porous	4	HIP-processed 1500 F, 3 hr, 15,000 psi
1S	nonporous	2	" " " " "
2P	porous	4	HIP-processed 1400 F, 3 hr, 15,000 psi
2S	nonporous	2	" " " " "
3P	porous	4	HIP-processed 1250 F, 3 hr, 15,000 psi
3S	nonporous	2	" " " " "

(1) Original condition of porosity was determined in each case by helium gas permeation testing.

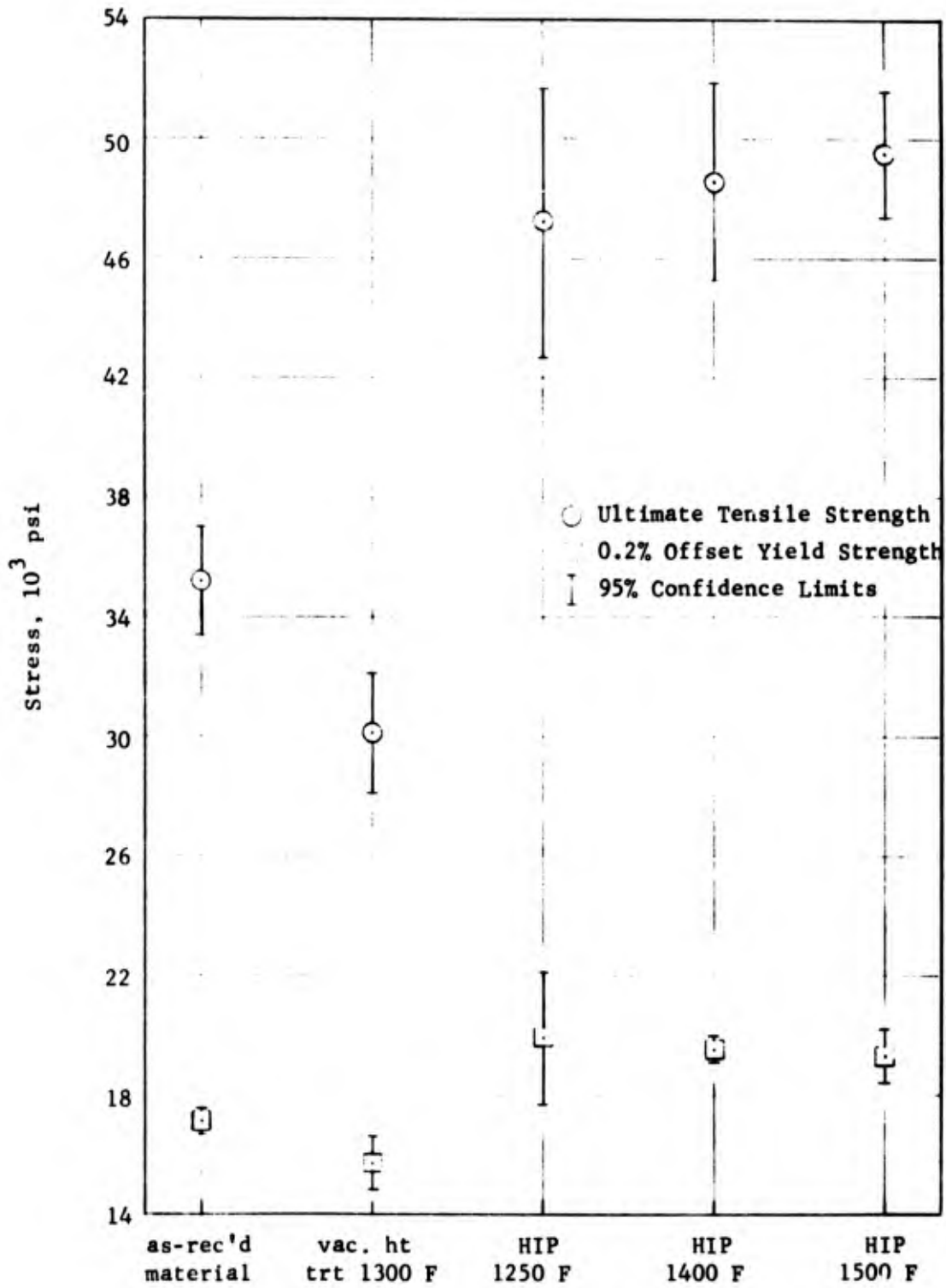


FIGURE 3. EFFECT OF HIP PROCESSING ON STRENGTHS OF CAST COPPER ALLOY NO. 903

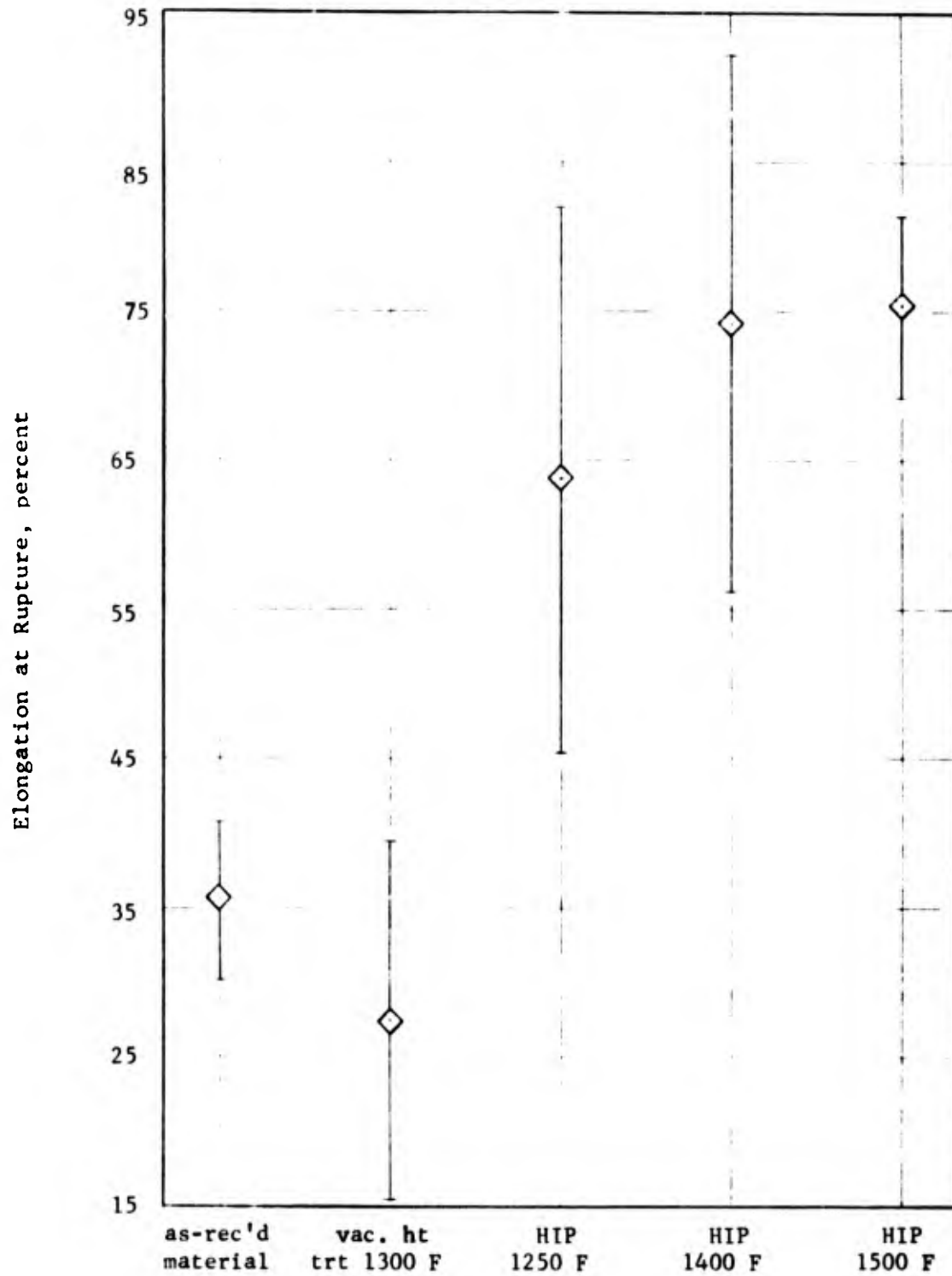


FIGURE 4. EFFECT OF HIP PROCESSING ON DUCTILITY OF CAST COPPER ALLOY NO. 903

alloy components as evidenced by a metallic deposit on the cooler regions of the furnace muffle used for the heat treatment.

In addition to mechanical property and gas permeation testing, a study was made of the effects of HIP processing on the microstructure of the cast bronze material. Representative metallographic samples were selected from the grip ends of originally porous specimens HIP processed at each of the three temperatures discussed above. In addition to these and the as-received specimen shown in Figure 2, specimens were prepared from porous material and material exhibiting no surface-connected porosity which had been vacuum/hydrogen treated at 600 F but not HIP processed. The macrostructural effects of the hydrogen/vacuum heat treatment and HIP processing are presented in Figure 5. A comparison of Figures 2 and 5a indicates that the alternating vacuum/hydrogen treatment did not significantly affect the overall cast structure in any way. HIP processing, however, appears to have had a significant effect. Homogenization of the highly segregated cast structure becomes increasingly apparent as the HIP temperature is increased. Considerable recrystallization and fine twin formation was readily apparent after HIP at 1400 F. While the recrystallization twins were still present in the specimen HIP at 1500 F, they were considerably larger and fewer in number and showed a tendency to transform the original segregated dendrite structure to one more indicative of a large grained wrought material.

Micrographic examination of these same specimens, as shown in Figure 6, further revealed the effects of HIP processing. As shown in Figure 6a, a second phase was found in the as-cast material, usually associated with shrinkage porosity. Electron probe microanalysis indicated that this was probably the tin-rich delta phase. Figure 6b shows that the delta phase was redissolved by HIP processing at 1250 F, and this probably aided in nucleation of the recrystallization twins associated with incompletely healed shrinkage porosity. These twins were too small to be observed in the macrograph of Figure 5b. Increasing the HIP processing temperature to 1400 and 1500 F permitted essentially complete closure of the shrinkage voids during the 3-hour HIP cycle and allowed the recrystallization twins to increase in size as shown in Figure 5c and d. The practically void-free structure contained only oxide inclusions and recrystallization twins. The remains of prior porosity could only be detected where diffusion across the collapsed void interface was prevented by the presence of contamination, probably in the form of an oxide film, on the surfaces of the original pores. This is shown in Figure 6d.



OH897 20 percent  $(\text{NH}_4)_2\text{S}_2\text{O}_8$   
(dark field) 5X

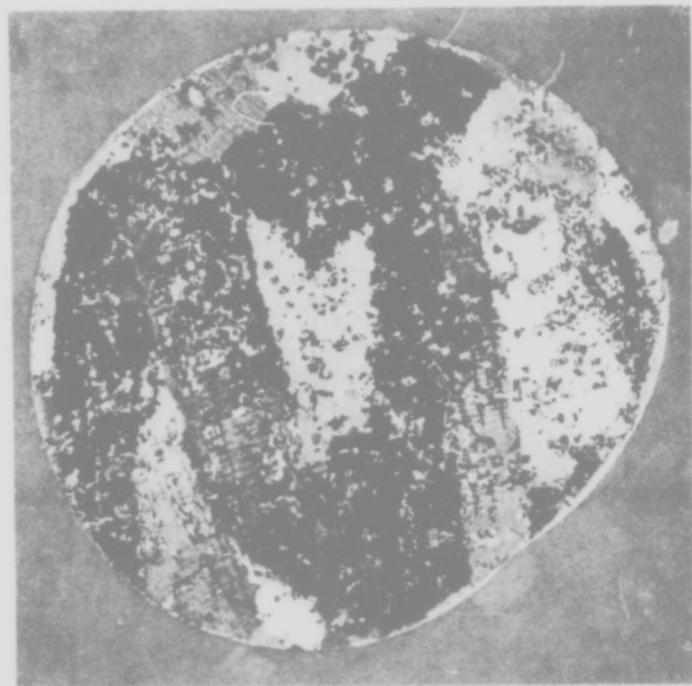
a. As-cast + vacuum/ $\text{H}_2$  outgassed  
material



OH900 20 percent  $(\text{NH}_4)_2\text{S}_2\text{O}_8$   
(dark field) 5X

b. Material HIP processed at 1250 F,  
15,000 psi, 3 hr

FIGURE 5. MACROSTRUCTURAL EFFECTS OF HIP PROCESSING  
ON CAST COPPER ALLOY NO. 903



OH899      20 percent  $(\text{NH}_4)_2\text{S}_2\text{O}_8$       5X  
 (dark field)

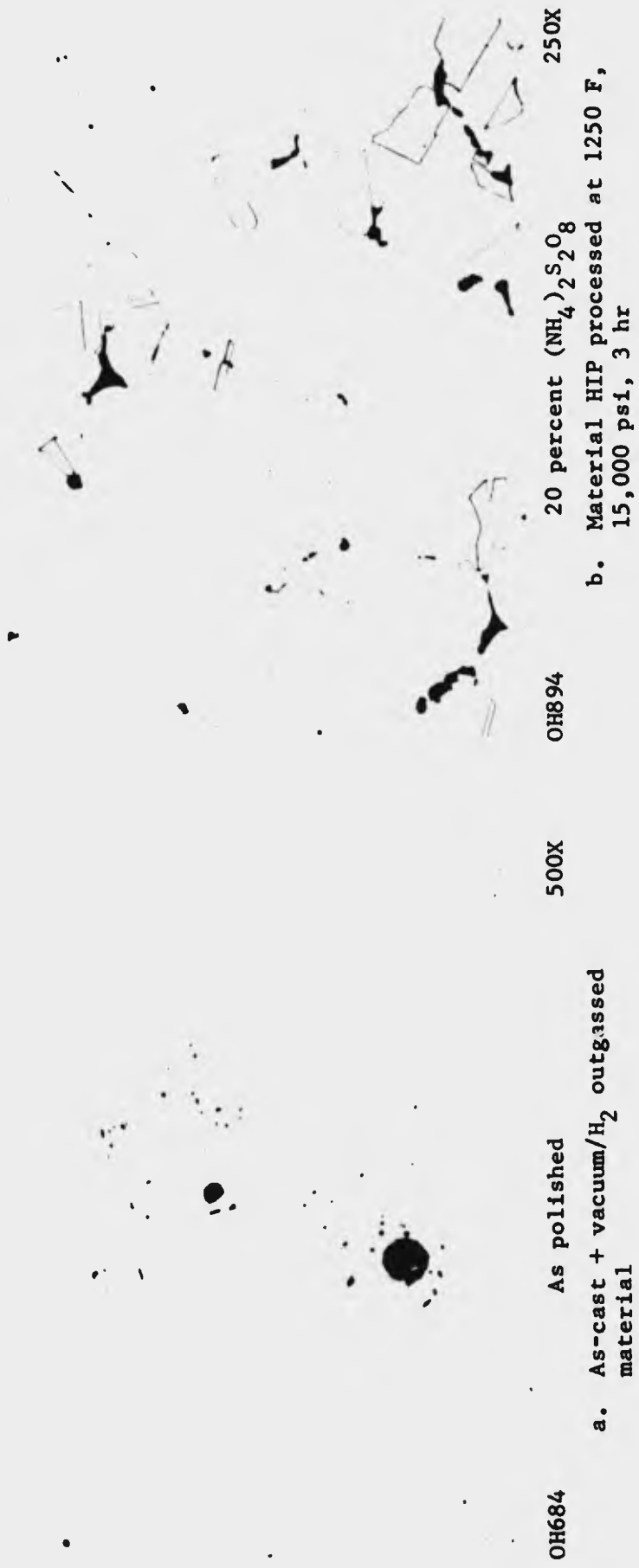
c. Material HIP processed at  
 1400 F, 15,000 psi, 3 hr



OH898      20 percent  $(\text{NH}_4)_2\text{S}_2\text{O}_8$       5X  
 (dark field)

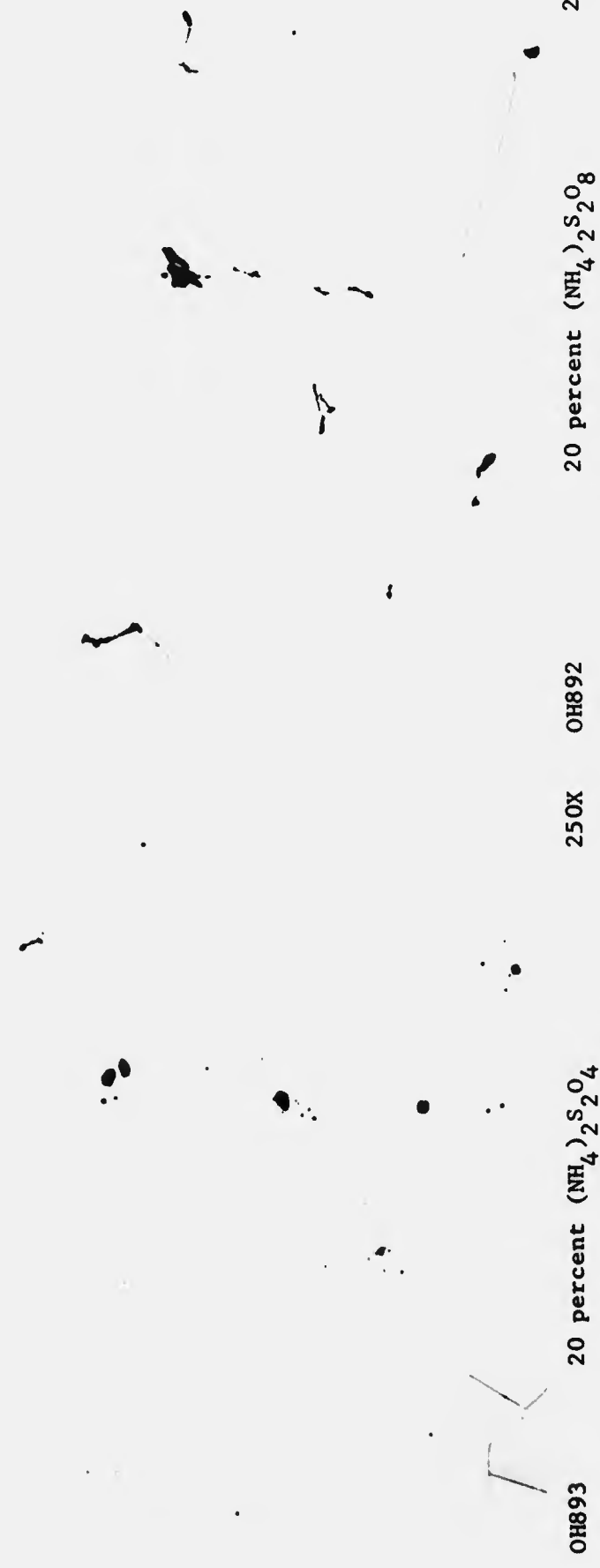
d. Material HIP processed at 1500 F,  
 15,000 psi, 3 hr

FIGURE 5. (Continued)



OH684 As polished 500X  
 a. As-cast + vacuum/H<sub>2</sub> outgassed material  
 20 percent (NH<sub>4</sub>)<sub>2</sub>S<sub>2</sub>O<sub>8</sub> 250X  
 b. Material HIP processed at 1250 F, 15,000 psi, 3 hr

FIGURE 6. MICROSTRUCTURAL EFFECTS OF HIP PROCESSING ON CAST COPPER ALLOY NO. 903



c. Material HIP processed at 1400 F, 15,000 psi, 3 hr

d. Material HIP processed at 1500 F, 15,000 psi, 3 hr

FIGURE 6. (Continued)

Quantitative determination of the degree of pore closure resulting from HIP processing was accomplished with a "Quantimet" image analyzing computer. The four specimens discussed above and the original casting cross section shown in Figure 2 were used for this study. Fifty fields of view, randomly selected, were examined for each specimen with the results presented in Table 3. These data show conclusively that the inherent porosity in these cast bronze specimens was reduced dramatically by HIP processing at all three of the temperatures investigated. The twenty-fold reduction in porosity observed after HIP processing at even the lowest temperature investigated probably accounts for a substantial portion of the increase in mechanical properties discussed above. Accordingly, the very low volume fraction of porosity in all of the HIP processed specimens would account for the lack of statistical significance of the mechanical property differences observed for the various HIP processing temperatures.

The data presented in Table 3 also indicate that the presence or lack of porosity as determined by gas or liquid permeation tests bears no significant relation to the actual presence of porosity in castings. These tests only indicate whether cast-in porosity, which can be interconnecting at volume fractions as low as 0.05, is connected to either the original surface or a machined surface of cast parts. Mechanical properties, on the other hand, do appear to have a direct relationship to the presence of porosity in cast material. Of the properties studied, ductility and ultimate strength appear to be more sensitive to porosity than yield strength although all are affected. This degradation of mechanical properties is thought to be caused, in part, by a reduction of the real cross-sectional area and notch effects resulting from the presence of porosity and other casting defects. HIP processing, in eliminating or reducing these defects, has the net effect of increasing bulk mechanical properties of cast material.

### Phase II Investigation

It was the purpose of the second phase of the program to demonstrate that the improvements in structure and properties of cast G-metal could be realized in full-sized cast structures. This part of the program was conducted jointly with the Philadelphia Naval Shipyard Foundry under the direction of Mr. John Carosiello. One heat (Serial No. CUCO 4329) of six 4-inch flex connector bodies and two Webbert test bar castings was cast using techniques known to be less reliable than the

TABLE 3. EFFECT OF HIP ON VOLUME FRACTION POROSITY  
IN G-METAL CASTINGS

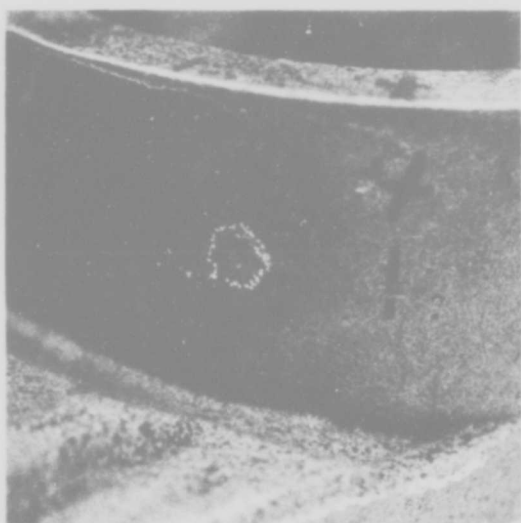
Specimen Identification	Condition	Volume Fraction of Porosity (a)		
		Minimum	Maximum	Average
Flange Cross Section	as-received (cast and machined)	0.03	0.16	0.076
HP	communicative porosity, H <sub>2</sub> /Vac. treated	0.006	0.14	0.05
HS	no communicative porosity, H <sub>2</sub> /Vac. treated	0.01	0.18	0.06
3P-1	HIP 1250 F, 15,000 psi, 3 hrs	0.0002	0.0025	0.001
2P-1	HIP 1400 F, 15,000 psi, 3 hrs	0.0	0.0028	0.0006
1P-1	HIP 1500 F, 15,000 psi, 3 hrs	0.0	0.0	0.0

(a) Results based on analysis of 50 randomly selected areas for each sample tested.

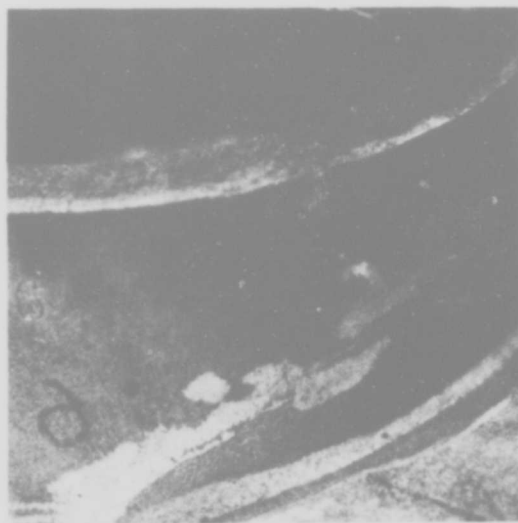
latest practice would dictate. After the parts had solidified, they were removed from the molds and the gates cut off at about 1 inch from the casting bodies. Risers were left intact to preserve, as much as possible, the dense original cast surface needed to provide the pressure transfer medium during HIP that was artificially supplied by the steel cans during the Phase I study. The cast bodies and Webbert castings were X-ray inspected in the as-cast condition at PNSY. Two of the bodies, Part Numbers C-2 and C-4, had X-ray detectable but acceptable porosity and one, Part Number C-5, contained sufficient porosity to judge it unacceptable.

The six cast bodies and one of the Webbert castings were shipped to BCL for HIP processing. Upon arrival, the ends of the gates were fused with a TIG arc to seal any porosity which might have been exposed when the gates were cut. The entire lot of castings was then HIP processed at 15,000-psi pressure and temperatures between 1420 and 1448 F for 4 hours without further preparation. The extra hour at temperature was provided arbitrarily to compensate for possible section size effects on heating time. Post-HIP evaluation of the castings at BCL was limited to visual inspection of the surfaces for evidence of large pore collapse. As shown in Figure 7, Part Numbers C-2, C-4, and C-5 had surface depressions indicative of pore collapse whose positions corresponded very closely to the X-ray detected porosity in these parts. Sizeable surface depressions were also found in Part Number C-6 which had originally been judged acceptable. A considerable increase in overall surface roughness after HIP was noted for all the parts indicating the probable collapse of near-surface porosity too fine to be detected by X-ray inspection.

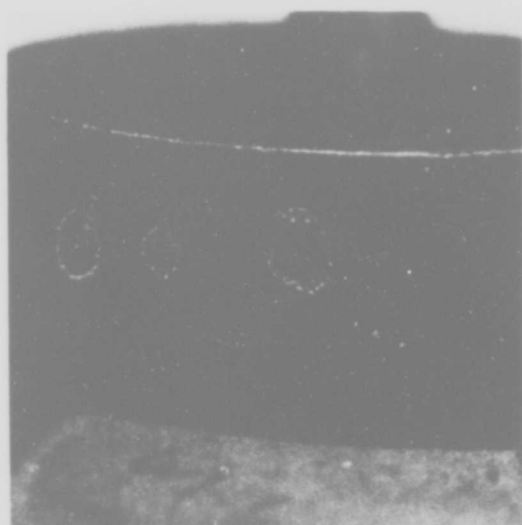
A more thorough evaluation of the castings was made after their return to PNSY. Part Numbers C-2 and C-5 were re-X-rayed with apparently inconclusive results. Comparative examination of the X-ray plates from identical locations on the castings both before and after HIP processing indicated that what appeared to be microshrinkage was, in some areas, seemingly unaffected while in others it appeared partially altered in configuration. Areas containing large pores also appeared to be only partially affected by HIP. In some instances the porosity was no longer detectable while in others the indications remained. Figure 8 shows a cross section of the partially collapsed wall of a large, spherical, porous area lying about 1/16 inch below the surface of one of the cast parts. The size of the pore and its proximity to the surface of the casting suggest that deformation or strain-induced leakage probably occurred during HIP processing, thus preventing its complete collapse.



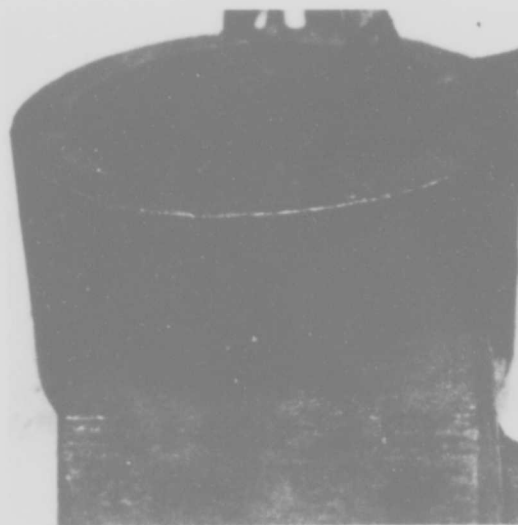
Part No. C-2



Part No. C-4

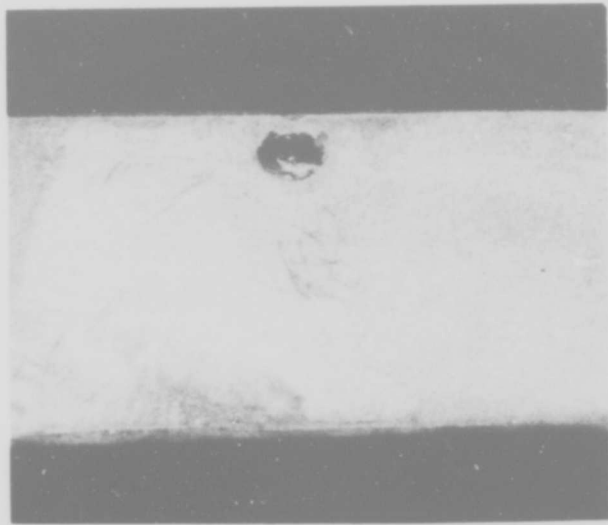


Part No. C-5



Part No. C-6

FIGURE 7. SURFACE DEPRESSIONS IN CAST BODIES  
RESULTING FROM HIP PROCESSING



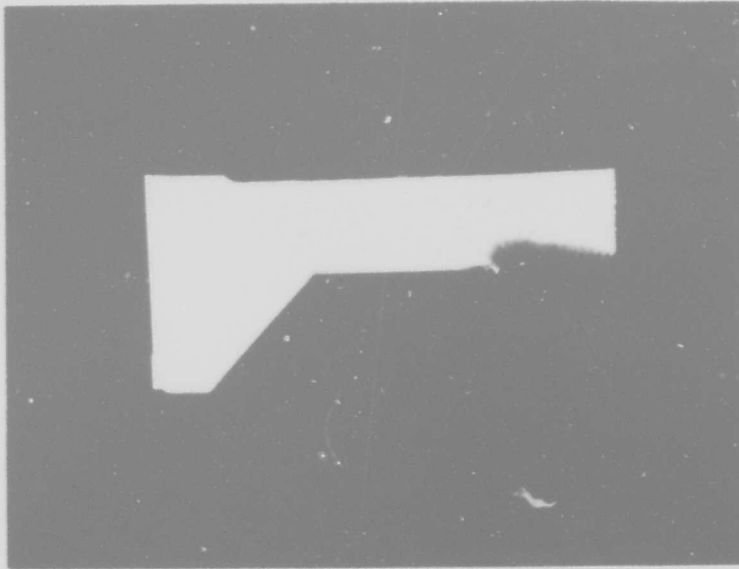
PNSY

FIGURE 8. SECTION OF HIP PROCESSED BODY  
CASTING SHOWING PARTIALLY  
COLLAPSED LARGE PORE

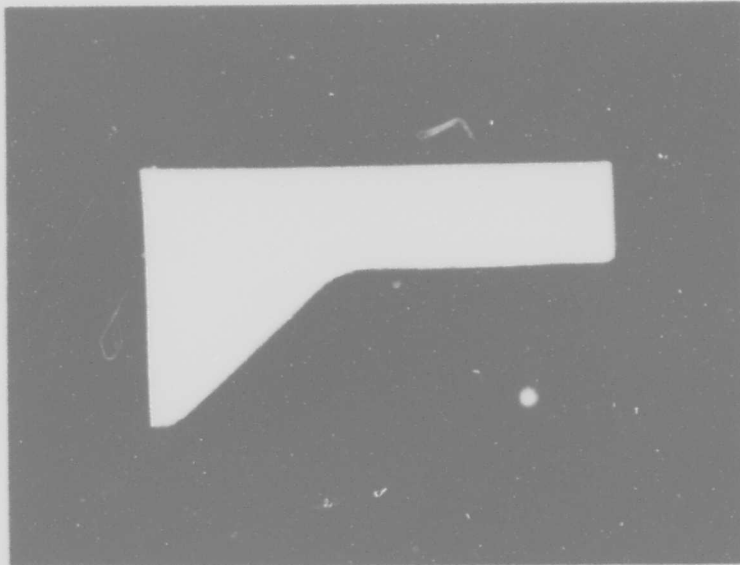
Dye penetrant examination was carried out on four 1-inch-thick sections removed from random locations in Castings C-2 and C-5. There were no indications of interdendritic microshrinkage on any of the eight surfaces examined. Six of the surfaces were perfectly clear and two showed only trace amounts of scattered indications of porosity. A comparison between the dye-penetrant examined surfaces from a rough machined, as-cast body and a HIP-processed body is shown in Figure 9. The remaining four castings were machined into finished connector bodies and hydrostatically inspected according to standard Navy practice. None of the bodies showed any evidence of porosity or water leakage through the casting walls under pressure testing, indicating that HIP processing at 1400 F successfully eliminated porosity.

Mechanical property evaluations were conducted on tensile specimens machined from both the HIP and control Webbert castings. One of the control specimens was heat treated at 1400 F to simulate the HIP temperature. Tensile test results are presented in Table 4. As indicated by the tabulated data, an approximately 15 percent decrease in yield strength was noted as a result of both HIP and thermal treatment. Ultimate strength was relatively unaffected, being increased only slightly by HIP processing. A substantial increase in ductility of approximately 90 percent was noted as a result of HIP processing. No conclusions could be drawn regarding the amount of increase in ductility due to thermal treatment alone as this specimen contained an inclusion at the fracture surface which caused premature failure.

Metallographic examination of the grip sections of the fractured test bars showed a 50-fold increase in grain size in both the thermally treated and HIP specimens as shown in Figure 10. This probably accounts for the observed decrease in yield strength. Twinning similar to that observed during the Phase I study was noted in the structure of the HIP specimen but not in the heat-treated one, evidence of the effect of simultaneous exposure to both pressure and temperature. Since no increase in grain size as a result of either HIP or thermal treatment was noted during the Phase I portion of this study, it would appear that cast-to-shape tensile specimens are not structurally representative of full-sized cast parts and thus should not be used to assess the effects of HIP processing on castings of considerably greater mass.



PNSY a. As-Cast and Rough Machined



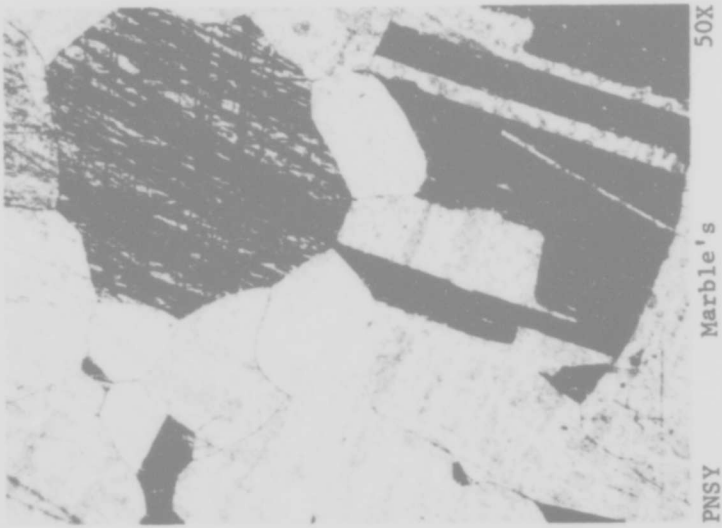
PNSY b. HIP-Processed

FIGURE 9. COMPARISON OF TYPICAL DYE PENETRANT INSPECTION RESULTS FOR AS-CAST AND HIP-PROCESSED BODY SECTIONS

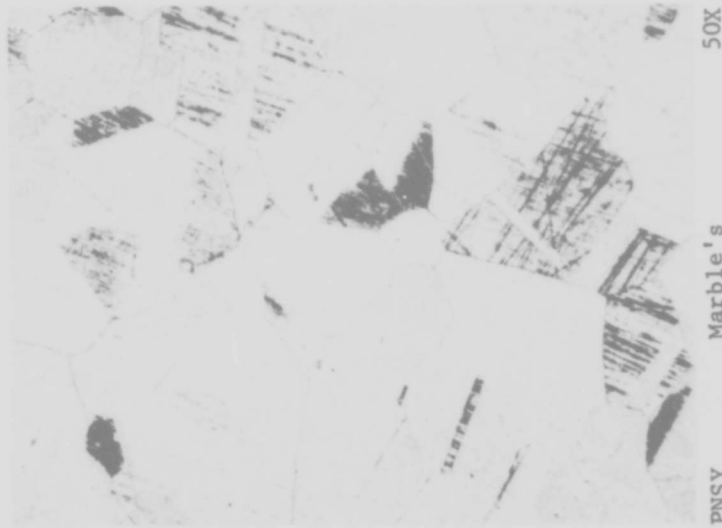
TABLE 4. MECHANICAL PROPERTIES OF WEBBERT TEST BARS  
FROM HEAT NO. CUCO 4329

Condition	0.2% Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation at Rupture, %
As-Cast	23,750	50,000	38.0
Cast + Heat-Treat	20,000	50,000	52.0 <sup>(a)</sup>
HIP	20,000	51,000	70
	20,000	51,500	72.5

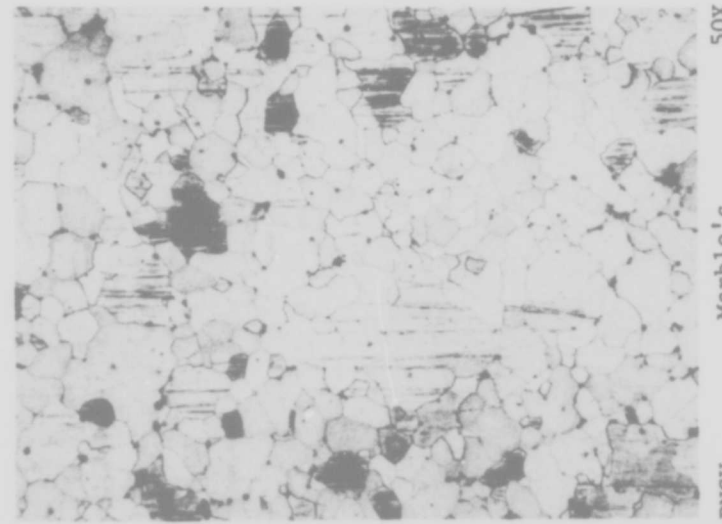
(a) Inclusion present in fracture surface.



c. HIP-Processed



b. Heat-Treated



a. As-Cast

FIGURE 10. MICROSTRUCTURAL EFFECTS OF THERMAL TREATMENT AND HIP-PROCESSING ON CAST WEBBERT TEST BARS

CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated by the work described above that hot isostatic pressure (HIP) processing has the potential to significantly increase the quality and production efficiency of Navy Gun Metal castings by eliminating porosity, reducing microstructural segregation, and improving mechanical properties. The various facets leading to this general conclusion are enumerated below.

(1) HIP processing at temperatures of 1250 F or above was completely successful in closing all porosity detectable by gas permeation in specimens taken from full-sized bronze castings. Hydrostatic permeability of cast 4-inch flex connector bodies was successfully precluded by HIP-processing of the castings at 1400 F prior to machining and finishing.

(2) The mechanical properties of specimens cut from relatively heavy bronze castings were significantly improved by HIP processing at 15,000-psi pressure and temperatures between 1250 and 1500 F. There was, however, no statistical evidence to indicate that a relationship existed between the degree of property improvement and HIP temperature in the range of these investigations. As a corollary, the ability to detect porosity by gas permeation bore no relation to the actual presence of micropores in the as-cast material and had no statistically significant effect on the as-cast mechanical properties.

(3) HIP processing caused microstructural improvements in bronze castings by closing or shrinking porosity, redissolving second phase material, and reducing or eliminating the dendritic segregation which results from the long solidification times associated with large castings. The amount of pore closure observed, although significant at all HIP temperatures, was greatest at the highest temperature used. The only instances where complete pore closure was not observed occurred where extremely large voids or gas pockets were so close to the cast surface that partial collapse of the por. walls produced enough strain to permit the pressurizing gas to enter through a microcrack or other small fissure.

(4) The effects of HIP processing on cast-to-size mechanical test specimens are not a valid measure of the effects of HIP processing larger, more massive castings because the considerably shorter solidification time results in a morphology and grain structure which is not representative of that of large-sized cast parts.

On the basis of the demonstrated ability of HIP processing to eliminate communicative porosity and enhance mechanical properties in G-metal castings it is recommended that investigations be conducted to determine whether similar

improvements can be realized for other casting alloys of interest to the Navy through the application of HIP processing. An engineering study of the technical and economic aspects of implementing HIP processing as a logical step in the casting production sequence also appears warranted. Some additional development may also be beneficial to investigate the means by which large near-surface porosity could be economically detected and treated to permit its closure by HIP processing.

APPENDIX

TABLE A-1. SUMMARY OF MECHANICAL PROPERTY DATA

Specimen Identification	Initial Communicative Porosity? (Yes/No)	0.2% Offset Yield Strength, $10^3$ psi	Ultimate Tensile Strength, $10^3$ psi	Elongation at Rupture, percent	Elastic Modulus, $10^6$ psi
Specimens tested in the as-cast condition.					
OP-1	Yes	17.95	36.17	32.7	14.07
OP-2	Yes	17.23	36.22	30.8	11.82
OP-3	Yes	16.20	31.65	28.8	10.75
OP-4	Yes	17.38	34.80	30.6	20.72
OS-1	No	16.93	34.72	34.7	11.77
OS-2	No	17.58	37.91	46.8	14.56
OS-3	No	16.71	32.66	38.0	12.03
OS-4	No	17.06	37.84	42.0	14.02
Specimens heat-treated at 1300 F for 3 hrs under partial vacuum.					
OP-5	Yes	15.88	31.71	27.0	10.56
OP-6	Yes	15.71	28.95	24.5	15.01
OP-7	Yes	14.91	30.96	38.0	9.53
OP-8	Yes	16.43	28.99	20.1	14.01
Specimens HIP processed at 1250 F; 15,000 psi; 3 hrs.					
3P-1	Yes	16.11	50.12	69.4	14.80
3P-2	Yes	20.18	39.66	32.3	13.40
3P-3	Yes	21.65	49.65	56.4	15.88
3P-4	Yes	21.30	48.36	78.2	15.81
3S-1	No	21.24	50.60	68.1	15.9
3S-2	No	19.06	44.66	78.2	11.23
Specimens HIP processed at 1400 F; 15,000 psi; 3 hrs.					
2P-1	Yes	19.88	50.05	72.9	16.78
2P-2	Yes	19.64	50.97	86.8	13.89
2P-3	Yes	19.57	50.60	79.1	15.95
2P-4	Yes	18.84	48.23	89.9	14.49
2S-1	No	19.84	49.23	75.0	19.74
2S-2	No	19.60	47.50	41.9	14.00
Specimens HIP processed at 1500 F; 15,000 psi, 3 hrs.					
1P-1	Yes	19.13	48.10	64.5	16.28
1P-2	Yes	20.74	52.72	79.1	17.49
1P-3	Yes	19.0	49.75	80.8	15.15
1P-4	Yes	19.15	49.75	74.9	16.40
1S-1	No	19.4	49.75	74.5	14.75
1S-2	No	18.14	46.78	79.1	13.24

TABLE A-2. ANALYSIS OF VARIANCE FOR MECHANICAL PROPERTY DATA

Case No.	Population Identity	Sample Size	Mean	S.S.D.	Deg. Fr.	Variance	Std. Dev.	Std. Error	95% Confidence Limits
Tensile Strength Data ( $10^3$ psi) for specimens									
1	HIP at 1500 F	6	49.4750	19.9105	5	3.9821	1.9955	.8146	2.0945
2	HIP at 1400 F	6	48.5966	49.4631	5	9.8926	3.1452	1.2840	3.3012
3	HIP at 1250 F	6	47.1750	90.7339	5	18.1467	4.2599	1.7390	4.4712
4	as-cast	8	35.2012	33.9682	7	4.8526	2.2028	.7788	1.8419
5	Heat-treated at 1300 F	4	30.1525	5.8752	3	1.9584	1.3994	.6997	2.2265
Yield Strength Data ( $10^3$ psi) for Specimens									
6	HIP at 1500 F	6	19.2600	3.5610	5	.7122	.8439	.3445	.8857
7	HIP at 1400 F	6	19.5533	.6775	5	.1355	.3681	.1502	.3863
8	HIP at 1250 F	6	19.9233	21.9629	5	4.3925	2.0958	.8556	2.1998
9	as-cast	8	17.1300	2.0336	7	.2905	.5389	.1905	.4506
10	Heat-treated at 1300 F	4	15.7100	1.0658	3	.3552	.5960	.2980	.9483
Elongation Data (%) for specimens									
11	HIP at 1500 F	6	75.4833	176.3683	5	35.2736	5.9391	2.4246	6.2337
12	HIP at 1400 F	6	74.2666	1474.8533	5	294.9706	17.1747	7.0115	18.0266
13	HIP at 1250 F	6	63.7666	1511.5733	5	302.3146	17.3871	7.0982	18.2497
14	as-cast	8	35.5500	275.6400	7	39.3771	6.2751	2.2185	5.2469
15	Heat-treated at 1300 F	4	27.4000	174.2200	3	58.0733	7.6205	3.8102	12.1243
Elastic Modulus Data ( $10^6$ psi) for specimens:									
16	HIP at 1500 F	6	15.5516	11.1550	5	2.2310	1.4936	.6097	1.5677
17	HIP at 1400 F	6	15.8083	25.1102	5	5.0220	2.2409	.9148	2.3521
18	HIP at 1250 F	6	14.5033	17.5733	5	3.5146	1.8747	.7653	1.9677
19	as-cast	8	13.7175	69.0075	7	9.8582	3.1397	1.1100	2.6253
20	Heat-treated at 1300 F	4	12.2775	20.9666	3	6.9888	2.6436	1.3218	4.2060

TABLE A-3. STUDENT'S "t" COMPARISON OF VARIOUS POPULATIONS  
OF MECHANICAL PROPERTY DATA

Case vs. Case	Deg. Fr.	"t"	Probability of Getting Larger "t" by Chance	Sample Populations
1 2	10	.5776	.60>P>.50	Same
1 3	10	1.1976	.30>P>.25	Same
1 4	12	12.4732	<.001	Different
1 5	8	16.6734	<.001	Different
2 3	10	.6576	.60>P>.50	Same
2 4	12	9.4067	<.001	Different
2 5	8	10.8641	<.001	Different
3 4	12	6.8776	<.001	Different
3 5	8	7.5886	<.001	Different
4 5	10	4.1303	.005>P>.001	Different
6 7	10	-.7803	.50>P>.40	Same
6 8	10	-.7191	.50>P>.40	Same
6 9	12	5.7762	<.001	Different
6 10	8	7.2316	<.001	Different
7 8	10	-.4259	.70>P>.60	Same
7 9	12	9.4402	<.001	Different
7 10	8	12.7546	<.001	Different
8 9	12	3.6575	.005>P>.001	Different
8 10	8	3.8471	.005>P>.001	Different
9 10	10	4.1651	.005>P>.001	Different
11 12	10	.1639	.90>P>.80	Same
11 13	10	1.5620	.20>P>.10	Same
11 14	12	12.0478	<.001	Different
11 15	8	11.2524	<.001	Different
12 13	10	1.0523	.40>P>.30	Same
12 14	12	5.9355	<.001	Different
12 15	8	5.0570	<.001	Different

TABLE A-3. STUDENT'S "t" COMPARISON OF VARIOUS POPULATIONS OF MECHANICAL PROPERTY DATA (Continued)

Case vs. Case	Deg. Fr.	"t"	Probability of Getting Larger "t" by Chance	Sample Populations
13 14	12	4.2811	.005>P>.001	Different
13 15	8	3.8810	.005>P>.001	Different
14 15	10	1.9842	.10>P>.05	May Same
16 17	10	-.2334	.90>P>.80	Same
16 18	10	1.0712	.40>P>.30	Same
16 19	12	1.3139	.25>P>.20	Same
16 20	8	2.5313	.05>P>.025	May Differ
17 18	10	1.0940	.30	Same
17 19	12	1.3823	.20>P>.10	Same
17 20	8	2.2792	.10>P>.05	May Same
18 19	12	.5416	.60	Same
18 20	8	1.5710	.20>P>.10	Same
19 20	10	.7839	.50>P>.40	Same