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# EVALUATION OF TITANIUM AIRCRAFT PARTS
## SEMI-FINISHED PRODUCTS

*F. J. GILLIG*
*L. W. SMITH*

*CORNELL AERONAUTICAL LABORATORY, INC.*

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# FOREWORD

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## ABSTRACT

A contact survey of the major commercial producers of aircraft engines and aircraft in the United States was conducted for the purpose of determining the difficulties and problems that have been encountered in the fabrication and processing of titanium and titanium alloys for aircraft applications. Thirty-four companies were contacted, some of which were visited several times.

Upon the completion of the contact survey, the results were assembled and analyzed for trends and outstanding difficulties. Three specific problem areas were selected for further evaluation. In order to obtain additional pertinent information on these problems, questionnaires were sent out to the aircraft companies contacted previously who had reported encountering one or more of the problems. These questionnaires were returned together with test data and reports that substantiated the answers contained therein.

All of the above data have been summarized and are presented in a generalized form in this report.

## PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

M.R. Whitmore

M.R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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# INTRODUCTION

Titanium and titanium alloys are destined to become important aircraft structural materials. They possess a combination of mechanical and physical properties that are ideally suited to aircraft applications. Because of their strength-weight ratios at temperatures up to 600°F, they are in a position to effectively replace both aluminum and steel for a number of applications in aircraft engines and air frames with a resultant increase in aircraft performance. The high melting points of the commercially pure grades make them natural replacements for heavier stainless steels in fire wall and fire seal applications. The corrosion resistance of titanium is excellent.

These materials are, however, relatively new and untried for many applications for which designers would like to put them to use. Besides the uncertainty of the design data and the effects of unforeseen variables, it appeared very probable that many difficulties would be encountered in fabrication and processing which might also influence the quality of the end product. It was felt, by the Light Metals Section, Materials Laboratory, Wright Air Development Center, that these application problems caused by the nature of the current production process for titanium or by the unique processing procedures evolved by the aircraft manufacturers should be enumerated and correlated for the over-all benefit of the aircraft industry. It was desired that the firsthand experience of the aircraft engine and air frame titanium users be summarized so as to focus attention on the particular difficulties or irregularities that occur in production or fabrication procedures and the extent to which they are detrimental to the final aircraft application. This could best be accomplished by a general contact survey of the aircraft industry. A more specific evaluation of selected problem areas could then follow. A project was set up to accomplish the above objectives. This is the final summary report for the project. The information obtained is presented in generalized form. The details of the various contact reports were given in preceding progress reports.

The contact survey was accomplished by visits to the major commercial producers of aircraft engines and air frames in the United States. Background information was obtained for the survey by first visiting the four major producers of titanium. People involved in the intermediate processing of titanium, such as forge shops and other fabricators, were also contacted with regard to their experiences with titanium. The contact survey was started on March 17, 1953 and ended on July 29, 1953. A detailed listing of the companies visited and the dates of these contacts is given in Table II.

The titanium picture is changing rapidly and some of the data obtained in the early parts of the survey may not be entirely pertinent at the present time. It is, therefore, cautioned that use and interpretation of the data presented be made with this fact in mind and that efforts be made to ascertain the latest possible information at the time of application.

It is also to be noted that the information in this and the other reports on this project was given verbally at the time of contact and represents the understanding, interpretation, and opinions of the survey parties who are the authors of this report. The titanium industry is conducting much of its technical processing on a secret or proprietary basis. Information of this type which was disclosed to the authors confidentially has been carefully withheld.

## CONTACT SURVEY RESULTS

### Production Background

In order to obtain the best over-all picture of the titanium situation, the logical starting point for the survey seemed to be to contact the producers of this metal and its alloys.

The Mallory-Sharon Corporation is located in Niles, Ohio. The Niles Rolling Mill Division of the Sharon Steel Corporation was chosen by the Mallory-Sharon Corporation for their titanium operations because it is a specialty steel mill and its equipment is ideally suited to the handling of titanium. The bulk of their titanium production is being concentrated on the output of their MST Grade III commercially pure sheet. All MST Grade III titanium is arc melted. This material is turned out as hot rolled sheet with a pickled finish. It is pack rolled to as low as 0.016 inch thick in packs of two to eight sheets, depending upon the finished gauge desired.

One forging alloy, MST 3 Al- 5 Cr, is being induction melted in small quantities. A special melting practice is being used to hold the carbon below 0.50%. Development work is in progress on an all-alpha alloy with a 100 - 115,000 psi yield strength. Adequate rolling capacity is available for much more titanium than is being melted due to a restricted sponge supply. Eventually, when large enough ingots become available, the Sharon Division will roll them on their continuous mills.

The Remington Arms Corp. started work on titanium as far back as 1947 and by 1950 decided to go into large scale production. They became associated with Crucible Steel at Midland, Pa. because this mill is a specialty mill making alloys which require special handling similar to titanium and its alloys. Some of the rolling is done in other Crucible mills. All of the melting is being done by the arc melting process at the Midland plant. Ingots as large as 4,000 pounds are now being produced regularly. The present bottleneck in Rem-Cru's titanium production is the sponge supply. Melting facilities are being increased in anticipation of increased sponge supplies.

The personnel contacted at Rem-Cru emphasized the fact that the titanium picture is changing rapidly and the quality of their product has shown a steady improvement.

Republic Steel started working with titanium as early as 1947 when they were rolling experimental sheets for Remington. Early in 1950 the decision was made to put in a small melting unit which was in operation by August of that year. The Korean incident and the resulting pressure by the armed forces gave impetus to a period of rapid expansion. All material produced up until November 1952 was used experimentally. Actual production for orders did not begin until this time.

Large changes have been made in sponge quality and melting practice and the quality of the end product is constantly being improved. Improvement in the sponge quality has resulted in lower strength alloys with higher ductility in some cases and some Republic grades equivalent to those of other suppliers carry lower numbers because they have been revised to indicate the actual properties.

The Titanium Metals Corporation of America have their sponge producing and melting facilities at Henderson, Nevada. Sheet is rolled at their Brackenridge, Pa. Plant and bar is produced at the Watervliet, N. Y. plant. They are expecting to announce a line of extruded shapes in the future.

Two production methods are presently in use for melting titanium and its alloys. The induction melting method accounts for only a very minor percentage of the total material produced. The main objection to this method is the resultant high carbon content of the melt due to pickup from the carbon crucible. An induction melting method has been devised which is said to keep the carbon content somewhat below 0.50%. This is still considered to be quite high for most applications. The induction method has great potentialities for large tonnage production if a suitable refractory can be obtained.

The greatest proportion of the titanium metal that is being produced is melted by the arc melting process. This method builds up the ingot by fusing the ingredients locally under the arc which is moved over the upper surface of the ingot, or has sufficient energy input to maintain a molten pool over the cross-section of the ingot. As additional feed material is added, the fused metal is gradually built up to form an ingot of the desired size. The furnaces usually used for arc melting are of the "cold mold" type. They consist of a water cooled copper vessel which the molten titanium will not wet. The mold and accessory equipment are evacuated at the start of the process and then an inert gas is admitted into the melting chamber to protect the molten metal and to sustain the arc.

Most of the objectionable defects found in the finished stock, whether it be sheet, bar, or forging stock, are directly traceable to the melting method. Hard spots, segregation, unfused inclusions, large grain size areas, abrupt changes in properties between samples from the same sheet of material, and the general nonuniformity of properties in a given heat are at least partly due to the arc melting method. However, it is the only practicable method available for production usage at present and improvements in this method are being made as rapidly as possible. Because of the secret and proprietary status of the titanium melting equipment used by the producers, little is known as to the nature of these improvements. The records of scrap and rejections and the comments made by the various aircraft companies contacted during the course of the survey leave little doubt that considerable improvements in the melting practice have been made. Comparison of the rejection figures for 1952 and 1953 show a marked drop in the amount of defective material received.

The problem areas associated with the production of titanium are, as noted previously, associated with the melting process used. The homogeneity that is obtained in steels and other alloys that are melted in a bath where the whole charge is molten cannot be achieved by the arc melting process. This is reflected in the spread of mechanical properties that has been noted by the users of titanium. The extreme reactivity of molten titanium which is responsible for the difficulties encountered in induction melting also affects the final properties of arc melted titanium because of the surface absorption of gases during hot rolling, heat treating, and hot processing. At least one producer is making some progress on the utilization of titanium scrap, but the problem is far from being adequately solved. Some chips and light scrap are being used as feed material in the arc furnace, but the reclamation of heavy scrap such as forgings and billets is still awaiting further development of "skull" melting and other processes. "Skull" melting is carried out using a crucible similar to the usual steel melting furnace but which is water cooled so that a lining of unmelted titanium is in contact with the refractory. The regulation of melting conditions permits control of the titanium "skull" to any desired thickness. It is felt that some of the nonuniformity and directionality of properties is due to the rolling schedules employed and research is being directed toward this end.

All of the producers of titanium feel that they have adequate melting and processing capacity to handle much more sponge than they are receiving at present. On the other hand, a number of air frame producers have indicated a reluctance to enter into the use of titanium because of the uncertainty of delivery schedules. As a result, large production orders for titanium are not on the books as backlog business. The sponge supply appears to be the bottleneck in the titanium production picture. Recent government support for increasing sponge producing facilities should help to alleviate the sponge supply situation.

## Forging

Forging companies that made the decision to explore the titanium field when the metal appeared a few years back are well along in finding out the problems concerned in working titanium to desired shapes. The item using the greatest amount of titanium as forgings is the compressor wheels or disks. These are now being produced on a production basis.

Compressor disks are forged at approximately 1750°F, higher temperatures being used for the larger forgings and some alloys. After forging, a 1200°F stress relief treatment is used to reduce stresses set up in the forging operation. The titanium alloys used for this part to date have been Ti-155AX, 150A, 140A, and RC-130-B. Considerable material evaluation is conducted by some companies before and after forging each disk. A one-inch slice is cut from each billet as it is received from the producer. Billet size is usually from 9 to 12 inches in diameter. One section of a slice is reserved for a forging upset evaluation test where the metal is reduced 50% in thickness. From this upset section an Izod impact test and three tensile tests are made. From the other portion of the original one-inch slice, two chemical analyses, one Izod, and three tensile tests are made. The test time involved for each billet is about 65 man-hours. If these tests are satisfactory, approval is given to proceed with the forging of the billet into disks. Some disks have excess metal provided at the outer rim for machining test specimens from the finished forging while other companies remove metal from the center of the disks for this purpose.

Some of the first forging stock which was received from the producers had a checked surface which was believed to be due to grinding the billet. The residual grinding stresses caused cracking during the stress relief treatment. These cracks could not be detected by visual examination, but upon upsetting the billet they became readily apparent. This situation has not occurred since the billet surfaces have been machined.

One important point in using titanium forgings, at present, at least, is the recommendation that the surface be completely machined. This is to remove the oxygen exposed surface of the titanium which is quite hard and brittle. This layer is part of the surface of the metal which remains after the regular loose forging scale has been removed by shot blasting. The influence of the oxygen reacted surface layer on the properties of the part has not been fully evaluated, but it is believed to be very detrimental to the fatigue life.

In forging titanium, the die design is somewhat similar to steel. Larger radii with thicker webs are important changes. The titanium alloys seem to possess a high coefficient of friction with the dies at elevated temperatures and do not flow as easily as other materials.

Proper lubricants may solve this problem.

Another condition found besides the cracks in the billets mentioned previously is unmelted materials. Large particles of the original additions to the melt are sometimes found. Detection of these by sonic testing devices has not been reliably worked out thus far, although some progress along these lines has been reported. Grain size variation within the as-received billet is another problem. Forging tends to reduce this variation. Surface wrinkles and forging laps which are encountered with some metals do not seem to be problems in forging titanium.

The handling of the different alloys has been found to be complicated to some extent. For instance, in the case of Ti-150A, reheating to forging temperature without adequate rework (50% reduction) produces embrittlement of the metal. Ti-140A and RC-130-B can be reheated without harming the properties. The tendency to use high heat to gain added workability of the metal must be guarded against. This is especially true with alloys like Ti-155AX which has Mo added for high temperature strength and is stiffer to work. Dies must be well lubricated or firing (sparks) occurs. Any titanium to die metal contact results in titanium diffusion into the die steel.

Another forging which is receiving considerable attention is the gas turbine compressor blade. These are being forged from Ti-140A, Ti-150A, and RC-130-B. The rough stock is supplied as bars ranging from 3/8 inch to about 2 inches in diameter. One company uses resistance heating to bring the slugs up to temperature. Acceptance tests are made on the stock by taking representative slugs and heating them for an upset test. It was found that any material that will pass this test, which is roughly equivalent to the first blade forming operation, will make acceptable forgings. It was pointed out that even poor stock which gets past the preliminary acceptance tests is weeded out in the first forming operation. Segregated and seamy material has a tendency to split open.

Some of the early material that was received was very bad, but recent shipments have shown considerable improvement. Occasional lots of the first material gave 100% rejection on the upset test. One company now reports its rejection rate down around 5%.

In blade forging one of the most troublesome problems is the thin sections which cool very rapidly. Die wear is not too bad when proper lubrication is applied.

If the blade forging temperature is kept below 1700°F, very little surface contamination takes place and the resultant scale is less than 0.001 inch. After forging an abrasive blast and pickle operation are sufficient to completely remove this scale. Fatigue tests show a marked increase in fatigue life when the oxidized layer is properly removed. Some producers check their blades by a unique impact bend test made on a small tab which is forged integral with the blade. It has been found that the blades must be within a range of 30-37 Rockwell C to pass this test.

Spacer rings for separating the compressor disks in the engines have been successfully forged. These are, however, being replaced with flash welded rings which will be discussed in this report under welding. Other forgings in the form of clips, brackets, etc. have been made up for limited use. Forgings for air frames have been tested by some aircraft manufacturers and have shown very poor fatigue life. This may be due either to improper removal of subscale by machining the entire surface or to a rough machined surface. Titanium has been reported to be very notch sensitive by some investigators. The engine manufacturers have not reported unsatisfactory fatigue properties and the subject of fatigue of titanium forgings appears to be one that should be investigated further.

A summary of the experience of the small number of forging companies contacted shows the following problems associated with forging titanium. Close temperature control must be exercised and a maximum temperature of 1750°F is recommended, although temperatures up to 1850°F have been used for heavier sections in some alloys. In the case of Ti-150A, reheating to forging temperature without adequate rework (about 50% reduction) results in embrittlement of the metal. RC-130-B alloy has been found to have a lower ductility than Ti-140A when forged using the same heating schedule. Titanium forging alloys have also been found to be very sensitive to time at temperature when heated for forging. Special considerations must be taken in the design of titanium forging dies. The titanium alloys do not flow as readily as steel and seem to possess a high friction coefficient with the die. The development of forging alloys which are less sensitive to heating and time at temperature would be welcomed by the titanium forgers.

## Extrusions

The extrusion of titanium has been accomplished by a number of different companies. The alloys which have been extruded to date are as follows: Ti-150A, RC-130-B and Mallory Sharon 3 Al- 5 Cr alloy. The process is still in the development stage, but orders can be placed on an experimental basis.

Metallurgical evaluation of the extruded parts shows that grain size is uniform regardless of thickness of the sections. Full evaluation, involving static and dynamic testing, is not complete.

One forging company is reported to be using the extrusion process as a preliminary blocking operation for titanium prior to forging. Titanium tubing up to six inches in diameter has been successfully extruded.

## Castings

Many aircraft accessory parts because of the intricate machining required when made from bar stock or forgings are ideally suited to the casting process if and when it can be developed for titanium. The skull melting process offers possibilities along these lines and experimental castings are being made by this method at the present time. The reactivity of the molten titanium with air necessitates casting in an inert atmosphere or vacuum using special molds. The auxiliary equipment required is expensive and the size of the castings is somewhat limited using present equipment. If skull melting furnaces are developed for titanium production purposes, the size restriction will be removed. However, the cost of the specialized equipment will always result in a high price for titanium castings and it is doubtful if they will ever be used for any but specialized applications where their unique properties will make them economically advantageous.

## Forming Sheet Material

Titanium of both the commercially pure and alloy grades is being fabricated by all of the processes normally used in aircraft production. Drop hammers, hydraulic and crank presses, power brakes, stretch formers, Hydroform presses, Marform presses, etc., are all used in forming titanium sheet into the required sections and forms. Some companies do all of their forming with the material heated to approximately 800°F. They find that the material works much easier and their rejections are at a minimum. The greater plasticity of the metal when heated allows the forming of parts from material which would not form cold. Other fabricators, because of economy and ease of handling, prefer to work the material cold. They feel that the increase in scrap and rejections is offset by the decrease in equipment and handling costs that are entailed in hot forming. The answer to the question of whether to form the material hot or cold would probably require a careful cost analysis of any particular operation. As the quality and consistency of the unalloyed material improve, the balance may tend to swing toward cold forming. However, as higher strength alloys are developed, hot forming may become more necessary as strength is usually gained at the expense of ductility.

Hot forming on the Hydropress and Marforming presses is done in the following manner: The material is heated to 800-1000°F and placed on heated form blocks. The blank is then covered with powdered asbestos or asbestos fiber before placing a pad of hard, heat-resistant rubber over it. The Marforming process appears to be ideally suited to the working of titanium.

Stretch forming must be done very slowly to get best results. One company experienced considerable difficulty with their cold brake-forming operations prior to stretch forming. Scrap used to run as high as 35-40%. This operation was much more successful when it was performed hot. It was also found that polishing the edges of the stock instead of simply deburring them, especially those at right angles to the bend line, further reduced the scrap percentage. Increasing the allowable bend radius from 3T to 3-1/2T eliminated scrap entirely.

Drop hammer work is ordinarily done on Kirksite female dies and copper coated lead male dies. The dies are not heated, but the blanks are. Some experimental work is in progress using heated dies.

One of the aircraft companies doing drop hammer work discovered that they could take the titanium sheet and heat it to 1000°F and then place it in the finishing Kirksite dies that were normally used for stainless steel parts and form the titanium part to proper size and shape by holding it in closed dies until it cooled off. Considerable trial and error experiments were conducted before this method was evolved. The procedure has been used with satisfactory results on difficult forming jobs. A gun port fairing which was originally of type 302 stainless in the annealed condition and 0.051 inch thick gave considerable trouble when made from 0.051 inch RC-70 titanium sheet. Thirty seconds holding time in the cold finishing dies gave a perfectly formed titanium part with no spring back even after subsequent stress relief treatment at 600°F. Another difficult job was the case and link access door which worked out satisfactorily using this forming technique. Numerous test specimens were cut from formed parts and tests showed that the properties of the pure titanium sheet were not affected by this forming procedure.

A company with considerable experience in deep drawing steel has done some work on the deep drawing potentialities of commercially pure titanium. They are presently working on a government sponsored project on the "Evaluation of the Drawability of Titanium" which involves the drawability of several titanium alloys of various thicknesses at several strain rates and temperatures. This study should provide valuable information which will be applicable to many forming operations.

The results of their experience to date, which is based on room temperature deep drawing tests, may be summarized as follows:

1. Commercially pure titanium possesses sufficient ductility to take conventional deep drawing operations with maximum reductions of approximately 40%.

2. Where several draws are involved, it is usually necessary to anneal between drawing operations. Annealing at 1325°F restores sufficient ductility for subsequent draws (commercially pure Ti-75A and RC-70).

3. Annealing produces considerable scale which can be removed by the DuPont process or the Hooker process. (These processes are both molten salt immersion treatments.)

4. Draw pressures are greater than for mild steel and appear to compare with pressures required for stainless steel.

5. Titanium seems to be sensitive to the rate of deep drawing. Tests were run at 1/2 to 2/3 the usual speed for mild steel.

6. The biggest problem to be overcome is the tendency to gall or score. Frequent polishing of the dies is necessary to avoid a complete freeze-up. Best results have been obtained with Bonderizing, dry film lubricant, copper plating, and anodizing.

## Welding

The high chemical reactivity of titanium at elevated temperatures, especially its affinity for oxygen, nitrogen, and water vapor, small quantities of which result in embrittlement, calls for special care in joining it by welding. Titanium at melting temperatures (3315°F) will absorb the above gases at an almost instantaneous rate. Success in welding titanium, therefore, requires the exclusion of these gases from the weld area by inert gas shielding or by the use of methods such as spot or flash welding where the molten metal is protected by the surrounding material.

Commercially pure titanium has been successfully welded by both resistance and fusion welding methods. The inert gas shielded arc process is used for fusion welding and with proper technique, which includes an inert gas backup, little or no embrittlement of the weld results. The use of a sealed inert atmosphere chamber fitted with rubber gloves and double sealed gas-lock doors has proven to be excellent for welding small parts. Special welding wire is available for automatic consumable electrode welding.

The fusion welding of most alloy titanium causes embrittlement in the weld zone due to the microstructural changes brought about in the two phase alloys. One aircraft company has reported a post weld treatment that restores the welded two phase alloys to their original strength and ductility.

Spot welding of the commercially pure grades of titanium presents no difficulties. No protective atmosphere is required in that the electrode pressure on the sheets themselves provides an envelope which is sufficient to protect the molten metal for the short times involved. Welding conditions of time, current and pressures are essentially the same as used for stainless steels. Spot welding of alloy titanium is practical in some cases. Tests on the fatigue strength of such welds are now in progress.

Seam welding is also accomplished using standard techniques for stainless steel. Less electrode force is required to weld an equivalent thickness of titanium.

The single phase all-alpha alloy RC-A-110 has been recently introduced by Rem-Cru and preliminary production welding tests have been favorable. However, the strength level of this alloy is not up to that of the two phase alloys and higher strength weldable alloys are still desired by aircraft designers. Other all-alpha alloys have been developed and they are expected to become available soon.

Flash welding is being used to fabricate spacer rings. These rings are used as spacers between the various compressor stages in gas turbine engines. The alloy presently being used for this application is Ti-150. Experimental work has also been done with RC-130-A and some Republic alloys.

The bars are heated to 1200°F in a furnace and then rolled into a ring which is given a final set in a bulldozer. They are then flash welded. After flash welding they are rounded hot in the bulldozer and then reheated and expanded to size. They are again reheated to 1300°F and air cooled. The problem in processing is to get the hardness below 38 Rockwell C in the finished part. The difficulties encountered in the above fabrication procedure for making flash welded titanium rings are reported not to be any greater than those previously encountered with new alloys, such as stainless steel, N-155, etc.

Brazing of titanium is possible using the standard silver brazing alloys and a special flux. The joints are somewhat brittle and have limited application. A method of resistance brazing silver plated titanium surfaces is under development at one aircraft company. The joints produced by this method have good ductility and strength but have the limitations of only being applicable to designs which can be seam welded.

## Heat Treatment

The thermal treatment of titanium that is being done by the fabricators is limited at present to two operations: stress relief and anneal. The stress relief treatment is applied to remove residual stresses that result from forming the material. These stresses have been reported to cause spontaneous cracking at a later date. The different producers recommend stress relief treatments for their alloys which are all somewhat similar. The commercially pure grades are stress relieved at 1000°F while for the alloy grades the temperature is somewhat higher in the range of 1100-1200°F. Stress relief may also be accomplished at lower temperatures using longer times but precipitation hardening and loss of ductility may occur in some alloys.

Annealing is used to obtain maximum ductility and is usually used as an intermediate step between forming operations. For the 8% Mn alloys, a temperature of 1300°F is recommended followed by slow cooling at a maximum rate of 5°F per minute to 1050°F or below and then air cooling.

Surface hardening of titanium has been accomplished on an experimental basis by various methods. The easiest of these methods involves a controlled oxidation by heating in air for a definite length of time. It has been found that this greatly improves the abrasion resistance. If the oxidized layer is kept thin enough, the fatigue strength is not seriously affected. Nitriding in pure nitrogen and dissociated ammonia have been successful with the former giving deeper cases. However, the metal is seriously embrittled by the nitriding treatments, especially by the hydrogen in dissociated ammonia. Carburizing has also been investigated. None of the above processes are considered acceptable for use on aircraft components as yet.

Heat treatment of the two phase alloys by quenching and aging has shown some promise and the method offers the possibility of producing higher strengths with fair ductility in some of the presently available alloys. The experimental data are still meager, but additional work is in progress. The development of new heat treatable alloys does not appear to be too far distant. Such alloys will further add to the strength-weight advantage of titanium for aircraft use.

## Engine Applications

Five manufacturers of jet engines were contacted during the course of the survey. Two of them are quite actively engaged in using titanium on a production basis on experimental engines. Two of the remaining three are doing experimental work with the various titanium alloys and anticipate going into production shortly. One of the companies is doing some evaluation work, but is following a policy of watchful waiting. This company believes that if and when the time comes that the Air Force requests the use of titanium in its engines, sufficient data will be available to quickly convert.

Much of the titanium that is presently being incorporated into engines is on a part for part substitutional basis. Although a weight saving is accomplished purely on the basis of the different densities of the metals, the full weight saving possibilities are not utilized because the various load carrying members in the remainder of the engine and airplane are still the same. This is especially true under conditions of dynamic loading where mass becomes an important factor such as the centrifugal force encountered in turbine blades and air frame and engine stresses due to maneuvering of the plane. In these cases supporting members are not stressed as highly when the lighter titanium alloys are substituted for stainless steels. At least one company is working on the design of an engine based specifically on the use of titanium. This engine or one similar will be the first real test of the maximum utility to be gained from the use of titanium in aircraft engines. Another factor which tends to complicate simple substitution is the difference in modulus values, the modulus of elasticity of titanium being approximately half that of steel. In applications where deflection is the limiting factor, a part for part substitution of titanium for steel cannot be made. The part must be redesigned for greater rigidity.

Titanium forgings are being used for compressor disks, spacer rings, and both stator and rotor compressor blades. Flash welded spacer rings are being used by most manufacturers. Compressor disks are being forged from alloys Ti-150A, Ti-140A, and RC-130-B. Ti-150A was one of the first alloys to be used for this application and several companies are specifying it because all their original data were obtained on this alloy. With the announcement that the Ti-150A alloy would be discontinued, evaluation work has been started on the Ti-140A and RC-130-B alloys. These two alloys are being used exclusively or are alternates on the bill of materials for compressor disks of nearly all manufacturers at present. An experimental turbojet was tested by one company in which the compressor disks were made from the Mallory-Sharon 3 Al- 5 Cr alloy. The alloy had very good properties except for low ductility, and poor machinability.

Unalloyed titanium is being used for shrouds, bearing and shaft housings, heat shields, oil vapor shields, brackets and clips. Nearly all of these applications require the material to be formed to shape and joined by welding. Very little alloyed sheet is used in engine applications. Through-bolts which are used to hold the various compressor stages together are being considered as an application for RC-130-B by one engine manufacturer.

Parts for reciprocating engines have also been tested. These include: master rods, rocker arms, push rods, and one experimental gear.

In the opinion of the engine manufacturers, the original difficulties that were encountered in forming, joining, and machining titanium have been largely overcome. This is believed to be due chiefly to increased knowledge of the difference in properties of titanium as compared to other metals and adoption of applicable techniques. Concurrent with the above, the quality of the material has been improving steadily. Some inhomogeneity in the form of segregation and hard spots is still found occasionally, but the general quality of the material is greatly improved. Rejects at one company run about 5% at their plant and about 15% at their vendor's. They do not feel alarmed about this rate since in some of their high temperature alloy applications rejections are often higher.

## Air Frame Applications

There are two general areas of application of titanium and its alloys in air frames. The first of these is in fire seals where the commercially pure grades of titanium are used as substitutes for stainless steel on a gauge for gauge basis. These are not highly stressed members and the favorable flame and heat resistance of titanium compared to that of stainless steel is the primary consideration. The second general area of application is for structures involving slightly elevated temperature conditions such as exist around the exit end of the jet engines. This is usually the aft section of fighter planes and the power pods for bomber jets. In these locations the temperature exceeds 250°F which is usually considered the top working temperature for aluminum alloys but is below 600°F where the strength of titanium begins to fall off rapidly. When parts in these applications are stressed members, alloy titanium is specified for its higher strength. These parts are in the shape of formers, stiffeners, and flat sheet. Forgings are also used around the landing gear section of at least one airplane.

The comparable alloys and grades of the four titanium producers are used interchangeably by most aircraft companies and choice is usually dictated more by availability than other considerations. Some companies have a preference for a particular alloy because their experimental data were all obtained on that alloy. Every aircraft engine and air frame producer contacted during the course of the survey has had some experience with titanium. Some companies are using it as a production material, others are still in the experimental stage with anticipated production use, while still others have completed some experimental evaluation work but are following a policy of watchful waiting before putting the material in production.

## Specifications and Quality Control

In general, the procurement specifications used by fabricators of titanium have been based upon those set up by the titanium producers themselves.

The Ordnance Corps has drawn up two specifications, one for titanium sponge and the other for wrought titanium in an attempt to control the quality of titanium being purchased. The numbers are MIL-T-12118 and MIL-T-12117. These specify the chemical and physical properties of the various grades. At the present time the producers of titanium will not accept orders to these specifications.

An aircraft company that has accumulated considerable mechanical test data on their incoming titanium has arrived at the conclusion that the uniformity of the spread between the yield and ultimate strengths greatly affects their fabrication practices. In an attempt to control this spread, they have written up two procurement specifications for titanium. One of these specifications calls for a minimum spread of 12,000 psi between the tensile and yield strengths with a 15% minimum elongation for the 70,000 psi yield strength grades of titanium. The other specification covering the alloyed titanium sheet calls for a minimum spread of 10,000 psi in the longitudinal direction with a 12% minimum elongation and a minimum spread of 8,000 psi in the transverse direction with a 10% minimum elongation. This specification covers the 8% manganese alloy and requires a 110,000 psi minimum yield strength. Other items are covered in these specifications such as chemical composition limits, mechanical property ranges, gauge tolerances, reports of vendors' tests, identification of the material by the vendor, etc., but the most important factor is the spread between the yield and ultimate strengths. The titanium vendors will not accept the spread feature in these specifications. One producer would not accept an order specifying that only 30% of the titanium shipped on the order meet the spread item in the specification. Quality control records show that this percentage would be less than the normal amount received without the specification.

These instances point up the fact that the titanium producers will not work to other than their own specifications at the present time. As production difficulties are eased and a better background of statistical control data is accumulated, the producers will undoubtedly be more lenient in this respect. The present emphasis of the producers is on raising the general over-all quality level and narrowing the range of property spread to a small and reproducible value. The consumers, on the other hand, are plagued with special handling problems and segregation if they are to achieve the utmost in strength-weight gains by using titanium. Where segregation is not practiced, the designs are based on minimum values and much of the potential value of titanium is lost. Hot forming alleviates the difficulties encountered in forming operations due to variance in mechanical properties where this is a problem.

Quality control at the production level is at an advanced stage when compared to production of most other metal products. Full use of statistical analysis and scientific principles is being practiced at every stage of production from the making of the sponge to the finished mill product. Sponge is blended by both the sponge producer and the consumer in order to reduce variations from this factor. Melting procedures are standardized and controlled as accurately as possible. Double melting is being practiced on some alloys to reduce segregation. This involves first melting and alloying the sponge and rolling it to a size which can be used as an electrode in a second arc melting operation. New melting methods are under development which should further reduce mechanical property variations.

Most of the titanium fabricators are engaged in only experimental work and their quality control standards and methods do not represent production practice. A few companies are using what might be termed production quantities. As outlined in the Engine Applications section of this report, the titanium going into compressor disks undergoes rigid quality control tests. These include: forging upset tests, etch tests, and mechanical property determinations. Blade forging stock is accepted according to less rigid standards inasmuch as the first blade forming operation segregates the good and bad material. One company finds that a maximum hardness specification of Rockwell C-37 is necessary to insure sufficient ductility in the finished blades. Some blades are inspected 100% by making a bend test on a small tab provided for this purpose. Several air frame manufacturers have accumulated a considerable amount of mechanical property data because they have tested every sheet of material that they have purchased. Other companies have checked only one sheet per heat and still others have been satisfied to accept the producers statement of properties or have conducted only hardness checks. One of the large companies has gone beyond the stage which would be considered as quality control. They have conducted tensile tests from subzero to elevated temperatures, creep, stress-rupture, impact, and fatigue tests.

One of the companies that has tested every sheet of incoming material in the past has decided to discontinue this program because they are satisfied that the quality of incoming material has improved. Spot checking or statistical sampling will be used.

At the plant of one aircraft fabricator, all scrap titanium is inspected by a scrap screening committee that attempts to determine the cause of the part being scrapped and decides upon its disposition. Two such surveys have been made to date.

The first titanium scrap survey was made after approximately 10,000 pounds of material had been used. The "scrap" amounted to 2,395 pounds or almost 25% of the amount processed. However, the term "scrap" in this instance includes all material which does not go into the finished parts such as trimmings, flash, etc. Only 94 pounds of this "scrap" was considered to be due to defective material. This amounts to less than 1% of the material processed.

In a second survey which was made only scrap parts were reviewed and the reason for scrappage noted. The total number of acceptable parts formed compared to the total scrap parts is not available. Of the 130 pieces that were surveyed only 9 pieces were considered to be due to defective material. The remaining pieces were scrapped due to defective tooling, attempting to work the material too cold and mistakes on the part of workmen.

These records indicate that successful titanium fabricating procedures have been worked out. They are even more demonstrative of this fact when one considers that the figures represent a good percentage of alloy titanium most of which was processed from material purchased before the sponge improvement around the beginning of 1953.

It is the general opinion that the titanium which is being received is getting better all along. The uniformity, consistency, amount of segregation, variation in gauge, and flatness of sheet have steadily improved. Concurrent with quality improvements has been the increase in the knowledge of how to handle this metal during processing. This latter fact has probably contributed as much to the success of new titanium applications as the former.

## Problem Areas

At the conclusion of the contact survey the results were reviewed with regard to the problems that existed with respect to the full utilization of titanium as an aircraft structural material. Most of the problems were of a minor nature and appeared to be working themselves out in the normal evolution of titanium technology. Three of the problems appeared to be more serious than the others and worthy of further study:

1. Mechanical property variation in both unalloyed and alloyed titanium sheet.

2. Fatigue of forged titanium.

3. Proper stress relief procedures for titanium.

In order to obtain additional pertinent data on the above three problems, questionnaires were sent out to those aircraft companies who had reported the existence of one or more of the problems. It was requested that company reports and laboratory data which substantiated their statements be included with the information desired in the questionnaire.

Fourteen companies returned the completed questionnaires together with such reports and data that they were willing to submit regarding the problems involved. For quick reference purposes, the following table lists the companies who replied and indicates the extent of the experience that they have had regarding each of the problems discussed. Following the reference table the correspondence survey results are given. This information is broken down under the three individual problem headings and the replies of the various companies are listed under each question asked regarding the problems.

# LIST OF COMPANIES AND EXPERIENCE WITH SURVEY PROBLEMS

| | Company | Problem 1<br>Mechanical Property Variance in Unalloyed and Alloyed Titanium Sheet | Problem 2<br>Fatigue of Forged Titanium | Problem 3<br>Stress Relief Procedures |
|---|---|---|---|---|
| 1. | Aerojet Engineering Corp., Azusa, California | Encountered both conditions in commercially pure titanium. | No experience. | Stress relief based on vendors' literature. |
| 2. | Boeing Airplane Company Seattle, Washington | Both conditions encountered in commercially pure grades. | Forging and bolts. | Stress relief based on vendors' literature. |
| 3. | Chance Vought Aircraft Div., Dallas, Texas | Alloy grades show both conditions. | Bolts. | $800-900^{\circ}F$ used after stretching to restore compressive yield. |
| 4. | Consolidated Vultee Corp., San Diego, California | Test data illustrate both conditions in pure and alloy grades. | Forgings. | Stress relief is not used. Experimental data cited. |
| 5. | Douglas Aircraft, Inc., Santa Monica, California | Have experienced large spread in strength properties from heat to heat in pure grade. | Evaluating some bolts. | Full anneal C.P. titanium at $1250^{\circ}F$ stress relieve at $550^{\circ}F$. |
| 6. | General Electric Co., Cincinnati, Ohio and Lynn, Mass. | No alloy grade used. No unsolvable problems encountered in commercially pure grades to date. | Forgings and bolts. | $1300^{\circ}F$ furnace cooled to $950^{\circ}F$. |
| 7. | Lockheed Aircraft Corp., Burbank, California | Spread in properties from heat to heat has been a problem. | Forgings and bolts. | $1100^{\circ}F$ for one-half hour for C.P. titanium. |
| 8. | McDonnell Aircraft Corp., St. Louis, Missouri | Have encountered these two conditions in both unalloyed and alloyed titanium sheet. | Forgings. | Stress relief $800^{\circ}F$ for one-half hour per inch thickness. |

## LIST OF COMPANIES AND EXPERIENCE WITH SURVEY PROBLEMS

| Company | Problem 1<br>Mechanical Property Variance in Unalloyed and Alloyed Titanium Sheet | Problem 2<br>Fatigue of Forged Titanium | Problem 3<br>Stress Relief Procedures |
|---|---|---|---|
| 9. North American Aviation, Inc., Columbus, Ohio | These conditions have caused trouble, particularly in alloy sheet. | No experience. | 700$^{\circ}$F - 60-70 minutes<br>800$^{\circ}$F - 40-50 minutes<br>900$^{\circ}$F - 30-40 minutes<br>1000$^{\circ}$F - 20-30 minutes<br>(standard) |
| 10. North American Aviation, Inc., Los Angeles, California | Feel that emphasis should be placed on reducing variation in properties between heats and within same sheet rather than spread between yield strength and tensile strength. | Bolts | 700$^{\circ}$F - 1000$^{\circ}$F to relieve forming stresses. |
| 11. Northrop Aircraft Inc., Hawthorne, California | Feel that limited experience is not sufficient to draw definite conclusions. | No experience | 800-1000$^{\circ}$F stress relief. |
| 12. Republic Aviation Corp., Farmingdale, New York | Both problems encountered, particularly variation in strength. | Preliminary survey on forgings | 1100$^{\circ}$F for 20 minutes and air cooled. |
| 13. Rohr Aircraft Corp., Chula Vista, California | Variation in Properties is one of the most serious production problems that they have. | No experience. | Anneal at 1200$^{\circ}$F for one hour. |
| 14. Ryan Aeronautical Co., San Diego, California | Have encountered both conditions to a noticeable degree in C.P. titanium. | No experience. | One-half hour at 1300$^{\circ}$F. |

## CORRESPONDENCE SURVEY RESULTS

### PROBLEM NUMBER 1 - MECHANICAL PROPERTY VARIANCE IN UNALLOYED AND ALLOYED TITANIUM SHEET

Two conditions have been encountered with this problem. The spread between the yield and ultimate strengths varies considerably. When the spread is small forming difficulties are usually encountered. Hence, it is desirable to have the spread as large as possible and uniform. The other problem connected with this property variance is the large spread in strength properties from one heat to another in the same grade of titanium.

Question 1. Has your company encountered either or both of these conditions in your testing of titanium sheet, unalloyed and/or alloyed?

Answer: Both conditions have been encountered in unalloyed and alloyed titanium, although most experience has been with the unalloyed type; the alloyed titanium has not been found sufficiently weldable for extensive use. A relatively small part of this company's work to date has required forming operations, therefore, the spread between yield and ultimate strengths has not been of major significance. In one case, failure of a test part was probably attributable to the close relationship of yield and ultimate strength because of short-duration overloading (in excess of yield strength used as the design level). In other cases, using alloyed titanium, inconsistency of the spread between yield and ultimate plus variation in ultimate strength from heat to heat has necessitated the use of higher temperatures for forming, thus increasing the complexity of the basic forming problems. Because this company has done only limited forming of titanium, no actual data are available showing the results of the use of large-spread material. Data such as tensile test results show the same general information as those published in the literature, and are therefore not included herewith.

Answer: Yes. In commercially pure titanium sheet. We have not tested sufficient titanium alloy sheet to determine whether these two problems exist.

See Exhibit A in appendix for test data.

Answer: Yes, both. Data on this point are voluminous. The final report on an investigation of the properties of RC-130-A sheet under contract has been submitted to BuAer. Copies of progress reports submitted under this contract may be obtained from that agency.

Answer: Yes. This is a general condition and is common to all mill products of titanium sheet. The large number of test data that are shown plotted in Exhibit B substantiate the foregoing statement.

Answer: We have not particularly noticed the spread between yield and ultimate of the commercially pure grade. We have experienced large spread in strength properties from heat to heat of the pure grade.

Answer: We have found some variation in RC-70 and Ti-100A sheet stock in fabrication. This has not been specifically tied in with tensile test results. We use no alloy grade titanium sheet at present.

Answer: The large spread in strength properties from one heat to another and even within one heat from sheet to sheet has been a problem. A summary of spot check tests is given in Exhibit C.

Answer: Yes. We have encountered these two conditions with both unalloyed and alloyed titanium sheet although the variations from average values appear to be much less for the alloyed sheet than for the unalloyed. The material is tested by conventional tensile testing methods, using two-inch gage length specimens milled to the proper configuration. All tests were made within a few days after receipt of the material. See Exhibit D.

Answer: These conditions have caused trouble, particularly in alloy sheet. A small spread between yield and ultimate might cause difficulty in stretch forming but be suitable for hydropress or drop hammer parts. Mechanical property variation is not only from heat to heat but also from lot to lot rolled from the same ingot. See Exhibit E.

Answer: The variation in the spread between yield and ultimate has not proven troublesome in forming unalloyed or alloyed titanium sheet to date. In the case of alloyed titanium only, the strength variance from one heat to another and even within the sheet has proven troublesome in forming. Yield strength variations are particularly troublesome from the standpoint of spring back. See Exhibit F.

Answer: No. Limited experience has not been sufficient to verify reports from other manufacturers.

Answer: Yes. Both problems have been encountered particularly variation in strength from heat to heat, sheet to sheet of the same heat and within a particular sheet (RC-130-A).

Answer: Both of these conditions have been encountered, to a noticeable degree, in C.P. titanium.

Question 2. Has the occurrence of this problem changed within the last six months? For example, has it improved for the pure or unalloyed grade and remained the same for the alloyed grade?

Answer: The occurrence of this problem has not changed materially; this is based on observations of component tests using the unalloyed titanium as late as October 1953.

Answer: Since we have not fabricated production parts within the past two years, we can only speak from our subcontractor's experience, which indicates that this problem still exists.

Answer: No recent experience with unalloyed grade. No indication of substantial improvement in alloyed grade.

Answer: The rejections for commercially pure and alloy titanium have reduced over the past six months, when classified according to minimum mechanical properties. There has also been some improvement in the quality of the material received.

Answer: Condition is slowly improving.

Answer: No accurate data can be referenced for this question; however, in general we have been encountering less difficulty as time goes on. Perhaps this is achieved through better processing rather than better material.

Answer: No.

Answer: Apparently the situation has remained relatively unchanged during the past six months. Most of our material has been received during this period.

Answer: Material during the past six months has been fairly uniform. In the previous six-month period, a definite improvement in quality was noticed toward the latter part of that period. Alloy segregation within a sheet and surface contamination has been minimized.

Answer: The problem still exists with the alloy grade. No particular difficulty is being or has been encountered in the pure grade (80,000 p.s.i. min. tensile strength).

Answer: Yes. Alloy material received within the last three months is more consistent (RC-130-A) and variations in properties from sheet to sheet have been reduced. Ultimate-yield spread is still small and nonuniform.

Answer: For commercially pure grades, the average tensile strength of current shipments is going up; approximately 10,000 p.s.i. increase in the last year.

Answer: Some improvement on commercially pure grades. No information on the alloyed.

Question 3. How does your company process and/or fabricate titanium shipments that show wide spread of mechanical properties?

Answer: No special processing and/or fabrication techniques based on spread of mechanical properties are used. If the material in question is satisfactory considering yield strength alone, the design is fabricated by conventional titanium procedures. No segregation on this basis is practiced; segregation to date has been limited to the specific type of material by vendor and grade.

Answer: Fabrication requirements are based on properties of relatively poor material.

Answer: We test each alloy sheet and classify it into Class I and Class II according to Table I. Class I material is used for parts requiring forming operations.

Answer: Special handling, i.e., restricting individual sheets to part numbers which can be adequately formed (high side sheets) or which are usable strengthwise (low side sheets).

Answer: Our practice is to purchase material according to prescribed specifications on strength, chemistry, etc. All material which meets these requirements is processed and fabricated in the same manner.

Answer: Have set up two classes of material with approximate specification, i.e. one with Ftu ranging from 55,000 to 75,000 p.s.i. Material purchased and stocked according to these classes. Material not sorted at our plant.

Answer: We make no distinction between various shipments of titanium, either for processing or for fabrication, unless the properties fall below the minimums established by our material specification, as follows:

TABLE I

COMMERCIALLY PURE AND ALLOYED TITANIUM

| MATERIAL | MINIMUM MECHANICAL PROPERTIES | | | | MECHANICAL PROPERTIES REQUIRED FOR CLASSIFICATION | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CLASS I | | | | | | CLASS II |
| | | | | | WITH GRAIN | | | | CROSS GRAIN | | |
| | TENSILE KIPS (1000 PSI) | | ELONG. % | MIN. BEND RADII | TENSILE KIPS (1000 PSI) YIELD | RATIO YIELD/ULT. | ELONG. % | BEND RADII | ELONG. % | BEND RADII | |
| | YIELD | ULT. | | | | | | | | | |
| **SHEET**<br>PURE<br>Stds. & Mtrl.<br>Rpt. (0.01001) | | | | | | | | | | | |
| RC-70 | 70 | 80 | 15 | 3t | | NOT REQUIRED | | | | | |
| RS-70 | 70 | 80 | 15 | 3t | | | | | | | |
| Ti-75A | 70 | 80 | 15 | 3t | | | | | | | |
| MST-III | 70 | 80 | 15 | 3t | | | | | | | |
| **SHEET**<br>ALLOY<br>Stds. & Mtrl.<br>Rpt. (0.01002) | | | | | | | | | | | |
| RS-110A | 110 | 120 | 10 | 3t | 145 Max. | 0.92 Max. | 15 | 2.5t | 10 | 2.5t | All Others |
| RS-120 | 110 | 120 | 10 | 3t | " | " | 15 | 2.5t | 10 | 2.5t | |
| RC-130A | 110 | 120 | 10 | 3t | " | " | 15 | 2.5t | 10 | 2.5t | |
| **BAR** | | | | | | | | | | | |
| RC-70B | 70 | 80 | 15 | - | | NOT REQUIRED | | | | | |
| RC-130B | 130 | 140 | 10 | - | | | | | | | |
| MST-3 Al | 140 | 150 | 8 | - | | | | | | | |

ROOM TEMPERATURE PROPERTIES

After being heated in air to
(a) 800°F + 20 for 1/2 hour or
- 0
(b) 600°F + 20 for 10 hours or
- 0
(c) 450°F + 20 for 100 hours
- 0
and cooled to room temperature, the material shall meet the following requirements when tested in tension using a maximum strain rate of 0.005 in./in./minute.

| | TYPE A | TYPE B | TYPE C | TYPE D |
|---|---|---|---|---|
| Minimum Ultimate Strength, psi | 80,000 | 120,000 | 140,000 | 160,000 |
| Minimum Yield Strength, psi | 70,000 | 110,000 | 130,000 | 150,000 |
| Minimum Elongation, % in 2 in. | 15 | 10 | 10 | 6 |
| *Modulus of Elasticity (psi x $10^6$) | 15 | 15 | 15 | 15 |

Answer: No special processing or fabrication measures are used.

Answer: We give no special consideration to shipments because of spread in mechanical properties. We do not practice segregation as a general policy, although we are separating titanium alloy sheet on the basis of bend ductility utilizing material with poorer bend ductility for parts requiring limited forming.

Answer: Small experimental lots have not been segregated.

Answer: Most forming done at high temperatures so that even marginal or inconsistent material can be used. Where cold forming is required, generous radii and simple construction are called for. No production as yet - all work is experimental and if necessary, material is allocated for particular operation or use depending on requirements.

Answer: Segregation and hot forming.

Question 4. How do you dispose of off mechanical property shipments of titanium, that is, titanium whose mechanical properties do not meet your specifications?

Answer: Quantity orders of titanium not meeting required mechanical properties are not accepted from the producers. All purchase orders carry specific instructions as to the requirements, and certified reports are required. Only in cases where variations in properties can be tolerated is the material accepted, and then only on the specific authority of the project group which initiated the order.

Answer: We have disposed of unsatisfactory material by rejection.

Answer: Problem has not yet arisen.

Answer: Reject and return to mill if material does not meet our minimum mechanical properties.

Answer: When not usable per our specifications, return to vendor.

Answer: We do not purchase material not meeting specifications, except for nominal deviations which are processed with the acceptable material.

Answer: 1. Rejected by receiving inspection. 2. Reviewed by Material Review Board to determine: (a) If strength level is satisfactory for proposed parts; and (b) if parts can be satisfactorily formed. 3. Either bought by Material Review Board or rejected and returned to vendor.

Answer: In the past, those shipments have been accepted by salvage action and designated to be used only for specific parts which do not require the higher properties or the more severe forming.

Answer: Return shipment to vendor.

Answer: Initially we attempted to use "off mechanical property" material for certain designated parts where strength was not critical but this is no longer practical due to increased production usage. Now we are rejecting material which does not meet our specifications. Our rejection rate is quite low, however, as our specification requirements are sufficiently realistic so that over 95% of the incoming material will meet the requirements specified. It should be noted that our specifications do not specify maximum strength properties but rather minimum only.

Answer: If considered unusable for any purpose (after strength and metallurgical tests), material returned to vendor.

Answer: We are using material under protest.

Answer: Only small experimental lot used to date.

Question 5. What is your opinion of the scope and importance of this problem?

Answer: This problem would naturally be of vital importance to manufacturers of production parts using titanium. In an industry where titanium is being evaluated for component use on an extensive but nevertheless developmental basis, this problem has not proved critical.

Answer: We believe that this problem is widespread and is of importance in that, if not solved, it will lead to excessively complicated material handling problems and costs.

Answer: Problem is important in the economical use of titanium. Since alloys such as RC-130-A have been under development for several years without substantial improvement, the problem is obviously a difficult one. The development of heat treatable alloys may provide the best solution.

Answer: The importance of this problem is major. Uniformity of material and spread between yield and ultimate strength is essential to high production of titanium parts. Scarcity of titanium can be reduced substantially if there is a reduction of rejections by the fabricators. If this problem cannot be solved with present alloys, development of more suitable alloys should be vigorously pursued. Local necking under load and non-uniform elongation is a problem needing improvement.

Answer: Scope (magnitude) not too great and assume producers can progressively improve if customers continue pressure for improvement. Believe importance sufficient to warrant improvement.

Answer: Spread between tensile strength and yield strength is helpful in fabricating sheet material. A spread below 10,000 p.s.i., which often happens, makes the problem more important as difficulty is more likely to occur. So far the average spread has been about 10,000 p.s.i. and we have not had unsolvable problems.

Answer: From a production viewpoint, this problem is of prime importance. Minimizing the present large spreads in the properties will result in more consistent forming results, and ultimately lower scrap rates and costs.

Answer: We believe that this problem is of prime importance and that, as more complicated parts are designed to be fabricated of titanium, it will become even more critical.

Answer: We feel that emphasis should be placed on reducing the variation in properties between heats of material and within the same heat (or sheet), rather than on the spread between yield and ultimate. Reducing the variation would be of great help in fabrication.

Answer: It is reported by volume fabricators to be troublesome.

Answer: It is necessary to have material of uniform quality before establishing design limitations and in order to take full advantage of the material properties.

## PROBLEM NUMBER 2 - FATIGUE OF FORGED TITANIUM

Several airplane manufacturers have determined that titanium forgings selected for use on airframes have shown very poor fatigue characteristics. This has been noted with both partially machined and unmachined forgings. Engine manufacturers make wide use of titanium forgings with apparently satisfactory results. The surfaces of titanium forgings for engine use are machined completely.

Question: Has your company evaluated titanium forgings for airplane use and what is your opinion on the use of titanium forgings on the air frame?

Answer: This company has not evaluated titanium forgings for aircraft use. Forgings have been considered for certain parts, but not beyond the preliminary stages.

Answer: Yes. Usage of titanium forgings will entail a close attention to forging practice, development of improved inspection techniques, re-examination of design practice and perhaps greater usage of proof loading.

Answer: Not yet. We are interested in such use but are concerned by delays in procurement.

Answer: Evaluation is now in progress on two different forgings. We cannot give opinion as to the usability of titanium forgings until tests are finished. Thus far they look promising.

Answer: No. We are considering them, but with caution.

Answer: Yes, alloys Ti-150A, Ti-140A, RC-130-B, and Ti-155A. In engines titanium forgings will be used successfully in large numbers. Air frames should likewise be able to make satisfactory application for parts not requiring welding.

Answer: Yes. The weight savings possible in air frame construction with the present strength levels of titanium alloy forgings do not justify the high costs involved.

Answer: Yes. We have tested a few titaninm alloy forgings. We are of the opinion at the present time that most titanium alloy forgings are not satisfactory for use in our airplanes.

Answer: We have held off in using forgings in critical design applications until some service experience with forgings in non-critical locations is obtained.

Answer: No. We feel that standardization of forging practices for titanium alloys is necessary before permitting extensive usage of titanium forgings in air frames.

Answer: No, not fatigue-wise. There appears to be an attractive potential in landing gear fittings, primary structural and hydraulic fitting applications.

Answer: Survey is in preliminary stage only. No production applications to date; substitutions for 125-150HT steels appear likely; definite application for medium temperature service.

Answer: We have not had any experience with either titanium forgings or bolts and made no comments on these questions.

Question: Has your evaluation of titanium forgings included fatigue testing? Give testing details.

Answer: Yes, both on machined specimens and actual parts. Test details are given in Exhibit G.

Answer: Yes. Testing has started. We are using a Sontag testing machine with axial loading in tension, $R = 0$. Specimens undergoing test are standard round and a rectangular shape. Rectangular shape will have single hole and rivet pattern holes.

Answer: Tensile test evaluations only have been completed.

Fatigue is expected to be lower since ultimate strength has shown a decrease over bar stock properties. Many forgings require an integral test specimen to be parted from the forging for test. Small forgings such as blades are tested as actual parts. Pneumatic fatigue is generally used. Specimens are machined, ground and lapped. All temperatures are tested. Tensile specimens are machined and polished. Standard 0.252 inch diameter specimens with a one-inch gage are most commonly used. Rate of strain has been standardized at 0.003 inch/inch/min. below yield and 0.060 inch/inch/min. between yield and fracture.

Answer: This evaluation has included both static and fatigue testing on actual air frame parts. Some fatigue tests have been conducted on material removed from these forgings.

Question: Are you using or evaluating titanium bolts with forged heads? Have you data and what does it show on the characteristics of these bolts with regard to their fatigue life?

Answer: We have recently obtained commercially-produced titanium bolts with forged heads for evaluation.

Answer: Yes. Our data show that titanium alloy bolts so far tested possess inferior fatigue life.

Answer: Some evaluation of bolts has been carried out. In general fatigue life for tensile loading at given percentages of static ultimate is lower than for standard steel belts but quite adequate for informed use in air frames.

Answer: Yes. No data. We are waiting for bolt deliveries. These bolts will be manufactured from forged and extruded rods, both in alloys of RC-130-B and MST 3Al-5Cr.

Answer: Not using. Are doing some evaluation work. For the high strength range, as replacement of 160,000-180,000 p.s.i. strength steel bolts, titanium bolts do not yet have adequate fatigue life.

Answer: Evaluation and engine tests are being made on titanium bolts. We anticipate successful results. We have no fatigue data on bolts. This is not anticipated as a problem but an investigation is being made.

Answer: Bolts were evaluated in 1951. No vendor has been able to supply satisfactory bolts. Our tests showed a very low fatigue life for the bolts tested.

Answer: We have very recently initiated an evaluation program of titanium bolts. The program includes hot headed bolts with rolled threads and machined head bolts with rolled threads.

Answer: No data as yet.

## PROBLEM NUMBER 3 - STRESS RELIEF PROCEDURES

The status of the necessity and the proper treatments for the elimination of residual stresses caused by machining and forming procedures in the fabrication of titanium aircraft parts is confused. Some aircraft manufacturers report a decrease rather than an increase in the endurance strength after their parts are stress relieved. Cracking of alloy sheet after assembly has been encountered even though the manufacturer claims to have given the titanium a stress relief treatment after forming. Some manufacturers do not stress relieve unalloyed titanium after hot forming while others do.

Question: What are your standard stress relief procedures for titanium, unalloyed and alloyed?

Answer: To date it has not been found necessary to stress relieve machined titanium parts fabricated for test purposes. Some consideration was given to stress relieving early in this company's titanium program; however, no definite requirement was ever established for such treatment.

Answer: A stress relief at 800-900°F has been found necessary to restore original compressive yield strength of alloyed sheet after stretching operations.

Answer: See Exhibit H. We do not stress relieve alloy titanium after stretch forming shapes on the Hufford stretcher. In only one instance, after forming many hundred pounds of titanium alloy sheet, have we detected a crack after forming which may have developed during forming. This one crack was in a severe compression wrinkle. Cracking under these conditions is not unusual for commonly used metals.

Answer: For full anneal of commercially pure titanium, one hour at 1250°F. For partial anneal without softening of cold work, one hour at 550°F.

Answer: Parts which will not be affected by distortion or poor surface finish are annealed at 1300°F for two hours followed by furnace cool to 950°F. Some fabricated parts are not stress relieved.

Answer: An anneal at 1100°F for one-half hour for unalloyed titanium is used. We have not used alloyed titanium sheet in production as yet. Tests are being initiated to determine if stress relief is necessary and the procedure required.

Answer: Our standard stress relief procedure is 800°F ± 25°F for one hour per inch of thickness with a thirty minute minimum, followed by cooling in still air.

Answer: For both alloy and commercially-pure titanium parts a stress relief is required after all forming is complete.

| Temp. | Time |
|---|---|
| 700°F | 60-70 minutes |
| 800°F | 40-50 " |
| 900°F | 30-40 " |
| 1000°F | 20-30 " (Standard) |

Answer: All hot or cold formed titanium and titanium alloy parts, except roll or stretch formed exterior skins are stress relieved at 700-1000°F following forming. Skins are excluded as being formed to large contours and thereby having relatively low and uniform internal stresses due to forming.

Answer: All formed parts (alloy and commercially pure) are annealed - 1100°F for 20 minutes and air cooled.

Answer: No stress relief for commercially pure.

Answer: Commercially pure titanium - one-half hour at 1300°F in an air atmosphere.

Answer: Stress relieve cold formed parts at 800 to 1000°F (one-half hour per inch of thickness) and air cool.

Question: How were your stress relief procedures determined?

Answer: Vendors' literature.

Answer: Stress relieving that has been done was based on vendor's recommendation.

Answer: From data of Exhibit I and Exhibit J.

Answer: For full anneal, published literature values accepted. For partial anneal, tests for compressive yield strength of stretched parts indicate stated practice desired.

Answer: Through experience over a period of several years.

Answer: From manufacturer's data.

Answer: Our procedure was proposed to each of the four major titanium producers and, upon its acceptance by all four, was established as our standard treatment.

Answer: Test specimens were cold worked by stretching to various percentages. The specimens were then stress relieved at various combinations of time and temperature. The recovery of original mechanical properties was compared.

Answer: Stress relieving was set up as a precautionary measure after several instances of spontaneous cracking were observed in formed parts. Stress relieving temperatures and times were established on the basis of recommendations by Rem-Cru Titanium, Inc.

Answer: From Rem-Cru recommendations and shop experience.

Answer: An extensive program was run on the embrittling of commercially pure titanium in an air atmosphere at various temperatures and times, using bend tests as the criterion of embrittlement.

Question: Have you any experimental test data to show the effect of stress-relief and/or annealing procedures for titanium on the fatigue strength or other mechanical properties of the metal?

Answer: A slight amount of data on commercially pure titanium sheet which indicates that there is inconsequential effect on tensile properties.

Answer: No such data are available except information which may be found in the literature.

Answer: Yes. See Exhibits I and J.

Answer: We have not made an attempt to determine the effect of various annealing treatments on fatigue strengths. Data on tensile properties and ductility indicate that this should not be a problem.

Answer: See Exhibit K - "Effects of Various Stress Relieving Times and Temperatures on Alloy Titanium Sheet".

Answer: We have tests in progress but no test data as yet.

Answer: No data on effect on fatigue strength; limited data on tensile properties.

Answer: Effect on bend ductility was used as criterion for setting up procedures.

Question: When stress relief and annealing procedures are specified for titanium and titanium alloys in your company, on what basis has it been determined that such procedures are necessary or desirable?

Answer: Based on vendor's recommendation.

Answer: See Exhibit H for this procedure. Annealing procedures have been established as aid in shop forming as in difficult stage forming but it is not mandatory, based on data of Exhibits I and J.

Note: Exhibits I and J are taken from Consolidated Vultee Reports No. 7768 and No. 7629 respectively. These reports contain additional pertinent information.

Answer: Annealing procedure specified to permit completion of forming. Partial anneal procedure specified to improve compressive yield strength.

Answer: An anneal is incorporated into the processing of any part in which either the manufacturing or the life of the part can be benefited. Nearly every part made is annealed at some stage of manufacture and all material is purchased in the annealed condition. Stabilization of the alpha phase in two phase alloys is our primary purpose when using an anneal.

Answer: To remove effects of cold work and permit further forming.

Answer: Information received from other fabricators indicated that stress relieving and annealing procedures might be required. Since the titanium producers agreed that it could do no harm and that it might be beneficial, it was decided to establish these procedures as standard.

Answer: Cracks have developed in some parts that were not stress relieved. Thus far we do not have any service data on production parts.

Answer: Information received from several fabricators and titanium producers indicates that a stress relief anneal is desirable for cold formed parts to relieve residual forming stresses. These stresses have been reported to cause failures detected on final assembly as well as "on the shelf" parts.

Answer: Cracking of parts during forming requires two stage operation with interstage anneal; parts also crack some time after forming due to residual stresses. Annealing relieves these stresses.

Answer: Annealing at 1200°F for one hour is used to aid in forming problems such as "oil canning" or in order to obtain a wet part.

Answer: Principally on the basis of fabrication requirements.

## DISCUSSION OF CORRESPONDENCE SURVEY RESULTS

The answers to the questionnaires left little doubt as to the existance of the problems outlined in them. Conferences were arranged with the technical personnel at Rem-Cru Titanium, Inc., at Midland, Pa. and Titanium Metals Corp. at Henderson, Nevada to discuss the accumulated survey results. Both of these producers agreed that their own data correlates with that obtained from the aircraft companies regarding mechanical property variation. They also agreed that the solution to this problem is their responsibility.

The producers are attacking the problem of mechanical property variation from all possible angles. The various influencing factors that are being studied at Rem-Cru are as follows:

1. Characterization and blending of sponge and remelt material. Sponge is not uniform as received from the supplier and varies between

130 to 200 BHN. It is purchased according to specifications but these must necessarily allow for variations because of the inhomogeneity resulting from the batch type sponge-making process. Sponge is bought in lots which are made of blended batches. When these lots are received from the supplier, they are checked by melting an experimental ingot for each lot. This ingot is rolled into sheet and the mechanical properties are determined. The sponge lots are then blended so as to eliminate the extremes and yield properties which are as nearly reproducible as possible.

2. Improved melting facilities. This company has been continuously developing three major types of titanium melting furnaces since 1948:

a. Carbon electrode

b. Consumable electrode

c. Skull

It is felt that no one furnace type is the cure-all for titanium ills. Each has its own field.

Carbon Electrode has been perfected to a point where, particularly for unalloyed titanium and alloys especially adapted to it (like A-110AT and those containing low-melting alloying elements like aluminum and manganese), it offers the best combination of quality and low cost. It also is well adapted to using finely-divided remelt material. Two-ton carbon electrode ingots are being melted as regular production.

Consumable Electrode is useful where carbon must be kept below the 0.05-0.10% typical of current carbon electrode melting practice. Alpha alloys are improved by carbon up to about 0.25% but alpha-beta alloys should contain no more than about 0.20% and beta alloys should have less than 0.05%. The consumable process can also advantageously handle medium-sized pieces of remelt stock. Consumable ingots 19 inches in diameter are being melted in pilot production lots.

Skull melting is admirably adapted to melting all sizes of remelt material, including quite massive pieces; it also is the only method capable of making cast shapes. A 1,000-pound skull furnace, 40 times larger than any known to be in operation is currently under construction.

3. Double melting is useful to salvage reject ingots having unusual porosity or off chemistry and to get refractory alloying

elements like Mo into solution. However, the material is thereby subjected to double contamination and the melting cost is increased. Rem-Cru is double melting 19-inch consumable ingots in special pilot production cases.

4. Improved Processing. Shorter times at temperature; lower processing temperatures; reduced H exposure and pickup; etc.

5. Means of controlling preferred orientation in titanium sheet products. It is known that this variable is responsible for the anisotropy displayed by some titanium products. It is also believed to be related to the spread between the yield and tensile strengths. Chemistry has a great effect on orientation as twinning, which is found to be profuse in pure titanium, is absent in the commercially pure and alloy grades. The relationship of the amount and distribution of the two phases in the alpha-beta alloys is also important. Process control variables, especially in the rolling schedules, have a definite effect.

6. Development of modified and new alloy grades having inherently less tendency toward property variation and improved properties.

The low fatigue properties that were encountered in the testing of titanium forgings by the air frame manufacturers are not in accord with fatigue data obtained by Rem-Cru. However, it was pointed out that the data were obtained on polished fatigue specimens, whereas the forgings were tested in a relatively rough machined or in some cases an unmachined condition. The success of the great number of forgings tested by engine manufacturers may be attributed to the following factors:

1. Better forging practice with regard to forging temperatures, reheatings, and amount of deformation.
2. Complete removal of subscale.
3. Operation temperatures above the brittle transition temperature which is around 200°F for titanium that is low in interstitials.

Stress relief treatments have been recommended based upon securing adequate stress relief without serious surface damage. From this point on they feel that the stress relief practice to be used for any particular application is the responsibility of the fabricator since warpage and related considerations make each case an individual problem.

Rem-Cru expects a general improvement in quality to take place gradually over the next year or two. This will be the result of better melting methods, processing control and knowledge of the fundamental properties of titanium and its alloys. They emphasize that advancement of titanium technology is entirely dependent upon the continuation of over-all support by the government and/or industry. Problems must be worked out at the production level if the answers are to be in terms of production results. New equipment must be designed especially for titanium production in order to obtain the most economical results. The stainless steel hand mills that are being used for titanium at present are fast becoming outmoded.

Titanium Metals Corp. has also taken steps to solve the problem of mechanical property variation in both alloyed and unalloyed titanium. Control information on all the heats now being made along with statistical analysis has been initiated and should provide pertinent knowledge on the factors involved in this problem. Metallurgical control has been established throughout the complete processing schedule by having individual plant metallurgists responsible for each step of the manufacturing procedure.

Recently they have started double melting a portion of their production ingots up to 3500 pounds. This step will reduce the possibilities of unmelted sponge and other causes for nonuniformity. The double melting procedure has not been in effect long enough to provide full information on the variation that will be experienced as a result of double melting nor has the double melted material been evaluated by the aircraft companies to date. Additional capacity is being installed but whether or not all production will be double melted will depend upon customer demands and economic factors.

Oxygen is the main element to be considered in the causes of property variation. It is felt that unalloyed titanium containing oxygen is not the right material for a 70,000 psi minimum yield composition. At present to reach a 70,000 psi minimum yield, titanium sponge of 195-210 Brinell has to be used. They are shortly coming out with an 80,000 psi minimum yield low alloy titanium composition with good forming properties. This alloy will have a standard controlled oxygen content. They also intend to reduce oxygen in the unalloyed grade so that the yield strength will be approximately 50,000. At this oxygen level the material forms quite satisfactorily. To do this, titanium sponge of 170 Brinell or an oxygen content of 0.1% has to be used. It should be noted that even if all of the sponge used was uniformly of a given Brinell there would be a spread in properties due to rolling and other processing variables.

Last year's melting record showed that for unalloyed titanium using the single melting technique, only 2% of the heats made fell below 70,000 psi yield strength and 6% of the heats fell above the 110,000 ultimate strength. This spread of properties shown by the record agrees with the field results reported in the survey. With any given hardness of sponge, a portion of the heats evaluated fell below 70,000 psi yield strength and a portion fell above 110,000 ultimate strength.

It was pointed out, however, that if formability was sufficient, the aircraft companies could probably work with only a minimum strength requirement and the need of a smaller spread in properties to meet both strength and fabrication requirements would most practically be taken care of in this manner rather than by narrowing of the property range. It was pointed out that the range of 70,000 psi minimum yield strength and 110,000 psi maximum ultimate strength is very restrictive and narrower than those used for even such alloys as stainless steel.

The problem of spread between the yield and ultimate strengths is being attacked from two main angles, that of composition and that of processing. Titanium Metals Corp. personnel felt that at present their data were insufficient to make any comments as they are only now beginning to get a good picture of the variations brought about by rolling and heat treating practice on commercial ingots.

No specific program is being conducted on the evaluation of titanium forgings, as such. However, they take full responsibility for any forging failures or defects attributable to metal quality and investigate and carry out metallurgical examination on all such instances brought to their attention. They did find in one instance that their Ti-150 alloy gave a better production yield when it was supplied with a lower oxygen content. This resulted in improved ductility.

In the case of titanium bolts, a cooperative program has been initiated with bolt manufacturers and two air frame producers. It is felt that this problem involves suiting the alloy composition to the severe type of forming operation used by bolt manufacturers and will require further development of both alloys and manufacturing processes.

No studies are being conducted on the third problem involved in the titanium usage survey which is stress relieving. With the exception of the general recommendations contained in their handbook on titanium, the stress relieving procedure is left up to the consumer. Their recommendation is 700 to 1050°F for 30 minutes for titanium alloys.

## TABLE II

## CONTACTED COMPANIES

| Company | Date of Visit |
|---|---|
| Carborundum Co., Niagara Falls, N.Y. | 3-17-53 |
| Watertown Arsenal, Watertown, Mass. | 3-24-53 |
| Wyman-Gordon Co., Worcester, Mass. | 3-25-53<br>7-14-53 |
| Titanium Metals Corp. of America, N.Y., N.Y. | 3-26-53 |
| Navy Department, Washington, D.C. | 4-14-53 |
| Mallory-Sharon Titanium Corp., Niles, Ohio | 4-21-53 |
| Rem-Cru Titanium Inc., Midland, Pa. | 4-22-53 |
| Republic Steel Corp., Massillon, Ohio | 4-23-53 |
| American Welding & Mfg. Co., Warren, Ohio | 4-23-53 |
| General Electric Co., Evandale, Ohio | 4-28-53 |
| North American Aviation, Inc., Columbus, Ohio | 4-29-53 |
| General Electric Co., Lynn, Mass. | 5-12-53 |
| Pratt & Whitney Aircraft Division, East Hartford, Conn. | 5-13-53 |
| Bell Aircraft Corp., Niagara Falls, N.Y. | 6-5-53 |
| Wright Aeronautical Div., Curtiss-Wright Corp., Wood-Ridge, N.J. | 6-9-53 |
| Westinghouse Electric Corp., Philadelphia, Pa. | 6-10-53 |
| Allison Div., General Motors Corp., Indianapolis, Ind. | 6-22-53 |
| McDonnell Aircraft Corp., St.Louis, Mo. | 6-24-53 |
| Bell Aircraft Corp., Fort Worth, Texas | 6-26-53 |
| Chance-Vought Aircraft Div., United Aircraft Corp., Dallas, Texas | 6-29-53 |

TABLE II (Contd.)

| Company | Date of Visit |
|---|---|
| Convair, Fort Worth, Texas | 6-30-53 |
| Rohr Aircraft Corp., Chula Vista, Calif. | 7-7-53 |
| Ryan Aeronautical Co., San Diego, Calif. | 7-10-53 |
| Solar Aircraft Co., San Diego, Calif. | 7-9-53 |
| Convair, San Diego, Calif. | 7-10-53 |
| North American Aviation, Inc., Inglewood, Calif. | 7-14-53 |
| Worcester Pressed Steel Co. Worcester, Mass. | 7-15-53 |
| North American Aviation, Inc., Downey, Calif. | 7-15-53 |
| Utica Drop Forge and Tool Corp., Utica, N. Y. | 7-16-53 |
| Northrop Aircraft, Inc., Hawthorne, Calif. | 7-16-53 |
| Lockheed Aircraft Corp., Burbank, Calif. | 7-20-53 |
| Aerojet Engineering Corp., Azusa, Calif. | 7-22-53 |
| Douglas Aircraft Co., Santa Monica, Calif. | 7-23-53 |
| Boeing Airplane Co., Seattle, Wash. | 7-29-53 |

EXHIBIT A

## UNIFORMITY OF COMMERCIALLY PURE TITANIUM SHEET

## TITANIUM METALS - COMMERCIALLY PURE TITANIUM SHEET

| Number of Sheets | Heat No. | Gage In. | UTS KSI | TYS KSI | EL % 2 In. | Remarks |
|---|---|---|---|---|---|---|
| 4 | L90 | .025 | 104 | 89-92 | 20-24 | 3 |
| 1 | L89 | .062 | 101 | 86 | 28 | - |
| 1 | L93 | .062 | 94 | 79 | 25 | - |
| 2 | L84 | .025 | 98-107 | 81-89 | 20-24 | 3 |
| 1 | L107 | .025 | 102 | 84 | 22 | - |
| 1 | L108 | .025 | 91-93 | 73-83.5 | 20-22 | 2 |
| 1 | L108 | .025 | 90-95 | 73-77 | 20-24 | 2 |
| 1 | L107 | .025 | 91-94 | 73-78 | 24-24 | 2 |
| 7 | L111-L118 | .042 | 84-102 | 69-89 | 25-25 | 3 |
| 1 | L121 | .042 | 81-95 | 68-80 | 21-26 | 2 |
| 1 | L116 | .042 | 95 | 80 | 25 | - |
| 1 | L117 | .042 | 77 | 64 | 28 | - |
| 1 | L125 | .042 | 99-105 | 85-94 | 25-27 | 2 |
| 6 | L124 | .042 | 80-107 | 64-93 | 20-23 | 3 |
| 3 | L145 | .062 | 84-106 | 69-89 | 21-25 | 3 |
| 17 | L142-L203 | .042 | 76-109 | 60-95 | 19-27 | 3 |
| 1 | L34 | .035 | 115 | 112 | 14 | - |
| 8 | L161-L237 | .062 | 76-91 | 54-77 | 21-25 | 3 |
| 1 | 3021A4 | .016 | 106 | 78 | 17 | - |
| 6 | L242-L257 | .025 | 86-91 | 69-74 | 19-27 | 3 |
| 6 | L220-L255 | .062 | 76-94 | 60-78 | 20-25 | 3 |
| 4 | L281-L307 | .062 | 78-85 | 66-72 | 22-24 | 3 |
| 4 | L287-L288 | .040 | 80-91 | 69-81 | 21-24 | 3 |
| 16 | L241-L373 | .025 | 81-103 | 64-86 | 18-24 | 3 |

2 Range resulting from several tests on one sheet.

3 Range resulting from one test on each sheet.

These tests were conducted on standard 0.5 inch gage width sheet specimens at a loading rate of 300 lbs/min. on an Olsen Tensile Machine. The tests covered a period from 1950 to, and not including, 1952.

EXHIBIT A (Contd.)

## ENCLOSURE A

## UNIFORMITY OF COMMERCIALLY PURE TITANIUM SHEET

### Rem-Cru Commercially Pure Titanium Sheet

| Number of Sheets | Heat No. | Gage In. | UTS KSI | TYS KSI | EL % 2 In. | Remarks |
|---|---|---|---|---|---|---|
| 30 | - | .025 | 89-103 | - | - | 1 |
| 6 | - | .025 | 84-97 | - | - | 1 |
| 2 | - | .025 | 76-98 | - | - | 1 |
| 6 | - | .030 | 97-124 | - | - | 1 |
| 4 | 879 | .035 | 88-89 | 66-69 | 24-30 | 2 |
| 1 | 887 | .030 | 94 | 75 | 23 | - |
| 1 | 948 | .042 | 91 | 77 | 24 | - |
| 1 | 959 | .030 | 100-107 | 88-98 | 18-23 | 3 |
| 4 | 942-7 | .025 | 90 | 82 | 25 | 2 |
| 1 | 971 | .016 | 92-99 | 80-89 | 19-25 | 3 |
| 1 | 975 | .035 | 103 | 96 | 23 | - |
| 1 | 931 | .025 | 89 | 82 | 23 | - |
| 1 | 939 | .025 | 84 | 74 | 26 | - |
| 1 | 987 | .025 | 94 | 84 | 24 | - |
| 11 | 978-86 | .016 | 94-103 | 81-94 | 23-25 | 4 |
| 1 | 2023 | .050 | 106 | 92 |  | - |
| 1 | 2044 | .025 | 104 | 91 | 21 | - |
| 1 | 2044A | .025 | 108 | 92 | 23 | - |
| 1 | 979 | .016 | 99 | 85 | 21 | - |
| 3 | 976 | .016 | 99 | 91 | 22 | 2 |
| 1 | 2102-B3 | .025 | 93 | 87 | 25 | - |
| 1 | 3015-A4 | .020 | 90 | 83 | 25 | - |
| 4 | 21864-62 | .016 | 94-107 | 83-99 | 18-25 | 4 |

1 Converted from hardness tests.

2 Tested one sheet only.

3 Range resulting from several tests on one sheet.

4 Range resulting from one test on each sheet.

EXHIBIT A (Contd.)

TITANIUM METALS - COMMERCIALLY PURE TITANIUM SHEET

| Number of Sheet | Heat No. [4] | Gage In. | UTS KSI | TYS KSI | EL % 2 In. | Remarks |
|---|---|---|---|---|---|---|
| 2 | - | .062 | 114-116 | 92-95 | 9-10 | 3 |
| 2 | x555 | .050 | 80 | 62 | 23 | 1 |
| 1 | x548 | .050 | 95-100 | 73-75 | 19-20 | 2 |
| 1 | x593 | .050 | 72-81 | 64-65 | 14-16 | 2 |
| 2 | x599 | .025 | 82 | 62 | 19 | 1 |
| 2 | x619 | .020 | 72 | 56 | 23 | 1 |
| 2 | x592 | .025 | 90-99 | 73-78 | 17-19 | 3 |
| 2 | x622 | .016 | 73 | 51 | 27 | 1 |
| 2 | x590 | .020 | 78 | 58 | 22 | 1 |
| 2 | x620 | .030 | 83 | 64 | 22 | 1 |
| 2 | x651 | .025 | 77-83 | 62-64 | 22 | 3 |
| 1 | x667 | .042 | 81 | 72 | 22 | - |
| 1 | x909 | .035 | 92 | 76 | 22 | - |
| 6 | x909 | .025 | 65 | 50 | 23 | 1 |
| 1 | x696 | .062 | 81 | 63-72 | 21 | - |
| 1 | x667 | .025 | 76-78 | 59-67 | 23 | 2 |
| 1 | x667 | .025 | 89 | 62-70 | 22 | - |
| 1 | x651 | .035 | 76-78 | 58-68 | 22 | 2 |
| 1 | x905 | .025 | 67 | 53 | 25 | - |
| 12 | L12-L40 | .025 | 74-95 | 56-75 | 21-25 | 3 |
| 1 | L 12 | .025 | 78-85 | 60-66 | 22-25 | 2 |
| 1 | L 31 | .030 | 81 | 65 | 25 | - |
| 6 | L57-L100 | .035 | 77-108 | 61-94 | 18-23 | 3 |
| 1 | L 79 | .042 | 98 | 79 | 23 | - |
| 1 | L 70 | .042 | 107 | 85 | 22 | - |
| 1 | L 95 | .062 | 99 | 84 | 25 | - |
| 1 | L 44 | .025 | 95-103 | 74-82 | 17-23 | 2 |
| 1 | L 90 | .025 | 117 | 99 | 22 | - |

1 Tested one sheet only

2 Range resulting from several tests on one sheet

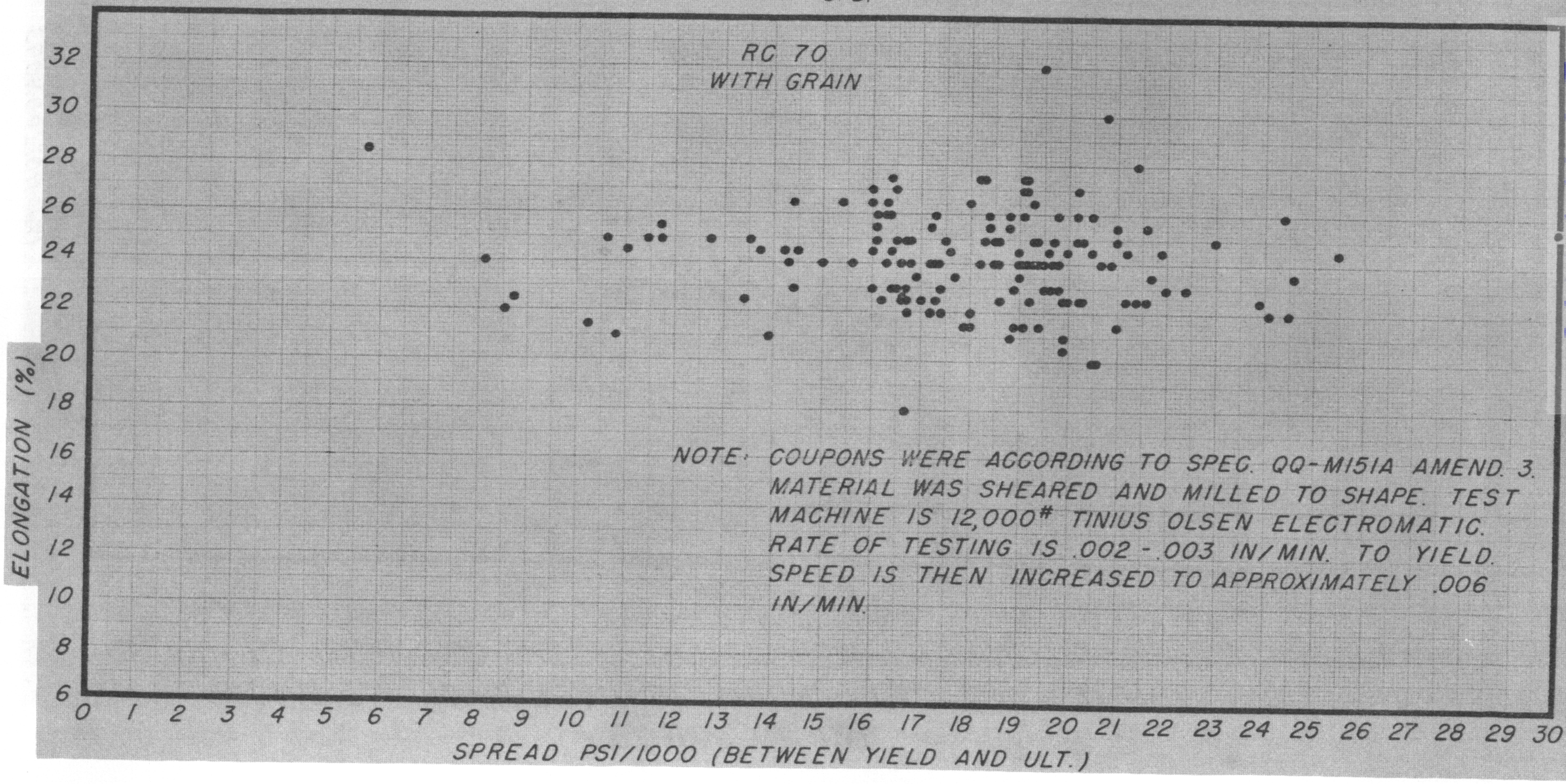
3 Range resulting from one test on each sheet

4 "X" heats are considered experimental heats. "L" heats are considered production heats

## EXHIBIT B (I)

## VARIATION IN SPREAD BETWEEN YIELD AND ULTIMATE STRENGTH OF RC-70 TITANIUM SHEET TESTED PARALLEL TO ROLLING DIRECTION

PREPARED IN JULY 1953
CONVAIR - S D.

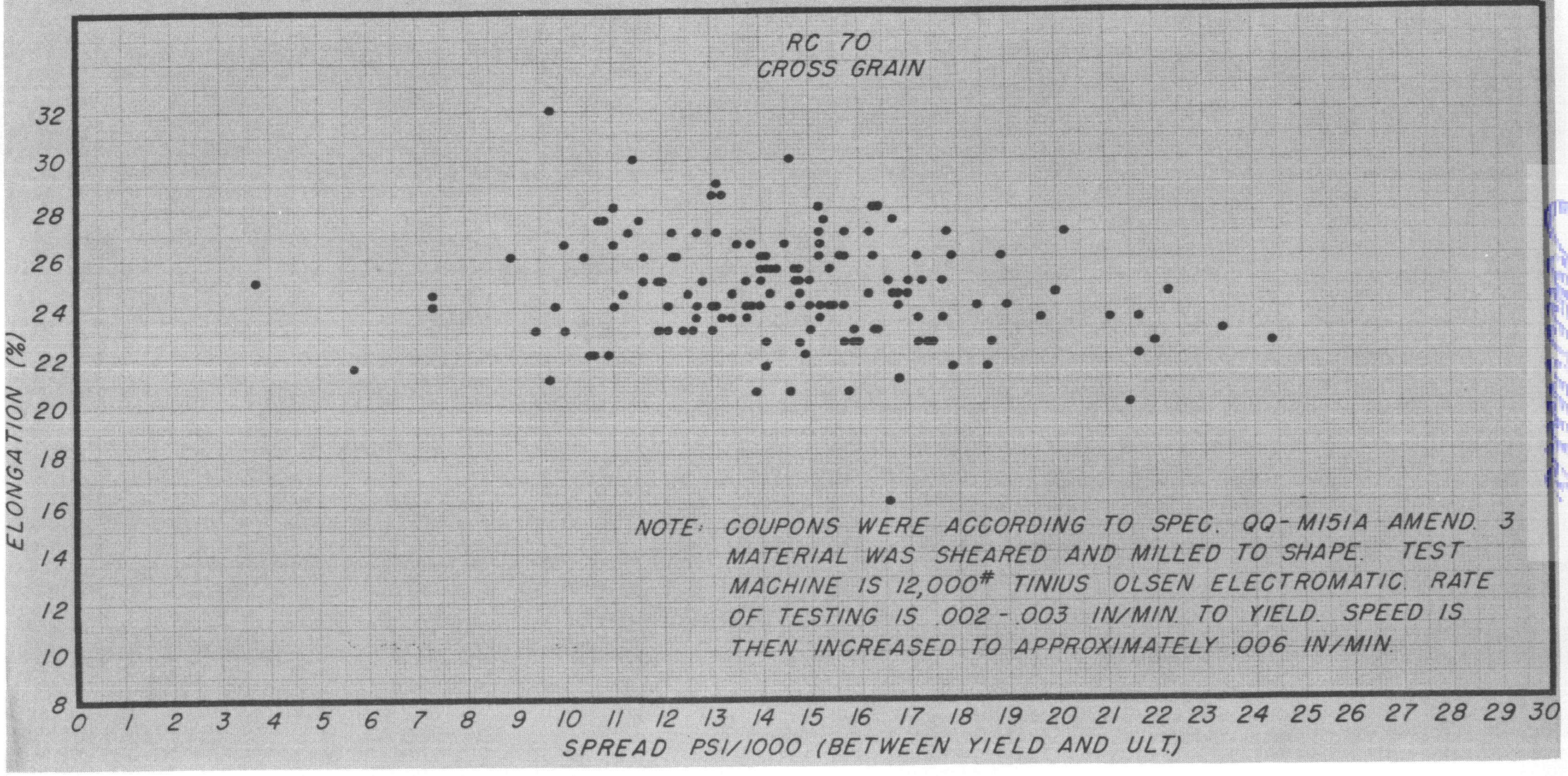


NOTE: COUPONS WERE ACCORDING TO SPEC. QQ-M151A AMEND. 3. MATERIAL WAS SHEARED AND MILLED TO SHAPE. TEST MACHINE IS 12,000# TINIUS OLSEN ELECTROMATIC. RATE OF TESTING IS .002 - .003 IN/MIN. TO YIELD. SPEED IS THEN INCREASED TO APPROXIMATELY .006 IN/MIN.

EXHIBIT B (2)

## VARIATION IN SPREAD BETWEEN YIELD AND ULTIMATE STRENGTH OF RC-70 TITANIUM SHEET TESTED PERPENDICULAR TO ROLLING DIRECTION

PREPARED IN JULY 1953
CONVAIRE - S. D.

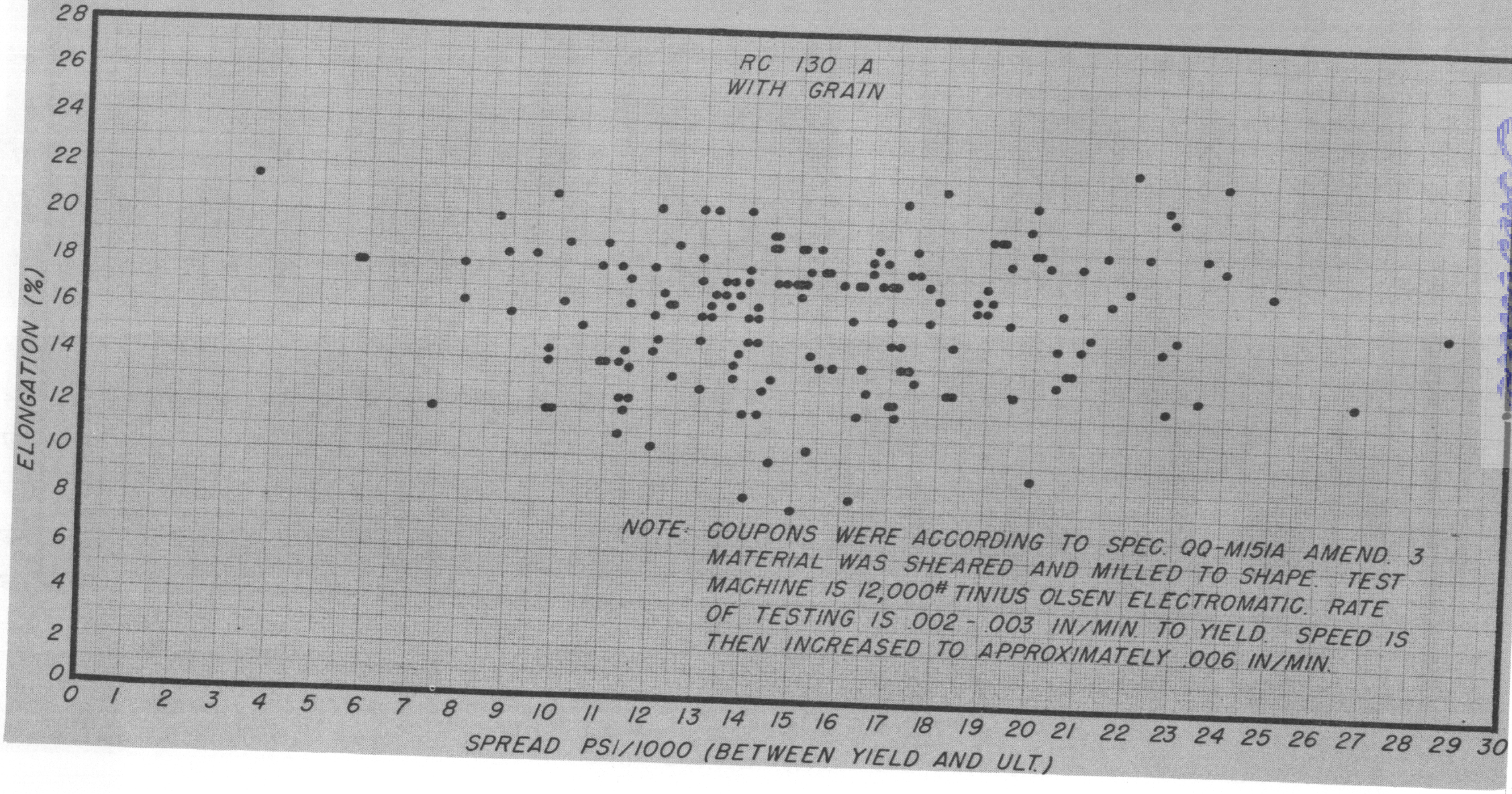


NOTE: COUPONS WERE ACCORDING TO SPEC. QQ-M151A AMEND. 3 MATERIAL WAS SHEARED AND MILLED TO SHAPE. TEST MACHINE IS 12,000# TINIUS OLSEN ELECTROMATIC. RATE OF TESTING IS .002 - .003 IN/MIN. TO YIELD. SPEED IS THEN INCREASED TO APPROXIMATELY .006 IN/MIN.

# EXHIBIT B (3)

# VARIATION IN SPREAD BETWEEN YIELD AND ULTIMATE STRENGTH OF RC-130A TITANIUM SHEET TESTED PARALLEL TO ROLLING DIRECTION

PREPARED AND TESTED JULY 1953
CONVAIR - S. D.

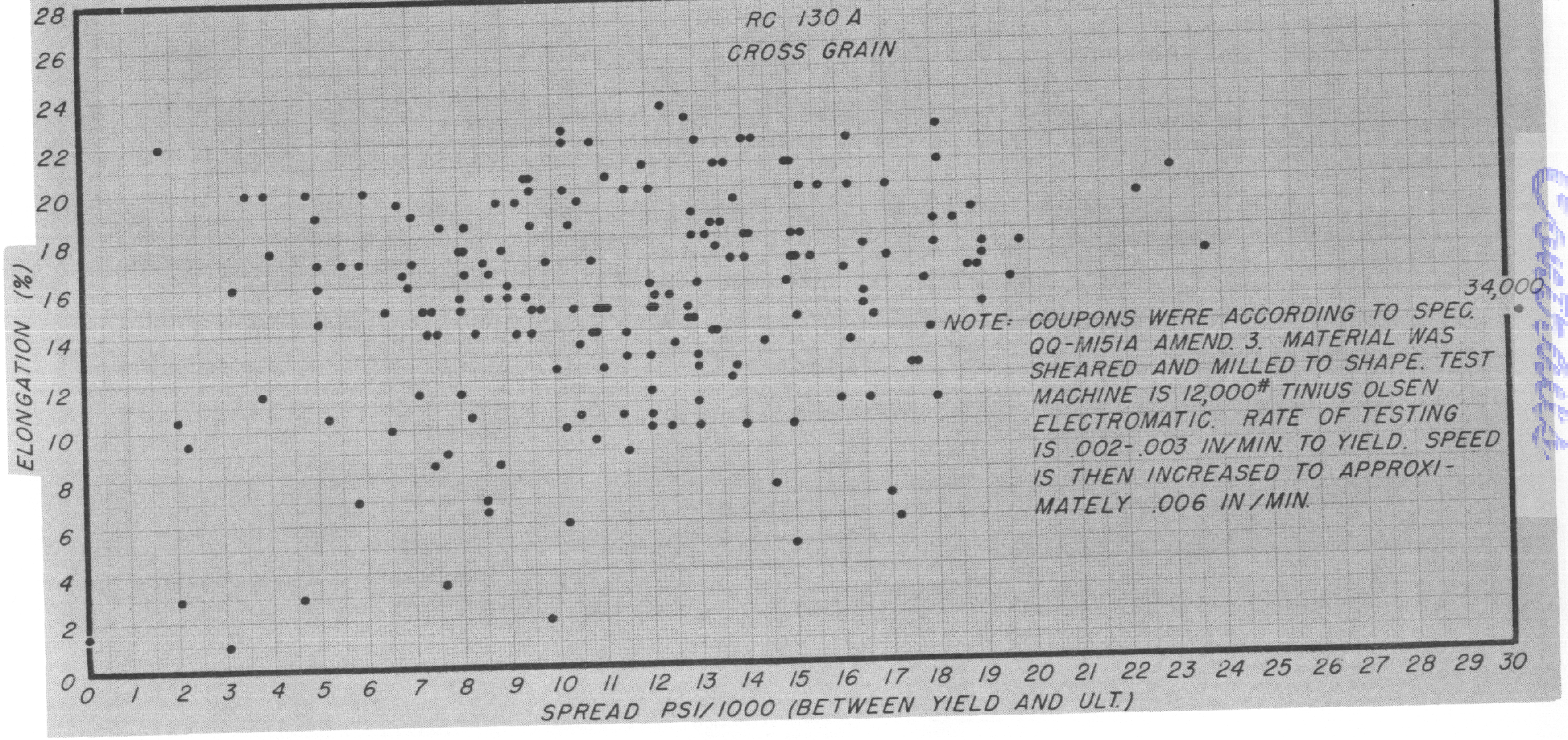


NOTE: COUPONS WERE ACCORDING TO SPEC. QQ-M151A AMEND. 3 MATERIAL WAS SHEARED AND MILLED TO SHAPE. TEST MACHINE IS 12,000# TINIUS OLSEN ELECTROMATIC. RATE OF TESTING IS .002 - .003 IN/MIN. TO YIELD. SPEED IS THEN INCREASED TO APPROXIMATELY .006 IN/MIN.

## EXHIBIT B (4)

## VARIATION IN SPREAD BETWEEN YIELD AND ULTIMATE STRENGTHS OF RC-130A TITANIUM SHEET TESTED PERPENDICULAR TO ROLLING DIRECTION

PREPARED IN JULY 1953
CONVAIR - S. D.



NOTE: COUPONS WERE ACCORDING TO SPEC. QQ-M151A AMEND. 3. MATERIAL WAS SHEARED AND MILLED TO SHAPE. TEST MACHINE IS 12,000# TINIUS OLSEN ELECTROMATIC. RATE OF TESTING IS .002-.003 IN/MIN. TO YIELD. SPEED IS THEN INCREASED TO APPROXIMATELY .006 IN/MIN.

## EXHIBIT C

## SUMMARY OF LABORATORY STANDARD TENSILE TESTS ON COMMERCIALLY PURE TITANIUM

| Date | Lab. No. | Vendor | Heat No. | | Fty KSI | Ftu KSI |
|---|---|---|---|---|---|---|
| 9-16-53 | 23127 | Republic | R2A-255 | min. | 59.1 | 80.6 |
| | | | | max. | 80.8 | 107.9 |
| | | | R2A-251 | min. | 67.6 | 91.5 |
| | | | | max. | 84.7 | 105.9 |
| 9-24-53 | 23219 | Titanium Metals Corp. | M-567 | min. | 81.7 | 101.1 |
| | | | | max. | 91.5 | 110.1 |
| | | | M-576 | min. | 76.8 | 95.9 |
| | | | | max. | 87.6 | 106.5 |
| | | | M-710 | min. | 77.6 | 94.8 |
| | | | | max | 99.4 | 117.5 |
| 9-25-53 | 23224 | Republic | R1A-552 | min. | 70.1 | 89.9 |
| | | | | max. | 90.5 | 107.1 |
| 11-16-53 | 23679 | Rem-Cru | -- | min. | 81.5 | 101.5 |
| | | | | max. | 91.5 | 107.5 |

EXHIBIT D

## LIST OF TITANIUM SHIPMENTS AND PROPERTIES AS RECEIVED BY MCDONNELL AIRCRAFT CORP.

## TITANIUM PROPERTIES

### LOT NO.1

Producer - Titanium Metals Corp.
Grade - MMS-101 Type A - Ti-75A
Gage - .017"
Date Rec. - 9-21-53

| Ultimate Stress | Yield Stress | Yield/Ten. Ratio | Elong. %. |
|---|---|---|---|
| 109,647 | 93,882 | .86 | 20 |
| 106,823 | 87,882 | .83 | 22 |
| 115,529 | 96,470 | .84 | 19 |
| 106,824 | 99,764 | .93 | 23 |

### LOT NO.2

Producer - Mallory-Sharon Titanium Corp.
Grade - MMS-101 Type A - MST Grade III
Gage - .017"
Date Rec. - 9-23-53

| | | | |
|---|---|---|---|
| 110,500 | 94,000 | .85 | 19 |
| 100,500 | 85,000 | .85 | 23 |
| 92,500 | 79,000 | .85 | 21 |
| 121,000 | 104,000 | .86 | 18 |
| 98,500 | 84,000 | .85 | 23 |
| 103,500 | 87,500 | .85 | 23 |

### LOT NO.3

Producer - Titanium Metals Corp.
Grade - MMS-101 Type A - Ti-75A
Gage - .017"
Date Rec. - 10-2-53

| | | | |
|---|---|---|---|
| 102,000 | 82,000 | .80 | 19 |
| 96,000 | 76,000 | .79 | 19 |
| 93,500 | 71,500 | .76 | 20 |
| 99,000 | 78,500 | .79 | 21 |
| 93,000 | 75,500 | .81 | 20 |
| 93,000 | 72,000 | .77 | 21 |
| 97,000 | 77,000 | .79 | 20 |
| 94,500 | 74,000 | .78 | 23 |
| 98,500 | 80,000 | .81 | 21 |

## EXHIBIT D (Contd.)

### LOT NO.4

Producer - Mallory-Sharon Titanium Corp.
Grade - MMS-101 Type A - MST Grade III
Gage - .017"
Date Rec. - 9-23-53

| Ultimate Stress | Yield Stress | Yield/Ten. Ratio | Elong. % |
|---|---|---|---|
| 105,000 | 98,000 | .93 | 16 |
| 107,000 | 99,500 | .93 | 17 |
| 103,500 | 96,000 | .93 | 16 |
| 105,000 | 84,000 | .80 | 18 |
| 100,000 | 80,000 | .80 | 21 |
| 83,000 | 64,500 | .78 | 24 |
| 113,000 | 95,000 | .84 | 17 |
| 100,500 | 77,500 | .77 | 20 |
| 100,000 | 79,000 | .79 | 20 |
| 95,500 | 74,000 | .77 | 22 |
| 95,000 | 73,000 | .77 | 19 |
| 83,500 | 61,500 | .74 | 19 |
| 84,000 | 61,000 | .73 | 20 |

### LOT NO. 5

Producer - Titanium Metals Corp.
Grade - MMS-101 Type A - Ti-75A
Gage - .017"
Date Rec. - 9-23-53

| | | | |
|---|---|---|---|
| 100,000 | 84,000 | .84 | 21 |
| 101,500 | 85,000 | .84 | 20 |
| 102,500 | 83,000 | .81 | 24 |
| 102,500 | 85,000 | .83 | 20 |
| 97,500 | 79,000 | .81 | 20 |
| 102,000 | 87.500 | .86 | 22 |
| 98,000 | 78,500 | .80 | 23 |
| 101,000 | 83,000 | .82 | 19 |
| 101,500 | 83,500 | .82 | 19 |
| 99,000 | 82,000 | .83 | 21 |
| 99,500 | 83,500 | .84 | 20 |
| 95,500 | 78,500 | .82 | 35 |
| 100,500 | 83,000 | .83 | 20 |
| 103,000 | 85,000 | .83 | 20 |
| 96,500 | 80,000 | .83 | 20 |
| 101,000 | 84,000 | .83 | 19 |
| 100,500 | 83,000 | .83 | 21 |

## EXHIBIT D (Contd.)

### LOT NO. 6

Producer - Republic Steel Corp.
Grade - MMS-101 Type A - RS-70
Gage - .032"
Date Rec. - 10-6-53

| Ultimate Stress | Yield Stress | Yield/Ten. Ratio | Elong. % |
|---|---|---|---|
| 103,500 | 96,500 | .93 | 24 |
| 105,500 | 100,000 | .95 | 24 |
| 107,500 | 100,500 | .93 | 23 |

### LOT NO. 7

Producer - Republic Steel Corp.
Grade - MMS-101 Type A - RS-70
Gage - .032"
Date Rec. - 9-16-53

| | | | |
|---|---|---|---|
| 92,000 | 82,000 | .89 | 25 |
| 93,500 | 83,500 | .89 | 24 |
| 92,500 | 82,000 | .89 | 23 |
| 96,500 | 86,000 | .89 | 24 |

### LOT NO. 8

Producer - Republic Steel Corp.
Grade - MMS-101 Type A - RS-70
Date Rec. - 8-17-53
Gage - .041"

| | | | |
|---|---|---|---|
| 96,500 | 85,500 | .89 | 26 |
| 90,500 | 78,500 | .87 | 26 |
| 91,500 | 76,000 | .84 | 27 |

### LOT NO. 9

Producer - Republic Steel Corp.
Grade - MMS-101 Type B - RS-120
Gage - .026"
Date Rec. - 8-28-53

| | | | |
|---|---|---|---|
| 144,000 | 132,000 | .92 | 15 |
| 142,000 | 133,000 | .94 | 18 |
| 151,000 | 139,500 | .92 | 17 |

## EXHIBIT D (Contd.)

### LOT NO. 10

Producer - Republic Steel Corp.
Grade - MMS-101 Type B - RS-120
Gage - .026"
Date Rec. - 8-28-53

| Ultimate Stress | Yield Stress | Yield/Ten. Ratio | Elong. % |
|---|---|---|---|
| 142,000 | 120,500 | .85 | 17 |
| 137,500 | 119,500 | .87 | 16 |
| 140,500 | 125,500 | .89 | 12 |

### LOT NO. 11

Producer - Republic Steel Corp.
Grade - MMS-101 Type B - RS-120
Gage - .026"
Date Rec. - 9-16-53

| | | | |
|---|---|---|---|
| 157,000 | 142,500 | .91 | 18 |
| 150,000 | 145,500 | .97 | 20 |
| 152,000 | 147,000 | .97 | 20 |

### LOT NO. 12

Producer - Rem-Cru Titanium, Inc.
Grade - MMS-101 Type B - RC-130-A
Gage - .042"
Date Rec. - 9-10-53

| | | | |
|---|---|---|---|
| 143,000 | 128,000 | .90 | 15 |
| 143,000 | 132,500 | .93 | 17 |
| 152,000 | 143,500 | .94 | 16 |
| 136,000 | 122,500 | .90 | 15 |
| 136,500 | 124,000 | .91 | 17 |
| 146,500 | 137,000 | .94 | 18 |
| 136,500 | 125,000 | .92 | 20 |

EXHIBIT E

## TEST REPORT DATA FROM PRODUCTION DEVELOPMENT LABORATORY, NORTH AMERICAN AVIATION, INC., COLUMBUS, OHIO

The following values were picked at random from tests on various lots of material. Each set of values represent one lot, heat, and gage tested on the date indicated.

| DATE | MATERIAL | GAGE | ULTIMATE STRENGTH P.S.I. | YIELD STRENGTH P.S.I. | ELONGATION % IN TWO INCHES |
|---|---|---|---|---|---|
| 5 Apr. 53 | RC-130-A | .025 | 150,000 | 124,000 | 14.0 |
| " | " | " | 157,000 | 153,000 | 14.2 |
| " | " | " | 154,000 | 146,000 | 14.2 |
| " | " | " | 146,000 | 136,000 | 11.2 |
| 6 Apr. 53 | RS-110 | .080 | 141,000 | 133,000 | 16.0 |
| " | " | .090 | 142,000 | 134,000 | 16.0 |
| " | " | .125 | 144,000 | 141,000 | 17.5 |
| 24 Apr. 53 | RC-130-A | .050 | 141,000 | 124,000 | 13.4 |
| " | RS-110 | .080 | 128,000 | 118,000 | 16.7 |
| 27 Apr. 53 | " | .080 | 138,000 | 128,000 | 16.7 |
| 28 Apr. 53 | " | .071 | 132,000 | 122,000 | 17.6 |
| 7 May 53 | RC-130-A | .125 | 149,000 | 144,000 | 15.5 |
| 18 May 53 | " | .187 | 137,000 | 124,000 | 17.5 |
| " | " | " | 144,000 | 129,000 | 19.7 |
| " | " | " | 143,000 | 131,000 | 20.0 |
| 19 May 53 | " | .050 | 148,000 | 134,000 | 14.6 |
| " | " | " | 140,000 | 123,000 | 14.6 |
| 22 May 53 | " | .040 | 149,000 | 145,000 | 14.0 |
| " | " | " | 147,000 | 145,000 | 13.0 |
| 22 Aug. 53 | " | " | 147,000 | 132,000 | 14.6 |
| " | " | .025 | 146,000 | 144,000 | 11.3 |
| 9 Sept. 53 | " | .032 | 150,000 | 141,000 | 17.5 |
| 1 Oct. 53 | " | .025 | 144,000 | 139,000 | 14.0 |
| 1 Oct. 53 | " | .125 | 143,000 | 132,000 | 16.8 |
| 7 Oct. 53 | " | .040 | 149,000 | 139,000 | 16.4 |
| " | " | .063 | 152,000 | 139,000 | 18.7 |
| 16 Oct. 53 | " | .025 | 140,000 | 128,000 | 14.0 |
| 19 Oct. 53 | " | .125 | 146,000 | 131,000 | 17.0 |
| " | " | " | 142,000 | 134,000 | 16.2 |
| " | " | .063 | 150,000 | 137,000 | 13.5 |
| " | " | .080 | 152,000 | 146,000 | 20.0 |

EXHIBIT F

# MECHANICAL PROPERTY VARIANCE IN UNALLOYED AND ALLOYED TITANIUM SHEET RECEIVED AT NORTH AMERICAN AVIATION, LOS ANGELES, CALIFORNIA

## Method of Tensile Testing:

A crosshead speed of 0.05 in/min is used until the 0.2% offset yield strength is reached. Then the speed is increased to 0.1 in/min and maintained until fracture.

NOTE: The crosshead speed of 0.05 in/min results in a time elapse of about 1.5 minutes to yield.

## Test Specimens:

Standard flat specimens with a two inch gage length, per Federal Specification QQ-M-151, Type 2 are used. Specimen edges are milled and deburred.

## Property Variation:

In testing incoming stock during the past six months, the following spread was observed between heats:

| | | |
|---|---|---|
| Unalloyed: | Tensile Yield Strength | 70,000-106,000 psi |
| | Tensile Ultimate Strength | 82,000-120,000 psi |
| Alloyed: | Tensile Yield Strength | 110,000-152,000 psi |
| | Tensile Ultimate Strength | 121,000-165,000 psi |

NOTE: The above data was obtained on as-received material from four producers in the case of the unalloyed sheet, and from two producers of the alloyed sheet.

EXHIBIT G

## Tests of Three Titanium Alloy Forgings

Three Ti-150A forgings of the form shown in Fig. 1 were produced by General Drop Forge Company for static and dynamic tests. Each forging was inspected by zyglo and X-ray with negative results throughout. For comparison with material of which the parts are now produced, three 4340 steel parts were also obtained for test.

The results of these tests are shown in Table I and Figure 1.

The results of tensile tests on specimens machined from the tension flange of one steel and one titanium alloy part (after static test), are summarized in Table II.

### TABLE I. SUMMARY OF RESULTS ON TEST PARTS

Static Tests

| Test Part No. | Ultimate Load | Remarks |
|---|---|---|
| 4340 #1 | 28,000 lbs. | Tear out failure of loading lug. |
| Ti-150 A #2-1 | 12,900 lbs. | Failure in tension flange at a large crack probably caused by grinding off flash. |
| Ti-150 A #2-2 | 21,000 lbs. | Tension failure of reaction lug |

Dynamic Tests

Load History for all parts: 3,220 lbs. ± 1,900 lbs. for 100,000 cycles followed by 6,500 lbs. ± 2,000 lbs. until failure at the number of cycles indicated below.

| Material | Approximate UTS | No. of Cycles |
|---|---|---|
| 4340 #2 | 176,000 p.s.i. | 616,000 |
| 4340 #3 | 150,000 p.s.i. | 478,000 |
| Ti-150 A #2-3 | 150,000 p.s.i. | 25,400 |

EXHIBIT G (CONTD.)

## STATIC AND DYNAMIC LOADS 4340 AND Ti-150 A PARTS

BOEING AIRPLANE COMPANY
SEATTLE 14, WASHINGTON

WEIGHT OF PART

| | |
|---|---|
| Ti-150 A | 3.76 lbs. |
| 4340 | 6.15 lbs. |

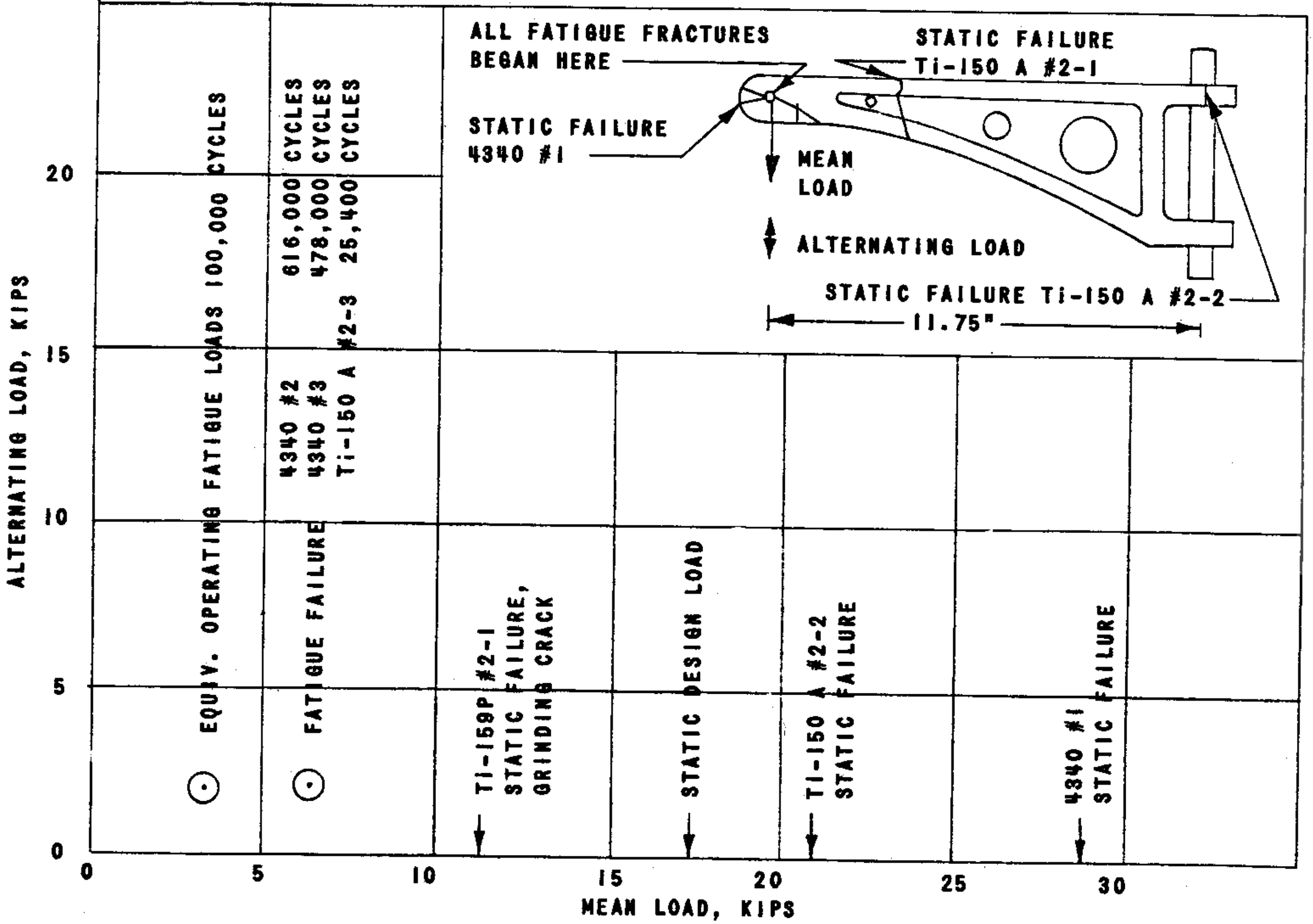


Fig. 1

EXHIBIT G (Contd.)

## TABLE II. TENSILE TESTS FROM PARTS AFTER STATIC TEST FAILURE

| 4340 #1 | Ultimate PSI | Yield PSI | % Elongation In One Inch | % R.A. |
|---|---|---|---|---|
| Avg. of 6 spec. | 167,100 | 148,000 | 10.5 | 50 |
| Ti-150 A #2-1 | | | | |
| Center of Flange | 150,600 | 143,250 | 12.5 | 35 |
| Relative grain size small<br>Avg. of 4 spec. | - | | | |
| Sides of Flange<br>Relative grain size large<br>Avg. of 4 spec. | 150,400 | 143,200 | 8.5 | 33 |

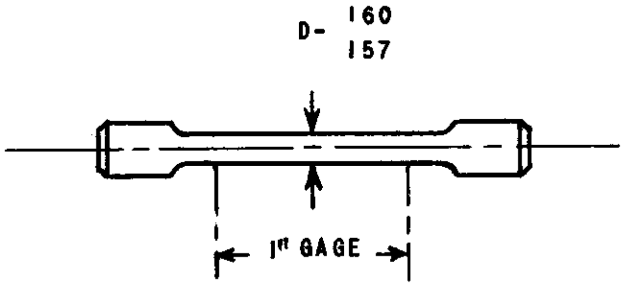


EXHIBIT H

## NON-HEAT TREATABLE TITANIUM, PROCESS INSTRUCTION FOR

**PURPOSE**

To provide a procedure for the process control of non-heat treatable pure titanium and alloyed titanium.

**ANNEALING**

Annealing may be used if necessary to remove strain hardening in stage forming.

1. Soak for 10 minutes at 1075 ± 25°F in slightly oxidizing temperature.
2. Reduce controller setting to 1000°F and hold part in furnace until temperature stabilizes at 1000°F.
3. Cool in air.

If for any reason the alloyed titanium has been heated above 1150°F and cooled rapidly, heat same to 1300°F for 10 minutes and reduce controls to 1000°F and hold part in furnace until temperature stabilizes at 1000°F. Parts are then removed and cooled in air.

NOTE: Alloyed titanium shows pronounced and drastic hardening effects if cooled quickly from above 1150°F and reheated to between 500 and 800°F.

**HOT FORMING**

Commercially pure titanium parts shall be preheated in a temperature controlled heating medium at 550 ± 50°F for a minimum of 10 minutes and forming tool temperature shall be maintained at 550 ± 50°F.

Alloyed titanium production parts may be hot formed in the temperature range of 800-1000°F provided the temperature is controlled as follows:

1. Pyrometric control of either the heating medium, heated tool, or heated part, or two tempilsticks, one melting at 800°F and one melting at 1000°F may also be used. Tempilstick (800°F) must melt but tempilstick (1000°F) must not melt, in order to control the heating in the range 800-1000°F.

The use of either a gas torch (oxy-acetylene, oxy-hydrogen, oxy-gas) or blast torch is dangerous often resulting in local overheating and brittleness unless the following precautions are observed:

1. Heating must be accomplished using a soft nonoxidizing flame.

2. Heating must comply with requirements above.

An open flame from a gas burner is less dangerous and should be used when the part can be formed or straightened at lower temperatures 500-600°F. If the nature of the part is such that it can be heated to 800-1000°F, using an open flame from a gas burner, it is advisable to do so.

**HOT DIMPLING**

Tools shall be at 550 ± 50°F; hold parts in contact until 500°F tempilac melts before forming the dimple. (Commercially pure and alloy titanium.)

1. The actual time-temperature will depend on the thickness and hardness of material; Process Control should be contacted if cracking is experienced.

EXHIBIT I

## RC-130-A TITANIUM ALLOY ANGLES FATIGUE LIFE

| SPEC NO. | GRAIN DIRECTION | ANNEAL F° | WIDTH IN. | GAGE IN. | ARM. IN. | MIN - MAX STRESS - PSI | FATIGUE LIFE CYCLES |
|---|---|---|---|---|---|---|---|
| 1P | PERP. | NONE | 1.995 | .0676 | 1.125 | 0 - 134,000 | 27,000 |
| 2P | PERP. TO BEND | NONE | 2.020 | .0681 | 1.125 | 0 - 100,000 | 74,000 |
| 3P | | | 2.017 | .0671 | 1.125 | | 52,000 |
| 4P | | | 2.000 | .0671 | 1.130 | | 41,000 |
| | | | | | | | AVE: 55,600 |
| 5P | PERP. | NONE | 2.023 | .0672 | 1.133 | 0 - 80,000 | 136,000 |
| 6P | | | 2.000 | .0674 | 1.132 | | 173,000 |
| 7P | | | 2.000 | .0677 | 1.132 | | 1,117,000 |
| | | | | | | | AVE: 475,000 |
| 8P | PERP. | NONE | 2.005 | .0646 | 1.132 | 0 - 60,000 | 501,000 |
| 9P | | | 2.008 | .0636 | 1.125 | | 5,003,000* |
| 10P | | | 2.003 | .0644 | 1.132 | | 332,000 |
| | | | | | | | AVE: ------- |
| 11P | PERP. | 1/4 HR. at 750°F | 1.998 | .0663 | 1.125 | 0 - 100,000 | 34,000 |
| 12P | | | 2.001 | .0668 | 1.125 | | 26,000 |
| 14P | | | 2.000 | .0655 | 1.335 | | 23,000 |
| | | | | | | | AVE: 27,700 |
| 15P | PERP. | 1 HR. at 750°F | 2.002 | .0660 | 1.129 | 0 - 100,000 | 24,000 |
| 16P | | | 2.000 | .0661 | 1.125 | | 22,000 |
| 17P | | | 2.022 | .0665 | 1.124 | | 26,000 |
| | | | | | | | AVE: 24,000 |
| 20P | PERP. | 1 HR. at 750°F | 2.028 | .0690 | 1.130 | 0 - 80,000 | 82,000 |
| 21P | | | 2.020 | .0692 | 1.129 | | 53,000 |
| 26P | | | 2.002 | .0670 | 1.128 | | 46,000 |
| | | | | | | | AVE: 60,000 |
| 27P | PERP. | 1 HR. at 750°F | 2.004 | .0672 | 1.129 | 0 - 60,000 | 214,000 |
| 28P | | | 2.001 | .0669 | 1.113 | | 195,000 |
| 29P | | | 2.000 | .0663 | 1.121 | | 288,000 |
| | | | | | | | AVE: 232,000 |
| 30P | PERP. | 1/4 HR at 930°F | 2.016 | .0655 | 1.114 | 0 - 100,000 | 31,000 |
| 32P | | | 2.029 | .0658 | 1.122 | | 51,000 |
| 33P | | | 2.025 | .0670 | 1.128 | | 34,000 |
| | | | | | | | AVE: 38,600 |

EXHIBIT I (CONT.)

| SPEC NO. | GRAIN DIRECTION | ANNEAL F° | WIDTH IN. | GAGE IN. | ARM. IN. | MIN - MAX STRESS - PSI | FATIGUE LIFE CYCLES |
|---|---|---|---|---|---|---|---|
| 34P | PERP. | 1 HR. | 2.022 | .0670 | 1.128 | 0 - 100,000 | 43,000 |
| 35P | | at 930°F | 2.020 | .0665 | 1.123 | | 37,000 |
| 36P | | | 2.025 | .0655 | 1.124 | | 20,000 |
| | | | | | | | AVE: 34,000 |
| 37P | PERP. | 1/4 HR. | 2.016 | .0650 | 1.125 | 0 - 100,000 | 44,000 |
| 38P | | at 1050°F | 2.020 | .0675 | 1.116 | | 27,000 |
| 39P | | | 2.025 | .0662 | 1.122 | | 22,000 |
| | | | | | | | AVE: 31,000 |
| 40P | PERP. | 1 HR. | 2.023 | .0658 | 1.125 | 0 - 100,000 | 19,000 |
| 41P | | at 1050°F | 2.027 | .0652 | 1.119 | | 21,000 |
| 42P | | | 2.027 | .0672 | 1.108 | | 39,000 |
| | | | | | | | AVE: 26,300 |
| 43P | PERP. | 1 HR. | 2.028 | .0648 | 1.114 | 0 - 80,000 | 86,000 |
| 44P | | at 1050°F | 2.010 | .0669 | 1.128 | | 43,000 |
| | | | | | | | AVE: 64,500 |
| 45P | PERP. | 1 HR. | 1.979 | .0624 | 1.148 | 0 - 100,000 | 62,000 |
| 46P | | at 1050°F | 1.992 | .0605 | 1.148 | | 64,000 |
| 47P | | & ETCHED | 2.007 | .0628 | 1.151 | | 69,000 |
| | | | | | | | AVE: 65,000 |
| 48P | PERP. | 1 HR.<br>at 1050°F | 2.010 | .0654 | 1.125 | 0 - 60,000 | 9,560,000* |

* No failure - test discontinued

NOTE: Specimens 1P - 44P were cold formed
45P - 48P were pressure formed

## EXHIBIT I (CONT.)
## RC-130-A TITANIUM ALLOY ANGLES
## FATIGUE LIFE

| SPEC. NO. | GRAIN DIRECTION | ANNEAL F° | WIDTH IN. | GAGE IN. | ARM IN. | MIN - MAX STRESS - PSI | FATIGUE LIFE CYCLES |
|---|---|---|---|---|---|---|---|
| 1C | PARALLEL TO BEND | NONE | 2.008 | .0671 | 1.125 | 0 - 100,000 | 16,000 |
| 2C | | | 2.000 | .0664 | 1.139 | | 75,000 |
| 3C | | | 2.000 | .0662 | 1.129 | | 36,000 |
| | | | | | | | AVE: 42,000 |
| 5C | PARALLEL | NONE | 1.997 | .0648 | 1.134 | 0 - 80,000 | 50,000 |
| 6C | | | 1.996 | .0672 | 1.140 | | 41,000 |
| 7C | | | 1.992 | .0662 | 1.103 | | 105,000 |
| | | | | | | | AVE: 65,000 |
| 8C | PARALLEL | NONE | 2.013 | .0660 | 1.125 | 0 - 60,000 | 5,140,000* |
| 9C | | | 2.017 | .0656 | 1.118 | | 6,129,000* |
| 10C | | | 1.994 | .0645 | 1.115 | | 466,000 |
| | NOTE: Specimens 1C - 10C were cold formed | | | | | | |
| 17C | PARALLEL | 1/4 HR. at 930° | 2.005 | .0570 | 1.109 | 0 - 100,000 | 18,000 |
| 20C | | | 2.006 | .0623 | 1.119 | | 12,000 |
| 21C | | | 2.008 | .0625 | 1.112 | | 11,000 |
| | | | | | | | AVE: 13,600 |
| 22C | PARALLEL | 1 HR. at 930° | 2.005 | .0604 | 1.107 | 0 - 100,000 | 12,000 |
| 24C | | | 2.003 | .0580 | 1.108 | | 12,000 |
| 26C | | | 2.007 | .0625 | 1.118 | | 10,000 |
| | | | | | | | AVE: 11,300 |
| 30C | PARALLEL | 1/4 HR. at 1050° | 2.007 | .0610 | 1.119 | 0 - 100,000 | 11,000 |
| 34C | | | 2.007 | .0625 | 1.118 | | 12,000 |
| 36C | | | 2.008 | .0618 | 1.116 | | 10,000 |
| | | | | | | | AVE: 11,000 |
| 37C | PARALLEL | 1 HR. at 1050° | 2.006 | .0625 | 1.116 | 0 - 100,000 | 11,000 |
| 38C | | | 2.004 | .0629 | 1.113 | | 13,000 |
| 39C | | | 2.008 | .0611 | 1.112 | | 12,000 |
| | | | | | | | AVE: 12,000 |
| 11C | PARALLEL | 1 HR. at 1050° & ETCHED | 2.002 | .0557 | 1.113 | 0 - 100,000 | 44,000 |
| 12C | | | 2.005 | .0536 | 1.110 | | 38,000 |
| 15C | | | 2.000 | .0525 | 1.103 | | 30,000 |
| | | | | | | | AVE: 37,300 |

## EXHIBIT I (CONT.)
## RC-130-A TITANIUM ALLOY ANGLES
## FATIGUE LIFE

| SPEC. NO. | GRAIN DIRECTION | ANNEAL F° | WIDTH IN. | GAGE IN. | ARM IN. | MIN - MAX STRESS - PSI | FATIGUE LIFE CYCLES |
|---|---|---|---|---|---|---|---|
| 41C | PARALLEL | 1 HR. | 2.008 | .0622 | 1.119 | 0 - 80,000 | 26,000 |
| 42C | | at 1050° | 2.010 | .0625 | 1.118 | | 26,000 |
| 43C | | | 2.005 | .0605 | 1.103 | | 34,000 |
| | | | | | | | AVE: 28,600 |

NOTE: Specimens 17C - 43C were pressure formed

EXHIBIT J

## EFFECT OF STRESS RELIEVING TEMPERATURE (1) ON THE DUCTILITY IN THE RADII OF A COLD FORMED HAT-SECTION OF RC-130A TITANIUM ALLOY SHEET

Length of section parallel to grain direction (2)

| Specimen No | Temperature °F | Ultimate Str., psi | Average of adj. spec. | increase in str., psi | Bend Angle, deg | Average of adj. spec. | increase in angle, deg | Hardness Rc |
|---|---|---|---|---|---|---|---|---|
| 1L | none | 15,200 | | | 17.5 | | | 35.9 |
| 2L | 500 | 17,000 | 16,800 | +200 | 21.0 | 20.2 | +0.8 | 35.7 |
| 3L | none | 18,500 | | | 23.0 | | | 35.8 |
| 4L | 600 | 20,200 | 21,800 | -1,600 | 24.5 | 28.0 | -3.5 | 35.6 |
| 5L | none | 25000 | | | 33.0 | | | 36.0 |
| 6L | 700 | 22,000 | 27,200 | -5,200 | 30.5 | 36.2 | -5.7 | 35.6 |
| 7L | none | 29,300 | | | 39.5 | | | 36.0 |
| 8L | 750 | 18,100 | 22,600 | -4,500 | 19.0 | 29.8 | -10.8 | 35.9 |
| 9L | none | 15,900 | | | 20.0 | | | 36.0 |
| 10L | 800 | 22,700 | 15,400 | +7,300 | 27.0 | 19.8 | +7.2 | 36.0 |
| 11L | none | 14,800 | | | 19.5 | | | 35.9 |
| 12L | 900 | 18,300 | 19,600 | -1,300 | 25.0 | 24.2 | +0.8 | 36.0 |
| 13L | none | 24,500 | | | 29.0 | | | 36.0 |
| 14L | 1000 | 19,700 | 20,000 | - 300 | 25.0 | 24.5 | +0.5 | 35.5 |
| 15L | none | 15,400 | | | 20.0 | | | 35.8 |
| 16L | 1100 | 16,800 | 17,500 | - 700 | 18.5 | 23.0 | - 4.5 | 35.8 |
| 17L | none | 19,600 | | | 26.0 | | | 35.5 |
| 18L | 1200 | 21,200 | 21,900 | - 700 | 26.0 | 25.5 | +0.5 | 35.6 |
| 19L | none | 24,200 | | | 25.0 | | | 36.1 |
| 20L | 1250 | 19,200 | 22,500 | -3,300 | 22.0 | 23.5 | -1.5 | 36.2 |
| 21L | none | 20,800 | | | 22.0 | | | 35.8 |
| 22L | 1300 (3) | 18,600 | 19,500 | - 900 | 26.0 | 23.0 | +3.0 | 33.7 |
| 23L | none | 18,200 | | | 24.0 | | | |

Length of section transverse to grain direction (2)

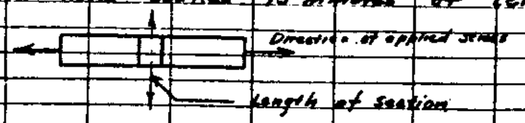
| Specimen No. | Temperature °F | Ultimate Str., psi | Average of Adj. spec. | increase in str., psi | Bend angle, deg | Average of Adj. spec. | increase in angle, deg |
|---|---|---|---|---|---|---|---|
| 1T | none | 47,500 | | | 60 | | |
| 2T | 500 | 137,000 | 93,800 | 44,200 | 90 | 75 | +15 |
| 3T | none | 137,000 | | | 90 | | |
| 4T | 600 | 144,000 | 139,500 | +4,500 | 90 | 90 | 0 |
| 5T | none | 142,000 | | | 90 | | |
| 6T | 700 | 148,000 | 143,000 | +5,000 | 90 | 90 | 0 |
| 7T | none | 144,000 | | | 90 | | |
| 8T | 750 | 145,000 | 144,500 | +500 | 90 | 90 | 0 |
| 9T | none | 145000 | | | 90 | | |
| 10T | 800 | 144,500 | 144,500 | 0 | 90 | 90 | 0 |
| 11T | none | 144,000 | | | 90 | | |
| 12T | 900 | 143,000 | 143,800 | -800 | 90 | 90 | 0 |
| 13T | none | 143,500 | | | 90 | | |
| 14T | 1000 | 142,000 | 143,800 | -1,800 | 90 | 90 | 0 |
| 15T | none | 144,000 | | | 90 | | |
| 16T | 1100 | 141,000 | 145,500 | -4,500 | 90 | 90 | 0 |
| 17T | none | 147,000 | | | 90 | | |
| 18T | 1200 | 143,000 | 143,500 | - 500 | 90 | 90 | 0 |
| 19T | none | 140,000 | | | 90 | | |
| 25T | none | 141,000 | | | 90 | | |
| 26T | 1250 | 143,000 | 140,800 | +2,200 | 90 | 90 | 0 |
| 27T | none | 140,500 | | | 90 | | |
| 28T | 1300 (3) | 134,500 | 140,800 | -6,300 | 90 | 90 | 0 |
| 29T | none | 141,000 | | | 90 | | |

### TABLE II-A EFFECT OF TEST TEMPERATURE ON THE DUCTILITY IN THE RADII OF A COLD FORMED HAT SECTION

| Test temp. °F | Specimen No | Temperature °F | Ultimate Str., psi | Average of adj. spec. | increase in str., psi | Bend Angle, deg | Average of adj. spec. | increase in angle, deg | Specimen No. | Temperature °F | Ultimate Str., psi | Bend angle, deg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RT | 25L | none | 8,400 | | | 2.0 | | | | | | |
| 750 | 26L | none | 53,000 | 12,000 | +41,000 | 67.5 | 8.0 | +59.5 | 30T | none | 94,000 | 90 |
| RT | 27L | none | 15,600 | | | 14.0 | | | | | | |
| 750 | 28L | none | 71,800 | 16,600 | +55,200 | 84.0 | 16.5 | +67.5 | 31T | none | 97,000 | 90 |
| RT | 29L | none | 17,600 | | | 19.0 | | | | | | |

(1) Specimens soaked 15 minutes at temperature and air cooled to room temperature

(2)



(3) Specimens soaked 15 minutes at 1300°F, cooled 50°F per hour to 1000°F and air cooled to room temperature

EXHIBIT K

## EFFECTS OF VARIOUS STRESS RELIEVING TIMES AND TEMPERATURES ON ALLOY TITANIUM SHEET

North American Aviation, Inc., Columbus, Ohio

The following are average values obtained from three to eight tests on individual heats of alloy material:

| | ELONGATION % IN 2 IN. | YIELD PSI | ULTIMATE PSI |
|---|---|---|---|
| Standard Specimen as Received Properties | 16.2 | 128,000 | 147,000 |

| TREATMENT | | | DEVIATION FROM STANDARD TEST SPECIMEN | | |
|---|---|---|---|---|---|
| Amount of Prestress % | Stress Relief Temp. °F | Time at Temp. (Min.) | Elongation % In 2 In. | Yield Strength PSI | Ultimate Strength PSI |
| 3 | 700 | 10 | -2.6 | +14,000 | + 2,000 |
| 3 | 700 | 60 | -2.2 | +15,000 | + 3,000 |
| 3 | 1000 | 10 | -0.2 | - 5,000 | - 1,000 |
| 5 | 700 | 60 | -2.7 | +16,000 | + 3,000 |
| 5 | 1000 | 10 | -0.2 | + 2,000 | + 1,000 |
| 10 | 700 | 60 | -3.7 | +22,000 | +10,000 |
| 10 | 1000 | 10 | -3.7 | + 6,000 | + 4,000 |
| 10 | 1000 | 20 | -0.6 | + 1,000 | + 3,000 |
| 10 | 1050 | 20 | -3.5 | + 1,000 | + 0 |
| 10 | 1100 | 20 | -6.8 | + 2,000 | + 0 |